Pollen and macrofossil-inferred palaeoclimate at the Ridge Site, Hudson Bay Lowlands, Canada: Evidence for a dry climate and significant recession of the Laurentide Ice Sheet during Marine Isotope Stage 3

APRIL S. DALTON, MINNA VÄLIRANTA, PETER J. BARNETT AND SARAH A. FINKELSTEIN

Dalton, A.S., Väliranta, M., Barnett, P. J. & Finkelstein, S.A: Pollen and macrofossil-inferred palaeoclimate at the Ridge Site, Hudson Bay Lowlands, Canada: Evidence for a dry climate and significant recession of the Laurentide Ice Sheet during Marine Isotope Stage 3.

We examine pollen, macrofossils and sedimentological proxies from the Ridge Site, an 18-m sequence of glacial and non-glacial sediments exposed along the bank of the Ridge River in the southern Hudson Bay Lowlands (HBL), Canada. Since the HBL is located in the previously-glaciated region of North America, palaeorecords from this region have important implications for understanding ice sheet palaeogeography and climate for the late Pleistocene. Two diamicton units were interpreted as subglacial till deposited by a glacier actively flowing toward the south-southwest (lower diamicton) and west-southwest (upper diamicton), respectively. Confined between these tills is a 6-m non-glacial unit, constrained to Marine Isotope Stage 3 (MIS 3; *c*. 57 000 to *c*. 29 000 a BP) by 3 radiocarbon dates. Quantitative analyses of the pollen record (dominated by Sphagnum, Cyperaceae, *Pinus*, *Picea*, *Salix*, *Alnus* and *Betula*) suggest that average summer temperature (June, July, August) was 14.6±1.51°C, which is similar to present-day at the site. Total annual precipitation was 527±170 mm as compared to 705 mm present-day. The macrofossil record confirmed the local presence of *Betula*, *Salix* and conifers. Our results, in combination with other records from the periphery of the Laurentide Ice Sheet, suggest that vast boreal forest-type vegetation, along with a drier interstadial climate, existed in the region during MIS 3. We also compare pollen-derived palaeoclimate reconstructions from the Ridge Site with reconstructions from a previously published site along the Nottaway River, HBL, which was dated to MIS 5 a-d (*c*. 109 000 to *c*. 82 000 a BP). This comparison suggests that, with additional data, it may be possible to differentiate MIS 3 and MIS 5 deposits in the HBL on the basis of relative continentality, with MIS 3 characterized by lower total annual precipitation, and MIS 5 by values similar or greater than present-day.

April S. Dalton (aprils.dalton@mail.utoronto.ca) and Sarah A. Finkelstein, Department of Earth Sciences, University of Toronto, Toronto, Canada, M5S 3B1; Minna Väliranta, Department of Environmental Sciences, University of Helsinki, Finland, FIN-00014; Peter J. Barnett, Department of Earth Sciences, Laurentian University, Sudbury, Canada, P3E 2C6

Quantitative palaeoenvironmental analyses of Pleistocene records allow for a better understanding of the role of carbon (Kleinen *et al.* 2015), abrupt climate variability (Helmens *et al.* 2015) and oceanic circulation (Böhm *et al.* 2015) in the climate system. Records from previously-glaciated regions are particularly valuable since, when dated accurately, their age(s) can be used to infer the absence of regional ice, and therefore ice sheet palaeogeography. For example, basal radiocarbon dates have been used to reconstruct the maximum extent and subsequent recession of the Laurentide Ice Sheet over North America (Dyke *et al.* 2002; Dyke 2004; Peteet *et al.* 2012). However, considerably less is known about the extent of glaciation during periods prior to the Last Glacial Maximum (LGM), since available records are often highly fragmented, poorly preserved and difficult to date. Therefore, when available, these rare palaeorecords are critically important for constraining numerical ice sheet models (Stokes *et al.* 2015).

The Missinaibi Formation is a suite of non-glacial sediments which underlie till in the Hudson Bay Lowlands (HBL), Canada (Fig. 1). Due to the position of the HBL at the centre of growth of many Pleistocene ice sheets, the age(s) of the Missinaibi Formation is important for understanding the palaeo-configuration of pre-LGM ice sheets. Chronology data suggests that some sites belonging to the Missinaibi Formation may date to Marine Isotope Stage 3 (MIS 3; *c*. 57 000 to *c*. 29 000 a BP; based on the chronology of Lisiecki & Raymo (2005)), indicating the possibility of a reduced or significantly different structure for the Laurentide Ice Sheet during the middle of the Wisconsin Glaciation (Andrews *et al.* 1983; Berger & Nielsen 1990; Dalton *et al.* 2016). However, many sub-till sites in the HBL remain undated due to ages approaching or exceeding the limit of radiocarbon dating, and the scarcity of suitable materials for optically stimulated luminescence dating and uranium-thorium dating (Dalton *et al.* 2016). As a result, it is not known whether all sub-till sites in the HBL were deposited during MIS 3, or whether the Missinaibi Formation may represent both interstadial and interglacial periods during the late Pleistocene (Terasmae & Hughes 1960; Skinner 1973).

Owing to the close relationship between vegetation and climate (Seppä & Birks 2001; Väliranta *et al.* 2015), pollen and macrofossils may play a key role in resolving the age(s) of the Missinaibi Formation. For example, if edaphic and hydrological conditions were suitable, it may be possible to recognize warmer MIS 5e (peak: *c.* 123 000 a BP) deposits by the presence of temperate tree pollen such as *Acer, Ulmus* and *Fraxinus,* all of which are found today in more temperate wetland regions (Bunting *et al.* 1998). However, none of the sub-till pollen records from the HBL report significant amounts of any such temperate taxa, and it is therefore unlikely that MIS 5e deposits are preserved as part of the Missinaibi Formation. Instead, most sub-till deposits contain boreal and wetland-type pollen dominated by *Picea* and *Pinus*, along with small amounts of *Salix*, *Alnus* and *Betula*. Some of these deposits appear to date to MIS 3 (Wyatt 1989; Dalton *et al.* 2016), or MIS 5 a-d (*c*. 109 000 a BP to *c*. 82 000 a BP; henceforth referred to as "off-peak MIS 5") (Allard *et al.* 2012), but many are undated (e.g. Terasmae & Hughes 1960; Netterville 1974; Dredge *et al.* 1990). It is not known whether vegetation in the HBL is sufficiently sensitive to distinguish between interstadial (MIS 3) and off-peak interglacial (MIS 5 a-d) sites.

The main objective of this study is to reconstruct past vegetation and palaeoenvironment using pollen, macrofossils and sedimentological proxies at a purported MIS 3 site in the HBL. Fossil pollen data will be used to reconstruct a quantitative palaeoclimate signature for MIS 3 (total annual precipitation and average summer temperature). We use the North American Pollen Database (Whitmore *et al.* 2005), along with 49 newly compiled sites from the HBL region, as the basis for our modern-day calibration set. Results from our palaeoclimate reconstruction are discussed in context of other MIS 3 sites in the periphery of the Laurentide Ice Sheet, with the goal of developing an understanding of regional-scale climate during the interstadial period. We then reconstruct palaeoclimate at a previously published off-peak MIS 5 site (Allard *et al.* 2012) to determine whether subtle vegetation and/or climate differences existed between MIS 3 and off-peak MIS 5. If quantitative statistical methods are able to discern subtle changes in vegetation assemblages and inferred palaeoclimate between MIS 3 and off-peak MIS 5 deposits, then it may be possible to use pollen records to assign ages to many of the undated sub-till sites in the HBL (e.g. Terasmae & Hughes 1960; Netterville 1974; Dredge *et al.* 1990).

Study site

The present-day HBL is a remote region which covers an area of >325 000 km^2 south and west of the Hudson and James Bays (Fig. 1). Bound to the south by the Canadian shield, this coastal plain is largely Paleozoic and Mesozoic limestone overlain by Pleistocene glacial deposits and extensive Holocene-aged peatlands (Riley 2003). Present-day isostatic rebound, paired with thick deposits of unconsolidated alluvial and glacial material, causes rivers in the HBL to meander northward at a very gradual gradient (Riley 2003). The HBL is situated in the boreal forest zone, with tundra only occurring in the extreme northwest region and some coastal areas (MacDonald & Gajewski 1992). The landscape is composed of ombrotrophic bogs (36%), minerotrophic fens (24%), permafrost wetlands (22%), swamps (13%) and marshland (5%), occurring in wooded or non-wooded environments (Riley 2003).

The study site (referred to in the field as “11-PJB-020”, but referred to here as the “Ridge Site”) is an 18-m sequence of Quaternary-aged sediments of both glacial and non-glacial origin, and is located along the Ridge River, a tributary of the Albany River, at 50.48° N, -83.88° W (Fig. 1). This site was first examined by Riley & Boissonneau (n.d.) who identified the presence of organic-bearing muds below till, but no subsequent studies were conducted. Elevation is approximately 115 metres above sea level (m.a.s.l) at the river level and 133 m.a.s.l. at the top of the section. Present-day total annual precipitation is estimated to be 705 mm and average summer temperature (June, July, August) is 15.5 °C based on interpolated climate data between the closest weather stations (Natural Resources Canada 2015).

Methods

Stratigraphic descriptions and diamicton analyses

The Ridge Site was visited by helicopter in June 2011 and again in July 2013. Three distinct units are noted: a lower diamicton, a non-glacial unit, and an upper diamicton (Fig. 2). Stratigraphic boundaries were determined by visual inspection of the section after overlying slump material was removed. Particle size for the diamicton was determined using a combination of sieves for the coarse fraction, and a Microtrac Particle Size Analyzer for the finer (silt/clay) fraction of the matrix. Carbonate content and the calcite-to-dolomite ratio for the silt and clay fraction (<0.063 mm) of the diamictons was measured on 0.85 g samples using a Chittick apparatus (Dreimanis 1962).

Multi-proxy analyses on the non-glacial unit

Three organic-bearing samples were collected from the non-glacial unit of the Ridge Site and submitted for radiocarbon dating (Fig. 2; Table 1). Organic matter was separated from the clay-rich sediment matrix by ultrasound with the addition of distilled water and sieving with a 90-µm mesh, followed by a standard acid-alkali-acid radiocarbon treatment (Hatté & Jull 2007). No rootlet structures were observed in the radiocarbon samples. One sample from the non-glacial unit was submitted for OSL dating (indicated on Fig. 2), however only 4 of 40 total aliquots had a ‘fast component’ exceeding >15 (Durcan & Duller 2011), as a result the ages were non-interpretable (data not shown). We did not pursue OSL dating at this site any further.

A set of 35 pollen samples was collected at 5- or 10-cm intervals from the non-glacial unit. The lower 20 samples were collected from the faintly bedded clay and silts, and the upper 15 samples were collected from the sandy and silty infill sediment facies (Fig. 2). Sub-samples of 1 cm^3 were processed for palynology using standard methods including acid digestion and sieving (Faegri & Iversen 1975). Pollen was identified using the pollen reference collection at the Paleoecology Laboratory at the University of Toronto and at the Royal Ontario Museum (Toronto, Canada), in addition to Kapp *et al.* (2000) and McAndrews *et al.* (1973). Pollen concentrations were estimated by the addition of a known number of exotic *Lycopodium* spores (Stockmarr 1971). An average of 156 arboreal, shrub and herb pollen grains were counted at each fossil interval. Only intervals where pollen concentration exceeded 5000 grains per cm^3 were considered for this study.

