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Varve and radiocarbon dating support the rapid advance of Jakobshavn Isbræ during the Little Ice Age

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ABSTRACT

Large outlet glaciers draining the Greenland Ice Sheet significantly influence overall ice sheet mass balance. Considerable short term (years to decades) retreat and fluctuations in velocity of Jakobshavn Isbræ, western Greenland, illustrate the complex nature by which large outlet glaciers respond to climate change, making predictions of future ice sheet change challenging. To provide a longer-term view (centuries), we investigate the geological record of Jakobshavn Isbræ change. We use continuous sediment records from lakes that were influenced by the recent advance of Jakobshavn Isbræ, which took place during the Little Ice Age. In particular, we explore the use of annually laminated lake sediments (varves) to precisely constrain the advance of the ice margin as it approached its late Holocene maximum extent. We find that the ice margin advanced recently, at least after ~1650 to ~1700 AD, and more likely ~1800 AD. We suggest that during this period Jakobshavn Isbræ advanced at a rate that was similar to its historically documented average retreat since ~1850 AD. Our results indicate that Jakobshavn Isbræ, and presumably other large marine calving glaciers, have the ability to advance quickly in response to climate forcing.

1. Introduction

The Greenland Ice Sheet (GIS) is an integral part of the global climate system, and its potential contribution to sea level is of considerable importance (Alley et al., 2010). In particular, ice streams exert a disproportionate control on overall GIS mass balance, and thus have received increasing attention in the recent literature (e.g., Abdalati et al., 2001; Rignot and Thomas, 2002; Bamber et al., 2007; Thomas et al., 2009). Recent observations have revealed the dynamic nature and short timescales over which Greenland ice streams can adjust (Joughin et al., 2004, 2008; Rignot and Kanagaratnam, 2006; Howat et al., 2007). In particular, the importance of dynamic processes has been highlighted, prompting significant focus on the interplay between climatic and dynamic controls on ice stream change (Thomas et al., 2003; Csatho et al., 2008; Holland et al., 2008; Nick et al., 2009; Straneo et al., 2010). A greater understanding of the controls on ice stream change can be aided by longer-term reconstructions of past ice stream activity that extend beyond the relatively brief historic interval.

The GIS, like many glaciers across the globe, most recently advanced during the Little Ice Age (LIA), and throughout the 20th century many sectors of the GIS have experienced retreat (Weidick, 1968). We acknowledge that the term "Little Ice Age" has varying use in meaning and time; in this paper we follow Grove (2001) and use the term as a broad period of glacier advances across Greenland and define it as the time period ~1300 to ~1900 AD. This is the case for Jakobshavn Isbræ, the largest ice stream draining the western GIS. Historical observations around 1850 AD place the floating terminus ~40 km beyond its 2010 AD ice extent (Engell, 1904; Weidick, 1968; Csatho et al., 2008; Fig. 1), which was its most extensive position in the last 8000 yr (Weidick and Bennike, 2007; Young et al., 2011). When Jakobshavn Isbræ arrived at its maximum late Holocene position, or the precise timing of its advance, has only been broadly constrained to within the LIA (Weidick et al., 1990; Weidick and Bennike, 2007). Whereas mapping and dating LIA terminal moraines and obtaining at least some information on post-LIA behavior from historic records is relatively straightforward, determining when glaciers advanced is much more challenging. However, reconstructions of entire advance-retreat cycles of glaciation are most ideal for constraining the sensitivity of glaciers to climate perturbations. Maximum ages of recent glacier advances in Greenland are sparse, but have been obtained by radiocarbon dating marine fauna reworked into LIA moraines (e.g., Weidick et al., 2004) and organic material in sediments from proglacial-threshold lake basins (e.g., Kaplan et al., 2002).

