Constraining the Late Pleistocene history of the Laurentide Ice Sheet by dating the Missinaibi Formation, Hudson Bay Lowlands, Canada

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Abstract

Well-dated paleorecords from periods prior to the Last Glacial Maximum (LGM) are important for validating models of ice-sheet build-up and growth. However, owing to glacial erosion, most Late Pleistocene records lie outside of the previously glaciated region, which limits their ability to inform about the dynamics of paleo-ice sheets. Here, we evaluate new and previously published chronology data from the Missinaibi Formation, a Pleistocene-aged deposit in the Hudson Bay Lowlands (HBL), Canada, located near the geographic center of the Laurentide Ice Sheet (LIS). Available radiocarbon (AMS = 44, conventional = 36), amino acid (n = 13), uranium-thorium (U-Th, n = 14), thermoluminescence (TL, n = 15) and optically stimulated luminescence (OSL, n = 5) data suggest that an ice-free HBL may have been possible during parts of Marine Isotope Stage 7 (MIS 7; ca. 243,000 to ca. 190,000 yr BP), MIS 5 (ca. 130,000 to ca. 71,000 yr BP) and MIS 3 (ca. 29,000 to ca. 57,000). While MIS 7 and MIS 5 are well-documented interglacial periods, the development of peat, forest bed and fluvial deposits dating to MIS 3 (n = 20 radiocarbon dates; 4 TL dates, 3 OSL dates), suggests that the LIS retreated and remained beyond, or somewhere within, the boundaries of the HBL during this interstadial. Ice sheet models approximate the margin of the LIS to Southern Ontario during this time, which is 700 km south of the HBL. Therefore, if correct, our data help constrain a significantly different configuration and dynamicity for the LIS than previously modelled. We can find no chronological basis to discount the MIS 3 age assignments. However, since most data originate from radiocarbon dates lying close to the reliable limit of this geochronometer, future work on dating the Missinaibi Formation using other geochronological methods (e.g. U-Th, OSL) is necessary in order to confirm the age estimates and strengthen the boundaries of the LIS during this period.

Keywords

MIS 3, MIS 5, interstadial, pre-LGM, mid-Wisconsin, land-based verification, marine incursion, meta-analysis, Canadian quartz

Highlights

- Synthesis of pre-LGM chronology data from the central region of the LIS
- Data consist of previously published (n=88) and new contributions (n=39)
- Results suggest an ice-free HBL during parts of MIS 7, MIS 5 and MIS 3
- Radiocarbon, OSL and TL ages form the basis for the MIS 3 assignment
- Implies more dynamicity for the LIS than previously modelled for MIS 3

1. Introduction

Understanding the quantitative relations amongst the biosphere, cryosphere and atmosphere is critically important towards formulating accurate predictions for future climates; and the growth and decay of ice sheets in the Late Pleistocene provides boundary conditions for testing Earth System Models (Kleinen et al., 2015; Loutre and Berger, 2003). To make such climate predictions, these models require empirically derived boundary conditions including the duration and dynamics of previous glaciations. To that end, the recent deglaciation sequence of the Laurentide Ice Sheet (LIS) from the Last Glacial Maximum (LGM) to the present-day is well understood owing to well constrained models of isostatic rebound (Peltier et al., 2015) and a plethora of radiocarbon ages (Dyke, 2004). However, because of glacial erosion, we have a highly incomplete understanding of the period prior to the LGM (Kleman et al., 2010).

Records of relative sea level (RSL) and the $\delta^{18}O$ from benthic foraminifera are important tools for approximating the volume of continental ice during the Pleistocene. For example, a decrease in RSL to -100 m (compared to present-day) (Grant et al., 2014), paired with an increase in the $\delta^{18}O$ from benthic foraminifera (Lisiecki and Raymo, 2005) from ca. 68,000 to 63,000 years before present (yr BP), implies moderate glaciation over North America at that time (Fig. 1). Immediately following this stadial was a partial deglaciation of the continent as shown by a rapid rise in RSL, maintaining a level between -70 m and -80 m until 40,000 yr BP (Grant et al., 2014), and a slight decrease in the $\delta^{18}O$ from benthic foraminifera (Lisiecki and Raymo, 2005). This period of implied partial continental glaciation corresponds broadly to the early part of Marine Isotope Stage 3 (MIS 3; ca. 57,000 to ca. 29,000 yr BP; Lisiecki and Raymo (2005)), where summer insolation was stable and higher than today at 60° N (Berger and Loutre, 1991).

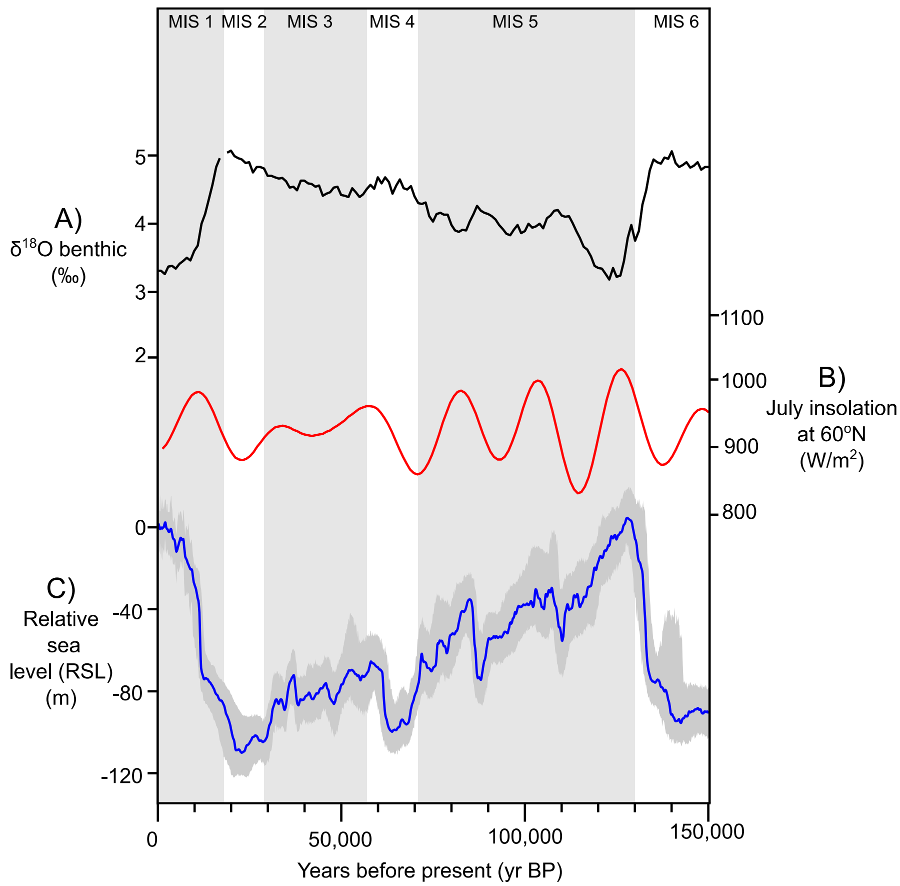

Fig. 1 *(single-column figure)* Climate proxies for the most recent 150,000 years. (A) $\delta^{18}O$ record from benthic foraminifera (Lisiecki and Raymo, 2005); (B) July insolation at 60°N (Berger and Loutre, 1991); (C) Relative sea level from the Red Sea (Grant et al., 2014).

Understanding the configuration of North American ice sheets during MIS 3 is important because it will help validate models which approximate ice-sheet build-up and growth for that time (e.g. Ganopolski and Calov, 2011; Ganopolski et al., 2010; Kleman et al., 2010; Stokes et al., 2012).

