An assessment of the minimum timing of ice free conditions of the western Laurentide Ice Sheet

Evan J. Gowan

Research School of Earth Sciences, The Australian National University, Acton 2601, ACT, Australia

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ABSTRACT

This study presents an investigation of the minimum timing of retreat of the western Laurentide Ice Sheet, which covered parts of Canada and the northern United States during the Wisconsin glaciation. The retreat of the ice sheet is poorly constrained due to low spatial resolution of chronological data that indicate ice free conditions. A limitation of radiocarbon and luminescence dating methods is that it is only possible to determine the time when it is certain that ice is absent from a region, which may differ substantially from the true date of ice margin retreat. The minimum timing of ice free conditions is determined using a model of ice sheet retreat, inferred from landforms that formed during the late stages of glaciation, and extrapolating the calibrated probability distribution of chronological data in the opposite direction. The analysis excludes radiocarbon samples from materials that have been shown to give artificially old ages, such as bulk sediments. The results of the analysis identify 55 dates that have the most impact on the model. The retreat of the western Laurentide Ice Sheet commenced by at least 15 000 cal yr BP, while the minimum timing of ice free conditions between the Laurentide Ice Sheet and the Cordillera is after 11 000 cal yr BP. A lack of data in the Keewatin sector prevents the determination of a precise timing of ice free conditions in the last vestiges of the Laurentide Ice Sheet. The model provides a guide to where additional samples could improve chronological control on ice margin location.

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1. Introduction

The Laurentide Ice Sheet covered most of Canada and parts of the northern United States, reaching a maximum extent at the Last Glacial Maximum, between 26.5 and 19 ka (Clark et al., 2009). The ice sheet retreated over a period of 14 000–16 000 years, affecting global climate and sea level. Dyke and Prest (1987) and Dyke (2004) presented reconstructions of the ice sheet margin during the retreat of the Laurentide Ice Sheet, based on median ages of uncalibrated radiocarbon dates (Dyke et al., 2003), glacial geomorphological features (i.e. moraines, ice contact deltas, meltwater channels), and glacial flow features that indicate the most likely direction of ice retreat. Uncertainties in margin position are one of the largest potential sources of error in ice sheet reconstructions and models (i.e. Tarasov et al., 2012). In this paper, I create a model of the minimum timing of ice free conditions in the western Laurentide Ice Sheet. The model is developed using techniques similar to those applied by past workers such as Dyke and Prest (1987) and Dyke (2004) though, instead of determining a model of margin positions,

chronological data are extrapolated in the direction opposite of retreat to determine the minimum timing of retreat. These results can be used as constraints for ice sheet models, by determining the region certain to be ice free for any time period. The model also serves as a basis for determining where more data would best improve temporal controls of ice margin reconstructions.

The western Laurentide Ice Sheet includes the region of ice that flowed from the Keewatin sector (Fig. 1). It converged with the Cordillera Ice Sheet to the west, and extended into northern mid-western United States (Dyke, 2004). The easternmost boundary of this sector lay in northwestern Ontario and Manitoba, where ice from northeastern sectors also influenced the direction of flow. The retreat of ice in this region has implications for major climatic events (i.e. Tarasov and Peltier, 2005; Broecker, 2006; Gregoire et al., 2012), the drainage of glacial lakes (i.e. Fisher et al., 2002; Teller et al., 2002; Teller and Leverington, 2004; Broecker, 2006; Fisher et al., 2009; Fisher and Lowell, 2012), and the migration of mammals in deglacial and post-glacial North America (i.e. Meltzer, 2003; Burns, 2010).

It is important to recognise that radiocarbon dates only provide a minimum timing of retreat. There is an unknown period of time between when ice retreated from a region and when organisms

E-mail address: evan.gowan@anu.edu.au.

In this paper, I determine the minimum timing of ice free conditions of the area covered by the western Laurentide Ice Sheet. This involves assessing the currently available chronological data that indicate ice free conditions, and rejecting samples that may be affected by contamination and give anomalously old ages. I produce a spatial and temporal model of the minimum timing of retreat using the calibrated age of these data.

2.1. Radiocarbon dating

The magnitude of the marine reservoir effect varied through time in glaciated regions (Barber et al., 1999; Kovanen and Easterbrook, 2002; Hutchinson et al., 2004; McNeely et al., 2006; Coulthard et al., 2010; Vickers et al., 2010), so the modern value may not be appropriate. For instance, Vickers et al. (2010) found that the postglacial reservoir offset in Hudson Strait was $\Delta R = 615 \pm 15$, which is 375 ± 25 years larger than the modern value of $\Delta R = 240 \pm 15$ (McNeely et al., 2006). Southampton Island, located at the northern end of Hudson Bay has a postglacial reservoir offset of $\Delta R = 263 \pm 48$ (Ross et al., 2012). The island is situated at the boundary of two oceanographic subdivisions used

by Coulthard et al. (2010). The postglacial reservoir age in that location is greater than the modern value for Hudson Bay ($\Delta R = 110 \pm 65$) and lower than the modern value of the Foxe Basin ($\Delta R = 310 \pm 90$), and $\Delta R = 352 \pm 52$ years lower than the early postglacial offset in Hudson Strait (Vickers et al., 2010). Ross et al. (2012) attributed the lower postglacial reservoir offset on Southampton Island relative to Hudson Strait to the presence of non-calcareous Precambrian bedrock. Coulthard et al. (2010) separated Hudson Bay and James Bay into two regions, finding offsets of $\Delta R = 110 \pm 65$ and $\Delta R = 395 \pm 115$, respectively. Barber et al. (1999) found a modern marine reservoir offset of $\Delta R = 310 \pm 50$ for southeastern Hudson Bay and James Bay. They stated that modern correction in the Hudson Bay region would be conservative compared to early postglacial time due to increased runoff from retreating ice sheets, and the abundance of freshly glacially eroded carbonate bedrock.