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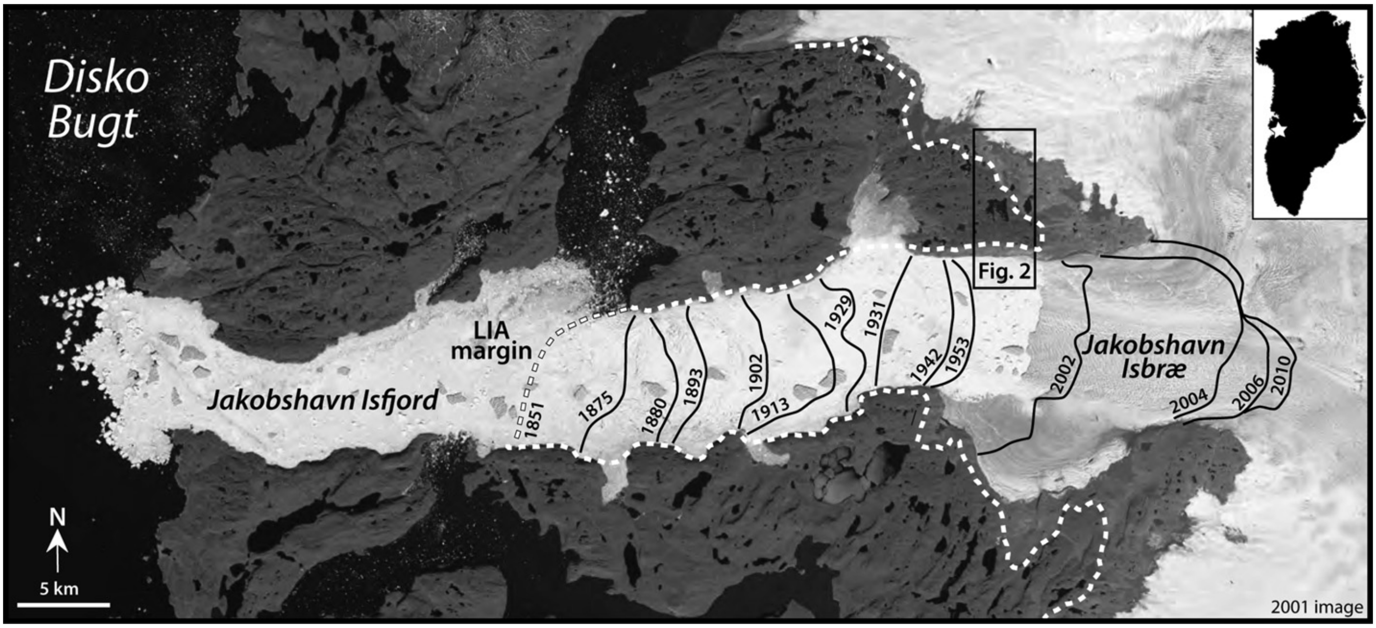

Fig. 1. Jakobshavn Isbrae region showing the maximum late Holocene extent (white dashed line) and historic positions of the marine terminus between 1851 and 2010. Inset shows map location (star) on west-central Greenland. Base map is 2001 Landsat image.

We build on our initial investigation of Jakobshavn ice margin change that used records from proglacial-threshold lakes (Briner et al., 2010). These are lakes that contain laminated minerogenic-rich glaciolacustrine sediments overlying non-glacial autochthonous organic-rich sediments, a sediment sequence diagnostic of advancing glaciers. We used radiocarbon ages from macrofossils nearest the transition from organic-rich to minerogenic-rich sediments to constrain the timing of GIS advance. Here, we utilize the lamination stratigraphy within glaciolacustrine sediments from two lakes to more precisely constrain the timing of the GIS advance during the LIA.

2. The Jakobshavn ice sheet margin

The west-central margin of the GIS is composed of land-terminating ice punctuated by marine-terminating outlet glaciers. Some of the marine-terminating glaciers are very large and fast-flowing; for example, Jakobshavn Isbræ flows many kilometers per year and drains ~7% of the GIS (Joughin et al., 2004; Rignot and Kanagaratnam, 2006). Between the western GIS margin near Jakobshavn Isbræ and Disko Bugt is an ice-free corridor of land 40–50 km wide containing ice-sculpted bedrock dotted with hundreds of lakes (Fig. 1). This landscape was covered by the GIS during the last glaciation and became ice-free during the early Holocene (Weidick and Bennike, 2007; Young et al., 2011). Following a time period when the GIS margin terminated inland (eastward) of its current position, the GIS advanced (westward) during Neoglaciation, culminating in a maximum position that deposited the 'historical moraine,' which occurred during the LIA (Weidick, 1968; Weidick and Bennike, 2007). To improve the chronology of the LIA advance, we investigated the sediment sequences from two lakes. Iceboom Lake is an extant proglacial-threshold lake that no longer receives GIS meltwater due to ice recession, and Glacial Lake Morten was an ice-dammed lake that is now drained due to ice recession.

