Near-constant retreat rate of a terrestrial margin of the Laurentide Ice Sheet during the last deglaciation

Lowell et al.

SUPPLEMENTAL MATERIAL

This file contains the Supplemental Material text, references, figures and captions. Figs. S1-S7 are at the end of this file. Supplemental tables (Tables S1-S7) are in an Excel file.

SUPPLEMENTAL TEXT

1. Sampling and age calculations

1.1 Field methodology

For consistency we first generated our own geomorphic maps from interpretation of topographic data derived from the Shuttle Radar Topography Mission (SRTM) data at three arc-second resolution. The major mapped geomorphic features replicate earlier mapping and syntheses (i.e., Zoltai, 1965; Sado, 1994, 1995; Richmond and Fullerton, 1983). This mapping is the basis for Fig. 1 in the main text. With the geomorphic framework established, instead of sampling boulders on moraines for ^{10}Be dating, we targeted boulders on and between moraines along a NE-SW-trending transect located west of Lake Superior to derive information on Laurentide Ice Sheet (LIS) retreat. This same transect was used in a prior study of basal radiocarbon ages of lakes and bogs interpreted as minimum-ages for deglaciation (Lowell et al., 2009). Distance along the transect is measured from 500 km at its southwestern end to 50 km at its northeastern end. This area of the LIS has been referred to as the “Rainy Lobe” (Wright, 1972).

We conducted two field seasons in the Thunder Bay, Ontario, region in 2006 and 2011 and accessed sample sites by helicopter and car. We sampled large (2–4 m diameter) boulders on and between moraines that showed little or no sign of post-depositional movement or modification (Table S1). We obtained ~0.5–1 kg samples from the upper 3–5 cm of boulder surfaces using a hammer and chisel or the drill-and-blast method of Kelly (2003). We measured the surface dip of each sample using a handheld Suunto compass and any shielding by topography using a Suunto clinometer. Where possible, we sampled flat rock surfaces with no dip to minimize potential uncertainties in the shielding correction. We recorded the sample locations using a handheld Garmin GPS. We averaged GPS measurements over the course of 2–5 minutes, sufficient to record 100 measurements. We then recorded the average location and elevation value for each sample (vertical error ± 3 m, horizontal error ± 1 m).

Fifteen of the fifty-one ^{10}Be ages presented were previously published in a paper about meltwater channels west and northwest of Lake Nipigon (Kelly et al., 2016) (Tables S1-S3).

1.2 Lab methodology

We measured the thickness of each sample to the nearest millimeter (± 1 mm) using hand-calipers before crushing and milling the sample to the 210-750 μm grain-size fraction. We then etched quartz and separated it from the whole-rock sample through a series of O-phosphoric acid, sodium hydroxide, and hydrofluoric-nitric acid leaches. Once we obtained pure quartz, we spiked each sample with a known mass of low-level ^9Be carriers made from a deeply buried beryl crystal and digested the sample in hydrofluoric acid (Table S2). We used a modified version of the procedures of Schaefer et al. (2009) to isolate beryllium. Samples previously published by Kelly et al. (2016) were prepared at Lamont-Doherty Earth Observatory using the carrier “carrier4” and measured with the beryllium standard KNSTD. All other samples were prepared at Dartmouth College using the carrier “4G Beryl” and measured using the beryllium standard 07KNSTD (Table S1). $^{10}\text{Be}/^9\text{Be}$ ratios of samples were measured at the Center for Accelerator Mass Spectrometry at Lawrence Livermore National Laboratory.

We ran three replicate samples (AF-21x, AF-24x and AF-25x) to check the internal consistency of the lab processing and measurements (Table S1). The replicate samples are from the same quartz sample as AF-21, AF-24 and AF-25, respectively, but were processed and measured separately (Table S2). The ^{10}Be ages of the replicate samples are the same within the internal uncertainty of the original samples (Table S3) and, therefore, we use the original sample ^{10}Be ages in our analyses.

1.3 ^{10}Be age calculation

We calculated the Thunder Bay region ^{10}Be ages using the online calculator formerly known as the CRONUS-Earth online calculator v3 (Balco et al., 2008) with the Northeast North America (NENA) production rate (Balco et al., 2009) and the time-independent (“St”) scaling scheme of Lal (1991) and Stone (2000) (Table S3). Calculating the ^{10}Be ages using other production rates such as the CRONUS-Earth global production rate (Borchers et al., 2016) and/or time-dependent (e.g., “Lm”, “LSDn”) scaling methods yields ^{10}Be ages within $\sim 3\%$ of the reported ages (Table S2). For all calculations, we assume a rock density of 2.7 g cm^{-3} . Our interpretations of the ^{10}Be ages do not change significantly depending on the ^{10}Be production rate or scaling scheme used to calculate the ages.