Sedimentological and macrofossil samples were taken along the lower 150 cm of the non-glacial unit during field sampling in 2013. Macrofossils were used to reconstruct local plant communities, as well as provide an independent qualitative proxy for temperature, since quantitative methods derived from pollen assemblages are subject to a variety of biases and errors (Birks & Birks 2000; Salonen *et al.* 2013a,b). In total, 14 samples in 10-cm intervals were analysed for plant macrofossils. Macrofossil samples of 15 cm^3 were cleaned under running water using a 100-µm mesh sieve. The residuals remaining on the sieve were analysed under a stereomicroscope. Some of the samples were soaked in $Na_4P_2O_7$ x H_2O solution overnight to disaggregate mineral clusters.

Organic, carbonate and minerogenic contents of the non-glacial unit were estimated using standard loss-on-ignition (LOI) methods (Heiri *et al.* 2001). Particle size analysis (PSA) was used to obtain size class distributions for inorganic sediments. Samples were heated in HCl to remove carbonates, then digested in H_2O_2 until all organic reaction ceased and finally soaked in 1% Na_2CO_3 for 2 hours to dissolve any diatoms. Samples were then disaggregated with sodium hexametaphosphate and particle size was determined by using a Malvern Mastersizer 3000 and Hydro MV wet dispersion unit.

Statistical analyses of pollen data

Palaeoclimate inferences are derived from the North American Modern Pollen Database (NAMPD; Whitmore *et al.* 2005), which has been shown to reliably estimate temperature and precipitation using the Modern Analogue Technique (MAT) over many vegetation biomes in North America (e.g. Fréchette & de Vernal 2013; O'Reilly *et al.* 2014; Gajewski 2015; Richerol *et al.* 2016). However, there are few data points in the NAMPD from the HBL. Thus, to ensure regional representation in the modern calibration set, and to improve the potential similarity of analogues, we first synthesized all available modern pollen data for the HBL and amalgamated this dataset with the NAMPD data. Sites not previously included in the NAMPD were obtained from several sources, including Potzger & Courtemanche (1956), Terasmae & Hughes (1960), Lichti-Federovich & Ritchie (1968), Terasmae & Anderson (1970), Skinner (1973), Farley-Gill (1980), Bazely (1981), Kettles *et al.* (2000), Dredge & Mott (2003), Glaser *et al.* (2004), Friel *et al.* (2014) and O'Reilly *et al.* (2014). We also contribute modern pollen assemblage data from 5 new sites, collected in the summer of 2010 and 2011, which were processed and counted using standard methods (Faegri & Iversen 1975). The locations of modern pollen data from the HBL region are shown in Fig. 1 and all newly compiled data are provided in Table S1.

Taxonomic harmonization was performed over the entire modern pollen dataset to enable statistical intercomparison of sites. This process involved grouping, for example, *Ambrosia*, *Artemisia*, Tubuliflorae, and Liguliflorae into “Asteraceae”. Similarly, *Picea glauca* and *P. mariana* were merged, since they were often not distinguished in the modern dataset. Family, genus and species names were then updated to reflect modern-day naming conventions as dictated by the Integrated Taxonomic Information System on-line database (http://www.itis.gov).

The original NAMPD contained 4833 sites, and we added 49 new sites from the HBL, resulting in a modern dataset of 4882 sites. However, to improve the accuracy of palaeoclimate estimates, only samples from the NAMPD which reached a sum of >150 grains of arboreal, shrub and herb pollen types were retained for analysis. Further, only those samples in the conifer/hardwood, boreal and forest-tundra biomes, as defined by Fedorova *et al.* (1994) were included in the modern-day calibration set (1617 modern sites). Our decision to include only sites from the present-day biome of the HBL (boreal and forest-tundra) as well as the conifer/hardwood biome was based on examining the general assemblage contained in all sub-till records from the HBL, which, in addition to boreal-type pollen, contains infrequent hardwood-type taxa (e.g. *Acer*, *Quercus*).

Temperature and precipitation data for sites not already included in the NAMPD were based on a 30-year average (1971 to 2000), and obtained from Natural Resources Canada (2015), which interpolates climate variables based on the closest weather stations. Four different variables were explored for the potential for reconstruction: mean annual temperature, total annual precipitation, mean summer temperature (June, July, August), and total precipitation for the summer months. We used a stepwise variance inflation factor test to remove any variables which exhibited collinearity in the calibration dataset (R package "usdm": Naimi 2015). This resulted in the removal of mean annual temperature. Next, the $\lambda1/\lambda2$ ratio was calculated (Ter Braak & Prentice 1988). Only variables with a ratio of >1 were retained for reconstruction (Juggins *et al.* 2014).

Prior to reconstructing palaeoclimate at the Ridge Site, fossil pollen counts were converted to relative abundance using a sum of all arboreal, shrub and herb pollen. Thirty pollen types were present at >0.5% in any one fossil sample and were included in the paleoclimate reconstruction. These were composed largely of *Picea*, *Pinus*, *Betula, Salix*, Asteraceae, *Alnus*, Poaceae, Ericaceae and Amaranthaceae, all of which had a mean abundance of >1%. The remaining <1% of pollen grains were *Corylus, Tilia,* Ranunculaceae, *Selaginella*, *Shepherdia*, Aquifoliaceae, *Abies, Carpinus/Ostrya*, Cupressaceae, *Lycopodium*, Juglandaceae, Polygonaceae, *Ulmus, Fraxinus*, *Larix,* Rosaceae, Rubiaceae, *Quercus*, *Acer,* Onagraceae, and *Sarcobatus*. Wetland elements (Cyperaceae and *Sphagnum*), were excluded from the reconstruction on the basis of high and variable local over-production. While we acknowledge that some of the taxa retained in the analysis are locally present (e.g. *Salix*), the elimination of the most variable and abundant local wetland taxa results in fossil pollen assemblages that largely reflect a more regional signal. This approach has been used successfully in other pollen-based reconstructions and has resulted in palaeoclimate reconstructions well-supported by independent proxies (e.g. Shuman *et al.* 2004; Viau & Gajewski 2009).

A squared chord distance dissimilarity coefficient, implemented using the R package 'analogue' (Simpson 2007; Simpson & Oksanen 2014), was used to determine the similarity of modern and fossil pollen assemblages (Overpeck *et al.* 1985). Any samples exceeding a dissimilarity index of 0.15 were taken to be non-analogues. Predicted climate variables were based on k = 3 closest analogues (Williams & Shuman 2008) and n = 500 bootstrap iterations. Errors for the quantitative estimates are based on the root mean squared error of prediction (RMSEP) at k = 3 analogues. Stratigraphic plots and constrained incremental sum-of-squares (CONISS) zoning by comparison to a broken stick model (Bennett 1996) were implemented using the R package 'rioja' (Juggins 2015).

Results

Stratigraphy of the Ridge Site

The lowermost exposed unit of the Ridge Site, the lower diamicton, consists of 6 m of massive to blocky very fine sandy silt, containing granules, pebbles, cobbles and boulders (Fig. 2). This diamicton contains isolated boulders with faceted and striated tops, with striations oriented between 180° and 220° Az. A boulder line observed one m above the exposed base of this unit had boulders with striated tops and a similar range of striation orientations. Low angle shear planes were observed within the diamicton and deformed lenses of sand and gravelly sand indicate movement toward the south-southwest. Particle size analysis of the matrix indicates that the lower diamicton consists of 36% sand, 56% silt and 8% clay. The carbonate content of the silt-clay fraction of the matrix is about 50% with a calcite-to-dolomite ratio of 1.6. At the time of sampling (June 2011 and August 2013), up to 1.5 m of slumped material covered the lower part of the exposure above river level. Thus, the full extent of the lower diamicton unit is not known, and it may extend below river level. The upper contact of the diamicton is irregular with low relief.

The middle unit at the Ridge Site, the non-glacial unit, is a 3.0-m sequence of stratified sediments (Fig. 2). This is the location of the biostratigraphic (pollen, macrofossil) sampling. The lower 20 to 30 cm is composed of stratified sand and silty sand with rare thin diamicton lenses, resting on an irregular lower contact (Fig. 3A). These sediments grade upward into approximately 280 cm of faintly laminated and colour-banded silty clay and clayey silt with finely disseminated organic matter and thin, discontinuous laminations of silt and rarely, very fine sand (Fig. 3B). The top of these fine-grained sediments is marked by an angular unconformity with at least 90 cm of negative relief, filled by sands and silts containing organic detritus (Fig. 3C,D). The entire Ridge Site can be seen in Fig. 3E. Organic content is 11 to 15% throughout the lower 150 cm of the non-glacial unit, and carbonates are generally less than 5%, but increase to 12% at the base of this section at the diamicton contact.

The upper unit at the Ridge Site, the upper diamicton, contains massive to blocky, very fine sandy silt with minor clay (Fig. 2). Granules, pebbles, cobbles and boulders are also present. This diamicton is about 6 m in thickness with a sharp lower contact with the underlying sediments. One large inclusion, up to 1.7 m, consisting of small pebble gravel and very fine sand and silt was observed within this diamicton layer. Rare, isolated boulders had striated tops with the orientations of 260° Az. Samples from the matrix of the diamicton average 26.5 % sand, 63 % silt and 9.5 % clay. The average total carbonate content in the silt-clay fraction is 43 % and the average carbonate ratio is 1.3. Overlying this massive, sandy silt diamicton is a 1.7-m to 3-m sediment sequence that coarsens upward toward the top of the exposure. The sequence consists of interbedded very fine sandy silt and very coarse sandy granule gravel, grading upward into pea-size pebble gravel with inter-beds of fine-grained sand.

Chronology

Two finite radiocarbon ages suggest that the non-glacial unit at the Ridge Site may date to MIS 3 (40 000±400 cal. a BP and 49 600±950 a ^{14}C), while one age was infinite (>48 800 a BP; Table 1).

Pollen and macrofossils

Overall, palynomorphs were moderately well-preserved at the Ridge Site, with 24 of 35 intervals containing sufficient concentrations (Fig. 4). Several intervals of poor pollen preservation correspond to the transition between clay-rich sediments toward more silt/sand rich sediments immediately above the unconformity, as well as the base and top of the non-glacial unit near the diamicton contact. Arboreal assemblages were dominated by *Picea* (mean 46%), and *Pinus* (mean 30%), with *Salix*, *Alnus* and *Betula*, all averaging less than 10%. The herbaceous component consisted of Asteraceae, Ericaceae, Amaranthaceae and Poaceae similarly averaging less than 10% throughout the non-glacial unit. Pollen of locally-abundant wetland indicators (*Sphagnum* and Cyperaceae) ranged from <10% to 110% of the herb, arboreal and shrub pollen sum. There are two significant zones in the pollen assemblages delineated using CONISS and the broken stick method: 0 to 230 cm, and 250 to 280 cm.