2.1. Iceboom Lake

Iceboom Lake (informal name, ~180 m asl) lies ~4 km west of the present ice margin (Fig. 2). The lake has a complex outline, contains several islands, a single outflow to the west, several minor inflows, and lies in a 5.18 km^2 catchment. Aerial photographs reveal that Iceboom Lake was glacier fed in 1944, 1953 and 1964, and that GIS meltwater had ceased to drain into the lake by 1985. An abandoned ~200-m-long channel spans between the eastern shoreline and the historical moraine, and a boulder-rich proglacial delta resides in the northeastern corner of the lake, fed when the historical moraine was emplaced ~280 m north of the delta. Iceboom Lake has complex bathymetry, with two relatively large basins ~30–40 m deep and several minor sub-basins (Fig. 3).

2.2. Glacial Lake Morten

Glacial Lake Morten (informal name), now drained, occupied a north-south trending valley ~1 km north of Iceboom Lake (Fig. 2). The lake formed when the GIS margin dammed the northward-draining valley. The resultant ice-dammed lake was ~0.3 km wide and extended 1.2 km to the south, where it overflowed a threshold at ~240 m asl. Aerial photographs acquired in 1944, 1953, 1964 and 1985 show a fully occupied lake basin, despite the ice margin having retreated from the historical moraine. The oldest available post-1985 cloud-free satellite image (1992) reveals a partially-drained lake, and the next available cloud-free images (starting in 1999) show the area beyond the historical moraine completely drained (Fig. 2). By 2001, the ice margin had retreated ~1.3 km north of the historical moraine, and dams a small lake with an area ~0.25 km^2 (Fig. 3).

The geomorphology and sedimentology of recently drained ice-dammed lakes provide rare insight into their history (Loso et al., 2004, 2006). Because a bedrock spillway controlled the level of Glacial Lake Morten, a prominent shoreline was formed that outlines the former lake (Fig. 3). Proglacial deltas along the lake's eastern shoreline reveal small ice-fed discharges into the lake, although the major source of inflow was likely the ice margin itself, which deposited a subaqueous moraine across the lake basin during its maximum Neoglacial extent. The lake basin itself is largely unvegetated, and in steep areas, its infill has been dissected by modern drainage. The basin floor proximal to the moraine lies