We corrected the ^{10}Be ages for subaerial erosion of the boulder surfaces since deglaciation. Many samples showed evidence of surface erosion such as exfoliation and raised quartz veins. Based on this evidence, we assume an erosion rate of 0.0003 cm a^{-1} . The ^{10}Be ages calculated with an erosion rate of 0.0003 cm a^{-1} are $\sim 2\text{--}4\%$ older than those with no erosion (Table 3). We did not correct the ^{10}Be ages for the potential influence of cover by snow, sediment or vegetation. Such corrections may change the individual ages, but are unlikely to have a significant impact on the estimated retreat rates.

We estimated the potential impact of post-glacial isostatic uplift on the ^{10}Be ages using the iceTEA (Tools for Exposure Ages from ice margins) “Correct for Elevation Change” tool (Jones et al., 2019; Table S4). We selected samples located at the southern (AF-109, 110), middle (AF-128, 129) and northern (AF-26, 26) sections of the transect and calculated the ^{10}Be ages of these samples assuming uplift after the ice models ICE-5G (Peltier, 2004) and ICE-6G (Peltier et al., 2015) and “Lm” scaling (Lal, 1991; Stone, 2000; Nishiizumi et al., 1989). The uncorrected ^{10}Be ages (Table S4) are different from the ^{10}Be ages reported in Table S3 because iceTEA uses

the CRONUScale calculation framework (Marrero et al., 2016) and the CRONUS-Earth global production rate (Borchers et al., 2016). The ^{10}Be ages calculated using the ICE-5G model are ~8-10% older than the ^{10}Be ages uncorrected for elevation change, and those calculated using the ICE-6G model are ~12-31% older than the ^{10}Be ages uncorrected for elevation change.

We chose not to correct the ^{10}Be ages for changes in elevation due to isostatic uplift since deglaciation for two reasons. First, the ICE-5G and ICE-6G models (Peltier, 2004; Peltier et al., 2015) use isochrons (i.e., ice-margin history) from Dyke (2004) to approximate and adjust ice-model thickness, and any inaccuracies in the isochrons are propagated into the ice models (Peltier et al., 2005). Since our research here shows discrepancies with the isochrons from Dyke (2004, updated by Dalton et al., 2020), we suggest that there are likely inaccuracies in the ice model for this region. Second, the ^{10}Be ages corrected for elevation change at the southern end of the transect are as old as ~25 ka. This is much older than any other reconstruction of ice-margin history (Wright, 1972; Mooers and Lehr, 1997). Therefore, we acknowledge that a correction for post-glacial uplift may make the ^{10}Be ages older, but we cannot make this correction accurately at this time. We note that this correction would increase the offset between the ^{10}Be ages and the existing isochron-based age of deglaciation along the transect.

1.4 Recalculation of ^{10}Be ages from Leydet et al. (2018)

In order to evaluate the ^{10}Be ages and interpretations presented here with those from Leydet et al. (2018), we recalculated the ages presented in Leydet et al. (2018) with the same methods used here (Table S5). Specifically, we use the online calculator formerly known as the CRONUS-Earth online calculator v3 (Balco et al., 2008) with the Northeast North America (NENA) production rate (Balco et al., 2009) and the time-independent (“St”) scaling scheme of Lal (1991) and Stone (2000). To make an “apples-to-apples” comparison between the ^{10}Be ages (i.e., to check for consistency of deglaciation among the sites), we use the uncorrected elevation given by Leydet et al. (2018; i.e., sample elevation not corrected for isostatic uplift), a rock density of 2.7 g cm^{-3} and an erosion rate of 0.0003 cm a^{-1} .

1.5 Radiocarbon ages along the transect

Radiocarbon ages provide minimum-limiting ages of deglaciation along the transect. For ages determined by Lowell et al. (2009), the sample locations are shown as green numbers in Fig. 1 in the paper. Lowell et al. (2009) also includes radiocarbon ages used to define the isochrons reported in Dyke (2004) and Dalton et al. (2020) and the sample locations for these are shown as green letters in Fig. 1. All radiocarbon ages from Lowell et al. (2009) are plotted as red triangles with uncertainties in the time-distance diagram in Fig. 2. Radiocarbon ages presented in the paper and discussed here are calibrated to calendar years before present using Calib 7.1 and IntCal13 (Reimer et al., 2013).

The green area in Fig. 2 represents the isochrons defined by Dalton et al. (2020), which were originally reported in radiocarbon years before present. We converted the radiocarbon age associated with each isochron using Calib 7.1 and IntCal13 (Reimer et al., 2013) using an assumed uncertainty as specified in Dalton et al. (2020) and generated an envelope that includes the uncertainties.