Macrofossils were present in all sampled intervals of the Ridge Site, however preservation was at times poor and fragments were small. Woody plant remains, bryophytes and charcoal were the most commonly preserved macrofossils (Fig. 5). Bryophytes consisted of intact *Scorpidium* spp. and *Sarmentosum* group *exannulatum* spp., as well as rare/fragmented

Polytrichum spp., *Calliergon* spp., *Sarmentypnum sarmentosum*, *Sphagnum* spp. and *Tomenthypnum nitens*. Despite no obvious succession in the macrofossil sequence, some plant remains become more abundant within the 40-cm interval which corresponds to an increase in the clay fraction of the stratigraphy. In particular, conifer remains were continuously present in the samples above the 40-cm interval, indicating the persistent local presence of these taxa.

Pollen-derived palaeoclimate reconstruction

The pollen-climate model resulted in a predictive ability which is similar to what is reported in other studies (e.g. Williams & Shuman 2008; Richerol *et al.* 2016). The coefficient of determination (R^2) between observed and predicted annual precipitation was 0.79, while mean summer temperature was 0.83. The RMSEP values were 170 and 1.51, respectively. Further details on the underlying statistical model are shown in Fig. S1. Each fossil interval at the Ridge Site had >20 potential analogues, therefore satisfying the criteria for reconstruction using the modern analogue technique (Overpeck *et al.* 1985). Of the 72 possible analogues (e.g. k = 3 analogues for each of the 24 fossil intervals), only 32 unique sites were used for palaeoclimate reconstructions. Four of these sites were from our newly-compiled data used to supplement the NAMPD. Based on the 3 closest analogues, the total annual precipitation throughout the fossil interval was 527±170 mm per year, as compared to an estimated 705 mm per year at that site in present-day (Fig. 4). Estimates for summer temperature averaged 14.6±1.51 °C, which is 0.8 °C lower than the present-day temperature estimates for the Ridge Site.

Discussion

Lower and upper diamicton

The lower diamicton is interpreted to be a subglacial till deposited by an actively flowing glacier moving toward the south-southwest (180° to 220° Az) over Middle Devonian formations dominated by limestone. This interpretation is supported by the boulder line with consistent orientation of striae in the lower part of the exposure, and the isolated boulders with striated tops that are similarly oriented. In addition, the low angle shear planes within the diamicton, and the direction of movement indicated by them, are consistent with the direction of movement indicated by the striae on the boulder tops, all of which would indicate the direction of ice flow that deposited the diamicton. In comparison to other till samples collected in the Ridge River area (Barnett & Yeung 2012; Nguyen *et al.* 2012; Nguyen 2014), the lowermost till contains the highest amount of total carbonates in the silt/clay fraction and the highest calcite-to-dolomite ratio.

The upper diamicton is also interpreted as till. Its massive nature and inclusion of clasts with striated tops indicate glacial movement to the west-southwest, which would traverse an even longer distance over the Middle Devonian limestone rocks. This is consistent with fluting that occurs on remotely sensed images and digital surface models in the area (Barnett *et al.* 2009). The large inclusion of gravelly sand may have been eroded from the underlying fluvial sediments in the non-glacial unit. The lower calcite and higher dolomite content in this till, however, might suggest that the underlying bedrock formations were covered during this advance, and that the more-distant dolomitic rocks of Upper Silurian and Lower Devonian formations sub-cropping in James Bay (Ontario Geological Survey 1991) may have influenced the final carbonate content of this till. The uppermost unit exposed in the section, the stratified sands and gravels, is interpreted as beach and near shore deposits likely formed at the regressing margin of the post-glacial Tyrrell Sea (Lee 1960).

Non-glacial unit

Age determinations from the non-glacial unit were previously discussed in a compilation of all available chronology data from the Missinaibi Formation, and contribute evidence towards an ice-free HBL during MIS 3 (Dalton *et al.* 2016). At the base of the non-glacial unit, the irregular 20-cm lower contact is interpreted as erosional and likely marks the base of a former river channel. Here, the infilling sediments are gravelly and likely the result of the erosion of the till below. The diamicton lenses are interpreted as debris flows from the flanks of the channel, however, it is possible that they are flow tills and that the lower part of the non-glacial unit was deposited along the ice margin rather than in a fluvial setting.

Overlying these sediments, the middle part of the non-glacial unit, the predominantly silts (excluding the angular unconformity), is similar to the sediments described from Marion Lake, a now drained, but once perennial closed-basin oxbow lake in southern Manitoba (Brooks 2003; Brooks & Medioli 2003). Sediments deposited within oxbow lakes have been described as massive to faintly laminated, and dominated by silt-sized particles with little to no vertical textural grading throughout the fill sequence (Allen 1965; Brooks 2003; Brooks & Medioli 2003), which is similar to the Ridge Site. However, aquatic indicators in the pollen and macrofossil data are in low abundance compared to other inferred lacustrine sites (Bos *et al.* 2009; Bajc *et al.* 2015), which suggests that standing water throughout the time of accumulation was unlikely. We therefore suggest that this interval may represent a drier surface, marginal to the river channel, possibly at the entrance to a cut-off meander, with local presence of shrubs including *Alnus* and *Salix*, as confirmed by macrofossil analyses. A modern-day example of such an environment can be seen in Fig. 6. We interpret the upper part of the non-glacial unit, the unit contained within an angular unconformity, to be the base of a channel that cut into the material below by renewed river activity or localized drainage. These fluvial sediments suggest drainage-related changes to the river system, which are frequent processes in the modern landscape, as shown by the many oxbow lakes and ancient river scars which are present in the HBL today.

Typical boreal peatland taxa such as Cyperaceae, *Picea*, *Pinus* and *Sphagnum* suggest that vegetation communities similar to the present-day HBL are preserved at the Ridge Site (Figs 4,5). Polypodiaceae spores suggest the local presence of ferns, and these, in combination with bryophyte remains, confirm the presence of riparian wetland conditions. Herbaceous taxa such as Asteraceae, Ericaceae, Amaranthaceae and Poaceae suggest an intermittently open canopy. The modest decline in *Sphagnum* spores paired with the small increase in pollen of Cyperaceae toward the top of the non-glacial unit may suggest increased nutrients over time in the local environment, reflecting stream dynamics. Occasional river flooding may have contributed to the sedimentological features of the preserved site, along with the occasional presence of aquatic indicators (*Potamogeton*, *Pediastrum*; Fig. 4). These wet/dry cycles may help explain the intervals of poor pollen preservation, since corrosion of pollen grains can be indicative of exposure of the grains and the sedimentary matrix to aerobic environments or wet/dry cycles.

Although abundances are low, macrofossil data permit key inferences about palaeoenvironmental conditions at the Ridge Site. The presence of *Betula* and *Salix* bark, along with *Betula* seeds confirm that these taxa were locally present. These taxa are generally intolerant to shade and tend to grow along recently disturbed river banks, suggesting that local parts of the forest canopy were open. Such environments are common in the HBL today. Furthermore, the presence of conifer bark and needles (cf. *Pinus)* also confirms the local presence of these taxa. However, conifer remains are difficult to differentiate when fragments are small, rare and not well preserved. If these remains are indeed *Pinus*, this would be notable because this tree is not common in the area today; recent vegetation surveys indicate that *Pinus banksiana* is only occasionally noted in well-drained regions of the HBL (Riley 2003). The presence of large (>1 mm) and small (<1 mm) charcoal fragments suggests local and regional forest fires. Although fire is a more significant process in the drier boreal regions of western Canada (e.g. Hickman & Schweger 1996; Philibert *et al.* 2003), it is a component of ecosystem dynamics in the eastern Canadian boreal forest as well (e.g. Cyr *et al.* 2005). Fires may have been more frequent and/or more intense under drier climatic regimes. Although macrofossil remains were rare and low in diversity at the Ridge Site compared to other interstadial and interglacial sites from northern Europe (Bos *et al.* 2009; Väliranta *et al.* 2009; Helmens *et al.* 2012, 2015; Houmark-Nielsen *et al.* 2016; Sarala *et al.* 2016), these data yield important supporting information for palaeoenvironmental inferences.

Palaeoclimate reconstruction

Our palaeoclimate reconstruction of the non-glacial unit of the Ridge Site suggests similar or perhaps somewhat cooler summer temperatures as compared to present-day, and lower total annual precipitation, as constrained by the errors on the reconstructions, and the limitations of the datasets available. Poaceae and *Salix* pollen in the fossil sequence are driving this result, and fossil pollen samples were, for the most part, most closely analogous to boreal/grassland transition sites in central and western Canada. This finding suggests that climate in the HBL may have been more continental in character during this period. These results are comparable to other records from North America suggesting that annual precipitation patterns may have been different from present-day during MIS 3 (Van Meerbeeck *et al.* 2009; Brandefelt *et al.* 2011; Sionneau *et al.* 2013) owing to partial continental glaciation (Grant *et al.* 2014).

There are few available MIS 3 palaeoclimate datasets for comparison with the Ridge Site, because such records are rare owing to glacial erosion, difficulty in dating, poor preservation, and, when present, climate estimates are largely qualitative. For example, Bajc *et al.* (2015) inferred a boreal forest or perhaps treeline/tundra-type environment in southern Ontario during MIS 3 on the basis of pollen and plant macrofossils. Similarly, Karrow & Warner (1984), Karrow *et al.* (2001) and Warner *et al.* (1988) document a *Pinus* and *Picea*-dominated assemblage indicating that a boreal forest and/or tundra environment was present during that time at other sites near the southern periphery of the LIS. These studies are notable since they are all located 100-300 km south of the present-day boreal forest. Thus, results from the Ridge Site, as well as other purported MIS 3 sites from the periphery of the Laurentide Ice Sheet, suggest an expanded boreal forest zone as compared to present-day, with generally cooler and drier conditions throughout much of the previously glaciated region.

Along with characterizing the palaeoenvironment of a site which we tentatively assign to MIS 3 on the basis of radiocarbon dates, till stratigraphy and biological proxies, one of the main objectives of this study was to determine whether deposits belonging to MIS 3 could be differentiated from deposits dating to off-peak MIS 5 on the basis of pollen assemblages. Fig. 7 shows a palaeoclimate reconstruction from the Nottaway River in the James Bay Lowlands, adjacent to our study region, using the same methods and modern calibration set as the Ridge Site. The Nottaway River site was chronologically constrained broadly to off-peak MIS 5 based on U-Th dating (Allard *et al.* 2012). Similar to the Ridge Site, reconstructed summer temperature was comparable to present-day at the Nottaway River site (data not shown). However, notably, reconstructed annual precipitation was an average of 865±192 mm as compared to 652 mm present-day at the MIS 5 Nottaway River Site (Fig. 7), suggesting increased moisture during MIS

5 relative to today. However, this stands in contrast to the drier conditions documented for the Ridge Site, hypothesized to date to MIS 3 (Figs 4,7). Thus, if chronology data and the resulting palaeoclimate interpretations from these sites are well supported, MIS 3 and off-peak MIS 5 sites from the HBL could be differentiated on the basis of relative continentality: MIS 3 is characterized by lower total annual precipitation and off-peak MIS 5 by similar or greater than present-day. Additional MIS 3 and off-peak MIS 5 sites are needed to further test this hypothesis. Moreover, there is a need to better understand and quantify the climate variability during MIS 5a-d, which fluctuated between relative cool stadials (MIS 5d, 5b; peaks: *c*. 109 000 a BP and *c*. 87 000 a BP) and warmer interstadials (MIS 5c, 5a; peaks: *c*. 96 000 a BP and *c*. 82 000 a BP). Nevertheless, our results suggest that, with additional sites and additional data, pollen-based reconstructions may hold the potential to be developed into a valuable tool for assigning ages and characterizing palaeoenvironments in sediments of the Missinaibi Formation.