The apparent age of marine samples from southwestern Hudson Bay after deglaciation provide evidence that the reservoir age is greater than the modern value. The age of marine organisms found in southwestern Hudson Bay must postdate the 8.2 ka event, a climate change event associated with the drainage of lakes Agassiz and Ojibway into the northern Atlantic Ocean, which happened between 8490 and 8040 cal yr BP (Lewis et al., 2012). The final drainage event may correspond to when Hudson Bay became ice free (Barber et al., 1999), though initial drainage may have been subglacial (Roy et al., 2011). Regardless, the calibrated age of marine organisms in this region must postdate this drainage event, as ice within Hudson Bay would have blocked the incursion of marine water. An estimate of the timing of marine inundation into southwestern Hudson Bay was made using OxCal's "boundary" functionality (Fig. 2, Bronk Ramsey, 2009). A total of 18 marine shell samples dating between 8200 and 7000 ^{14}C yr BP from northern Manitoba, derived from Morlan et al. (2000), were used to model the beginning of marine inundation into Manitoba. The timing of the event was tested using no additional marine reservoir correction ($\Delta R = 0$), the modern value ($\Delta R = 110 \pm 65$, Coulthard et al., 2010), and the sum of the modern correction and the additional offset of 375 ± 25 found in the Hudson Strait (Vickers et al., 2010; $\Delta R = 470 \pm 100$). The modelled age of marine inundation for northern Manitoba is older than the inferred timing of the 8.2 ka event using the modern reservoir correction (Table 1, Fig. 2). The modelled age of marine inundation falls within the 8.2 ka event using the larger value ($\Delta R = 470 \pm 100$) (Table 1). This ΔR value is used to correct marine samples from the Hudson Bay region. This correction is only a minimum value if the 8.2 ka event was caused by subglacial drainage of the lakes (i.e. Lajeunesse and St-Onge, 2008), rather than the complete deglaciation of Hudson Bay that would have allowed sea water to enter the region.

Fig. 2. Probability distributions for the timing of the initial inundation northern Manitoba by the Tyrrell Sea. The grey bar is the approximate timing of the 8.2 ka event (Lewis et al., 2012). The distributions correspond to models using the given ΔR values.

Table 1

Modelled age of the initial inundation of northern Manitoba by sea water.

ΔR	95% probability range	Median age	Mode age
0	8895–8470	8655	8630
110 ± 65	8920–8385	8575	8535
470 ± 100	8520–7960	8175	8120

The incorporation of pre-glacial organic material, lignite, hydrocarbons, carbonate rocks, and hardwater effects can cause radiocarbon dates on bulk sediments to appear older than their true age (i.e. Deevey et al., 1954; Ogden, 1977; Nambudiri et al., 1980; MacDonald et al., 1991; Shore et al., 1995). In regions previously glaciated by the western Laurentide Ice Sheet, measurements of bulk sediment can be several hundred to over 1000 years older than contemporaneously deposited terrestrial macrofossils (MacDonald et al., 1991; Grimm et al., 2009). The heterogeneous composition of sediments and peat can cause variability in the apparent age of material taken from the same horizon (e.g. Brock et al., 2010, 2011). Abbott and Stafford (1996) have also showed that anomalously old ages can occur in lakes in the Arctic, even when the local bedrock geology does not contain carbonates. The age of such sediments may be influenced by the input of old material from around the basin (Bertrand et al., 2012). Before the advent of accelerator mass spectrometry (AMS) dating methods that allowed the measurement of small samples, bulk sediment, peat and gyttja were used often to constrain the timing of ice sheet retreat. It may be appropriate to use bulk sediment or peat samples if it is clear that the material is predominately terrestrial plant material (i.e. Nilsson et al., 2001), but often this information is not reported or known. Dyke et al. (2003) rejected most samples that were most likely affected by recycled carbon and hardwater effects, but kept samples where it was less clear. Other studies of the retreat of the western Laurentide Ice Sheet (e.g. Clayton and Moran, 1982; Teller, 1989; Arnold, 2002; Fisher, 2007; Fisher et al., 2009) have rejected samples where the material sampled could be contaminated. In this study, where the purpose is determining the minimum timing of deglaciation, samples that may give anomalously old ages, such as bulk sediments and peat, are rejected. A comparison of the minimum timing of retreat with and without these samples is presented in the Supplementary material.