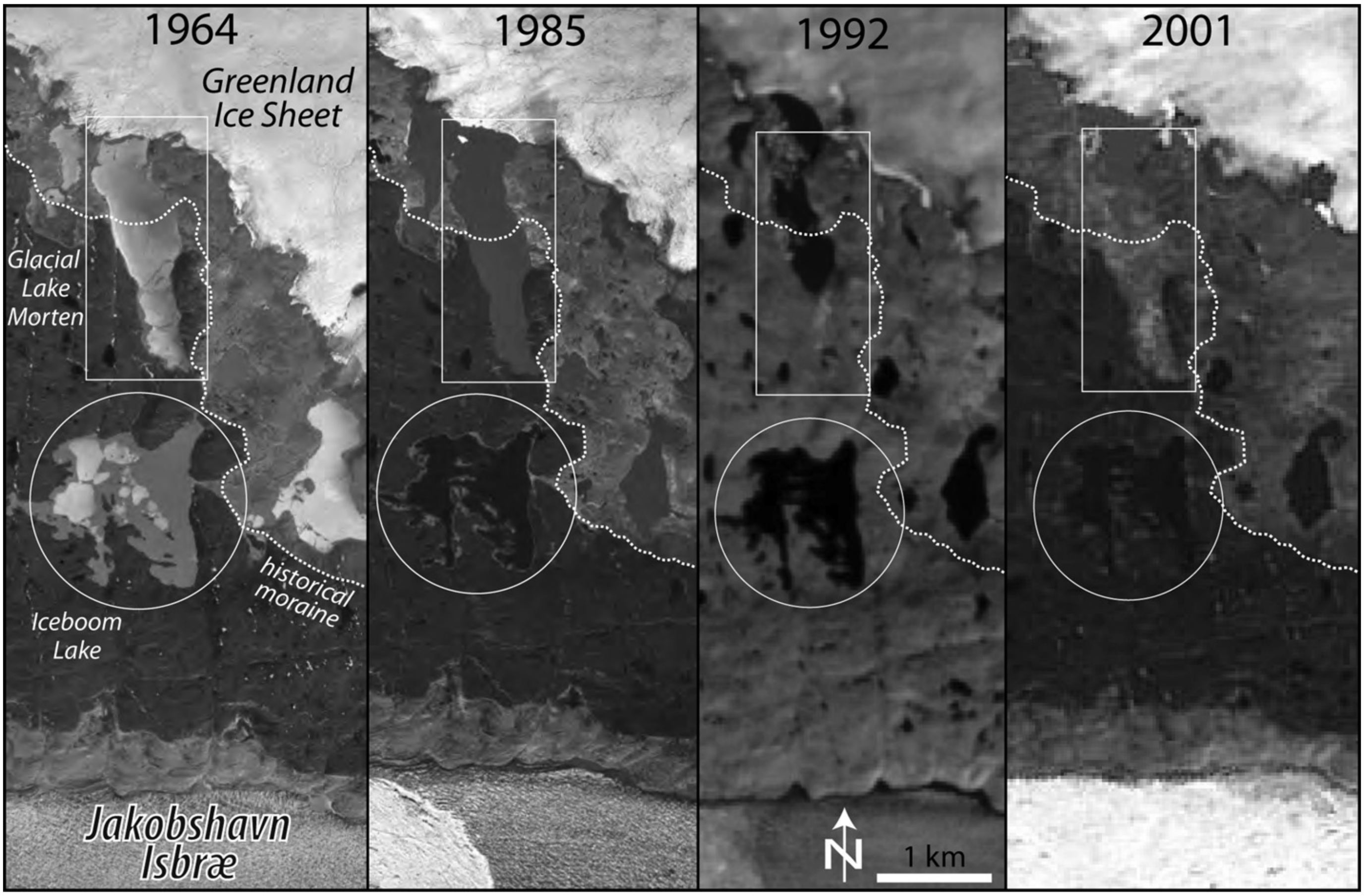

Fig. 2. Time series showing changes of the ice margin and adjacent lakes between 1964 and 2001 AD (area shown in Fig. 1). Jakobshavn Isbræ fills the bottom of the scene in 1964 AD, terminates within the scene in 1985 and 1992 AD, and is absent in the 2001 AD scene. 1964 and 1985 AD images are vertical aerial photographs; 1992 and 2001 AD images are Landsat.

~20 m below the shoreline, whereas the distal portion of the lake is only 3–5 m below the shoreline. Gullying in the lake bottom has exposed thick sections of finely-laminated sand and silt in the middle of the basin (Fig. 4a), whereas in the distal sector of the lake, only a thin drape of massive fine sand and silt is present (Fig. 4b). In many locations, modern dissection has eroded through the glaciolacustrine sediments and into the pre-lake deposits, which contain an intact soil profile and the pre-lake vegetated surface (Fig. 4).

3. Methods

Our approach is to determine if the laminations in these lakes are annual (ie, varves), and if so, to use them to add chronologic information to the lake basins' history, and thus, the history of Jakobshavn Isbræ. Annually laminated glaciolacustrine sediments have been shown to form in response to seasonal changes in sediment influx and ice cover (Lamoureux and Gilbert, 2004; Hodder et al., 2007). The spring and summer melt season carries glacial sediment to the lake. The coarse sediments settle rapidly, forming a coarse "summer" lamination, and the fine sediments settle during the winter under ice cover, forming a fine "winter" lamination. These laminations are visible in outcrop and thin section due to changes in color and texture associated with the changes in grain size. In proglacial lakes, sediment input is largely glacially sourced, although undoubtedly some non-glacial sediment is also deposited in a lake when it is ice-free during the summer.

Iceboom Lake bathymetry was collected using a Garmin GPSMAP 400 series GPS receiver connected to a dual beam depth transducer. A bathymetric map was created by importing GPS-derived waypoints into ArcGIS where contours were generated automatically. Coring was executed using a Universal Coring system in 2008; the sediment–water interface was preserved in all cores. Water above the surface sediments was iteratively drained using a small awl hole at the interface as the sediment cores were kept vertical for several days. Sediment cores were subsequently packed with foam and capped for transport and cold storage at the University at Buffalo. Upon splitting, each core was immediately photographed with a digital camera and tripod and logged to scale.