Although rare and spatially discontinuous, available paleorecords from North America suggest a dynamic and lobed margin of the LIS during MIS 3. For example, the Roxana Silt, a loess deposit dating to ca. 60,000 to ca. 30,000 yr BP, suggests that glacial activity reached the Mississippi watershed during that time (Forman and Pierson, 2002). Furthermore, several corroborative studies on sedimentological and biological records suggest that the LIS advanced into the continental United States at ca. 45,000 to ca. 42,000 yr BP, resulting in drainage southward toward the Gulf of Mexico (Hill et al., 2006; Sionneau et al., 2013; Tripsanas et al., 2007). Contrastingly, studies suggest an ice-free MIS 3 in Southern Ontario (Bajc et al., 2015; Karrow et al., 2001; Karrow and Warner, 1984; Warner et al., 1988), Atlantic Canada (Fréchette and de Vernal, 2013; Rémillard et al., 2013) and Repulse Bay (McMartin et al., 2015). These datasets indicate the possibility for a dynamic and regionally varied response of the ice sheet margin to MIS 3 paleoclimates. Additional terrestrial records, especially those from the previously glaciated region, are needed to further constrain the boundaries of the LIS during MIS 3.

1.1 Missinaibi Formation, Canada

The Late Pleistocene history of the Hudson Bay Lowlands (HBL), Canada (Fig. 2), has been identified as an important archive for constraining the history of glaciations over North America (Dredge and Thorleifson, 1987; Kleman et al., 2010). Importantly, the HBL contains the

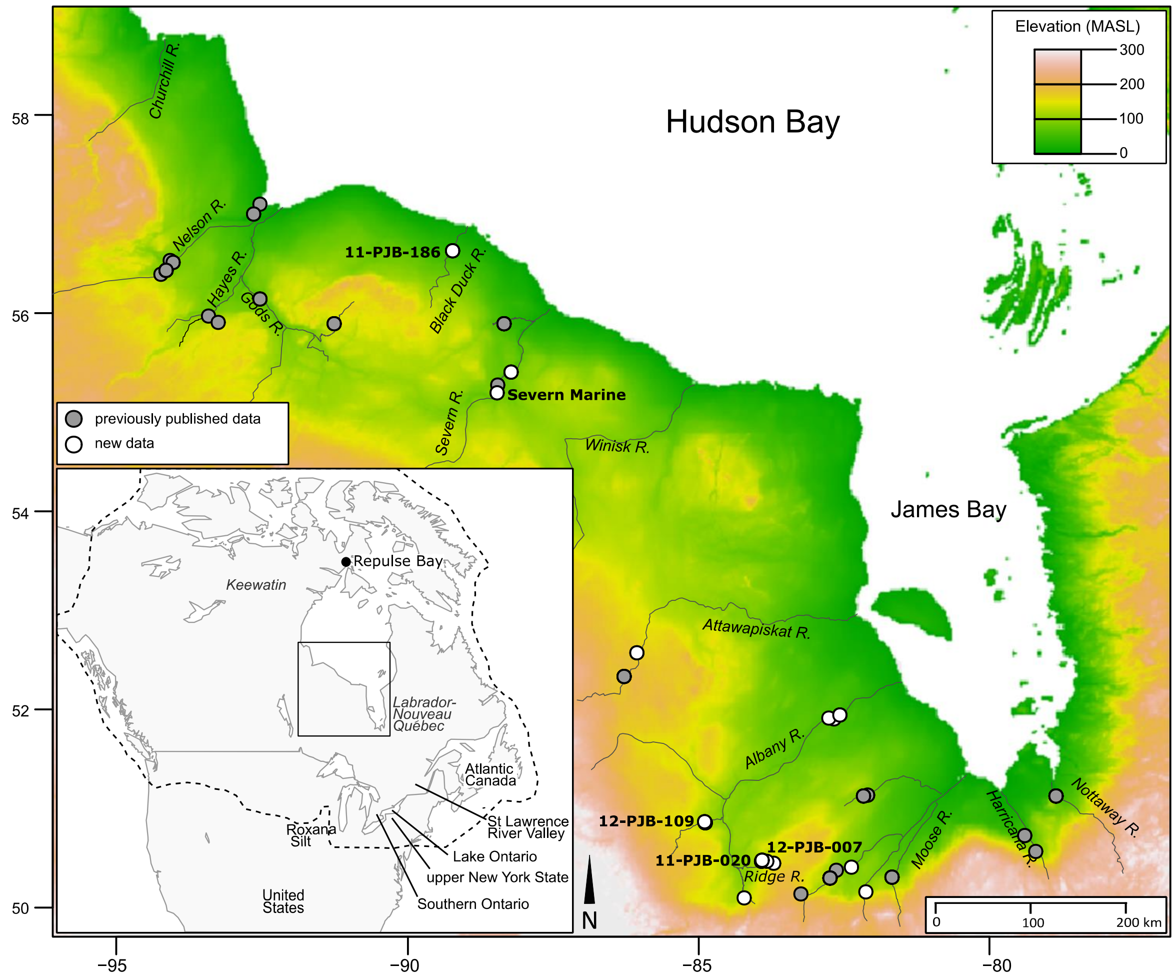

Fig. 2 *(2-column figure).* Map of the Hudson Bay Lowlands (HBL) region, showing the locations of Late Pleistocene age estimates, which are compiled for this study. The location of key sites are noted on this map. Some sites contain several dates; details from each site are available in Appendix A. Topographic data was compiled by Amante and Eakins (2009). Inset map shows the HBL region (box), approximate maximum extent of the Wisconsin Glaciation (hatched lined) (Dyke et al., 2002) and other sites/regions mentioned in the text. Names which are italicised represent sectors of the Laurentide Ice Sheet. Further details on the creation of this map are available in Appendix C.

Missinaibi Formation, a non-glacial deposit underlying till. Since the HBL is located near the geographic center of many Pleistocene ice sheets, the age of this non-glacial deposit can be used to infer the absence of regional ice sheets (e.g. Bos et al., 2009; Helmens et al., 2007; Helmens and Engels, 2010), therefore improving our understanding of the timing and spatial extent of ice-free regions during Late Pleistocene glaciations over North America. Furthermore, since this region is likely to have been a peatland for other ice-free periods in the Pleistocene (Allard et al., 2012; Terasmae and Hughes, 1960), constraining the age of this deposit will permit empirical validation of models which simulate carbon storage and potential methane release during that time (Kleinen et al., 2015).

Despite the importance of the Missinaibi Formation as a Pleistocene archive, there is no consensus on its age or whether the deposits are penecontemporaneous or span much of the Late Pleistocene. The inability to constrain the age of these deposits reflects that radiocarbon dating has mostly yielded infinite results and there is a scarcity of suitable material for geochronological methods such as optically stimulated luminescence (OSL) and uranium-thorium (U-Th) dating. Despite these issues, previous attempts to constrain the age of the Missinaibi Formation have resulted in the recognition of at least one MIS 5 (ca. 130,000 to 71,000 yr BP) site via U-Th and OSL dating (Allard et al., 2012; Dubé-Loubert et al., 2013), which is correlative to the penultimate interglacial period. Given the substantial glacial retreat during the MIS 5 period (Andrews and Dyke, 2007; NEEM community members, 2013), such deposits can be expected.

There are, however, several sites in the HBL which have yielded MIS 3 ages (Berger and Nielsen, 1990; McNeely, 2002; Wyatt, 1989). These results have ignited considerable debate, since an ice-free HBL during that time would imply a significantly different configuration of the LIS than predicted by glacial models (e.g. Stokes et al., 2012) and what was documented from the LGM to present-day (Dyke, 2004). Furthermore, chronology constraints are largely based on conventional radiocarbon dates (e.g. Wyatt, 1989), or accelerator mass spectrometry (AMS) radiocarbon determinations made on peat or shell samples (e.g. McNeely, 2002), which can be subject to contamination and wide error ranges, depending on the context of samples selected for dating. As a result, evidence for an ice-free HBL during MIS 3 has been largely dismissed, with a lack of AMS dates on wood being cited as "a benchmark consideration against the possibility of Middle Wisconsinan deglaciation of the Hudson Bay Lowland" (McNeely, 2002).