2.2. Surface exposure and luminescence

Surface exposure and luminescence methods are alternative dating methods that have been used to provide estimates on when regions became ice free, and avoids the problem with the unknown duration of time between deglaciation and the colonization of plants and animals (e.g. Jackson et al., 1997, 1999; Wolfe et al., 2004; Munyikwa et al., 2011). Surface exposure dating involves the measurement of the relative abundance of elements formed by cosmogenic radiation bombarding exposed rock (Zreda and Phillips, 2000; Gosse and Phillips, 2001). This method requires estimates of the erosion rate and how shielded the rock is from the direct exposure (i.e. snow cover, topographical relief). The studies that presented surface exposure dates concluded that these effects were small (e.g. Jackson et al., 1997, 1999; Davis et al., 2006; Bednarski and Smith, 2007). There also is the possibility that the rock was exposed prior to glaciation, which increases the apparent age of exposure (e.g. Jackson et al., 1997), or that the samples first became exposed after eroding out of glacial deposits, giving an age that post-dates deglaciation (e.g. Jackson et al., 1999). Due to these uncertainties, surface exposure dates are not used in the main analysis of the minimum timing of retreat. Luminescence dates

provide the timing of deposition and burial of silicate minerals such as quartz and feldspar (Forman et al., 2000). To acquire an accurate date, the minerals must be sufficiently exposed to light prior to burial to reset the signal. Dates from aeolian deposits are likely to have been fully exposed, and accurately record the timing of burial (e.g. Wolfe et al., 2004; Bateman and Murton, 2006; Munyikwa et al., 2011). Murton et al. (2010) collected samples from fluvial sediments, that are less likely to have been fully exposed to light. Since the material from that study was derived from post-glacial aeolian deposits, the dates should be reliable for the purposes of finding the minimum timing of retreat. Samples from studies dating strandlines were from the littoral zone of beaches (i.e. Lepper et al., 2007, 2011), maximizing the likelihood of material being exposed prior to burial. Ages from these two methods are reported in this paper as “ka” with 1σ error ranges. Luminescence and surface exposure ages are reported relative to the year the sample was measured, so in the modelling they are adjusted to be relative to 1950 A.D. for consistency with calibrated radiocarbon dates ages.

3. Chronological constraints on the minimum timing of retreat of the western Laurentide Ice Sheet

3.1. Radiocarbon dates

There are 604 radiocarbon dates available in the study region, most derived from an updated version of the compilation by Dyke et al. (2003) (A.S. Dyke pers. comm. 2010). A literature search was completed to find additional relevant radiocarbon samples from the study area.¹ The distribution of samples is biased to areas in the southern part of the study area and areas along the northern mainland coast (Fig. 3). There are few samples in the interior of mainland Northwest Territories and Nunavut, as well as northern Manitoba and Saskatchewan. For the analysis of the minimum timing of retreat, the radiocarbon dates were grouped into four different classes. There are 313 samples that are terrestrial materials, such as wood, charcoal, terrestrial plants and mammal fossils. These samples are regarded as having reliable dates. There are 49 samples of suspension feeding marine molluscs, and are deemed to be reliable after reservoir correction. There are 225 samples of sediment, peat, soil, marl, gyttja and aquatic plants and animals that have the potential of being affected by hardwater effects and old carbon, and were excluded from the main analysis. There are 17 samples that are deposit feeding marine molluscs, or where the species are not stated, which are excluded from the main analysis.

3.2. Luminescence dates

There are 84 luminescence dates that are relevant for determining the minimum timing of retreat in the study area. These data were collected for dating post-glacial sand dune formation (Wolfe et al., 2004, 2006, 2007; Munyikwa et al., 2011), the age of strandlines of glacial Lake Agassiz (Lepper and Sager, 2000; Lepper et al., 2007, 2011, 2013; Fisher et al., 2008) and late glacial events in the Mackenzie Delta (Bateman and Murton, 2006; Murton et al., 2007, 2010). In cases where a strandline can be traced to the contemporaneous ice margin, they provide a minimum timing of retreat for the entire length (i.e. Fisher and Lowell, 2012). Though not done in the main analysis, the Herman and Norcross strandlines impact the model from the period between 14 000 and 13 000 cal yr BP, while the Campbell strandline (Fig. 1) has a more limited impact from 11 000 to 10 000 cal yr BP.²

¹ A list of samples used in this study is included in the Supplementary material.

² Models including strandlines are included in the Supplementary material.

Fig. 3. Map showing the location of chronological constraints relevant to the minimum timing of the retreat of the western Laurentide Ice Sheet. The brown outline is the area investigated in this study.

3.3. Surface exposure dates

There are 38 surface exposure dates relevant to deglaciation of the western Laurentide Ice Sheet. Most of these are ^{36}Cl dates that come from locations near the convergence zone of the Laurentide and Cordilleran ice sheets (Jackson et al., 1997, 1999, 2011; Bednarski and Smith, 2007). The ages of the samples are variable (20–10 ka), and depend in part on the determination of an appropriate erosion rate.

4. Direction of ice margin retreat

The determination of the direction of retreat assumes time transgressive formation of landforms, such as moraines, streamlined landforms and eskers. This methodology has been used in prior margin models (i.e. Bryson et al., 1969; Prest, 1969; Boulton et al., 1985; Dyke and Prest, 1987; Dyke, 2004). End and recessional moraines and crevasse-fill ridges formed roughly parallel to the recessional ice margin, while flutings, drumlins and other streamlined landforms that formed in the recessional phase are roughly perpendicular to the margin. Eskers and meltwater channels are other features that can form perpendicular to the direction of late stage ice retreat (Clark and Walder, 1994; Kleman and Borgström, 1996). In the Keewatin sector, the final retreat may have been by downwasting of an inactive ice sheet (Aylsworth and Shilts, 1989a), and eskers may better reflect the direction of retreat than flutings. Landforms inferred to have formed prior to deglaciation and had been overridden were excluded from the model.