2. Deglaciation age modeling

2.1 Applications of Bayesian modeling approach

We employed the Bayesian modeling approach in the Bacon program v2.5.6 (<http://chrono.qub.ac.uk/blaauw/bacon.html>; Blaauw and Christen, 2011) in two ways: 1) to extend the transect to the southwest and constrain the age of the Vermilion Moraine, and 2) to generate retreat rate estimates of the LIS margin. The program uses an estimated sediment-accumulation rate and its variability (“memory”) as inputs for millions of Markov Chain Monte Carlo iterations to generate an age-depth model for a sediment sequence.

2.2 Extension of the transect to the southwest

To extend the transect to the southwest and constrain the age of the Vermilion Moraine, we included radiocarbon ages of sediment cores from Kylen Lake, Minnesota, located ~26 km south of the Vermilion Moraine (site “A” in Fig. 1). Three prior studies determined radiocarbon ages of sediments in Kylen Lake (Birks et al., 1981; Lund and Banerjee 1985; Norris, 2019; Fig. S1). Table S6 lists all radiocarbon ages from sediment cores from the lake. We were interested in the oldest reliable radiocarbon ages from the sediment cores, which provide a minimum-limiting age for deglaciation. Lund and Banerjee (1985) report a reversal of radiocarbon ages at the base of a core and suggest that some of the ages were too old or contaminated. Based on the stratigraphy established for core KLM-70 (Birks et al., 1981), we placed radiocarbon ages from cores KLM-75C and KLM-76C (Lund and Banerjee, 1985) on a common depth scale (Fig S1, Table S6).

Norris (2019) recovered a new sediment core from Kylen Lake in 2016 and added six new radiocarbon ages from the problematic interval at the bottom of the core. A correlation between this core and the prior cores was accomplished using lithology and loss-on-ignition patterns (Fig. S1). Norris (2019) evaluated the radiocarbon ages from prior work and omitted outliers and questionable results. He developed an age-depth model for the 20 retained radiocarbon ages (Fig. S2). Using these radiocarbon ages and the Bacon program v2.5.6, we estimate a basal age of 18,057 +562/-408 Cal yr BP for the lowest modeled depth of 1093 cm. The uncertainty estimate is derived from the 95% confidence interval. We use this age in the transect and associated retreat rate modeling, recognizing it is a minimum-limiting age for deglaciation.

2.3 Modeling LIS retreat

We assume that the time of ice retreat with distance along a transect is similar to age with depth in a sediment sequence. Therefore, we use age and distance to determine a retreat rate, instead of using age and depth to determine a sediment accumulation rate. As input to the model, we used the modeled basal age from Kylen Lake (see section 2.2, above) and the 51 ¹⁰Be ages (presented here and from Kelly et al., 2016, Table S3) and their respective distances along the transect, assuming that age is the youngest at the northeastern end of the transect. We ran two experiments. The first assumes that there are no hiatuses in the pattern of deglaciation (Fig. S3). The second assumes that the major moraine sets mark standstills or readvances of the ice-margin and, thus, hiatuses in the pattern of deglaciation (Figs. 2 and S4). The resulting retreat rates determined in both experiments reflect a pattern of deglaciation over time. Similar to our

approach here, a Bayesian modeling approach has been used to determine deglaciation of the Irish Sea ice stream (Chiverrell et al., 2013).

For the results shown in Figs. 2, S3 and S4, we used the Bacon program v2.5.6 prior default values of 20 a/m for retreat rate, 5 for shape factor, 4 for memory strength, and 0.7 for memory mean (Blaauw and Christen, 2011). We used the prior default values of $t.a=3$ and $t.b=4$ to specify the shape of the student's-t distribution which allowed identification of outliers based on ^{10}Be age external errors. We conducted preliminary modeling to assess whether the prior default values yielded reasonable results. Since they did, we used the values given above; however, we did not conduct a formal sensitivity analysis of the values. These settings resulted in 76 sections each of which is 5 km in length.

For one experiment (Figs. 2, S4), we modeled five hiatuses along the transect representing the Vermilion, Steep Rock, Eagle-Finlayson, Dog Lake and Lac Seul Moraines. We set the hiatus locations at 423, 308, 295, 227, and 200 km, respectively, and used a maximum hiatus duration of 1500 a. We chose not to include the Brule Creek Moraine as a hiatus because the actual location of the moraine on the transect line is uncertain (Zoltai, 1965). As mentioned in the paper, mapping by Zoltai (1965) shows the Brule Creek Moraine truncating an unnamed moraine between it and the Steep Rock Moraine, and parts of the Eagle-Finlayson Moraine overlapping the Steep Rock Moraine. Therefore, at least some moraines in this set register readvances.