1.2 Objectives

Here, we summarize all pre-LGM chronology data in the HBL and contribute new AMS radiocarbon, OSL and U-Th data to critically evaluate the age(s) of the Missinaibi Formation. Geochronological data originated from a range of government, academic and unpublished sources spanning several decades and covering a wide range of uncertainties and errors. To temper these uncertainties and ensure an objective research approach, we include a short discussion of all major issues inherent to dating Pleistocene deposits. This information is then used to rank the chronology data to distinguish between highly-reliable age determinations and those that have an increased chance of being erroneous. Particular attention is paid to radiocarbon age estimates, especially discussing the sample material and potential for modern-day contamination, since the MIS 3 period lies at the limit of this geochronometer. A similar approach was used by Wohlfarth (2010) to evaluate a pre-LGM chronology dataset from Sweden, by Hughes et al. (2016) for reconstructing the most recent 40,000 years of glaciation over Eurasia, and by Forman et al. (2014) for evaluating the chronology of Holocene-aged shells in Lake Turkana, Kenya.

2. Regional setting

The HBL is a coastal plain encompassing 325,000 km^2 of land, located in central Canada, and constrained by the uplands of the Canadian Shield, James Bay and Hudson Bay (Riley, 2003) (Fig. 2). This remote region is dominated by ombrotrophic bogs, minerotrophic fens and permafrost along the northern coast (Riley, 2003), all of which are underlain by Paleozoic and Mesozoic sedimentary rocks. The HBL is situated a maximum of ~170 m above sea level, with a gradual decrease in elevation towards the James and Hudson bays. Several major rivers are deeply incised, but meander through this region, discharging into the James and Hudson bays. A marine incursion, the Tyrell Sea, inundated large parts of the HBL region following the post-LGM deglaciation owing to high sea levels and isostatically depressed land (Lee, 1960).

In the HBL, non-glacial deposits underlying till were first noted in a series of exploratory trips in the late 19th century (Bell, 1879, 1886), and are comprised of marine, fluvial, peat and forest-bed units (Skinner, 1973). The marine unit has rarely been noted in the HBL. These deposits are commonly overlain by two tills (Nguyen, 2014; Skinner, 1973), and subsequently overlain by Holocene-aged marine, lacustrine and peat deposits. This Pleistocene-aged stratigraphy is exposed along river banks and ranges in height from 10 to 30 m, with the non-glacial Missinaibi Formation commonly ranging from 1 to 5 m in thickness. The regional extent of these deposits is unknown because the occurrence is disparate, but it may be correlative with non-glacial deposits from central and southern Ontario (e.g. Bajc et al., 2015; DiLabio et al., 1988).

While the reason for the preservation of the Missinaibi Formation is not well understood, the relatively low topography of the HBL, in combination with the confining topographic high of the

Canadian Shield, may have mitigated glacial erosion in this region, thus preserving these Pleistocene-aged sediments. Furthermore, the Missinaibi Formation commonly contains fluvial sequences, which would have presumably been deposited in river valleys similar to today, and these sheltered environments may have acted to protect these deposits from glacial erosion (Barnett and Finkelstein, 2013).

3. Critical evaluation of geochronological techniques

We assembled a database (n = 127) consisting of all previously published (n = 88) and new (n = 39) geochronological data for the Missinaibi Formation (Appendix A). These data consist of AMS radiocarbon (n = 44), conventional radiocarbon (n= 36), amino acid (n = 13), U-Th (n = 14), TL (n = 15) and OSL (n = 5) methods. All chronology data was ranked on a scale of 1 to 3, with ‘1’ representing most reliable dates; ‘2’ representing ages with somewhat more uncertainty owing to sample material or depositional context, and ‘3’ less reliable dates. Ranks and rationales are discussed below, and available in Appendix A.

3.1 Radiocarbon dating

Sample material, which can have a substantial bearing on the resulting data, varied widely in our database. So long as it is not reworked, wood is the ideal material for radiocarbon dating since cellulose does not exchange carbon with the atmosphere after formation (Bowman, 1990). As a result, we consider wood dates to be reliable (n = 27 ^{14}C AMS of which 25 are new contributions; n = 18 ^{14}C conventional).

Peat (n = 8 ^{14}C AMS; n = 15 ^{14}C conventional) and shell dates (n = 9 ^{14}C AMS; n = 12 ^{14}C conventional), which have unique contamination issues, are common in our database. To minimize the risk of modern-day contamination, peat samples were examined for root structures, and humic acids were removed prior to radiocarbon dating. Since no root structures were identified in the samples, and peat dates have been used commonly and accepted in Holocene HBL studies (Packalen et al., 2014), we assign high confidence to our newly contributed peat dates (n = 8). If similar details on the removal of humic acids and rootlets from the samples were noted for previously published peat dates, we consider those dates to be reliable as well.

Radiocarbon dating of marine shells from the HBL is problematic because most shells are located in till (e.g. McNeely, 2002), meaning that they are inherently transported and may not have originated in the HBL. These shell dates are assigned low confidence because they are not considered to have been deposited *in situ*. Furthermore, the calcium carbonate component of shells is commonly subject to post-death isotope fractionation, especially from modern carbon sources, which can cause artificially young dates (Oviatt et al., 2014; Pigati, 2002). Blake (1988) attempted to circumvent this issue by dating the inner and outer fraction of an *in situ* shell, but the inner fraction resulted in an infinite determination (sample GSC-1475 inner/outer), and is therefore of limited use in our analysis. The only other *in situ* marine shells in our dataset are from McNeely (2002) (samples AA-7563, TO-2503), however there is limited information about the pre-treatment and processing of those samples. As a result, we assign lower confidence to these shell dates in our database.

Radiocarbon ages up to 46,401 ^{14}C yr BP were calibrated using the CALIB Rev 7.0.4 and the INTCAL13 curve (Reimer et al., 2013; Stuiver and Reimer, 1993). Since finite ages greater than 46,401 (n = 5) exceed the calibration curve, they were left as radiocarbon years (yr ^{14}C). Following Stuiver and Polach (1977), all dates were rounded to the nearest 100, and error values were rounded up to the nearest 50-year increment. Some ages (n = 3) were not distinguishable from background (Stuiver and Polach, 1977), and were therefore considered to be the same age as background, which is ca. 49,600 ± 950 yr ^{14}C (Appendix B).

3.2 U-Th dating

Uranium-Thorium dating has provided a chronological constraint for the MIS 5 period in the HBL (Allard et al., 2012). This method measures the rate of decay of ^{238}U into daughter isotope species and can be used to date material up to ca. 350,000 yr BP (Geyh, 2008). The main requirements for this technique are that the material must contain uranium at deposition, and that it is not affected by uranium or thorium from the surrounding environment while buried (van Calsteren and Thomas, 2006). Wood is not commonly dated using this technique because it does not naturally contain uranium, therefore any uranium uptake must have originated from the surrounding sediment shortly after burial (Vogel and Kronfeld, 1980). Because U-Th dating of wood is dependent on initial uranium contamination of the sample, several corroborative age estimates from the same stratigraphic unit are needed to definitively assign an age (e.g. Allard et al., 2012; Causse and Vincent, 1989; De Vernal et al., 1986; Mott and Grant, 1985).