Glacial landforms used to infer the direction of margin retreat are derived from a variety of published surficial geology maps, with scales ranging between 1:50 000 to 1:5 000 000. Retreat features for the northern United States and adjacent regions of Canada are sourced from USGS 1:1 000 000 Quaternary Geological Atlas of the United States maps (Goebel et al., 1983; Hallberg et al., 1994; Swinehart et al., 1994; Sado et al., 1995; Fullerton et al., 1995, 2000, 2007). A map of glacial limits by Fullerton et al. (2004) is used to determine the inferred direction of retreat in Montana. Features for northern and central Manitoba come from a preliminary map of glacial features (Trommelen and Ross, 2010; McMartin et al., 2010; Trommelen et al., 2012a, b; M. Trommelen

pers. comm, 2012). Glacial features for Saskatchewan come from the Geological Atlas of Saskatchewan (McMartin et al., 2010; Hanson et al., 2011; Slimmon, 2011). In most of Alberta, recent interpretations of glacial features by Evans et al. (2008) are used. Features for much of mainland Northwest Territories are derived from Brown et al. (2011). Features for the Keewatin sector are predominantly derived from Aylsworth and Shilts (1989b). These sources are complemented by smaller scale maps in Alberta, British Columbia, Yukon, Northwest Territories and mainland Nunavut (a full list of sources is included in the Supplementary material). In regions without coverage, the 1:5 000 000 surficial materials map of Canada by Fulton (1995) is used. Maps that explicitly stated the relative chronology of glacial features were used as a guide to interpret the rest of the area (e.g. Little and Ferbey, 2003; McMartin and Dredge, 2005; Smith et al., 2007; Fisher et al., 2009; Trommelen and Ross, 2010; Bednarski, 2008; Brown, 2012).

A database of retreat direction vectors was compiled using ArcGIS 10.1 (ESRI, 2012) based on glacial and surficial geology maps. The vectors are perpendicular to margin normal features, such as recessional moraines, and parallel to flutings. The vectors are parallel to the trend of eskers that were used as constraints, with consideration of regional retreat patterns. Since the density of features is variable, the map of inferred direction of retreat was converted to a regular grid using a triangulated irregular network and linear interpolation of the vectors. The vectors were first interpolated onto a 1 km grid, and then averaged onto a 20 km grid. This size was chosen as a balance between the low resolution of landforms in some areas, and to be high enough to capture lobate ice margins and where significant changes in the direction of

Fig. 4. Map showing the direction of retreat on a 100 km grid. The black outline shows the region investigated in this study.

Fig. 5. Example of the scaling factor applied to a sample located at 45.789°N 95.763°W (gold star, ETH-32331, Lepper et al., 2007) at the northern end of the Des Moines lobe. The white arrows are the inferred direction of retreat at a grid resolution of 20 km. The scaling factor is close to one in areas in the opposite direction of retreat, but is zero in areas glaciated by the Superior Lobe (Goebel et al., 1983).

retreat occurred. Fig. 4 shows a map of the direction of retreat at a grid resolution of 100 km.³

5. Modelling the minimum timing of ice free conditions

A program was created in order to assess the minimum timing of retreat. The program extrapolates the probability distribution of the age of a dated sample in the direction opposite of retreat, using the assumption that the margin retreated in a time transgressive fashion (i.e. the margin retreated progressively from the Last Glacial Maximum limit to the Keewatin region). Instead of using the probability distribution to pinpoint an exact age of the sample, it is used to express increased confidence that the sample is older than a given date. For instance, if a sample has a normally distributed age of 9000 ± 50 yr BP, then at 9000 yr BP there is 50% confidence the sample is older than that, while at 9100 yr BP the confidence is 97.8%. Note that the calibrated probability distribution is generally not normally distributed, so the sum of the area under the probability curve up to the desired age is used. The probability is scaled directionally using an azimuthal $\cos^2$ function until it reaches zero in the direction normal to deglaciation. The scaling function changes direction at every grid point (20 km) defined by the retreat map. This allows the scaling function to be broader in areas where the direction of retreat is concave (such as lobate regions). The program imposes a tolerance to stop the extrapolation if the

³ A map with the 20 km grid is included in the Supplementary material.

Fig. 6. A comparison of the chronological constraints at 12 000 cal yr BP (a) without bulk sediment and peat samples (b) with bulk sediment and peat samples. The light blue line is the corresponding margin reconstruction by Dyke (2004) at 10.25 ^{14}C kyr BP. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

direction of retreat changes by more than 25° in adjacent grid points. This prevents extrapolation to areas glaciated by different sectors, such as the boundary between the Cordillera and Laurentide ice sheets. After extrapolation, the program stores the scaling factor on a 20 km grid. An example of the scaling function is shown on Fig. 5. The probability at each grid point is the sum of the age distribution of the sample up to the time of interest, multiplied by the scaling factor. For radiocarbon dates, the calibrated distribution determined by OxCal was used, while a scaled error function was used to calculate the probability of surface exposure and luminescence samples. At each grid point, the maximum value for all samples is taken as the confidence of ice free conditions.