2.4 Uncertainties with the modeling

The uncertainties in modeled deglaciation ages vary in magnitude with distance along the transect and are not symmetrical around the modeled mean age. Although the individual ^{10}Be ages have a Gaussian distribution, the distribution of ages with distance along the transect is not uniform and, therefore, uncertainty in deglaciation age varies over the transect. We summarized the uncertainties as histograms and plotted the positive and negative errors along the transect in Figs. S5 and S6. Overall, for the experiment with hiatuses, the mean of the positive error is 572 a with a standard deviation of 119 a (Fig. S5). The mean negative error is 563 a with a standard deviation of 199 a (Fig. S6).

Our approach has some caveats that should be noted. First, the Bayesian modeling approach assumes a constant retreat rate from one segment to the next. Although this may favor similar retreat rates among segments, the assumed values of retreat rates are reset between each segment and at each hiatus. The initial value was set at 20 m/a, so a resulting mean retreat rates of ~ 48 and 52 m a^{-1} (for experiments assuming no hiatuses and hiatuses, respectively) indicates that the models are honoring the data. The return of similar values along distinct portions of the transect indicates that our results are not simply a modeling artifact. Second, the analysis of the uncertainties indicates that, at the 95% confidence level, the uncertainties vary with distance along the transect (Figs. S5, S6). From the Vermilion Moraine to the Dog Lake Moraine, most positive/negative error values are ~ 650 a, whereas north of the Dog Lake Moraine they are ~ 450 a. The Bayesian modeling approach yields results with uncertainties lower than the reported ^{10}Be external uncertainties. This means that the modeling results are comparable with the dating technique employed. Third, it could be argued that the spatial density of the chronologic data could be improved. The advantage of sampling both between and on moraines along a spatial

transect is that we enabled insights into the deglaciation of the ice-sheet margin rather than determining just ages of major moraine sets.

2.5 Bacon modeling of ^{10}Be ages from Leydet et al. (2018)

Leydet et al. (2018) reported 23 ^{10}Be ages from four sites in the Thunder Bay region. The sites are not located directly on the transect used here but are generally north of the Brule Creek Moraine and just north of the Dog Lake Moraine (see Fig. 1). Instead of determining ages of deglaciation, Leydet et al. (2018) aimed to measure exposure ages for the hypothesized outlets for glacial Lake Agassiz. For comparison, we recalculate these ^{10}Be ages using the same parameters and methodology used for the ^{10}Be ages presented here (Table S5). We use all ^{10}Be ages from Leydet et al. (2018), including those identified as outliers by the authors. We plot the recalculated ^{10}Be ages at approximate distances along the transect presented here and run an experiment assuming hiatuses at the major moraine sets (Fig. S7). These modeling results yield a mean retreat rate of $\sim 99 \text{ m a}^{-1}$ for this part of the transect. They also show a deglaciation age younger than suggested by the ^{10}Be ages and modeling presented in this paper. Specifically, they show deglaciation at 12.5 ka at $\sim 295 \text{ km}$ and 11.3 ka at $\sim 200 \text{ km}$ along the transect compared to our estimates of 14.7 ka and 12.2 ka, respectively, at these locations (i.e., Figs. 2, S4, Table S7).

3. LIS margin retreat-rate and hiatus duration estimates

The Bacon approach provides an estimate of uncertainty for the retreat of the LIS retreat along the transect and we have selected a confidence level of 95%. For the discussion and conclusions of this paper, we use the most probable age model (shown in Fig. 2) and retreat rates calculated from this model. However, for completeness, we calculate the possible ranges of estimated retreat rates at 95% confidence levels (Table S7).

First, we tabulate the possible range of retreat rate estimates (Table S7). Given the locations of moraines are taken to represent hiatuses, we focus on the sections of the transect between hiatuses. For each of the five sections we report the weighted mean retreat rate and retreat rates calculated using the maximum positive and negative uncertainties at the 95% confidence level (Table S7). From these we estimate retreat rates (taken as positive number) in m/a . The maximum and minimum rates were computed from the respective 95% young and old ages at each end of the transect. The maximum retreat rate is derived from the youngest age at the start of the section and the oldest age at the end of the transect. The minimum retreat rate is derived from the oldest age at the start of the section and the youngest age at the end of the transect. We note that some calculations yield negative values which represent impossible scenarios. Although there is no reason to assume that retreat rates were constant over time, we note that they are similar. The two oldest sections between hiatuses have mean retreat rates (59.3 and 52.0 m a^{-1}) that are indistinguishable within error from the two youngest sections (54.7 and 54.7 m a^{-1}). For the maximum retreat rates, calculations for two of the sections yield negative values, but the remaining three are 119.5 , 107.4 and 91.2 m a^{-1} (from oldest to youngest). The minimum rates range from 9.4 to 37.0 m a^{-1} .