Wood pieces encased in clay result in limited permeability to surrounding groundwater, and are preferred for the U-Th method. Such conditions were met by Allard et al. (2012), who dated 9 wood logs from deposits underlying till along the Nottaway River. Although slightly different uranium concentrations were recorded on the outer edge of these logs, the inner, less permeable, portions yielded consistent age determinations (Allard et al., 2012), which we consider to be reliable. In the western HBL, two U-Th dates from Nielsen et al. (1986) are considered less reliable owing to the porosity of the surrounding environment (sand, silt), and evidence of thorium contamination, which are suspected to have caused dissimilar isotopic measurements on wood pieces from the same stratigraphic unit.

We made several new attempts to date wood from two sites in the HBL. Two wood pieces were submitted from 12-PJB-109 for analysis at Geotop, Université du Québec à Montréal, for which three dates were obtained (Appendix A). However, in all three cases, the system was believed to be open with respect to uranium, owing to significantly different results from the same stratigraphic unit. This exchange may have been caused by the composition of the sediment matrix, which, although clay-rich (~35%), contained ~50 % silt and ~15% sand. This texture may have promoted water infiltration. As a result, we consider these ages to be minimum estimates. A further attempt at 12-PJB-007 showed that there was no significant uranium uptake, therefore an age assignment was not possible at this site, and these results are excluded from our dataset.

3.3 OSL dating

Given that MIS 3, our period of interest, corresponds to the limit of radiocarbon dating, OSL techniques may hold potential to improve our understanding of the age of HBL deposits. However, OSL dating can be less successful on sediments derived from the Precambrian Shield, which yields quartz grains showing low light emissions with optical stimulation (“dim quartz”) (e.g. Demuro et al., 2013). The reason for this low luminescence signal may be that newly-eroded quartz has a limited ability to store charge given a minimal number of cycles of dosing and solar resetting (Sawakuchi et al., 2011). Glacial environments associated with rapid burial and high energy settings may also result in partial resetting of electron traps (King et al., 2014;

Lukas et al., 2007; Rhodes, 2011). As a result, there are no previously published studies which use OSL on quartz grains from the HBL.

In an attempt to resolve this issue, we used OSL dating on quartz at two separate sites, 12-PJB-109 as well as two samples from the Severn Marine site. An *a priori* assumption is that quartz grains in this fluvial system were not uniformly solar reset because of the short distance of transport in turbid water conditions and possible deposition during the fall and winter with sedimentation beneath ice cover. Single aliquot regeneration (SAR) protocols (Murray and Wintle, 2003; Wintle and Murray, 2006) were used to estimate the apparent equivalent dose for a different size fraction in each sample (Table 1). For 12-PJB-109, each aliquot contained approximately 10 to 30 quartz grains corresponding to a 2 mm circular diameter of grains adhered (with silicon) to a circular aluminum disc of 1-cm diameter. Such a small number of grains per aliquot was measured to isolate the youngest, full solar-reset grain population (cf. Duller, 2008). It is suspected that < 20% of grains of each aliquot emitted light, i.e. 2 to 6 quartz grains.

An Automated Risø TL/OSL–DA–15 system was used for SAR analyses with light from blue diodes. Optical stimulation for all samples was completed at an elevated temperature (125 °C) using a heating rate of 5 °C/s. All SAR emissions were integrated over the first 0.8 s of stimulation out of 40 s of measurement, with background based on emissions for the last 30- to 40-second interval. In this study, we used the threshold "fast ratio" of > 15 (cf. Durcan and Duller, 2011) to quantitatively determine aliquots that are dominated by a fast component and thus, only those aliquots are included in equivalent dose calculations. The majority of aliquots (>75%) exhibited a clear so called "fast component" (Fig. 3) which is one of the requirements of the SAR protocols (Murray and Wintle, 2003).

Table 1: Optically stimulated luminescence (OSL) ages on quartz grains from the sub-till Missinaibi Formation, Hudson Bay Lowland, Canada

Sample/ Horizon	Laboratory number	Aliquots[a]	Particle Size (µm)	Equivalent dose (Gray)[b]	Over-dispersion (%)[c]	U (ppm)[d]	Th (ppm)[d]	K (%)[d]	Cosmic Dose rate (mGray/yr)[e]	Dose rate (mGray/yr)[f]	OSL age (yr)[g]
12-PJB-109	BG3800	98/67	250-150	72.27 ± 3.87	62 ± 5	1.22 ± 0.01	6.65 ± 0.01	1.31 ± 0.01	0.16 ± 0.01	1.69 ± 0.09	42,845 ± 3740
Severn Marine 84HBL022	BG3807	90/62	100-63	97.36 ± 6.23	30 ± 3	1.31 ± 0.01	5.78 ± 0.01	1.53 ± 0.01	0.10 ± 0.01	1.64 ± 0.09	52,480 ± 5055
Severn Marine 84HBL023	BG3808	50/30	64-44	85.14 ± 5.26	55 ± 7	1.38 ± 0.01	6.49 ± 0.01	1.64 ± 0.01	0.10 ± 0.01	2.02 ± 0.10	42,190 ± 4010

[a]Aliquots used in equivalent dose calculations versus original aliquots measured.

[b]Equivalent dose calculated on a pure quartz fraction analyzed under blue-light excitation (470 ± 20 nm) by single aliquot regeneration protocols (Murray and Wintle, 2003; Wintle and Murray, 2006). A finite mixture model was used with overdispersion values >20% to determine the youngest equivalent dose population, with at least 10 aliquots defining this equivalent dose population (Galbraith and Green, 1990).

[c]Values reflects precision beyond instrumental errors; values of ≤ 20% (at 1 sigma limit) indicate low dispersion in equivalent dose values and an unimodal distribution.

[d]U, Th and K content analyzed by inductively-coupled plasma-mass spectrometry analyzed by ALS Laboratories, Reno, NV; U content includes Rb equivalent.

[e]A cosmic dose rate calculated from parameters in Prescott and Hutton (1994)

[f]Assumes a moisture content (by weight) of 25 ± 5% for the burial period

[g]Systematic and random errors calculated in a quadrature at one standard deviation. Datum year is AD 2010