While the errors associated with the palaeoclimate estimates from the Ridge Site (±1.51 °C for average summer temperature; ±170 mm for total annual precipitation) are similar to Holocene palaeoclimate reconstructions from the HBL and the forest-tundra transition zone of Canada (Bunbury *et al.* 2012; Richerol *et al.* 2016), further reducing these errors is important if pollen-based inferences are to be used as a chronological tool for assigning age(s) to the Missinaibi Formation. However, a main obstacle in reducing this error is that typical boreal/peatland taxa are found extensively across large biogeographic ranges in North America (Whitmore *et al.* 2005) and therefore have widespread climatic tolerances. One way to reduce this error may be the removal of extra-regional (wind-transported) pollen grains, which can lead to a pollen assemblage which is inconsistent with the local vegetation (Birks & Birks 2000). This technique permitted errors on palaeoclimate reconstructions from the Arctic to be reduced to

±0.6 °C for July temperature and ±19 mm for total annual precipitation (Peros & Gajewski 2008; Peros *et al.* 2010). However, this may not be appropriate in a treed landscape. Also, little is known about the distribution of local, regional or distant vegetation in the HBL during MIS 3 since macrofossil fragments were sparse and sometimes poorly preserved at the Ridge Site. In this case, the macrofossil record represents only a fraction of the local vegetation. The continued development of multi-proxy techniques and independent proxies for palaeoclimate such as chironomids, diatoms, insect remains, stable isotopes, leaf wax biomarkers or bacterial membrane lipids (Huang *et al.* 2006; Engels *et al.* 2008; Väliranta *et al.* 2009; Weijers *et al.* 2011; Helmens *et al.* 2012; Nichols *et al.* 2014; Helmens *et al.* 2015; Houmark-Nielsen *et al.* 2016) are critical for refining our understanding of the Missinaibi Formation and other Pleistocene palaeoenvironments.

Overall, there was less stratigraphic variation in pollen and macrofossil data at the Ridge Site as compared to sub-till interstadial and interglacial sites from northern Europe. This is likely the result of depositional setting, since non-glacial records from Fennoscandia more frequently originate from lacustrine settings (Bos *et al.* 2009; Helmens *et al.* 2012; Helmens *et al.* 2015), which often record more detailed vegetation dynamics. For example, a biostratigraphic investigation of an inferred oxbow lake at Sokli, northern Finland, allowed for the recognition of succession from a birch- to pine- to spruce-dominated local environment during MIS 5c (Helmens *et al.* 2012). Similarly, Helmens *et al.* (2015) used pollen and macrofossil data to document a short-lived cooling event during MIS 5e, which was preserved in a gyttja deposit. Such detailed vegetation data allows the different time periods (e.g. MIS 3 and MIS 5) in Fennoscandia to be distinguished based not only on temperature and/or precipitation, but also from understanding succession of the vegetation community during the time period of question.

An equally detailed pollen, diatom and macrofossil record dating to MIS 3 was also presented by Sarala *et al.* (2016). Since vegetation succession is not well preserved at the Ridge Site, there is less potential for detailed inferences of plant community changes during MIS 3 in the HBL. Nevertheless, oxbow lakes are common in the present-day HBL, so it is likely that lacustrine-type sediments are preserved as part of the Missinaibi Formation and will be the subject of future studies.

Conclusions

Since the HBL is located near the centre of growth of many Pleistocene ice sheets, the occurrence of non-glacial intervals in this region corresponds to either largely retreated or highly dynamic ice sheets over North America. Radiocarbon dating suggests that the non-glacial interval at the Ridge Site may date to MIS 3, which would mean significant reduction of the central part of the Laurentide Ice Sheet prior to the build-up toward the last glacial maximum. Such MIS 3 ages had been previously reported in the region (Andrews *et al.* 1983; Berger & Nielsen 1990), but remained tentative owing to errors and uncertainties in dating. Continued dating of similar Pleistocene-aged records is critical for developing an accurate understanding of past glaciation, and developing accurate climate models.

Pollen, macrofossils and sedimentological proxies at the Ridge Site provide one of the few quantitative accounts of palaeoenvironment from the previously-glaciated region. Palaeoclimate reconstructions from the Ridge Site, along with other sites from the periphery of the Laurentide Ice Sheet, suggest that dry, expansive boreal vegetation colonized much of the previously glaciated region. Our discovery of subtle vegetation (and thus, climate) differences between this purported MIS 3 site and an off-peak MIS 5 site in the adjacent James Bay

Lowlands highlights the potential for vegetation assemblages to be used as an inferential dating technique. The continued development of such quantitative techniques may prove to be a valuable tool for assigning ages to sub-till records in the HBL region, since pollen is well preserved and thoroughly documented at many undated sub-till sites.

Acknowledgements. - Funding for this study was provided by the Ontario Geological Survey and grants from the Natural Sciences and Engineering Research Council (Canada) to SAF, and from the Northern Scientific Training Program and University of Toronto Centre for Global Change Science to ASD. We thank Maurice Nguyen for valuable field assistance and for his work on the Ridge River till stratigraphies, along with Guillaume Allard and Martin Roy for providing pollen data from the Nottaway River site for comparative palaeoclimate analysis. A further thank you to D. Bazely for modern pollen records; J.-P. Iamonaco, M. Sobol, D. Valls, A. Megens and T. Hui for laboratory assistance; J. Desloges for the use of the Malvern Mastersizer 3000 and Hydro MV wet dispersion unit, and S. Forman for attempting an OSL date at the Ridge Site. Some data were obtained from the Neotoma Paleoecology Database (http://www.neotomadb.org), and the work of the data contributors and the Neotoma community is gratefully acknowledged. We also thank two anonymous reviewers whose insightful comments helped improve the paper.

References

Allard, G., Roy, M., Ghaleb, B., Richard, P. J. H., Larouche, A. C., Veillette, J. J. & Parent, M. 2012: Constraining the age of the last interglacial–glacial transition in the Hudson Bay lowlands (Canada) using U–Th dating of buried wood. *Quaternary Geochronology 7*, 37-47.

Allen, J. R. L. 1965: A review of the origin and characteristics of recent alluvial sediments. *Sedimentology 5*, 89-191.

Amante, C. & Eakins, B. W. 2009: ETOPO1 1 Arc-Minute Global Relief Model: Procedures, Data and Analysis. *NOAA Technical Memorandum NESDIS NGDC-24.* National Geophysical Data Center, NOAA. doi: 10.7289/V5C8276M.

Andrews, J.T., Shilts, W.W. & Miller, G.H., 1983: Multiple deglaciations of the Hudson Bay Lowlands, since deposition of the Missinaibi (Last-Interglacial?) Formation. *Quaternary Research 19*, 18-37.

Bajc, A. F., Karrow, P. F., Yansa, C. H., Curry, B. B., Nekola, J. C., Seymour, K. L. & Mackie, G. L. 2015: Geology and paleoecology of a Middle Wisconsin fossil occurrence in Zorra Township, southwestern Ontario, Canada. *Canadian Journal of Earth Sciences 52*, 386-404.

Barnett, P. J., Webb, J. L. & Hill, J. L. 2009: *Flow indicator map of the Far North of Ontario*. *Ontario Geological Survey, Preliminary Map P.3610, scale 1:1,000,000.*

Barnett, P. J. & Yeung, K. H. 2012: Field investigations for remote predictive terrain mapping in the far north of Ontario. *Summary of Field Work and Other Activities 2012: Ontario Geological Survey, Open File Report 6280*, 24-21 to 24-25.

Bazely, D. 1981: *The surface pollen spectra of La Pérouse Bay, Manitoba, Canada*. B.Sc. thesis, University of Toronto.

Bennett, K. D. 1996: Determination of the number of zones in a biostratigraphical sequence. *New Phytologist 132*, 155-170.

Berger, G.W. & Nielsen, E. 1990: Evidence from thermoluminescence dating for Middle Wisconsinan deglaciation in the Hudson Bay Lowland of Manitoba. *Canadian Journal of Earth Sciences 28,* 240-249.

Birks, H. H. & Birks, H. J. B. 2000: Future uses of pollen analysis must included plant macrofossils. *Journal of Biogeography 27*, 31-35.

Böhm, E., Lippold, J., Gutjahr, M., Frank, M., Blaser, P., Antz, B., Fohlmeister, J., Frank, N., Andersen, M. B. & Deininger, M. 2015: Strong and deep Atlantic meridional overturning circulation during the last glacial cycle. *Nature 517*, 73-76.

Bos, J. A. A., Helmens, K., Bohncke, S. J. P., Seppä, H. & Birks, H., J, B 2009: Flora, vegetation and climate at Sokli, northern Fennoscandia, during the Weichselian Middle Pleniglacial. *Boreas 38*, 335-348.

Brandefelt, J., Kjellström, E., Näslund, J. O., Strandberg, G., Voelker, A. H. L. & Wohlfarth, B. 2011: A coupled climate model simulation of Marine Isotope Stage 3 stadial climate. *Climate of the Past 7*, 649-670.

Brooks, G. R. 2003: Alluvial deposits of a mud-dominated stream: the Red River, Manitoba, Canada. *Sedimentology 50*, 441-458.

Brooks, G. R. & Medioli, B. E. 2003: Deposits and Cutoff Ages of Horseshoe and Marion Oxbow Lakes, Red River, Manitoba. *Géographie physique et Quaternaire 57,* 151-158.

Bunbury, J., Finkelstein, S. A. & Bollmann, J. 2012: Holocene hydro-climatic change and effects on carbon accumulation inferred from a peat bog in the Attawapiskat River watershed, Hudson Bay Lowlands, Canada. *Quaternary Research 78*, 275-284.

Bunting, M. J., Warner, B. G. & Morgan, C. R. 1998: Interpreting pollen diagrams from wetlands: pollen representation in surface samples from Oil Well Bog, southern Ontario. *Canadian Journal of Botany 76*, 1780-1797.

Cyr, D., Bergeron, Y., Gauthier, S. & Larouche, A. C. 2005: Are the old-growth forests of the Clay Belt part of a fire-regulated mosaic? *Canadian Journal of Forest Research 35*, 65-73.

Dalton, A. S., Finkelstein, S. A., Barnett, P. J. & Forman, S. L. 2016: Constraining the Late Pleistocene history of the Laurentide Ice Sheet by dating the Missinaibi Formation, Hudson Bay Lowlands, Canada. *Quaternary Science Reviews 146*, 288-299.

Dredge, L. A., Morgan, A. V. & Nielsen, E. 1990: Sangamon and Pre-Sangamon Interglaciations in the Hudson Bay Lowlands of Manitoba. *Géographie physique et Quaternaire 44*, 319-336.

Dredge, L. A. & Mott, R. J. 2003: Holocene Pollen Records and Peatland Development, Northeastern Manitoba. *Géographie physique et Quaternaire 57*, 7-19.

Dreimanis, A. 1962: Quantitative gasometric determination of calcite and dolomite by using Chittick apparatus. *Journal of Sedimentary Research 32*, 520-529.

Durcan, J. A. & Duller, G. A. T. 2011: The fast ratio: A rapid measure for testing the dominance of the fast component in the initial OSL signal from quartz. *Radiation Measurements 46*, 1065-1072.