Similar to our calculation of retreat rates above, we calculated the durations of hiatuses using the respective 95% young and old ages at each end of a hiatus. We combined the hiatuses of the Steep Rock and Eagle-Finlayson Moraines (at 308 and 295 km , respectively) because

there are no chronologic data that constrain the age of the Eagle-Finlayson moraine. Therefore, in Table S7, we refer to this 13-km segment as the “Steep Rock and Eagle-Finlayson” Moraines. The mean hiatus durations are 499, 607, 228, 93 a for the Vermilion, “Steep Rock and Eagle-Finlayson”, Dog Lake and Lac Seul Moraines, respectively (Table S7).

4. Estimating ice thickness at the study site used for the TraCE-21ka transient climate simulation

For the purposes of understanding how LIS reconstructions may influence climate model output, we estimated how ice thickness changed over time in the TraCE-21ka transient climate simulation (Liu et al., 2009). This simulation uses ice thickness prescribed by the ICE-5G (VM2) reconstruction (Peltier, 2004) which was developed using LIS isochrons from Dyke (2004). As a surrogate for the surface elevation in the simulation, we extracted the surface geopotential at the study site (center latitude: 50.1°N, center longitude: -90°W, Fig. 3). We converted it to geopotential height by dividing by the sea-level gravitational acceleration, 9.8 m/s². Since the ground surface at this site is generally <500 m asl, we assume that the geopotential height of ~3000 to 500 m asl from ~18 to 11 ka reflects a changing LIS thickness. Thus, from ~18 to 14 ka, we interpret an ~2000 m-thick LIS over the study site. This ice thickness is in contrast with what we have reconstructed here, with deglaciation of much of the region by ~12 ka. The estimated ice-thickness at this site would influence climate model output and, thus, interpretations of paleoclimate changes and mechanisms.

REFERENCES CITED

- Balco, G., Stone, J. O., Lifton, N. A., and Dunai, T. J., 2008, A complete and easily accessible means of calculating surface exposure ages or erosion rates from ¹⁰Be and ²⁶Al measurements: Quaternary Geochronology, v. 3, no. 3, p. 174-195.
- Balco, G., Briner, J., Finkel, R. C., Rayburn, J. A., Ridge, J. C., and Schaefer, J. M., 2009, Regional beryllium-10 production rate calibration for late-glacial northeastern North America: Quaternary Geochronology, v. 4, no. 2, p. 93-107.
- Birks, H. J. B., 1981, Late Wisconsin Vegetational and Climatic History at Kylen Lake, Northeastern Minnesota: Quaternary Research, v. 16, no. 3, p. 322-355.
- Blaauw, M., and Christen, J. A., 2011, Flexible paleoclimate age-depth models using an autoregressive gamma process: Bayesian Analysis, v. 6, no. 3, p. 457-474.
- Borchers, B., Marrero, S., Balco, G., Caffee, M., Goehring, B., Lifton, N., Nishiizumi, K., Phillips, F., Schaefer, J., and Stone, J., 2016, Geological calibration of spallation production rates in the CRONUS-Earth project: Quaternary Geochronology, v. 31, p. 188-198.