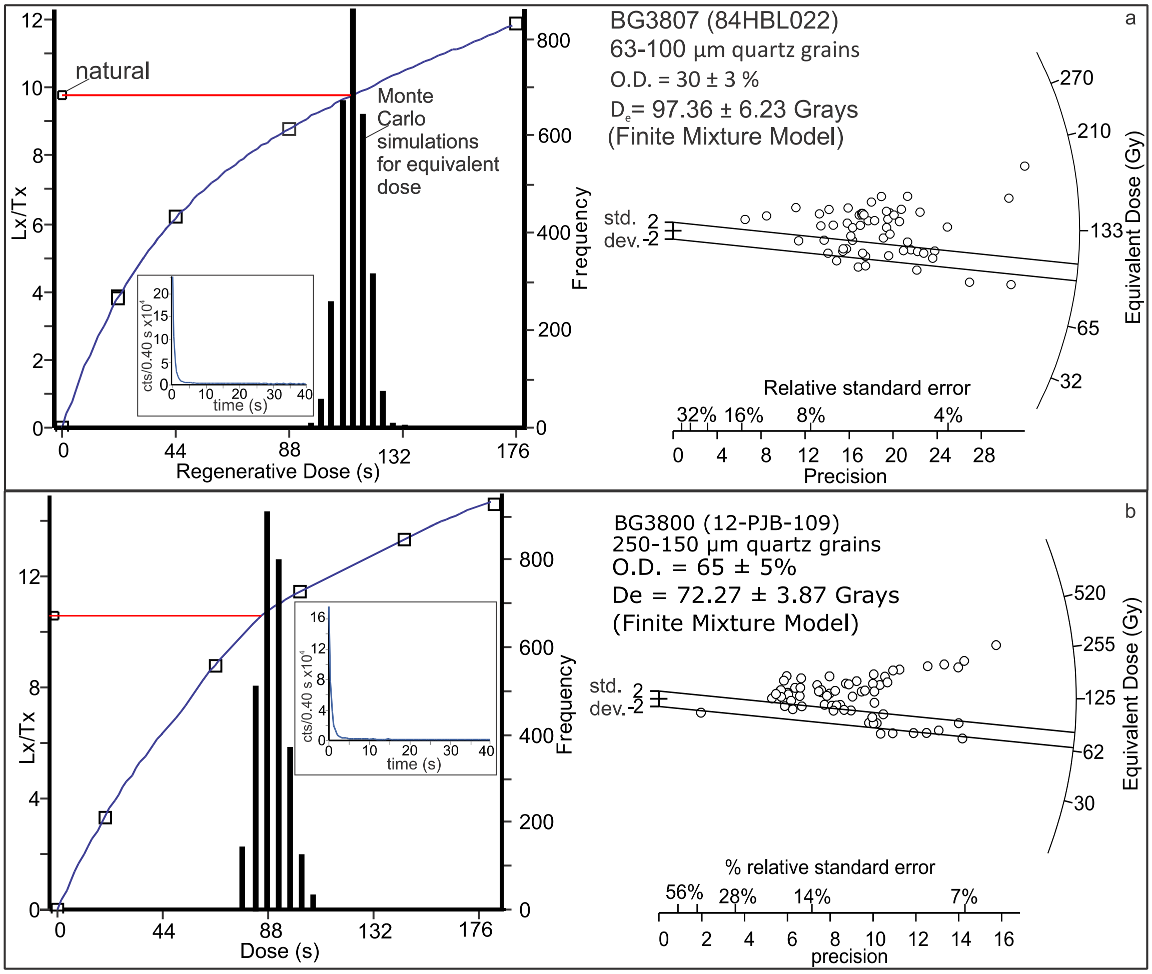

Fig 3 *(2 column figure).* Optically stimulated luminescence data for quartz grains (BG3807 and BG3800) from waterlain deposits. Inset figure is a representative shine down curve of natural luminescence. Shown are regenerative growth curves, with errors by Monte Carlo simulations and radial plots defining statistic parameters for equivalent dose determinations. Mean equivalent dose was determined by the Finite Mixture Model (FMMM) of Galbraith and Green (1990) because of high overdispersion values >25%; parallel lines denote the lowest significant equivalent dose population defined by at least 20 aliquots.

Calculation of equivalent dose by the single aliquot protocols was accomplished for a majority of aliquots (Table 1). Aliquots were removed from analysis if (1) the fast ratio was <15 (Durcan and Duller, 2011), (2) the recycling ratio was not between 0.90 and 1.10, (3) the zero dose was >5 % of the natural emission or (4) the error in equivalent dose determination is >10 %. Equivalent dose (D_e) distributions are log normal, highly negatively skewed and exhibited overdispersion values of 23 % to 103 % (Table 1; Fig. 3). An overdispersion percentage of a D_e distribution is an estimate of the relative standard deviation from a central D_e value in context of a statistical estimate of errors (Galbraith and Roberts, 2012; Galbraith et al., 1999). A zero overdispersion percentage indicates high internal consistency in D_e values with 95% of the D_e values within 2σ errors. Overdispersion values $\leq$ 20 % are routinely assessed for small aliquots of quartz grains that are well solar reset, like far-traveled eolian and fluvial sands (e.g. Meier et al., 2013; Olley et al., 2004; Wright et al., 2011) and this value is considered a threshold metric for calculation of a D_e value using the central age model of Galbraith et al. (1999). Overdispersion values >20 % may indicate mixing of grains of various ages or partial solar resetting of grains. The finite mixture model is an appropriate statistical treatment for such data (Galbraith and Green, 1990), and this model was used to calculate optical ages (Fig. 3; Table 1).

In addition to our new OSL data, Dubé-Loubert et al. (2013) dated sediments (n = 2) using feldspar grains, which can be used to date sediments back to 500,000 yr BP. However, feldspar is more commonly affected by anomalous fading, a process whereby electrons gradually vacate their traps in the absence of light or heat exposure, which can lead to underestimation of results (Huntley et al., 1985). Dubé-Loubert et al. (2013) applied an equivalent dose correction developed by Lamothe et al. (2003) to mitigate anomalous fading, and we therefore consider these data points to be reliable.

3.4 Thermoluminescence dating

Similar to OSL dating, TL dating measures the last exposure of a sediment to sunlight. However, TL dating can be impacted by anomalous fading, which can lead to underestimation of results (Huntley et al., 1985). This issue can be mitigated by introducing sample preheats or adding days to weeks of wait time to allow the laboratory-induced luminescence to pre-fade. Forman et al. (1987) dated two marine sediments samples from the Severn River in the northern HBL using this approach to mitigate the effects of anomalous fading, and Berger and Nielsen (1990) used prolonged sample storage to remove pre-fade for five samples along the Nelson River (Appendix A). Since effort was made to mitigate the issue with anomalous fading, we retained the data in our dataset and increased the error to 2σ.

Eight TL samples from non-glacial intervals overlain by till from sites along the Nelson River were also analyzed by Roy (1998) to determine the extent of solar resetting and anomalous fading. Seven samples are considered to be unreliable owing to large grain sizes (150 - 250 µm) which are suspected to have caused improper solar resetting. This insufficient solar resetting was confirmed by a Holocene-aged sample which resulted in two age estimates of ca. 50,000 yr BP (Roy, 1998). However, one sample (MOON 2C (delayed)) is more likely a close estimate to the true depositional age because the grain size is much smaller (4 - 8µm), which would have allowed for prolonged sediment suspension prior to deposition, and therefore more effective solar resetting. Furthermore, this sample was corrected for anomalous fading by storing for one year prior to taking this measurement. However, Roy (1998) acknowledges that anomalous fading may have continued after the one-year delay.

3.5 Amino Acid Epimerization

Amino acid epimerization of allo-isoleucine to isoleucine from molluscs has provided some of the first evidence for a large-scale recession of the LIS during MIS 3 (Andrews et al., 1983). This technique measures the post-mortem changes in amino acid chirality (e.g. racemization) for molluscs, such as *Hiatella arctica* or *Mya truncata* (Miller and Brigham-Grette, 1989; Rutter et al., 1979). Such changes to amino acid configuration can be detected for up to ca. 2,000,000 years, making this method suitable for materials of Pleistocene age (Miller and Brigham-Grette, 1989).

A disadvantage to amino acid dating is that it is a relative dating method. In the HBL, amino acid age inferences are based on the implicit assumption that the largest ratio corresponds to a marine incursion during MIS 5e. Younger dates are assigned an age according to this assumption. Consequently, the application of this technique in the HBL has been controversial (Andrews et al., 1983; Dyke, 1984), and we assign limited confidence to these age estimates. Nevertheless, we compiled age estimates from *in situ* shells in the database. Shells from till (e.g. Andrews et al., 1983; Nielsen et al., 1986; Shilts, 1982; Wyatt, 1989) are not included in this compilation because they were incorporated and resided within the glacier for an unknown amount of time where racemization may have ceased or slowed down (Barnett, 1992).

4. Results

Geochronological data for the Missinaibi Formation is largely confined to the most recent 130,000 yr BP, with one exception being an OSL date suggesting a fluvial deposit at ca. 211,000 ± 16,000 yr BP from the Harricana River, published by Dubé-Loubert et al. (2013) (sample 06HA30). This data point represents the oldest age estimate in the HBL region, and aligns with the interglaciation of MIS 7 (ca. 243,000 to ca. 190,000 yr BP) (Dubé-Loubert et al., 2013). Deposits dating to MIS 5 are situated along the Nottaway and Nelson Rivers, and have been described by Allard et al. (2012), Dubé-Loubert et al. (2013) and Roy (1998) (Fig. 4).