Dyke, A. S. 2004: An outline of North American deglaciation with emphasis on central and northern Canada. *In* Ehlers, J. & Gibbard, P. L. (eds.): *Quaternary Glaciations - Extent and Chronology, Part II*, 373-424 Elsevier, Amsterdam.

Dyke, A. S., Andrews, J. T., Clark, P. U., England, J. H., MIller, G. H., Shaw, J. & Veillette, J. J. 2002: The Laurentide and Innuitian ice sheets during the Last Glacial Maximum. *Quaternary Science Reviews 21*, 9-31.

Engels, S., Bohncke, S. J. P., Bos, J. A. A., Brooks, S. J., Heiri, O. & Helmens, K. F. 2008: Chironomid-based palaeotemperature estimates for northeast Finland during Oxygen Isotope Stage 3. *Journal of Paleolimnology 40*, 49-61.

Faegri, K. & Iversen, J. 1975: *Text Book of Pollen Analysis*. 295 pp. Munksgaard, Copenhagen.

Farley-Gill, L. D. 1980: Contemporary pollen spectra in the James Bay Lowland, Canada, and comparison with other forest-tundra assemblages. *Géographie physique et Quaternaire 34*, 321-334.

Fedorova, I. T., Volkova, Y. A. & Varlyguin, D. L. 1994: World vegetation cover. Digital raster data on a 30-minute cartesian orthonormal geodetic (lat/long) 1080x2160 grid. *USDOC/NOAA National Geophysical Data Center, Global Ecosystems Database Version 2.0.* Boulder.

Fréchette, B. & de Vernal, A. 2013: Evidence for large-amplitude biome and climate changes in Atlantic Canada during the last interglacial and mid-Wisconsinan periods. *Quaternary Research 79*, 242-255.

Friel, C. E., Finkelstein, S. A. & Davis, A. M. 2014: Relative importance of hydrological and climatic controls on Holocene paleoenvironments inferred using diatom and pollen records from a lake in the central Hudson Bay Lowlands, Canada. *The Holocene 24*, 295-306.

Gajewski, K. 2015: Quantitative reconstruction of Holocene temperatures across the Canadian Arctic and Greenland. *Global and Planetary Change 128*, 14-23.

Glaser, P. H., Hansen, B. C. S., Siegel, D. I., Reeve, A. S. & Morin, P. J. 2004: Rates, pathways and drivers for peatland development in the Hudson Bay Lowlands, northern Ontario, Canada. *Journal of Ecology 92*, 1036-1053.

Grant, K. M., Rohling, E. J., Ramsey, C. B., Cheng, H., Edwards, R. L., Florindo, F., Heslop, D., Marra, F., Roberts, A. P., Tamisiea, M. E. & Williams, F. 2014: Sea-level variability over five glacial cycles. *Nature Communications, DOI 10.1038/ncomms6076*.

Hatté, C. & Jull, A. J. T. 2007: Radiocarbon Dating: Plant Macrofossils. *In* Elias, S. A. (ed.): *Encyclopedia of Quaternary Science*, 2958-2965 Elsevier, Amsterdam.

Heiri, O., Lotter, A. F. & Lemcke, G. 2001: Loss on ignition as a method for estimating organic and carbonate content in sediments: reproducibility and comparability of results. *Journal of Paleolimnology 25*, 101-110.

Helmens, K. F., Salonen, J. S., Plikk, A., Engels, S., Väliranta, M., Kylander, M., Brendryen, J. & Renssen, H. 2015: Major cooling intersecting peak Eemian Interglacial warmth in northern Europe. *Quaternary Science Reviews 122*, 293-299.

Helmens, K. F., Väliranta, M., Engels, S. & Shala, S. 2012: Large shifts in vegetation and climate during the Early Weichselian (MIS 5d-c) inferred from multi-proxy evidence at Sokli (northern Finland). *Quaternary Science Reviews 41*, 22-38.

Hickman, M. & Schweger, C. E. 1996: The Late Quaternary palaeoenvironmental history of a presently deep freshwater lake in east-central Alberta, Canada and paleoclimate implications. *Palaeogeography, Palaeoclimatology, Palaeoecology 123*, 161-178.

Houmark-Nielsen, M., Bennike, O., Lemdahl, G. & Lüthgens, C. 2016: Evidence of ameliorated Middle Weichselian climate and sub-arctic environment in the western Baltic region: coring lake sediments at Klintholm, Møn, Denmark. *Boreas 45*, 347-359.

Huang, Y., Shuman, B., Wang, Y., Webb, T., Grimm, E. C. & Jacobson, G. L. 2006: Climatic and environmental controls on the variation of C3 and C4 plant abundances in central Florida for the past 62,000 years. *Palaeogeography, Palaeoclimatology, Palaeoecology 237*, 428-435.

Juggins, S. 2015: *rioja: Analysis of Quaternary Science Data. R package version (0.9-5).* http://cran.r-project.org/package=rioja.

Juggins, S., Simpson, G. L. & Telford, R. J. 2014: Taxon selection using statistical learning techniques to improve transfer function prediction. *The Holocene 25*, 130-136.

Kapp, R. O., Davis, O. K. & King, J. E. 2000: *Ronald O. Kapp's Pollen and Spores*. 279 pp. American Association of Stratigraphic Palynologists, College Station.

Karrow, P. F., McAndrews, J. H., Miller, B. B., Morgan, A. V., Seymour, K. L. & White, O. L. 2001: Illinoian to Late Wisconsinan stratigraphy at Woodbridge, Ontario. *Canadian Journal of Earth Sciences 38*, 921-942.

Karrow, P. F. & Warner, B. G. 1984: A subsurface Middle Wisconsinian interstadial site at Waterloo, Ontario, Canada. *Boreas 13*, 67-85.

Kettles, I. M., Garneau, M. & Jette, H. 2000: Macorfossil, pollen, and geochemical records of peatlands in the Kinosheo Lake and Detour Lake areas, Northern Ontario. *Geological Survey of Canada Bulletin 545*, 1-24.

Kleinen, T., Brovkin, V. & Munhoven, G. 2015: Carbon cycle dynamics during recent interglacials. *Climate of the Past Discussions 11*, 1945-1983.

Lee, H. A. 1960: Late Glacial and Postglacial Hudson Bay Sea Episode. *Science 131*, 1609-1611.

Lichti-Federovich, S. & Ritchie, J. C. 1968: Recent pollen assemblages from the Western Interior of Canada. *Review of Palaeobotany and Palynology 7*, 297-344.

Lisiecki, L. E. & Raymo, M. E. 2005: A Pliocene-Pleistocene stack of 57 globally distributed benthic $\delta^{18}O$ records. *Paleoceanography 20*, PA1003.

MacDonald, B. G. & Gajewski, K. 1992: The northern treeline of Canada. *In* Janelle, D. G. (ed.): *Geographical Snapshots of North America*, 34-37. The Guilford Press, New York.

McAndrews, J. H., Berti, A. A. & Norris, G. 1973: *Key to the Quaternary Pollen and Spores of the Great Lakes Region*. 74 pp. Royal Ontario Museum, Toronto.

Naimi, B. 2015: *usdm: Uncertainty Analysis for Species Distribution Model. R package version 1.1-15*, http://CRAN.R-project.org/package=usdm.

Natural Resources Canada 2015: *Obtain climate estimates at your locations*. http://gmaps.nrcan.gc.ca/cl_p/climatepoints.php. Date accessed: February 25, 2016

Netterville, J. A. 1974: *Quaternary Stratigraphy of the Lower Gods River Region, Hudson Bay Lowlands, Manitoba.* M.Sc. thesis, University of Calgary, 79 pp.

Nguyen, M. 2014: *Glacial Stratigraphy of the Ridge River Area, Northern Ontario: Refining Wisconsinian Glacial History and Evidence for Laurentide Ice Streaming*. M.Sc. thesis, University of Western Ontario, 68 pp.

Nguyen, M., Hicock, S. R. & Barnett, P. J. 2012: Quaternary Stratigraphy of the Ridge River Area in Support of Far-North Terrain Mapping. *Summary of Field Work and Other Activities 2012, Ontario Geological Survey, Open File Report 6280*, 25-21 to 25-23.

Nichols, J. E., Peteet, D. M., Moy, C. M., Castañeda, I. S., McGeachy, A. & Perez, M. 2014: Impacts of climate and vegetation change on carbon accumulation in a south-central Alaskan peatland assessed with novel organic geochemical techniques. *The Holocene 24*, 1146-1155.

O'Reilly, B. C., Finkelstein, S. A. & Bunbury, J. 2014: Pollen-Derived Paleovegetation Reconstruction and Long-Term Carbon Accumulation at a Fen Site in the Attawapiskat River Watershed, Hudson Bay Lowlands, Canada. *Arctic, Antarctic, and Alpine Research 46*, 6-18.

Ontario Geological Survey 1991: *Bedrock geology of Ontario, explanatory notes and legend, Map 2545*.

Overpeck, J. T., Webb, T., III & Prentice, I. C. 1985: Quantitative Interpretation of Fossil Pollen Spectra: Dissimilarity Coefficients and the Method of Modern Analogs. *Quaternary Research 23*, 87-108.

Peros, M., Gajewski, K., Paull, T., Ravindra, R. & Podritske, B. 2010: Multi-proxy record of postglacial environmental change, south-central Melville Island, Northwest Territories, Canada. *Quaternary Research 73*, 247-258.

Peros, M. C. & Gajewski, K. 2008: Holocene climate and vegetation change on Victoria Island, western Canadian Arctic. *Quaternary Science Reviews 27*, 235-249.

Peteet, D. M., Beh, M., Orr, C., Kurdyla, D., Nichols, J. & Guilderson, T. 2012: Delayed deglaciation or extreme Arctic conditions 21-16 cal. kyr at southeastern Laurentide Ice Sheet margin? *Geophysical Research Letters 39*, L11706.

Philibert, A., Prairie, Y. T., Campbell, I. & Laird, L. 2003: Effects of late Holocene wildfires on diatom assemblages in Christina Lake, Alberta, Canada. *Canadian Journal of Forest Research 33*, 2405-2415.

Potzger, J. E. & Courtemanche, A. 1956: A series of bogs across Quebec from the St. Lawrence Valley to James Bay. *Canadian Journal of Botany 34*, 473-500.

Reimer, P. J., Bard, E., Bayliss, A., Beck, J. W., Blackwell, P. G., Bronk Ramsey, C., Buck, C. E., Cheng, H., Edwards, R. L., Friedrich, M., Grootes, P. M., Guilderson, T. P., Haflidason, H., Hajdas, I., Hatté, 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, R. S. M. & van der Plicht, J. 2013: IntCal13 and Marine13 Radiocarbon Age Calibration Curves 0–50,000 Years cal BP. *Radiocarbon 55*, 1869-1887.

Richerol, T., Fréchette, B., Rochon, A. & Pienitz, R. 2016: Holocene climate history of the Nunatsiavut (northern Labrador, Canada) established from pollen and dinoflagellate cyst assemblages covering the past 7000 years. *The Holocene 26*, 44-60.

Riley, J. & Boissonneau, A. n.d.: Unpublished field notes and photographs. Ontario Ministry of Natural Resources, Peterborough, Ontario.