6. Comparison of the model with bulk dates

Fig. 6 shows a comparison of the results with and without using bulk sediment and peat samples at 12 000 cal yr BP, corresponding to a period within the Younger Dryas. Drainage of glacial lakes located in the western Laurentide ice sheet has been suggested as being one of the factors for causing and maintaining this cold period (e.g. Tarasov and Peltier, 2005; Condron and Winsor, 2012; Not and Hillaire-Marcel, 2012). Murton et al. (2010) suggested that Lake Agassiz could be a possible source of this water, though investigations of the northwestern outlet by Fisher et al. (2009) and Fisher and Lowell (2012) cast doubt that the it was available before the late Younger Dryas. A sample of lake sediment northwest of Great Slave Lake (GSC-3524, 12 600–12 100 cal yr BP, MacDonald, 1987) has a large impact on the model and, if accepted, indicates that it is certain the area between the Laurentide Ice Sheet and the Cordillera is ice free at this time. As previously discussed, lake sediment samples can be contaminated by hardwater effects and old carbon, and could potentially give an age that is older than the true age. If this sample is rejected on this basis, the oldest dates from this region include a bison bone with an age of 11 300–10 300 cal yr BP (I-9997, Harington, 2003), and wood with an age of 10 400–9300 cal yr BP (AECV-915C, Smith, 1992), both of which postdate

the Younger Dryas. Though there have been recently published dates related to the opening of the northwest outlet of Lake Agassiz (i.e. Fisher et al., 2009), there are still few constraints between the outlet and the Arctic Ocean, even with the inclusion of bulk dates. This is especially true in areas where the density of data is low, such as the area north of 60°N .⁴ The minimum timing of retreat of the region between the northwestern outlet of Lake Agassiz and the Arctic Ocean significantly postdates the start of the Younger Dryas when bulk sediment dates are excluded, and less so when they are included.

7. Minimum timing of ice free conditions

Maps of the modelled minimum timing of retreat are shown for the time intervals used by Dyke (2004) to compare the certainty of ice free conditions with the inferred margin position (Figs. 7–9). Dyke (2004) used 500 year intervals in radiocarbon years before present, and the actual timing in calendar years can be variable depending on how they are calibrated. To convert the margin model to calendar years, an error of 250 years at 1σ (half of the 500 year interval) is applied before calibration. The age used in the maps is the median calibrated age, rounded to the nearest 100 years. The following section highlights specific samples that have the most impact on the model.

7.1. Oldest dates constraining the minimum timing of retreat

The southwestern margin of the Laurentide ice sheet was marked by convergence with the Cordillera ice sheet (Dyke and Prest, 1987; Dyke, 2004). The oldest radiocarbon date from terrestrial material that postdates deglaciation in southwestern Alberta is a sample of wood, which has an age of 21 700–17 100 cal yr BP (TO-5190, Beierle and Smith, 1998). This sample lies in an area covered by till of Cordilleran origin (Bayrock and Reimchen, 1980),

⁴ See Supplementary material for maps comparing models with and without bulk dates at 500 year intervals.

Fig. 7. Minimum timing of retreat for the early deglaciation of the western Laurentide Ice Sheet. The light blue line is the margin reconstruction by Dyke (2004). The yellow circles are the samples discussed in the text that have the most impact on the model. (a) 17.6 cal kyr BP (14.5 ^{14}C kyr BP), (b) 17.1 cal kyr BP (14.0 ^{14}C kyr BP), (c) 16.5 cal kyr BP (13.5 ^{14}C kyr BP), (d) 15.7 cal kyr BP (13.0 ^{14}C kyr BP), (e) 14.7 cal kyr BP (12.5 ^{14}C kyr BP), (f) 13.9 cal kyr BP (12.0 ^{14}C kyr BP). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

and indicates the end of convergence between the Laurentide and Cordilleran ice sheets at this latitude. Several surface exposure ^{36}Cl dates from the Foothills erratics train, which is near the confluence of the Cordillera and Laurentide ice sheets, are older than 15 ka (Jackson et al., 1997, 1999, 2011). The large range in ages from these

boulders (28–11 ka) makes it difficult to use these to constrain the minimum timing of deglaciation. The oldest radiocarbon date that overlies Laurentide deposits is a sample of wood from northeastern British Columbia (TO-2742, 17 600–16 800 cal yr BP, Catto et al., 1996).

Fig. 8. Minimum timing of retreat for deglaciation of the western Laurentide Ice Sheet in the late Pleistocene and early Holocene. The light blue line is the margin reconstruction by Dyke (2004). The yellow circles are the samples discussed in the text that have the most impact on the model. (a) 13.4 cal kyr BP (11.5 ^{14}C kyr BP), (b) 12.9 cal kyr BP (11.0 ^{14}C kyr BP), (c) 12.3 cal kyr BP (10.5 ^{14}C kyr BP), (d) 11.6 cal kyr BP (10 ^{14}C kyr BP), (e) 10.8 cal kyr BP (9.5 ^{14}C kyr BP), (f) 10.1 cal kyr BP (9.0 ^{14}C kyr BP). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