Much of our newly contributed data suggests the possibility of an ice-free MIS 3 in the HBL. Firstly, wood from 11-PJB-186, an organic-rich sequence overlain by post-glacial marine sediments along the Black Duck River, suggests that organic accumulation began around 50,100 ± 3300 ^{14}C yr BP (sample ISGS A1995) and 49,600 ± 950 yr ^{14}C (sample UOC-0587), while the upper part of the unit dates to 46,300 ± 1750 cal. yr BP (sample ISGS A1656) (Fig. 5). Similarly, two sites located in close proximity (~ 1.3 km) along the Ridge River, 11-PJB-020 and 12-PJB-007 have yielded radiocarbon dates of 40,000 ± 400 cal. yr BP (sample UOC-0591), 49,600 ± 950 yr ^{14}C (sample UOC-0592; Appendix B), 46,300 ± 1750 cal. yr BP (sample UOC-0590) and ca. 46,500 ± 2100 ^{14}C yr BP (sample ISGS A2424) (Fig. 5). Both sites along the Ridge River are overlain and underlain by diamicton. At the Severn Marine site, our re-evaluation of TL samples using OSL techniques have yielded ages of 52,480 ± 5055 (sample BG3807) and 42,190 ± 4010 (sample BG3808) (Fig. 3).

Data from the western region of the HBL also suggests an ice-free MIS 3, where Berger and Nielsen (1990) published a suite of TL data from fluviolacustrine sediments along a ~100 km stretch of the Nelson River. Another purported MIS 3 site is 24M, which is considered to be the type location for the Missinaibi Formation (Skinner, 1973; Terasmae and Hughes, 1960). Our AMS radiocarbon result of ca. 39,700 ± 800 cal. yr BP (sample TO-1753) corresponds well with other finite determinations in the range of 39,000 to 41,000 yr BP (Olson and Broecker, 1957, 1959), however is in contrast with several infinite determinations,

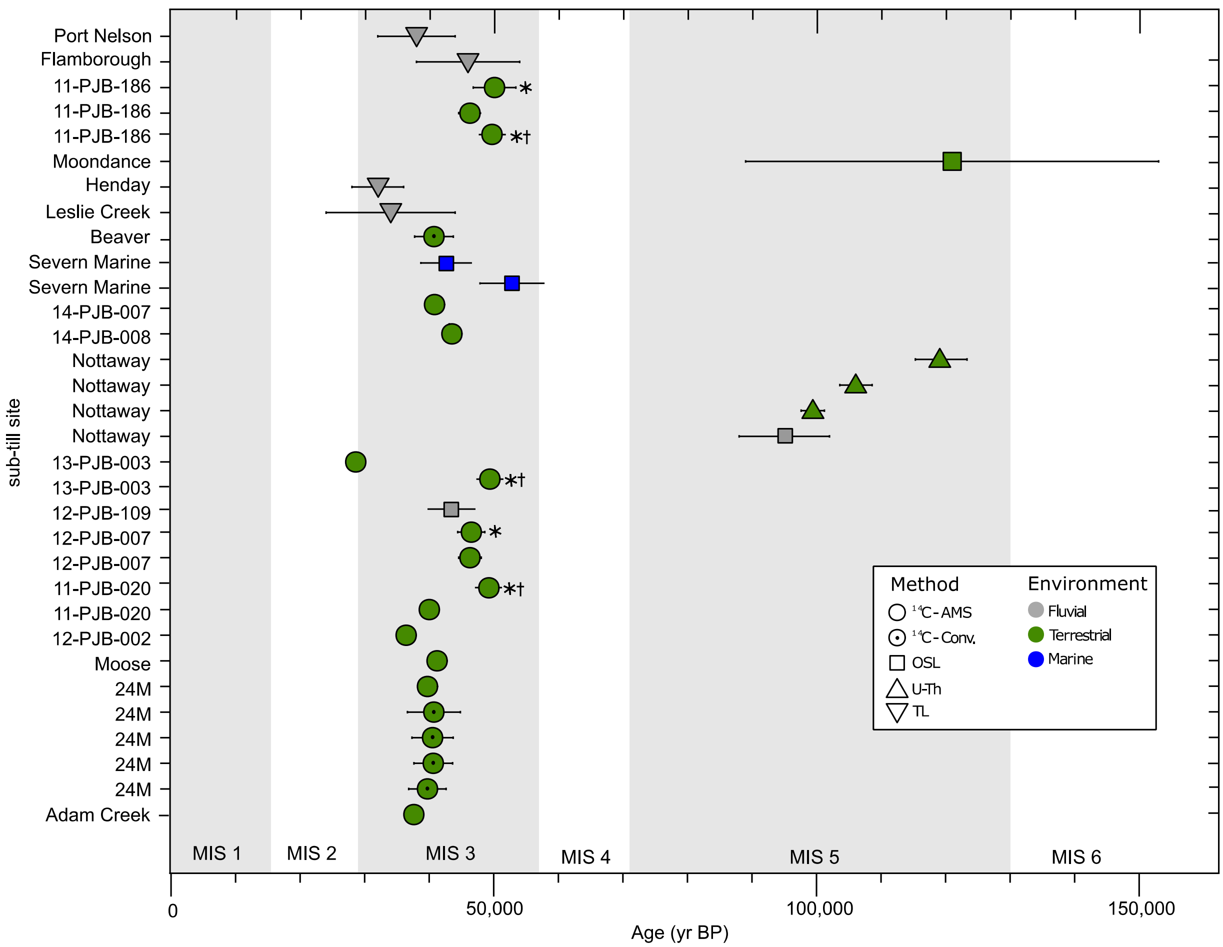

Fig. 4 *(2 column figure)* Summary of chronology data for Pleistocene-aged sites in the Hudson Bay Lowlands (HBL), Canada. Sites are arranged from north to south. Asterix (*) symbol represents radiocarbon dates which could not be calibrated because of exceeding the calibration curve. Cross (†) symbol represents finite ages which are not statistically distinguishable from background, and are therefore considered to be the same age as background. Infinite determinations, ages exceeding 150,000 yr BP (n = 1) and those with a high chance of being erroneous (rank 3) were excluded from this figure. See Appendix A for more details.