Riley, J. L. 2003: *Flora of the Hudson Bay Lowlands and its Postglacial Origins*. 237 pp. NRC Press, Ottawa.

Salonen, J. S., Helmens, K. F., Seppä, H. & Birks, H. J. B. 2013a: Pollen-based palaeoclimate reconstructions over long glacial-interglacial timescales: methodological tests based on the Holocene and MIS 5d-c deposits at Sokli, northern Finland. *Journal of Quaternary Science 28*, 271-282.

Salonen, J. S., Seppä, H. & Birks, H. J. B. 2013b: The effect of calibration data set selection on quantitative palaeoclimatic reconstructions. *The Holocene 23*, 1650-1654.

Sarala, P., Väliranta, M., Eskola, T. & Vaikutiene, G. 2016: First physical evidence for forested environment in the Arctic during MIS 3. *Scientific Reports 6*, 29054.

Seppä, H. & Birks, H. J. B. 2001: July mean temperature and annual precipitation trends during the Holocene in the Fennoscandian tree-line area: pollen-based climate reconstructions. *The Holocene 11*, 527-539.

Shuman, B., Newby, P., Huang, Y. & Webb, T., III. 2004: Evidence for the close climatic control of New England vegetation history. *Ecology 85*, 1297-1310.

Simpson, G. L. 2007: Analogue Methods in Palaeoecology: Using the analogue Package. *Journal of Statistical Software 22*, 1-29.

Simpson, G. L. & Oksanen, J. 2014: *analogue: Analogue matching and Modern Analogue Technique transfer function models. R package version 0.14-0*, http://cran.r-project.org/package=analogue.

Sionneau, T., Bout-Roumazeilles, V., Meunier, G., Kissel, C., Flower, B. P., Bory, A. & Tribovillard, N. 2013: Atmospheric re-organization during Marine Isotope Stage 3 over the North American continent: sedimentological and mineralogical evidence from the Gulf of Mexico. *Quaternary Science Reviews 81*, 62-73.

Skinner, R. G. 1973: Quaternary stratigraphy of the Moose River Basin, Ontario. *Geological Survey of Canada Bulletin 225*, 1-77.

Stockmarr, J. 1971: Tablets with spores used in absolute pollen analysis. *Pollen et Spores 13*, 615-621.

Stokes, C. R., Tarasov, L., Blomdin, R., Cronin, T. M., Fisher, T. G., Gyllencreutz, R., Hättestrand, C., Heyman, J., Hindmarsh, R. C. A., Hughes, A. L. C., Jakobsson, M., Kirchner, N., Livingstone, S. J., Margold, M., Murton, J. B., Noormets, R., Peltier, W. R., Peteet, D. M., Piper, D. J. W., Preusser, F., Renssen, H., Roberts, D. H., Roche, D. M., Saint-Ange, F., Stroeven, A. P. & Teller, J. T. 2015: On the reconstruction of palaeo-ice sheets: Recent advances and future challenges. *Quaternary Science Reviews 125*, 15-49.

Stuiver, M. & Polach, H. A. 1977: Discussion: reporting of ^{14}C data. *Radiocarbon 19*, 355-363.

Stuiver, M. & Reimer, P. J. 1993: Extended ^{14}C data base and revised Calib 3.0 ^{14}C age calibration program. *Radiocarbon 35*, 215-230.

Ter Braak, C. J. F. & Prentice, I. C. 1988: A Theory of Gradient Analysis. *Advances in Ecological Research 34*, 271-217.

Terasmae, J. & Anderson, T. W. 1970: Hypsithermal range extension of white pine (*Pinus stobus L*.) in Quebec, Canada. *Canadian Journal of Earth Sciences 7*, 406-413.

Terasmae, J. & Hughes, O. L. 1960: A palynological and geological study of Pleistocene deposits in the James Bay Lowlands, Ontario (45 N1/2). *Geological Survey of Canada Bulletin 62*, 1-15.

Väliranta, M., Birks, H. H., Helmens, K., Engels, S. & Piirainen, M. 2009: Early Weichselian interstadial (MIS 5c) summer temperatures were higher than today in northern Fennoscandia. *Quaternary Science Reviews 28*, 777-782.

Väliranta, M., Salonen, J. S., Heikkila, M., Amon, L., Helmens, K., Klimaschewski, A., Kuhry, P., Kultti, S., Poska, A., Shala, S., Veski, S. & Birks, H. H. 2015: Plant macrofossil evidence for an early onset of the Holocene summer thermal maximum in northernmost Europe. *Nature Communications, DOI: 10.1038/ncomms7809*.

Van Meerbeeck, C. J., Renssen, H. & Roche, D. M. 2009: How did Marine Isotope Stage 3 and Last Glacial Maximum climates differ? – Perspectives from equilibrium simulations. *Climate of the Past 5*, 33-51.

Viau, A. E. & Gajewski, K. 2009: Reconstructing Millennial-Scale, Regional Paleoclimates of Boreal Canada during the Holocene. *Journal of Climate 22*, 316-330.

Warner, B., Morgan, A. V. & Karrow, P. F. 1988: A Wisconsinan interstadial arctic flora and insect fauna from Clarksburg, southwestern Ontario, Canada. *Palaeogeography, Palaeoclimatology, Palaeoecology 68*, 27-47.

Weijers, J. W. H., Bernhardt, B., Peterse, F., Werne, J. P., Dungait, J. A. J., Schouten, S. & Sinninghe Damsté, J. S. 2011: Absence of seasonal patterns in MBT–CBT indices in mid-latitude soils. *Geochimica et Cosmochimica Acta 75*, 3179-3190.

Whitmore, J., Gajewski, K., Sawada, M., Williams, J. W., Shuman, B., Bartlein, P. J., Minckley, T., Viau, A. E., Webb, T., III, , Anderson, P. M. & Brubaker, L. B. 2005: North American and Greenland modern pollen data for multi-scale paleoecological and paleoclimatic applications. *Quaternary Science Reviews 24*, 1828-1848.

Williams, J. W. & Shuman, B. 2008: Obtaining accurate and precise environmental reconstructions from the modern analog technique and North American surface pollen dataset. *Quaternary Science Reviews 27*, 669-687.

Wyatt, P. H. 1989: *The stratigraphy and amino acid chronology of Quaternary sediments in central Hudson Bay Lowland.* M.Sc. thesis, University of Colorado, 119 pp.

Figures and Tables captions:

Fig. 1. Map of the Hudson Bay Lowlands showing the location of modern pollen samples from the North American Modern Pollen Database (NAMPD; blue circles) (Whitmore *et al.* 2005) along with modern data which were newly compiled for inclusion in this study (white circles;

Table S1). The Ridge Site is shown (black triangle), along with the Nottaway River Site (white triangle; Allard *et al.* 2012). Elevation data are from Amante & Eakins (2009). Inset map locates the study area (square) on the North American continent. Scale on inset map is approximated for 50° N.

Fig. 2. Stratigraphy of the 18-m section studied at the Ridge Site, along with sampling details for pollen and macrofossils in the non-glacial unit. Tick marks on the left-most stratigraphic plot indicate elevation above river level (in m). Black circles indicate pollen sampling locations and black squares indicate macrofossil sampling locations. Green circles indicate location of samples for radiocarbon dating. See Fig. 3 for corresponding field photographs taken at points A, B, C and D.

Fig. 3. Field photographs from the Ridge Site. The position of each photograph is indicated in the text as well as by letters A through D in Fig. 2. A. Lower 20 to 30 cm of the non-glacial unit where stratified sand and silty sand are separated with rare thin diamicton lenses. The irregular lower diamicton can be seen as the light-colored sediments at the bottom of the photograph. The dark interval at the top of the photograph is the location of pollen and macrofossil sampling. B. Upper part of the non-glacial unit at till contact. The dark interval at the bottom of the photograph is the location of pollen sampling. C and D. Close-up of interbedded sands and silts containing organic detritus. E. Aerial view of the Ridge Site in 2012. The vegetation line across the face of the river bank is where the organic-bearing muds occur.

Fig. 4. Palynology and pollen-derived palaeoclimate reconstructions from the Ridge Site. The stratigraphic plot shows the location of each pollen interval at the site (circles) as well as the location of macrofossil samples (squares). See Fig. 2 for an explanation of symbols in the

stratigraphy sketch. Shaded regions correspond to pollen samples which were excluded on the basis of poor preservation (e.g. <5000 pollen grains cm^{-3}). For intervals with good preservation, all pollen/spore taxa reaching 2.5% relative abundance in at least one sample are shown. See text and Supporting Information for a complete list of pollen taxa used in the palaeoclimate reconstruction. Total annual precipitation and average summer temperature were reconstructed for the Ridge Site using the modern analogue technique (see text for details). Vertical lines indicate present-day summer temperature (15.5 °C) and total annual precipitation (705 mm) at the Ridge Site. NB: For the purposes of this figure, the samples in the overlying unconformity were placed above those from the clay/silt-rich unit. This transition is indicated by the dashed line.

Fig. 5. Loss-on-ignition, particle size and macrofossil data from the lower 150-cm of the non-glacial unit at the Ridge Site. Macrofossil data are presented in raw counts, and crosses indicate present (+), frequent (++) and abundant (+++) representation in the sample. See Fig. 2 for the location of these samples relative to pollen samples.

Fig. 6. A modern-day example of the inferred palaeoenvironment preserved in the non-glacial unit at the Ridge Site: a shrub-covered area at entrance to cut-off meander (indicated by an arrow). The cutoff meander in this photograph is located ~50 m downstream from the Ridge Site.

Fig. 7. A comparison of reconstructed total annual precipitation at the Ridge Site (MIS 3) and the Nottaway River Site (MIS 5; Allard *et al.* 2012). Vertical lines represent the present-day values at each site: 705 mm and 652 mm, respectively. Note: differing sample intervals at each site.

Table 1. Radiocarbon dating results from the Ridge Site. ‘F14C’ indicates the percent of modern carbon measured in the sample. Where the F14C was not distinguishable from background, the

age is marked with a cross (†) and the background age was assigned to that sample (Stuiver & Polach 1977). Dates which are finite were calibrated using CALIB Rev 7.0.4 and the 2013 calibration curve (Stuiver & Reimer 1993; Reimer *et al.* 2013). Dates which exceed the calibration curve, denoted with an asterisk (*), could not be calibrated and are reported as radiocarbon years (a ^{14}C). All ages were rounded to the nearest 100 and errors were rounded to the nearest 50. All radiocarbon dates were analyzed at the A.E. Lalonde AMS Laboratory, Ottawa, Canada. Chronology data from the Ridge Site was previously reported in Dalton *et al.* (2016).