In the Dakotas, Minnesota and Iowa, the maximum extent of the Laurentide Ice Sheet was attained by the James and Des Moines lobes (Fig. 1, Clayton and Moran, 1982). The glacial history of this region is complicated, reflecting the dynamic nature of the southern margin of the Laurentide Ice Sheet. The minimum timing of

deglaciation of the Des Moines lobe from its maximum extent is from a wood sample, which has an age of 16 600–14 600 cal yr BP (W-626, Ruhe, 1969). There are no available deglacial terrestrial organic dates within the southern limits of the James Lobe, but a wood sample from below till near the southernmost extent has an

Fig. 9. Minimum timing of retreat for deglaciation of the western Laurentide Ice Sheet in the early Holocene. The light blue line is the margin reconstruction by Dyke (2004). The yellow circles are the samples discussed in the text that have the most impact on the model. (a) 9.5 cal kyr BP (8.5 ^{14}C kyr BP), (b) 8.9 cal kyr BP (8.0 ^{14}C kyr BP), (c) 8.4 cal kyr BP (7.6 ^{14}C kyr BP), (d) 7.9 cal kyr BP (7.0 ^{14}C kyr BP), (e) 7.4 cal kyr BP (6.5 ^{14}C kyr BP), (f) 6.9 cal kyr BP (6.5 ^{14}C kyr BP). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

age of 15 400–14 000 cal yr BP (Johnson and McCormick, 2005), indicating the maximum position may have been attained after the Des Moines Lobe.

In the northwestern Laurentide Ice Sheet, luminescence dates from sand that predates the last advance of the ice sheet have ages

between 22 000 and 16 000 yr BP (Murton et al., 2007; Murton, 2009). A saiga antelope bone from the Mackenzie Lowlands region that has an age of 18 600–17 700 cal yr BP (Beta-25119, Harington and Cinq-Mars, 1995) may postdate glaciation, though the stratigraphic context of the sample was not clear. The next

oldest dates are from grass samples in ice-proximal outwash, with ages of 16 400–15 200 and 16 200–15 100 cal yr BP (GSC-1995 and GSC-1784-2, [Rampton, 1988](#)).

7.2. Early retreat – 15 000 to 13 000 cal yr BP

By 15 000 cal yr BP, there is reasonable confidence that most of southern Alberta was free of ice, as indicated by luminescence dates from post-glacial sand dunes ([Fig. 7](#), [Wolfe et al., 2004](#); [Munyikwa et al., 2011](#)). Several dates from central Alberta have an impact on the model have ages of 15.7 ± 1.6 ka (SFU-O-275, [Wolfe et al., 2004](#)), 15.4 ± 1.1 ka (USU-524, [Munyikwa et al., 2011](#)) and 14.7 ± 1.6 ka (USU-524, [Munyikwa et al., 2011](#)). The oldest radiocarbon dates from southern and central Alberta are from a bison bone with an age of 13 800–13 200 cal yr BP (AECV-1203C [Burns, 1996](#)) and a horse bone with an age of 13 800–13 200 cal yr BP (OxA-14273 [Burns, 2010](#)). Luminescence dates from northeastern British Columbia and northwestern Alberta indicate ice free conditions by about 13 000 cal yr BP (13.9 ± 1.2 ka, SUV05309, and 13.4 ± 1.2 ka, SAW05-01 [Wolfe et al., 2007](#)).

The Des Moines and James lobes are certain to have retreated north of the North and South Dakota border by 14 000 cal yr BP ([Fig. 7](#)). Luminescence dates on sand from the Herman strandline of Lake Agassiz give an average age of 14.0 ± 0.3 ka ([Lepper et al., 2007, 2011](#)). Radiocarbon dates on wood from this region (e.g. ETH-32334, 14 500–13 800 cal yr BP, [Lepper et al., 2011](#)) support that areas south of 46°N were ice free. Terrestrial samples from southern Manitoba and Saskatchewan indicate ice free conditions existed north of the US-Canada border by 13 000 cal yr BP (GSC-1081, 13 900–13 100 cal yr BP [Lowdon et al., 1971](#); S-553, 14 900–13 500 cal yr BP, [Christiansen, 1979](#)).

By 13 000 cal yr BP, northwestern mainland Northwest Territories and northern Yukon are certain to be ice free ([Fig. 7](#)). Terrestrial radiocarbon dates in Yukon near the maximum limit of glaciation indicate that retreat began before 13 800–13 400 cal yr BP (GSC-2745, 13 800–13 400 cal yr BP, [McNeely, 1989](#); OxA-18549, 13 800–13 500 cal yr BP, [Zazula et al., 2009](#)). There are several dates on wood from the Mackenzie River southwest of Fort Good Hope with ages greater than 13 000 cal yr BP, the oldest being 13 800–13 400 (TO-1190) and 13 800–13 100 (I-15020) ([Smith, 1992](#)). A sample of *Hiattella arctica* east of the Mackenzie Delta on the northern coast of mainland Northwest Territories has an age of 13 700–12 900 cal yr BP (AECV-643Cc, [McNeely and Jorgensen, 1992](#)).