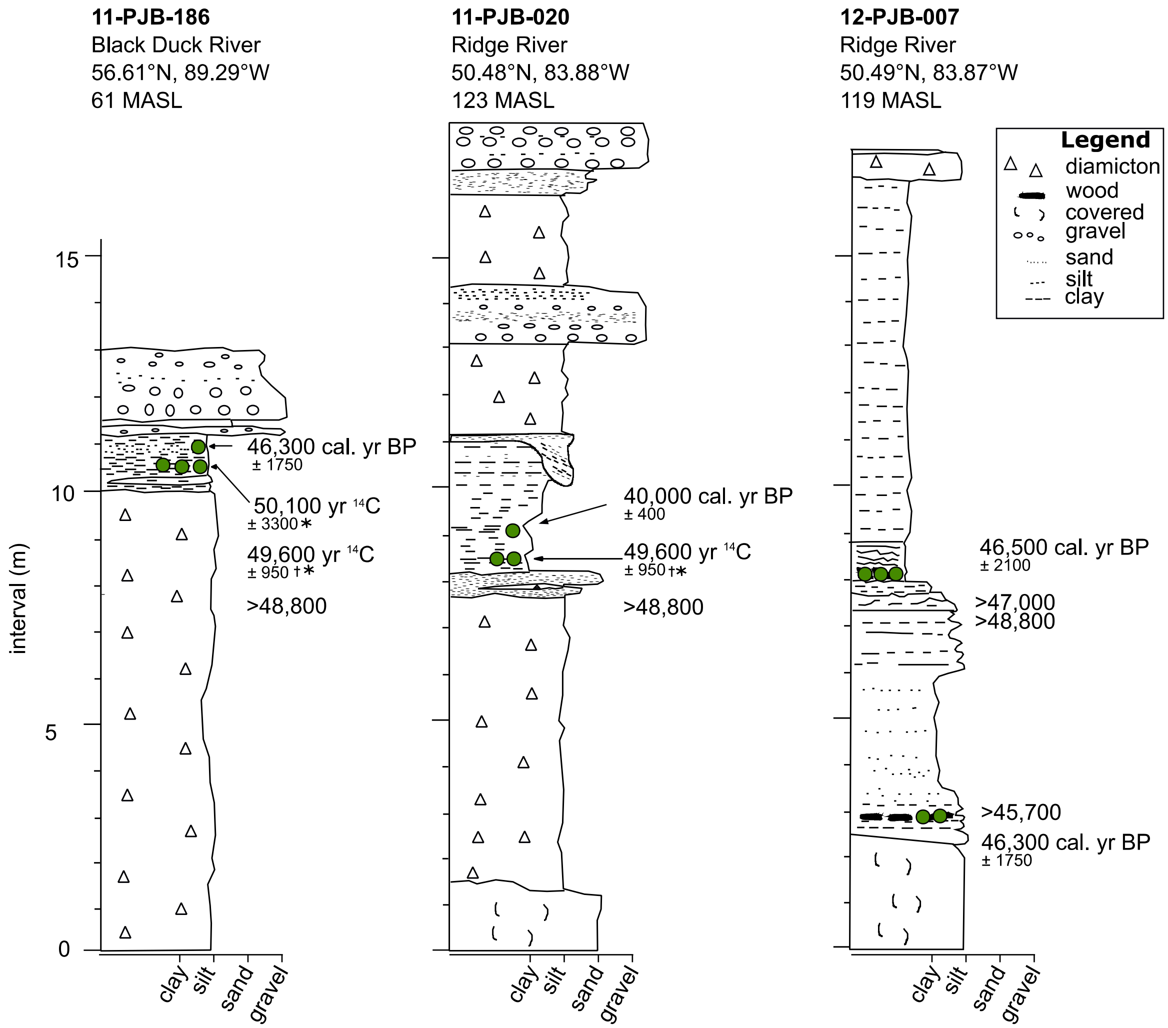

Fig. 5 *(2-column figure).* Detailed stratigraphy of three pre-LGM sites from the Hudson Bay Lowlands, Canada, which have the best evidence of being MIS 3 deposits. All chronology data presented in this figure are new. Asterix (*) symbol represents radiocarbon dates which could not be calibrated because of exceeding the calibration curve. Cross (†) symbol represents finite ages which are not statistically distinguishable from background, and are therefore considered to be the same age as background.

which suggest an older age (MacDonald, 1971; Olson and Broecker, 1959; Preston et al., 1955; Stuiver et al., 1978; Vogel and Waterbolk, 1972). We therefore consider the age of the 24M site to be unresolved.

In addition to the data listed above, there are several sites for which only one finite age estimate is available. Although not described in detail here, these samples are all included in Appendix A as well as plotted in Fig. 4.

5. Discussion

Our synthesis of available age estimates for non-glacial materials suggests that the HBL was ice-free during MIS 7 (Dubé-Loubert et al., 2013), MIS 5 (Allard et al., 2012; Roy, 1998) and possibly during MIS 3. Deposits dating to MIS 7 or MIS 5 are not surprising given that the LIS was thought to have retreated considerably at those times. However, if age estimations from the HBL are correct, deposits dating to MIS 3 imply significant reconfiguration of the LIS.

5.1 The validity of >40,000 yr BP radiocarbon dates

A major limitation of our results and subsequent interpretations is that radiocarbon dates are largely used to constrain the purported ice-free period during MIS 3. This is problematic because radiocarbon dates in the range of 40,000 to 50,000 yr BP have lost the majority of ^{14}C, and contamination by small amounts of modern carbon can cause otherwise infinite materials to appear finite (Andrews and Dyke, 2007; Beukens, 1990). For example, 0.2 % modern-day carbon contamination will cause a 45,000 year old sample to yield an age of 40,000 years (Olsson and Eriksson, 1972). It is therefore possible that modern or re-worked carbon is influencing our radiocarbon dates, thus erroneously suggesting an ice-free MIS 3 in the HBL.

There is no way to determine whether a single sample has been contaminated by modern-day carbon. Only repeated measurements showing a high degree of precision can increase confidence that a true representation of the material's age has been obtained (Scott, 2007). For example, Bajc et al. (2015) investigated a purported MIS 3 site in Southern Ontario, re-dating wood pieces using three different cellulose extraction techniques, resulting in age estimate of ca. 42,000 to ca. 50,000 ^{14}C years BP, therefore strengthening a MIS 3 age assignment at that site. A similar approach was used at a Late Pleistocene site from Atlantic Canada by Rémillard et al. (2013), where both peat and wood consistently yielded ages of ca. 47,100 to ca. 50,100 yr BP, all of which overlap at 1σ, thus supporting the MIS 3 interpretation.

In addition to repeated dating of samples, the stratigraphy of age determinations can help determine whether modern contamination is responsible for finite age estimates. For example, at the Pilgrimstad site in Sweden, radiocarbon estimates from ca. 40,000 to ca. 50,000 cal. yr BP were older at the bottom of the sequence and gradually became younger towards the top (Wohlfarth, 2010 and references therein). If modern-day carbon contamination had influenced these age estimates, we would expect all determinations to be artificially finite, as well as possible age reversals in the stratigraphic sequence. Since age estimates largely follow stratigraphic order, it re-enforces the MIS 3 age assignment.

Following the techniques outlined above, to strengthen age estimates for the Missinaibi Formation, we made an effort to (1) sample several intervals at a given site to determine if the resulting age estimates follow stratigraphic order, and (2) date samples multiple times, and at different radiocarbon laboratories, to test the precision and reproducibility of each age assignment. These efforts were focussed on three purported MIS 3 sites, 11-PJB-186, 11-PJB-020 and 12-PJB-007 and the results can be seen in Fig. 5 and Appendix A. Although some re-dating attempts were limited because of low material availability, chronology data at these sites largely follows stratigraphic order, and samples which have been dated multiple times show significant reproducibility. Such an agreement would not be expected if these finite estimates were the result of modern carbon contamination. Therefore, on the basis of radiocarbon dating, we find no reason to discount the chronology at these three sites. Results from OSL dating further support the MIS 3 interpretation (Fig 2). However, fluvial and/or marine sediments were often missing from the sub-till sites, thus a direct comparison of OSL and radiocarbon dates from the same site has not yet been done. Nevertheless, both radiocarbon and OSL results suggest an ice-free HBL during MIS 3. The discovery of new sub-till sites to perform OSL dating may hold potential to significantly improve our understanding of the age of the Missinaibi Formation.

The abundance of infinite radiocarbon dates (n = 47) is also worth considering, although the interpretation is challenging. Given that the MIS 3 period corresponds to ca. 29,000 to ca. 57,000 yr BP, radiocarbon dating should be able to capture any deposit up to ca. 50,000 yr BP, only missing those that lie at the lower boundary for MIS 3. It is possible that some of these infinite age estimates may be from that time. It is equally possible that these infinite dates represent multiple non-glacial intervals from earlier in the Pleistocene, perhaps correlative with the late MIS 5 ages from the Nottaway River (Allard et al., 2012). Based solely on chronological evidence, we do not consider the presence of infinite radiocarbon dates to be evidence in favor or against any particular age assignment for the Missinaibi Formation.