Lab ID	Material dated	Sample interval (cm)	F14C	Assigned age
UOC-0591	peat	160 cm	0.0092 ± 0.0003	40 000±400
UOC-0592	peat	50 cm	0.002 ± 0.0002	49 600±950 †*
UOC-0842	peat	50 cm	0.0019 ± 0.0001	> 48 800

Supporting Information

Table S1. Raw data counts for previously published and newly counted modern pollen sites in the Hudson Bay Lowlands, Canada. When raw pollen counts were not provided in the original publication, relative abundance data was approximated from the pollen figure(s) of the original publication and converted to raw data using the pollen sum. The column “ID” refers to a unique code assigned to that site, while “original ID” refers to the name/number of that site from the original publication. Elevation and climate data were collected from Natural Resources Canada (2015). Climate data are based on a 30-year average (1971 to 2000). An artificial pollen sum was used for Skinner (1973) and Terasmae & Hughes (1960), since no sum was indicated in the original publication. Despite being located in wetland settings, some of the modern sites were missing Cyperaceae and *Sphagnum* counts, or they were indicated in qualitative terms (e.g. “abundant” or “present”). Since wetland taxa are not incorporated into the palaeoclimate reconstruction in this paper, we retained these sites, compiling only the arboreal, herb and shrub counts. In the case of Bazely (1981), there were originally 21 sites (with different pollen counts) associated with the same geographic coordinate. To resolve this issue, we chose a representative sample by creating a DCA of the 21 sites and picking the central site to incorporate into our dataset. Most data in this table are from surface samples, however a few were extracted from the top (or modern) sample of a peat and/or lake core. Sites are ordered from east to west.

Fig. S1. Model performance for the modern pollen calibration set. Modern pollen data were taken from the North American Modern Pollen Database (Whitmore *et al.* 2005) as well as newly-compiled data from the Hudson Bay Lowlands (Table S1). See main text for details on which species were included in this analysis.

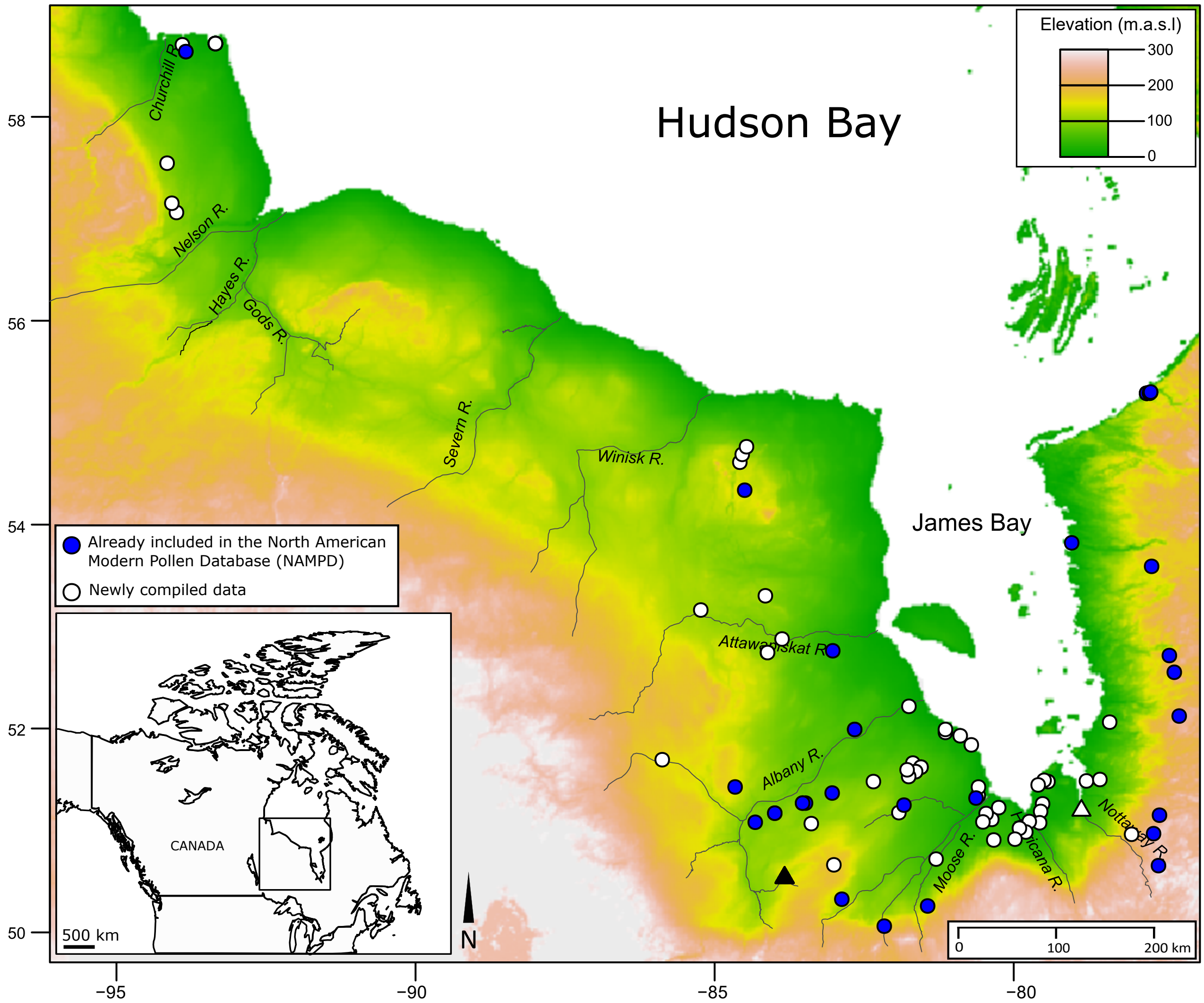

Fig. 1. Map of the Hudson Bay Lowlands showing the location of modern pollen samples from the North American Modern Pollen Database (NAMPD; blue circles) (Whitmore *et al.* 2005) along with modern data which were newly compiled for inclusion in this study (white circles; Table S1). The Ridge Site is shown (black triangle), along with the Nottaway River Site (white triangle; Allard *et al.* 2012). Elevation data are from Amante & Eakins (2009). Inset map locates the study area (square) on the North American continent. Scale on inset map is approximated for 50° N.

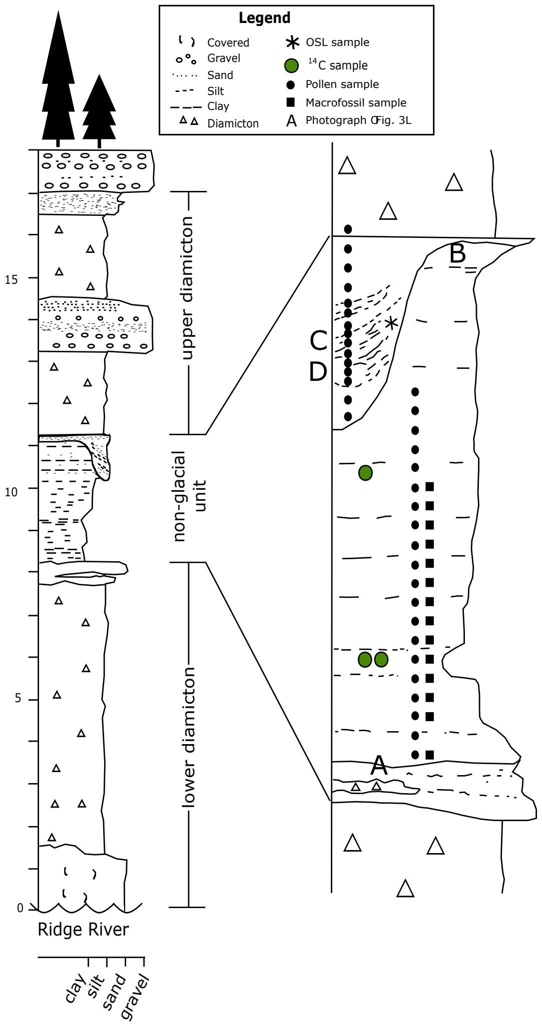

Fig. 2. Stratigraphy of the 18-m section studied at the Ridge Site, along with sampling details for pollen and macrofossils in the non-glacial unit. Tick marks on the left-most stratigraphic plot indicate elevation above river level (in m). Black circles indicate pollen sampling locations and black squares indicate macrofossil sampling locations. Green circles indicate location of samples for radiocarbon dating. See Fig. 3 for corresponding field photographs taken at points A, B, C and D.

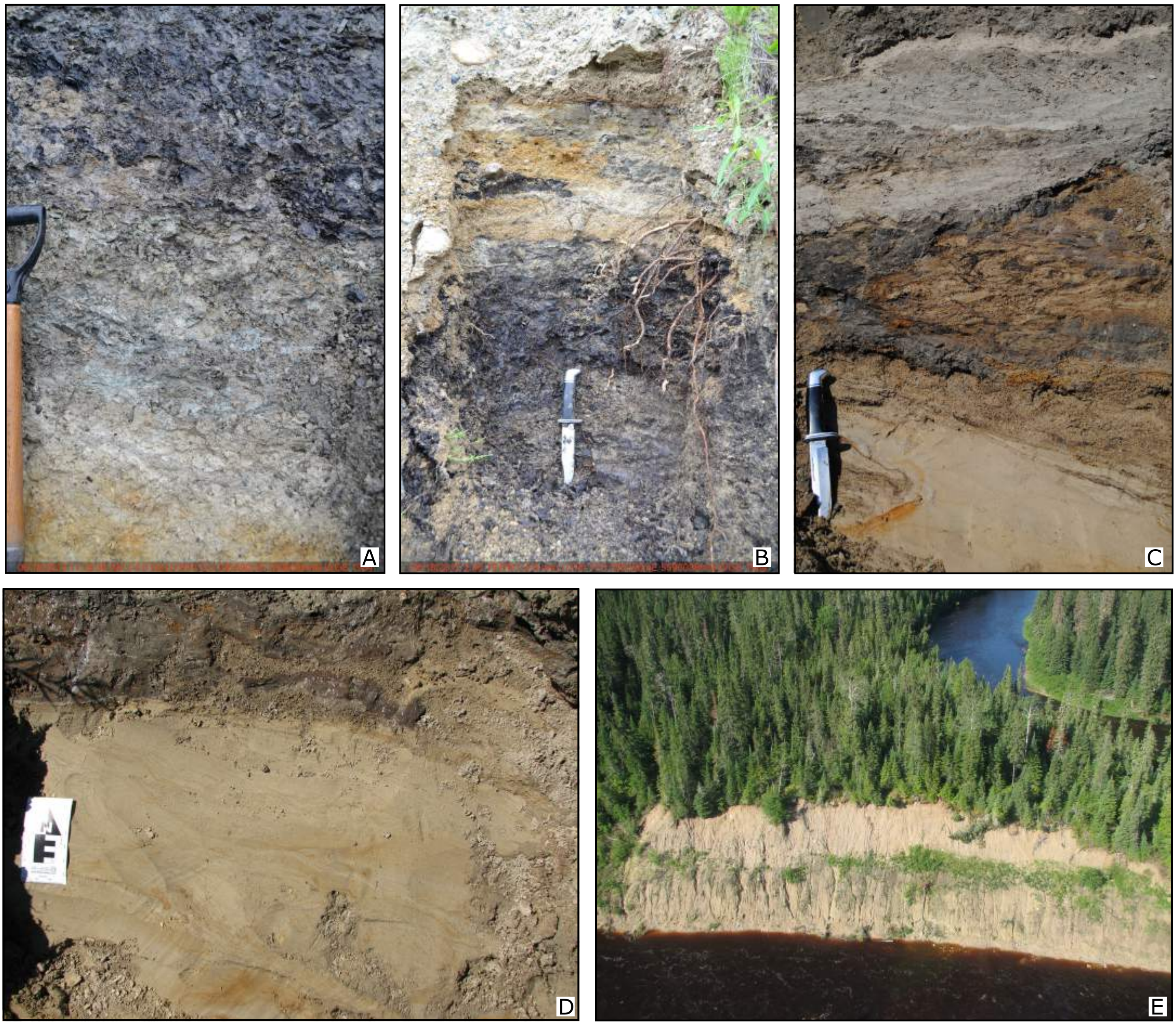

Fig. 3. Field photographs from the Ridge Site. The position of each photograph is indicated in the text as well as by letters A through D in Fig. 2. A. Lower 20 to 30 cm of the non-glacial unit where stratified sand and silty sand are separated with rare thin diamicton lenses. The irregular lower diamicton can be seen as the light-colored sediments at the bottom of the photograph. The dark interval at the top of the photograph is the location of pollen and macrofossil sampling. B. Upper part of the non-glacial unit at till contact. The dark interval at the bottom of the photograph is the location of pollen sampling. C and D. Close-up of interbedded sands and silts containing organic detritus. E. Aerial view of the Ridge Site in 2012. The vegetation line across the face of the river bank is where the organic-bearing muds occur.