7.3. Younger Dryas – 13 000 to 11 500 cal yr BP

Determining the chronology of potential northwest and eastern drainage routes of Lake Agassiz has been the focus of several recent studies (i.e. [Teller et al., 2005](#); [Lowell et al., 2005, 2009](#); [Fisher et al., 2009](#)), and several samples from these areas date to the Younger Dryas period ([Fig. 8](#)). The area near Lake Superior in northeastern Minnesota is certain to be ice free during the Younger Dryas, based on dates on wood (ETH-28939, 12 600–12 200 cal yr BP and ETH-31429, 12 600–11 800, [Lowell et al., 2009](#); TO-1504, 13 200–12 100 cal yr BP, [Bajc et al., 2000](#); W-827, 14 000–12 600 cal yr BP, [Wright and Watts, 1969](#)). Ice also had retreated north of the Minnesota-Ontario border, as indicated by a wood sample (ETH-32339, 12 600–12 100 cal yr BP, [Lowell et al., 2009](#)). In the vicinity of the northwestern drainage route in Alberta, there are two terrestrial samples that provide a minimum timing of retreat during the Younger Dryas (ETH-30586, 12 600–12 100 cal yr BP and ETH-32165, 12 400–11 800 cal yr BP, [Fisher et al., 2009](#)). Other dates from this period in the Prairies include a bison bone from western Manitoba (BGS-617, 12 600–11 400 cal yr BP, [Nielsen et al., 1984](#))

and wood from central Saskatchewan (S-3271, 13 500–11 500 cal yr BP, [Christiansen et al., 1995](#)). In the Northwest Territories, wood samples (AECV-917C, 12 600–11 400 cal yr BP, [Smith, 1992](#); 13 000–12 600 cal yr BP, GSC-6805, [Dyke et al., 2003](#)) indicate that much of the region occupied by glacial Lake Mackenzie was ice free during the Younger Dryas.

7.4. Early Holocene – 11 500 to 10 000 cal yr BP

There are a few samples that impact the minimum timing of retreat model in the early Holocene ([Fig. 8](#)). Several marine shell dates from northwestern mainland Nunavut are from this period, with the oldest ages of 11 500–10 800 cal yr BP (GSC-5999, [McNeely, 2006](#)) and 11 700–11 100 cal yr BP (GSC-6081, [Dredge et al., 1999](#)). A luminescence date south of Great Slave Lake has an age of 10.5 ± 0.5 ka (SFU-O-159 [Wolfe et al., 2004](#)). There are several dates from northeastern Alberta that are early Holocene in age, but the samples that impact the model the most are two wood samples from a delta that formed in glacial Lake McConnell, with ages of 11 400–11 200 cal yr BP (WAT-2661 and WAT-2662, [Smith, 1994](#)). In western Saskatchewan the most significant date is a sample of plant macrofossils that has an age of 11 700–11 300 cal yr BP (UCIAMS-34698, [Anderson, 2012](#)). A sample of wood from northwest of Lake Superior with an age of 11 600–10 700 cal yr BP (ETH-31001, [Lowell et al., 2009](#)) impacts the model in the area north of the Ontario-Minnesota border.

7.5. 10 000–8000 cal yr BP

A few samples during the period between 10 000 and 8000 cal yr BP significantly increase the area constrained to be ice free ([Fig. 9](#)). Twigs from an ice contact deposit with an age of 10 000–9200 cal yr BP (TO-4241, [Dredge et al., 1999](#)) provide the minimum timing of retreat for a large region between Great Bear Lake and north of Great Slave Lake. A wood sample with an age 10 400–9300 cal yr BP (AECV-915C, [Smith, 1992](#)) indicates that south-eastern glacial Lake Mackenzie was ice free. A twig (TO-7868, [Seppä et al., 2003](#)) and marine shell dates (GSC-110-2, [Lowdon and Blake, 1968](#)) indicate that the region southeast of Bathurst Inlet in Nunavut was ice free by 9000–8400 cal yr BP. Several wood samples from glacial Lake McConnell near the town of Fort Smith, Northwest Territories, date to this period, the oldest having an age of 9500–8700 cal yr BP (I-14568, [Smith, 1994](#)). Twigs from central Manitoba have an age of 8600–8400 cal yr BP (CAMS-32189 [Morlan et al., 2000](#)). Two marine shell samples with ages of 9000–7600 cal yr BP (BGS-813, [Nielsen et al., 1986](#)) and 8400–7900 cal yr BP (GSC-3070, [Morlan et al., 2000](#)) constrain the minimum timing of retreat to northern Manitoba. A charcoal sample from western Ontario has an age of 9400–8800 cal yr BP (Beta-111667, [Dyke et al., 2003](#)).

7.6. Final stages of glaciation – 8000–6000 cal yr BP

There are seven samples that are relevant to the minimum timing of retreat from 8000 to 6000 cal yr BP ([Fig. 9](#)). A woody scale from northern Manitoba has an age of 8200–7600 cal yr BP (CAMS-109288, [Camill et al., 2012](#)). Two marine shells from west of Hudson Bay in Nunavut have ages of 7400–6900 cal yr BP (GSC-5234, [McNeely and Atkinson, 1995](#)) and 7200–6700 cal yr BP (GSC-2042, [McNeely and Brennan, 2005](#)). In northeastern mainland Nunavut, a marine shell date has an age of 6400–6000 cal yr BP (GSC-6839, [Dredge and McMartin, 2005](#)). There are three dates west of the Keewatin sector divide including marine shells with ages of 6800–6300 and 6500–6100 cal yr BP (GSC-693, [Lowdon and Blake, 1968](#) and GSC-6857, [McMartin et al., 2006](#)) and a sample of *Salix* charcoal with an age of 6400–6100 cal yr BP (GSC-2152, [McNeely, 1989](#)).