- Chiverrell, R. C., Thrasher, I. M., Thomas, G. S. P., Lang, A., Scourse, J. D., van Landeghem, K. J. J., McCarroll, D., Clark, C. D., Cofaigh, C. Ó., Evans, D. J. A., and Ballantyne, C. K., 2013, Bayesian modelling the retreat of the Irish Sea Ice Stream: *Journal of Quaternary Science*, v. 28, no. 2, p. 200-209.
- Dalton, A. S., Margold, M., Stokes, C. R., Tarasov, L., Dyke, A. S., Adams, R. S., Allard, S., Arends, H. E., Atkinson, N., Attig, J. W., Barnett, P. J., Barnett, R. L., Batterson, M., Bernatchez, P., Borns, H. W., Breckenridge, A., Briner, J. P., Brouard, E., Campbell, J. E., Carlson, A. E., Clague, J. J., Curry, B. B., Daigneault, R.-A., Dubé-Loubert, H., Easterbrook, D. J., Franzi, D. A., Friedrich, H. G., Funder, S., Gauthier, M. S., Gowan, A. S., Harris, K. L., Hétu, B., Hooyer, T. S., Jennings, C. E., Johnson, M. D., Kehew, A. E., Kelley, S. E., Kerr, D., King, E. L., Kjeldsen, K. K., Knaeble, A. R., Lajeunesse, P., Lakeman, T. R., Lamothe, M., Larson, P., Lavoie, M., Loope, H. M., Lowell, T. V., Lusardi, B. A., Manz, L., McMartin, I., Nixon, F. C., Occhietti, S., Parkhill, M. A., Piper, D. J. W., Pronk, A. G., Richard, P. J. H., Ridge, J. C., Ross, M., Roy, M., Seaman, A., Shaw, J., Stea, R. R., Teller, J. T., Thompson, W. B., Thorleifson, L. H., Utting, D. J., Veillette, J. J., Ward, B. C., Weddle, T. K., and Wright, H. E., 2020, An updated radiocarbon-based ice margin chronology for the last deglaciation of the North American Ice Sheet Complex: *Quaternary Science Reviews*, v. 234, p. 106223.
- Dyke, A. S., 2004, An outline of North American deglaciation with emphasis on central and northern Canada, *in* Ehlers, J., and Gibbard, P. L., eds., *Quaternary Glaciations - Extent and Chronology, Part II North America*: Amsterdam, Elsevier B.V., 488 p.
- Jones, R.S., Small, D., Cahill, N., Bentley, M.J., and Whitehouse, P.L., 2019. iceTEA: Tools for plotting and analyzing cosmogenic-nuclide surface-exposure data from former ice margins: *Quaternary Geochronology*, v. 51, p. 72-86.
- Kelly, M.A. 2003. The late Würmian age in the western Swiss Alps: Last Glacial Maximum (LGM) ice-surface reconstruction and ^{10}Be dating of late-glacial features. Ph.D. Dissertation, University of Bern, Switzerland, 105 p.
- Kelly, M. A., Fisher, T. G., Lowell, T. V., Barnett, P. J., and Schwartz, R., 2016, ^{10}Be ages of flood deposits west of Lake Nipigon, Ontario: evidence for eastward meltwater drainage during the early Holocene Epoch: *Canadian Journal of Earth Sciences*, v. 53, no. 3, p. 321-330.
- Lal, D. 1991. Cosmic ray labeling of erosion surfaces: in situ nuclide production rates and erosion models. *Earth and Planetary Science Letters*: v. 104, p. 424–439.
- Leydet, D. J., Carlson, A. E., Teller, J. T., Breckenridge, A., Barth, A. M., Ullman, D. J., Sinclair, G., Milne, G. A., Cuzzone, J. K., and Caffee, M. W., 2018, Opening of glacial Lake

- Agassiz's eastern outlets by the start of the Younger Dryas cold period: *Geology*, v. 46, no. 2, p. 155-158.
- Liu, Z., Otto-Bliesner, B. L., He, F., Brady, E. C., Tomas, R., Clark, P. U., Carlson, A. E., Lynch-Stieglitz, J., Curry, W., Brook, E., Erickson, D., Jacob, R., Kutzbach, J., and Cheng, J., 2009, Transient simulation of last deglaciation with a new mechanism for Bolling-Allerod warming: *Science*, v. 325, no. 5938, p. 310-314.
- Lowell, T. V., Fisher, T. G., Hajdas, I., Glover, K., Loope, H., and Henry, T., 2009, Radiocarbon deglaciation chronology of the Thunder Bay, Ontario area and implications for ice sheet retreat patterns: *Quaternary Science Reviews*, v. 28, no. 17-18, p. 1597-1607.
- Lund, S. P., and Banerjee, S. K., 1985, Late Quaternary paleomagnetic field secular variation from two Minnesota Lakes: *Journal of Geophysical Research: Solid Earth*, v. 90, no. B1, p. 803-825.
- Marrero, S.M., Phillips, F.M., Borchers, B., Lifton, N., Aumer, R., and Balco, G., 2016. Cosmogenic nuclide systematics and the CRONUScal program: *Quaternary Geochronology*, v. 31, p. 160-187.
- Mooers, H.D., and Lehr, J.D., 1997. Terrestrial record of Laurentide Ice Sheet reorganization during Heinrich Events: *Geology*, v. 25, no. 11, p. 987-990.
- Nishiizumi, K., Winterer, E.L., Kohl, C.P., Klein, J., Middleton, R., Lal, D., and Arnold, J.R. 1989. Cosmic ray production rates of ^{10}Be and ^{26}Al in quartz from glacially polished rocks. *Journal of Geophysical Research*: v. 94, p. 17907–17915.
- Norris, N. 2019. The Mystery Interval: hydrologic changes and circulation pattern changes?, University of Cincinnati. MS Thesis, 63 p.
- Peltier, W.R., Argus, D.F., and Drummond, R., 2015. Space geodesy constrains ice age terminal deglaciation: The global ICE-6G_C (VM5a) model. *Journal of Geophysical Research: Solid Earth*, v. 120, 450-487.
- Peltier, W. R., 2004, Global Glacial Isostasy and the Surface of the Ice-Age Earth: The ICE-5G (VM2) Model and GRACE: *Annual Review of Earth and Planetary Sciences*, v. 32, no. 1, p. 111-149.
- Reimer, P. J., Bard, E., Bayliss, A., Beck, J. W., Blackwell, P. G., Ramsey, C. B., Buck, C. E., Cheng, H., Edwards, R. L., Friedrich, M., Grootes, P. M., Guilderson, T. P., Haflidason, H., Hajdas, I., Hatte, C., Heaton, T. J., Hoffmann, D. L., Hogg, A. G., Hughen, K. A., Kaiser, K. F., Kromer, B., Manning, S. W., Niu, M., Reimer, R. W., Richards, D. A., Scott, E. M., Southon, J. R., Staff, R. A., Turney, C. S. M., and van der Plicht, J., 2013,