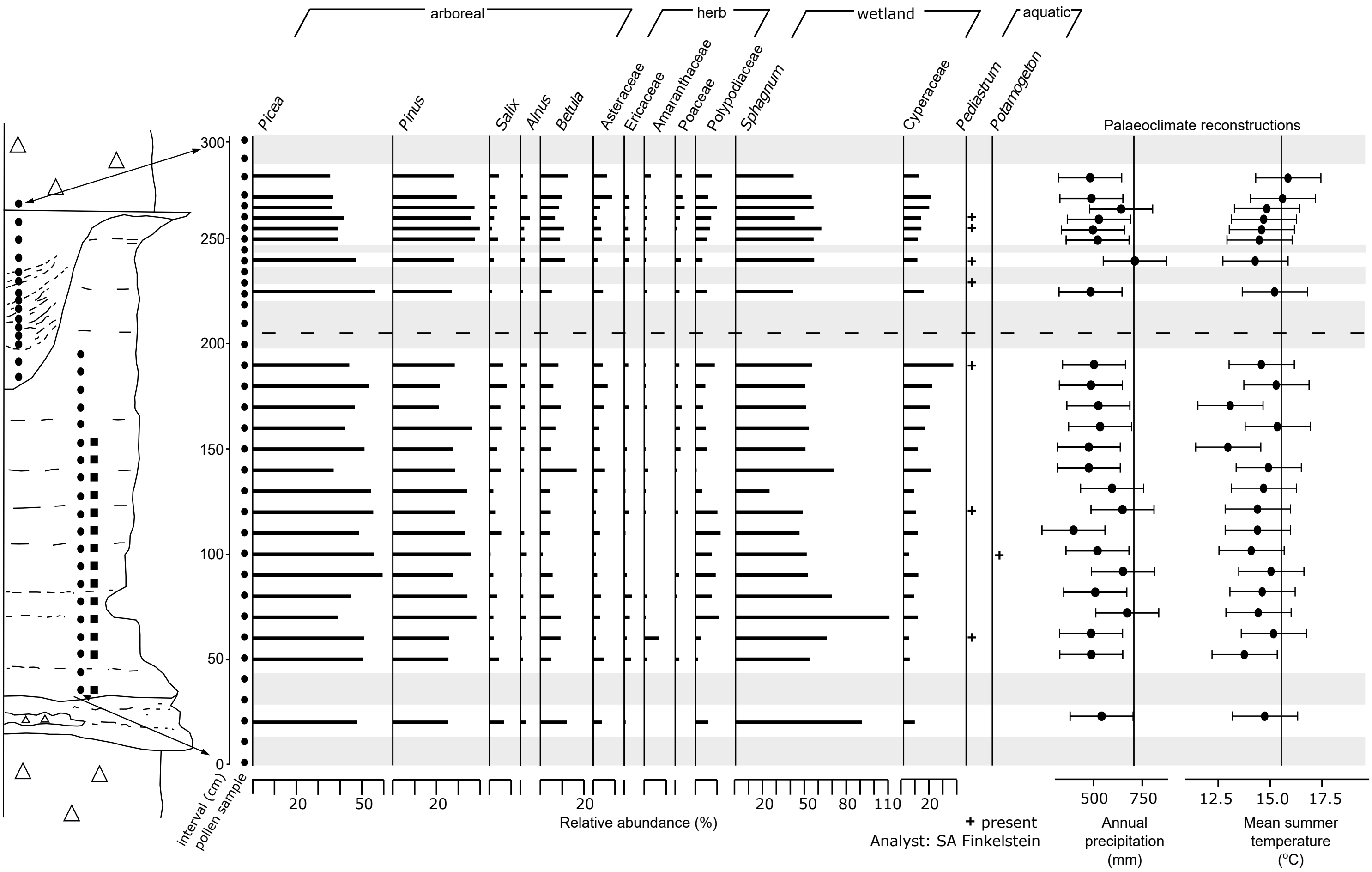

Fig. 4. Palynology and pollen-derived palaeoclimate reconstructions from the Ridge Site. The stratigraphic plot shows the location of each pollen interval at the site (circles) as well as the location of macrofossil samples (squares). See Fig. 2 for an explanation of symbols in the stratigraphy sketch. Shaded regions correspond to pollen samples which were excluded on the basis of poor preservation (e.g. <5000 pollen grains cm^{-3}). For intervals with good preservation, all pollen/spore taxa reaching 2.5% relative abundance in at least one sample are shown. See text and Supporting Information for a complete list of pollen taxa used in the palaeoclimate reconstruction. Total annual precipitation and average summer temperature were reconstructed for the Ridge Site using the modern analogue technique (see text for details). Vertical lines indicate present-day summer temperature (15.5 °C) and total annual precipitation (705 mm) at the Ridge Site. NB: For the purposes of this figure, the samples in the overlying unconformity were placed above those from the clay/silt-rich unit. This transition is indicated by the dashed line.

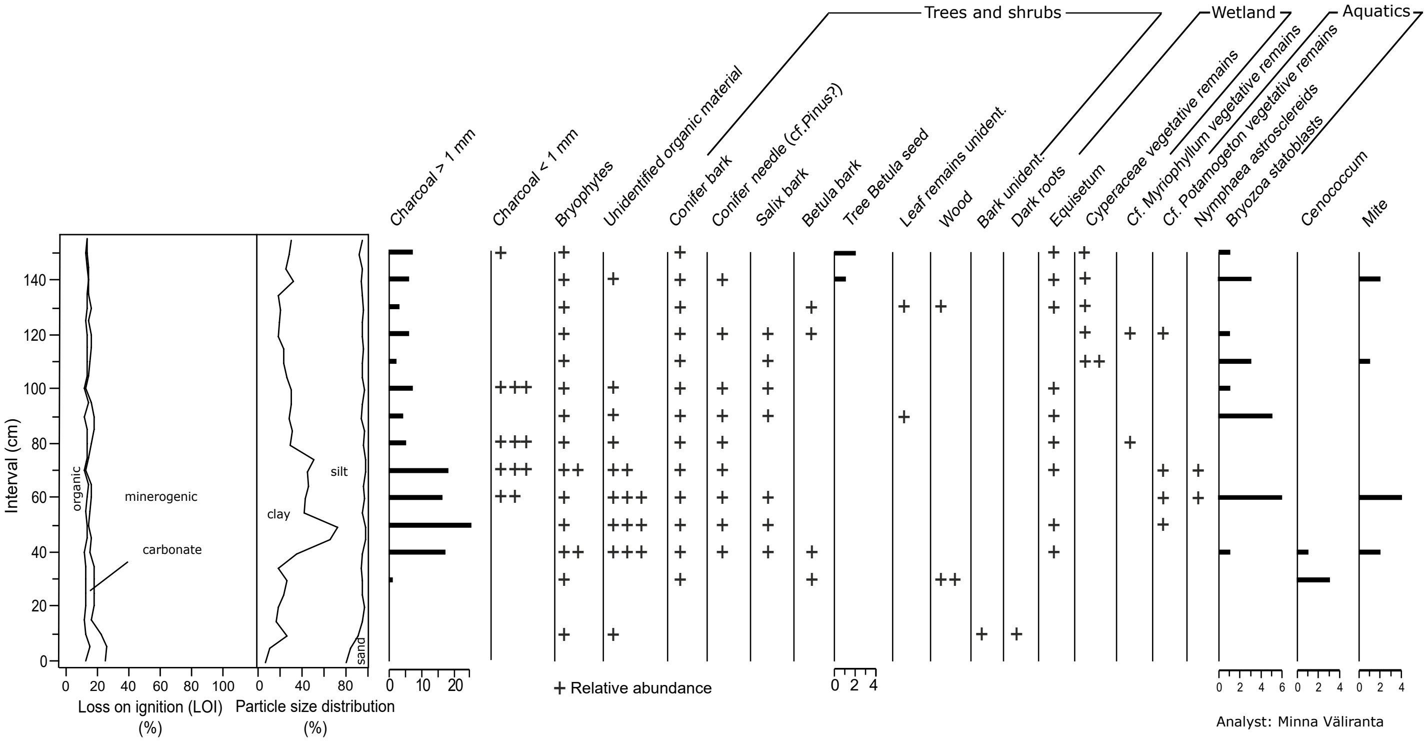

Fig. 5. Loss-on-ignition, particle size and macrofossil data from the lower 150-cm of the non-glacial unit at the Ridge Site. Macrofossil data are presented in raw counts, and crosses indicate present (+), frequent (++) and abundant (+++) representation in the sample. See Fig. 2 for the location of these samples relative to pollen samples.

Fig. 6. A modern-day example of the inferred palaeoenvironment preserved in the non-glacial unit at the Ridge Site: a shrub-covered area at entrance to cut-off meander (indicated by an arrow). The cutoff meander in this photograph is located ~50 m downstream from the Ridge Site.

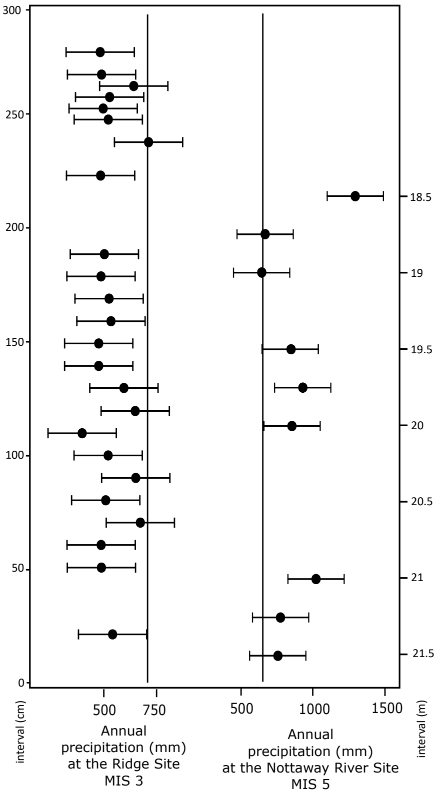

Fig. 7. A comparison of reconstructed total annual precipitation at the Ridge Site (MIS 3) and the Nottaway River Site (MIS 5; Allard *et al.* 2012). Vertical lines represent the present-day values at each site: 705 mm and 652 mm, respectively. Note: differing sample intervals at each site.