Glaciolacustrine sediments in surface core 08ICE-3 were made into sediment thin sections at the University at Buffalo following methods similar to Lamoureux (1994) and Francus and Asikainen (2001). Briefly, sediments were removed from the split core face in aluminum boats, flash frozen in liquid nitrogen and subsequently freeze dried. The freeze-dried slabs were placed in trays that were slowly filled with epoxy resin under vacuum and subsequently hardened in a vacuum oven. The impregnated brick was labeled, cut and shipped to Texas Petrographic Services, Inc. where thin sections were made. The thin sections were scanned at 1600 dpi resolution and the laminations were identified, marked and counted in Adobe Illustrator and lamination thicknesses were measured at an angle perpendicular to the laminations using ImageJ software.

The Glacial Lake Morten basin was investigated in 2008 and 2009. Laminations were counted, measured with calipers and

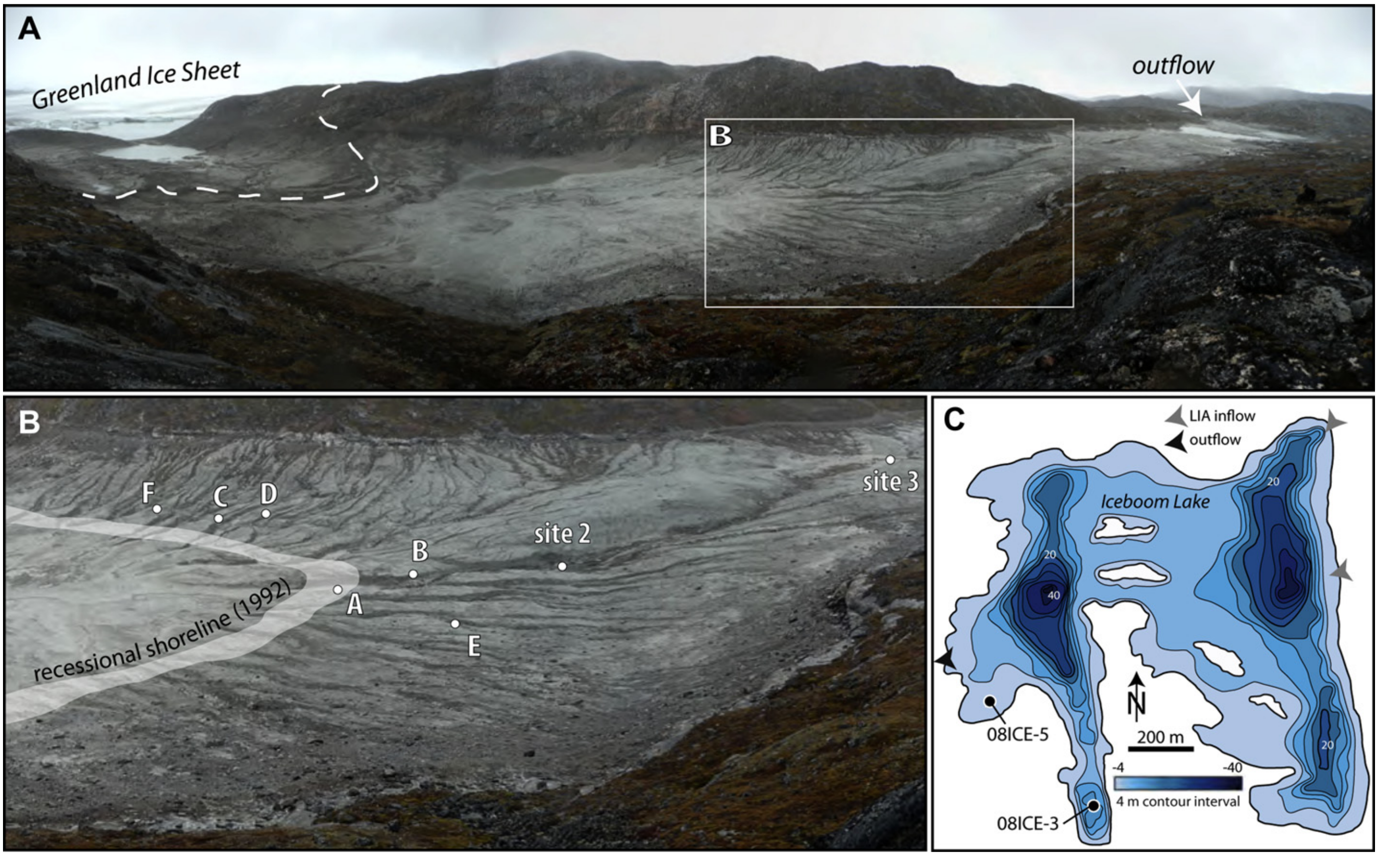

Fig. 3. A. Oblique photograph showing the Glacial Lake Morten basin in 2008 AD. Dashed line shows the moraine that delimits the maximum late Holocene ice extent; lake was dammed by the ice margin on the left (north) side of the image. B. Close up of the middle portion of the lake basin showing sites mentioned in text; also shown is the shoreline from the lake seen in the 1992 AD image (Fig. 1), the evidence of which was observed in the field. C. Bathymetric map of Iceboom Lake showing core sites.

digitally photographed in the field at six vertical excavations across the basin (sites A through F; Fig. 3). Pre-lake sediments were investigated at two additional locations (sites 2 and 3; Fig. 3). Measurements made in the field were checked against high-resolution digital logs created from the digital photographs taken on site. The lamination stratigraphy was cross-referenced between the six sites using marker beds such as easily identifiable sand layers.

We used the plutonium radionuclide ($^{239+240}$Pu) and its well-constrained fallout record to identify (1) the onset of atmospheric nuclear testing in 1954 AD, and (2) the height of testing in 1963 AD (e.g. Wolfe et al., 2004; Ketterer et al., 2004a). Dried aliquots (0.5 g) of the top 11.5 cm of core 08ICE-3 (0.5 cm increments, $n = 24$) were sent to the Northern Arizona