- Intcal13 and Marine13 Radiocarbon Age Calibration Curves 0-50,000 Years Cal Bp: Radiocarbon, v. 55, no. 4, p. 1869-1887.
- Richmond, G. M., and Fullerton, D. S., 1983, Quaternary Geologic Map of the Minneapolis 4° x 6° Quadrangle, United States, scale 1:1,000,000.
- Sado, E. V., Fullerton, D. S., Goebel, J. E., Ringrose, S. M., 1995. Quaternary Geologic Map of the Lake of the Woods 4° x 6° Quadrangle, United States and Canada, scale 1:1,000,000. U.S. Geological Survey, Report: I-1420 (NM-15). U.S. Geological Survey, Reston, VA. 1 sheet.
- Sado, E. V., Fullerton, D. S., and Farrand, W. R., 1994, Quaternary geologic map of the Lake Nipigon 4° x 6° quadrangle, United States and Canada, scale 1:1,000,000. U.S. Geological Survey, Report: I-1420 (NM-16). U.S. Geological Survey, Reston, VA. 1 sheet.
- Schaefer, J. M., Denton, G. H., Kaplan, M., Putnam, A., Finkel, R. C., Barrell, D. J., Andersen, B. G., Schwartz, R., Mackintosh, A., Chinn, T., and Schluchter, C., 2009, High-frequency Holocene glacier fluctuations in New Zealand differ from the northern signature: Science, v. 324, no. 5927, p. 622-625.
- Stone, J. O., 2000, Air pressure and cosmogenic isotope production: Journal of Geophysical Research: Solid Earth, v. 105, no. B10, p. 23753-23759.
- Wright, H. E. J., 1972, Quaternary History of Minnesota, in Sims, P. K., and Morey, G. B., eds., Geology of Minnesota: A centennial volume: St. Paul, Minnesota Geological Survey, p. 515-547.
- Zoltai, S. C., 1965, Glacial features of the Quetico-Nipigon area, Ontario: Canadian Journal of Earth Sciences, v. 2, p. 247-269.

SUPPLEMENTAL TABLES AND FIGURES

Supplemental Tables (see separate Excel file)

Table S1. ^{10}Be sample metadata needed to determine ^{10}Be ages formatted for the online calculator formerly known as the CRONUS-Earth online calculator v3 (Balco et al., 2008).

Table S2. ^{10}Be sample chemistry data including the amounts of quartz and ^9Be carrier used, as well as the $^{10}\text{Be}/^9\text{Be}$ ratios and uncertainties measured at CAMS LLNL. The Be standard 07KNSTD is an abbreviation for 07KNSTD3110.

Table S3. ^{10}Be ages and internal (int) and external (ext) uncertainties calculated using the online calculators formerly known as the CRONUS-Earth online calculators v3 (Balco et al., 2008) with the Northeastern North America (NENA) production rate (Balco et al., 2009). The ^{10}Be ages and external uncertainties calculated using the time-independent (“St”) scaling scheme of Lal (1991) and Stone (2000) and assuming an erosion rate of 0.0003 cm a^{-1} are used in our analysis (and are highlighted in green). ^{10}Be ages and uncertainties calculated assuming zero erosion are also shown (columns L-T). The percent change assuming an erosion rate of 0.0003 cm a^{-1} is shown in column U.

Table S4. ^{10}Be ages calculated using the iceTEA “Correct for Elevation Change” tool (Jones et al., 2019). The selected ^{10}Be ages are calculated using the ice models ICE-5G (I5G) and ICE-6G (I6G) and the percent change assuming uplift is shown in column L.