5.2 Ice Sheet dynamics during MIS 5

Based on available age estimates, the warmest part of the penultimate interglacial, MIS 5e (peak: ca. 123,000 yr BP), which has been identified elsewhere in Canada (e.g. Fréchette and de

Vernal, 2013; Karrow et al., 2001), is not preserved in the non-glacial sediments of the HBL at sites presented here. Instead, OSL data from the Nottaway River, and one TL age from the Nelson River correspond to the latter part of the MIS 5 interglaciation (Allard et al., 2012; Dubé-Loubert et al., 2013; Roy, 1998).

5.3 Laurentide Ice Sheet during MIS 3

Our data suggests that the HBL may have been deglaciated during ca. 50,000 to 40,000 yr BP, which, according to RSL and $\delta^{18}O$ from benthic foraminifera (Grant et al., 2014; Lisiecki and Raymo, 2005), corresponds to a time of partial deglaciation of the North American continent. If correct, data from the HBL constrains the ice-free eastern lobe of the LIS by 700 km westward and northward than what is suggested by most other Late Pleistocene sites. In Southern Ontario, these sites include conventional radiocarbon dates on sub-till material from a borehole and creek exposure (Karrow and Warner, 1984; Warner et al., 1988), three finite AMS dates on bone and peat samples from a sub-till site exposed along a railroad cut (Karrow et al., 2001) and six finite AMS dates on sub-till wood fragments from a quarry (Bajc et al., 2015). In Atlantic Canada, Rémillard et al. (2013) documented four finite AMS ages on sub-till peat, which suggests that this region may have also been deglaciated during MIS 3. Fréchette and de Vernal (2013) also infer a deglaciation in Atlantic Canada during MIS 3, but no geochronological data was available at that site, and instead, age control was based on the stratigraphic position of the sub-till deposits.

Radiocarbon data from Repulse Bay, northwest of the HBL, may provide corroborative evidence for a very significant glacial recession during MIS 3. Recently-obtained radiocarbon data suggests that this region was ice-free for several thousand years during MIS 3 (McMartin et al., 2015). However, notably, these data were based on marine shells, which may have associated uncertainties (see Section 3.1). Nevertheless, duplicate samples analyzed by different laboratories produced the same interpretation at that site (McMartin et al., 2015), which strengthens the interpretation. Together with data from the HBL, there seems to be a growing amount of evidence suggesting that large parts of eastern and central North America may have been ice-free during MIS 3.

If evidence for a significant glacial recession during MIS 3 is correct, other parts of North America must have been fully glaciated to compensate for the relatively low sea level during that time (Grant et al., 2014). It may be possible that the mid- and western regions of North America were glaciated. For example, TL, and radiocarbon data from the Roxana Silt suggest the presence of the LIS in the mid-continent during MIS 3 (Forman, 1992; Forman and Pierson, 2002). Records from the Gulf of Mexico, most of which are dated using a series of AMS dates on foraminifera, also suggest that the LIS spanned into the continental United States for large parts of MIS 3 (Hill et al., 2006; Sionneau et al., 2013; Tripsanas et al., 2007).

Based on available age estimates of the Missinaibi Formation, it seems that the western sector of the LIS (Keewatin) was highly active, and the eastern sector (Labrador-Nouveau Québec) may have experienced restricted growth following MIS 5 and into MIS 3. Expansion of the eastern sector may have been preferentially eastward onto the expanding continental shelf as RSL fell. Its southern extension may have been affected by the isostatically depressed St Lawrence River valley, slowing expansion into the lower Great Lakes. This eastern sector of the LIS may have only reached the western end of Lake Ontario during MIS 3. In this scenario, it is possible for parts of the HBL to have remained unglaciated.

The lack of a marine unit at the base of most dated MIS 3 sites may provide supportive evidence for a MIS 3 age assignment. In the HBL, marine incursions can be expected immediately following deglaciation as a result of isostatic depression of the land and the close proximity to Hudson Bay (e.g. Tyrell Sea; Lee, 1960). To account for this missing marine unit, the Missinaibi Formation could have been deposited at a time when ice had recently receded beyond the boundaries of the HBL, but when significant parts of the continent remained glaciated to maintain low RSL, thus preventing a large-scale marine incursion. The early part of MIS 3 is the only time during the Late Pleistocene when what may have been an extensive deglaciation is not followed by a substantial rise in sea level to levels similar to present-day (Grant et al., 2014). We would expect such conditions to prevent a large-scale marine incursion in the HBL, allowing instead the growth of peat, forest bed and fluvial deposits directly overlying till, corresponding to the observed Missinaibi Formation. However, two newly-contributed OSL dates from the Severn River suggest that a marine incursion may have inundated the outer region of the HBL during this time (Fig. 3, 4).

Irrespective of the configuration of the LIS during ca. 50,000 to ca. 42,000 yr BP, there is a general consensus of substantial continental glaciation between ca. 42,000 to ca. 35,000 yr BP which would likely have covered the entire HBL region. Karig and Miller (2013) document a proglacial lake in upper New York state from ca. 37,000 to ca. 34,000 yr BP, and Berger and Eyles (1994) document till in Southern Ontario at ca. 41,000 yr BP, indicating the proximal presence of a glacial lobe during that time. Furthermore, sedimentological evidence from the Gulf of Mexico suggests that the eastern lobe of the LIS was extended beyond Lake Ontario at that time (Sionneau et al., 2013; Tripsanas et al., 2007), and radiocarbon and OSL dating of cave sediments indicates that the LIS may have grown to almost the LGM limit between ca. 40,000 to ca. 30,000 yr BP (Wood et al., 2010).

Taken together, evidence suggests that the LIS covered large parts of North America from ca. 42,000 to ca. 35,000 yr BP, which would have undoubtedly glaciated all of the HBL during that time. Our shortage of age estimates from this time period may be taken as indirect evidence for a fully glaciated HBL, since this time period is well within the acceptable range of most geochronological methods. After this purported glaciation, there may have been a brief retreat of the LIS at ca. 30,000 yr BP (Dyke et al., 2002), followed by a rapid build-up of the ice sheet towards the LGM (Dyke et al., 2002; Lambeck et al., 2014).

6. Conclusions

Our review of chronology data from the HBL, Canada, helps to constrain the boundaries of the LIS for periods prior to the LGM, which can help validate important models of ice sheet extent, build-up and growth (Ganopolski and Calov, 2011; Ganopolski et al., 2010; Kleman et al., 2010; Stokes et al., 2012). Chronology data suggests that the HBL was ice-free during parts of MIS 7, MIS 5 and possibly during parts of MIS 3. While glacial retreats at MIS 7 and MIS 5 are well-documented, evidence for a ice-free central region of the LIS during MIS 3 is noteworthy, since these data extend the ice-free eastern lobe of the LIS by at least 700 km westward and northward from what is suggested by existing Late Pleistocene sites in Southern Ontario and Atlantic Canada (Bajc et al., 2015; Rémillard et al., 2013).

Although largely based on radiocarbon determinations, evidence for an ice-free HBL during the MIS 3 period is reinforced by (1) our successful efforts to re-date purported MIS 3 sites and test the reliability of radiocarbon dating at the limit of this geochronometer, (2) paleorecords from Atlantic Canada and Southern Ontario suggesting largely ice-free conditions during MIS 3 (e.g. Bajc et al., 2009; Bajc et al., 2015; Rémillard et al., 2013), and for which the western extent is unknown, and (3) a strong agreement between low RSL during MIS 3 and the lack of marine deposits in the Missinaibi Formation. Future iterations of relevant Earth system models should include land-based information of the layout and configuration of previous ice sheets, along with results from till correlations (Dubé-Loubert et al., 2013; Kaszycki et al., 2008; Nguyen, 2014), geomorphic evidence of ice flow regimes (Kleman et al., 2010; Veillette et al., 1999) and models of ice volume (Peltier et al., 2015).

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