University Department of Chemistry where they were analyzed for $^{239+240}$Pu concentrations using ICP-MS analysis following the methods of Ketterer et al. (2004b). Macrofossils for radiocarbon dating were picked and cleaned with de-ionized water and sent to the INSTAAR (University of Colorado) Laboratory for AMS Radiocarbon Preparation and Research for AMS radiocarbon dating. We calibrated all ages using CALIB html version 6.0 with INTCAL09 (Stuiver et al., 2005) and report the calibrated AMS ages with 2-sigma uncertainty rounded to the nearest decade (Table 1).

4. Results

4.1. Iceboom Lake

Two cores from Iceboom Lake were selected for detailed analysis and radiocarbon dating (for a complete description of the sediment cores collected from Iceboom Lake, see Briner et al. (2010)). The location of cores 08ICE-3 (69°13′58″ N, 50°35′00″ W) and 08ICE-5 (69°14′8″ N, 50°1′7″ W) are shown in Fig. 3, and their stratigraphy is shown in Fig. 5. Both cores contain a laminated minerogenic-rich unit that lies beneath ~1 cm of organic-rich surface sediment. The base of the minerogenic-rich unit is at 45 cm in 08ICE-3 and 22 cm in 08ICE-5. Beneath this unit lies weakly laminated, organic-rich sediments with sporadic macrofossils. We did not penetrate minerogenic sediments beneath the organic-rich sediments in 08ICE-3, but obtained ~6 cm of minerogenic-rich sediments at the base of 08ICE-5. Macrofossils from core 08ICE-3 from 45 cm and near the core base at 95 cm are 525 ± 15 and 5380 ± 15 ^{14}C yr BP (530 ± 20 and 6200 ± 80 cal yr BP), respectively (Table 1). Macrofossils were dated from core 08ICE-5 at 23 cm depth (335 ± 15 ^{14}C yr BP; 390 ± 80 cal yr BP), 36 cm depth (1840 ± 20 ^{14}C yr BP; 1770 ± 60 cal yr BP), 57 cm depth (3980 ± 20 ^{14}C yr BP; 4470 ± 50 cal yr BP), and 70 cm depth (6360 ± 25 ^{14}C yr BP; 7300 ± 120 cal yr BP; Table 1). The most relevant result for the present study is the uppermost radiocarbon age in each core, which is the closest maximum constraining age for the onset of minerogenic sediment deposition, and hence the arrival of the ice margin into Iceboom Lake's catchment. These radiocarbon ages, reported as 2-sigma calibrated age ranges, yield a single solution of 520–550 cal yr BP in 08ICE-3 and yield three solutions of 320–340, 350–410, and 420–470 cal yr BP in 08ICE-5.