Table S5. Leydet et al. (2018) recalculated ^{10}Be ages using the online calculators formerly known as the CRONUS-Earth online calculators v3 (Balco et al., 2008) with the Northeastern North America (NENA) production rate (Balco et al., 2009) and the time-independent (“St”) scaling scheme of Lal (1991) and Stone (2000). The Be standard 07KNSTD is an abbreviation for 07KNSTD3110.

Table S6. All radiocarbon ages of sediment from Kylen Lake, MN, from Birks (1981), Lund and Banerjee (1985) and Norris (2019). Based on the approach outlined in section 2.1 of the supplement, these ages are plotted on a common depth scale (Fig. S1). Not all ages were used in the construction of Fig. S1 for reasons provided in column I.

Table S7. Estimated LIS retreat rates and hiatus durations based on modeling with hiatuses (Figs. 2, S4). The transect distance, mean ages, and 95% confidence interval of both the younger (-) and older (+) bounds are in columns A, B, C, and D, respectively. Columns E, F, G show the rounded mean ages used in the main text and uncertainties. Column H shows the rounded average of the + and - uncertainty values. From these values a mean, maximum and minimum possible retreat rate is estimated in columns I, J, and K. We calculated the max retreat rate (column J) using the + bound at one end of a segment and the - bound on the other end of the segment. Similarly, we calculated the minimum retreat rate (column K) using the - bound on one

end of a segment and the + bound on the other end of the segment. Using a similar algorithm, we calculated the maximum and minimum hiatus durations at each of the hiatuses (columns M, N, and O). Row 19 shows summary information.

Supplemental Figures

Figure S1. Correlation of multiple sediment cores from Kylen Lake (site “A” in Fig. 1) from various studies (Birks et al., 2017; Lund and Banerjee 1985; Norris, 2019). We aligned the sediment cores to establish a common age-depth stratigraphy. The numbers in the red circles correspond to the numbers in Table S6. Figure adapted from Norris (2019).

Figure S2. Age-depth model for sediment cores from Kylen Lake generated using the Bacon program v2.5.6 and 20 radiocarbon ages from Norris (2019; Fig. S1, Table S5). The radiocarbon ages are in blue, the red line is the “best” model based on mean age for each depth, and the gray stippled lines show 95% confidence intervals (Blaauw and Christen, 2011). Based on this analysis, we assume that the estimated basal age of $18,057 \pm 562/-408$ Cal yr BP is the most robust age for the onset of sediment accumulation in the lake. We use this as the deglaciation age at this location in the LIS retreat modeling simulations.

Figure S3. Modeling experiment using the modeled basal age from Kylen Lake (farthest left green symbol) and 51 ^{10}Be ages (green symbols), assuming no hiatuses. The upper panels show the input parameters for the Bacon program v2.5.6 as described in section 2.3. The lower panel shows the modeled deglaciation age, with the red line representing the “best” model based on mean age for each distance and the gray stippled lines showing 95% confidence intervals (Blaauw and Christen, 2011).

Figure S4. Modeling experiment using the modeled basal age from Kylen Lake (farthest left green symbol) and 51 ^{10}Be ages (green symbols), assuming hiatuses at the major moraine sets. Dashed vertical lines show the locations of moraines sets along the transect. The upper panels show the input parameters for the Bacon program v2.5.6 program as described in section 2.3. The lower panel shows the modeled deglaciation age, with the red line representing the “best” model based on mean age for each distance and the gray stippled lines showing 95% confidence intervals (Blaauw and Christen, 2011).

Figure S5. The top panel shows a histogram of positive errors for 1-km long segments along the transect. The bottom panel shows the error value with distance along transect (bottom panel). The errors are larger (~ 600 a) along the southern, older portion of the transect than along the northern, younger portion of the transect (~ 450 a). The step changes occur at the modeled hiatuses.

Figure S6. The top panel shows a histogram of negative errors for 1-km long segments along the transect. The bottom panel shows the error value with distance along transect (bottom panel). The errors are larger (~650 a) along the southern, older portion of the transect than along the northern, younger portion of the transect (~400-500 a). The step changes occur at the modeled hiatuses.

Figure S7. Modeling experiment using the 23 recalculated ^{10}Be ages from Leydet et al. (2018; also see Table S5) (green symbols), assuming hiatuses at the major moraine sets. Dashed vertical lines show the locations of moraines sets along the transect. The distance along the transect is truncated to 180-300 km which encompasses the ^{10}Be sample locations for this dataset (shown in Fig. 1). The upper panels show the input parameters for the Bacon program v2.5.6 program as described in section 2.3. The lower panel shows the modeled deglaciation age, with the red line representing the “best” model based on mean age for each distance and the gray stippled lines showing 95% confidence intervals (Blaauw and Christen, 2011).