Fig. 10. Minimum timing of retreat for deglaciation of the western Laurentide Ice Sheet at 10.8 cal kyr BP (a) without extrapolating the minimum age of the Cree Lake Moraine, and (b) extrapolating the age of the minimum age of 11 200–10 800 cal yr BP across the length of the moraine. Orange line is the location of the Cree Lake Moraine (Fulton, 1995). The light blue line is the margin reconstruction by Dyke (2004) at 10.8 cal kyr BP (9.5 ^{14}C kyr BP). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

There are no samples that constrain the final timing of deglaciation for much of the Keewatin region of Nunavut.

8. Discussion

8.1. Comparison with margin reconstructions

Figs. 7–9 show the inferred margin positions of Dyke (2004) along with this study's models of the minimum timing of deglaciation. In most cases, the minimum timing of deglaciation lags the ice free areas determined by Dyke (2004). The only exceptions are in Alberta, where recently published luminescence dates indicate earlier ice free conditions. There are a few causes for the lag between margin reconstructions and the minimum timing of deglaciation. During early deglacial times, the vegetation records indicate a tundra climate (Dyke et al., 2004), so there was likely limited production of plants that could be preserved for radiocarbon dating. The delay of recolonization may not be present in all locations, as Fisher et al. (2009) suggested in the Fort McMurray area. Ice proximal lakes covered vast regions of the study area, and are often devoid of sufficient material suitable for radiocarbon dating (e.g. Risberg et al., 1999; Teller et al., 2000). Finally, the distribution of dates means that a single sample is often the only constraint on the timing of deglaciation over several hundred to thousands of km^2 .

Of the several hundred radiocarbon and luminescence dates used to produce the models on Figs. 7–9, only 55 have a significant impact on advancing the area constrained to be ice free based purely on absolute chronology. Additional constraints in key locations could greatly improve the model of the minimum timing of retreat. Extrapolation of constraints along broad moraines could provide the minimum timing of retreat over a wide area. For example, the Cree Lake Moraine in northern Saskatchewan (Fig. 1) has a minimum age of 11 200–10 800 cal yr BP (ETH-30175) according to Fisher et al. (2009). Fig. 10 shows the minimum timing of retreat when this age is extrapolated along its entire length at 10 800 cal yr BP. The reconstructed margin by Dyke (2004) at this time matches the boundary between where ice free conditions are

certain and unknown in the model. Fig. 10 illustrates the sensitivity of the modelling technique, and how additional data would change the minimum timing of retreat. Acquisition of early dates in areas where there are few data would greatly reduce the uncertainty of the timing of deglaciation.

8.2. Northwest drainage route of Lake Agassiz

The timing of drainage of Lake Agassiz through northern Alberta has been the subject of many recent investigations (i.e. Lowell et al., 2005; Teller et al., 2005; Teller and Boyd, 2006; Fisher, 2007; Couch and Eyles, 2008; Fisher et al., 2009; Murton et al., 2010; Anderson, 2012; Fisher and Lowell, 2012). There is considerable debate as to when the northwest outlet was available to flow towards the Arctic Ocean, and if it was at the start, and possibly the cause of the Younger Dryas. The model of minimum timing of retreat (Fig. 9) shows that in the region between the Mackenzie Delta and the northwestern outlet of Lake Agassiz is only certain to be ice free during the early Holocene (Section 7.4). Even when bulk dates are included (Section 6), the minimum timing of retreat post-dates the start of the Younger Dryas. This does not completely eliminate the possibility that a glacial lake drained from the southwestern part of the ice sheet in the early Younger Dryas to account for the erosional event observed in the Mackenzie Delta by Murton et al. (2010), as there are few data between the two locations. The geomorphic and chronological evidence presented by Fisher et al. (2009) and Fisher and Lowell (2012) indicates that it was unlikely to be Lake Agassiz.

9. Conclusions

This study presents an assessment of the minimum timing of ice free conditions in the area covered by the western Laurentide Ice Sheet using previously published radiocarbon and luminescence dates. A map of the direction of retreat was constructed using geomorphic features, such as moraines, streamlined landforms and eskers. The direction of retreat was used to extrapolate chronological constraints to determine when areas were certain to be ice free. The model shows that there is a deficiency of data for large

regions, with 55 samples identified as providing the greatest influence on the model. In many areas, the margin chronology reconstructed by Dyke and Prest (1987) and Dyke (2004) is up to several hundred kilometres from the nearest constraint. This is most evident in areas north of 60°N, where there a single data point can be the only constraint over large regions. Some areas with a high density of significant dates include the area west of Lake Superior, central Alberta, and the glacial Lake Mackenzie basin. Excluding radiocarbon dates of questionable material makes the minimum timing of retreat over 1000 years younger in some locations. This has potential implications for ice sheet modelling, as early retreat from a region could cause ice volume to be underestimated, and impact the timing of meltwater when entered the ocean. Considering the contributions of the western Laurentide Ice Sheet to sea level change and the proposed impacts of its retreat on global climate during the late Pleistocene and early Holocene, there is a need for focused studies in areas identified by the model to improve understanding of retreat history.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at <http://dx.doi.org/10.1016/j.quascirev.2013.06.001>.

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