Next, we present the lamination record. The sediment thin sections from 08ICE-3 reveal 147 alternating, well-defined couplets throughout the minerogenic-rich sediment unit that average 1.9 ± 0.9 mm thick (Fig. 5). The uppermost sediment thin section captures in detail the transition from minerogenic-rich laminated

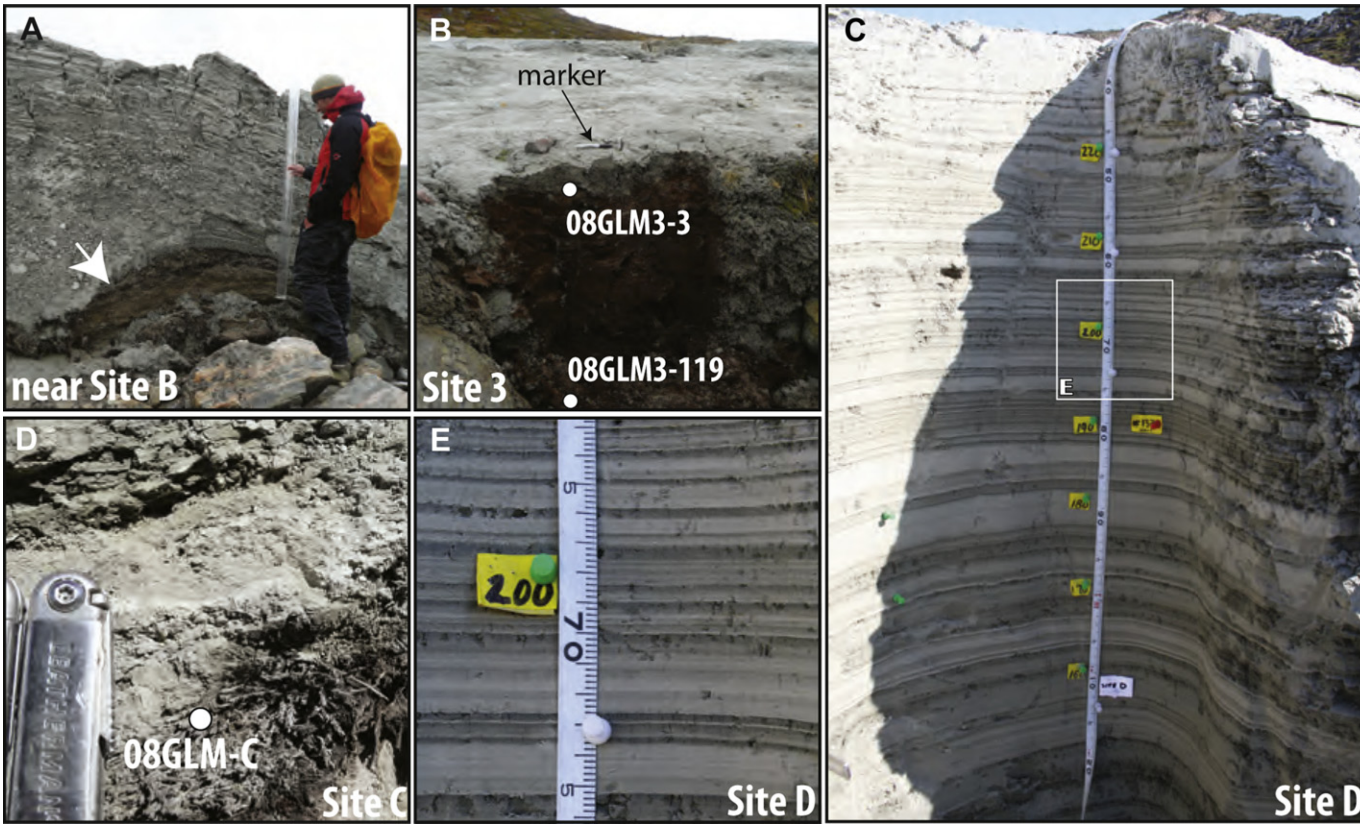

Fig. 4. Photographs from the Glacial Lake Morten basin taken in 2008 and 2009 AD. A. Glaciolacustrine sediment sequence overlying pre-lake tundra surface. B. Thin glaciolacustrine sediment drape over >1-m-thick peat section in the upper (southern) portion of the lake basin. C. Section from Site D showing laminations. D. Close up view of the base of the section at Site C showing in-situ tundra plant that was buried when Glacial Lake Morten was first impounded. E. Close up view of laminations from Site D; scale is metric.

sediment to the overlying homogenous organic-rich surface sediments (Fig. 6). The maximum $^{239+240}$Pu concentration occurs at 2.0–2.5 cm, which is just below the sediment transition exposed in the thin section, and the first detectable $^{239+240}$Pu occurs at 3.5–4.0 cm (Fig. 6); the onset and peak in $^{239+240}$Pu concentration are used to identify 1954 and 1963 AD, respectively (Wolfe et al., 2004).

4.2. Glacial Lake Morten

We obtained five radiocarbon ages from the organic sediments that lie beneath the Glacial Lake Morten sediment fill, all from unidentified tundra plant macrofossils. Two ages are from a thick section of peat that lies beneath a thin veneer of the

Table 1
Radiocarbon ages from lake sediment cores and stratigraphic sections (cores and sites listed in Fig. 3).

Core/Site	Depth (cm)	Lat	Long	Lab Number	Material Dated	Fraction Modern	δ^{13}C (‰PDB)	Radiocarbon Age (^{14}C yr BP)	Calibrated Age Ranges (cal yr BP ± 2σ)
Iceboom Lake									
08-ICE-5	23	69° 14′ 08″ N	50° 01′ 07″ W	CURL-10083	Terrestrial macrofossils	0.9591 ± 0.0015	−23.5	335 ± 15	320–340, 350–410, 208–470
08-ICE-5	36	69° 14′ 08″ N	50° 01′ 07″ W	CURL-10439	Terrestrial macrofossils	0.7952 ± 0.0019	−27.8	1840 ± 20	1710–1830
08-ICE-5	57	69° 14′ 08″ N	50° 01′ 07″ W	CURL-10434	Terrestrial macrofossils	0.6098 ± 0.0015	−30.7	3980 ± 20	4420–4450, 4470–4570
08-ICE-5	70	69° 14′ 08″ N	50° 01′ 07″ W	CURL-10441	Terrestrial macrofossils	0.4534 ± 0.0013	−30.5	6360 ± 25	7180–7190, 7250–7330, 7350–7380, 7390–7410
08-ICE-3	45	69° 13′ 06″ N	50° 35′ 00″ W	CURL-10081	Terrestrial macrofossils	0.9370 ± 0.0013	−22.4	525 ± 15	520–550
08-ICE-3	95	69° 13′ 06″ N	50° 35′ 00″ W	CURL-10093	Terrestrial macrofossils	0.5119 ± 0.0009	−28.4	5380 ± 15	6130–6140, 6180–6220, 6230–6280
Glacial Lake Morten									
08GLM-site 2	15	69° 15′ 17″ N	50° 00′ 05″ W	CURL-10442	In-situ tundra twig fragments	0.9803 ± 0.0024	−29.1	160 ± 20	0–30, 70–80, 80–100, 140–150, 170–220, 260–280
08GLM-site 3	3	69° 15′ 09″ N	49° 59′ 55″ W	CURL-10096	Terrestrial macrofossils	0.9373 ± 0.0013	−30.5	520 ± 15	520–540
08GLM-site 3	119	69° 15′ 09″ N	49° 59′ 55″ W	CURL-10102	Terrestrial macrofossils	0.5596 ± 0.0011	−27.1	4665 ± 20	5320–5330, 5350–5470
09GLM-site B	NA	69° 15′ 17″ N	50° 00′ 04″ W	CURL-11052	In-situ terrestrial macrofossil	0.9739 ± 0.0018	−28.2	210 ± 15	0–10, 150–170, 180–190, 270–300
09GLM-site C	NA	69° 15′ 20″ N	49° 59′ 56″ W	CURL-11053	In-situ terrestrial macrofossil	0.9781 ± 0.0018	−28.8	180 ± 15	0–20, 140–160, 170–220, 270–280

Note: Calibrated ages are rounded to the nearest decade.

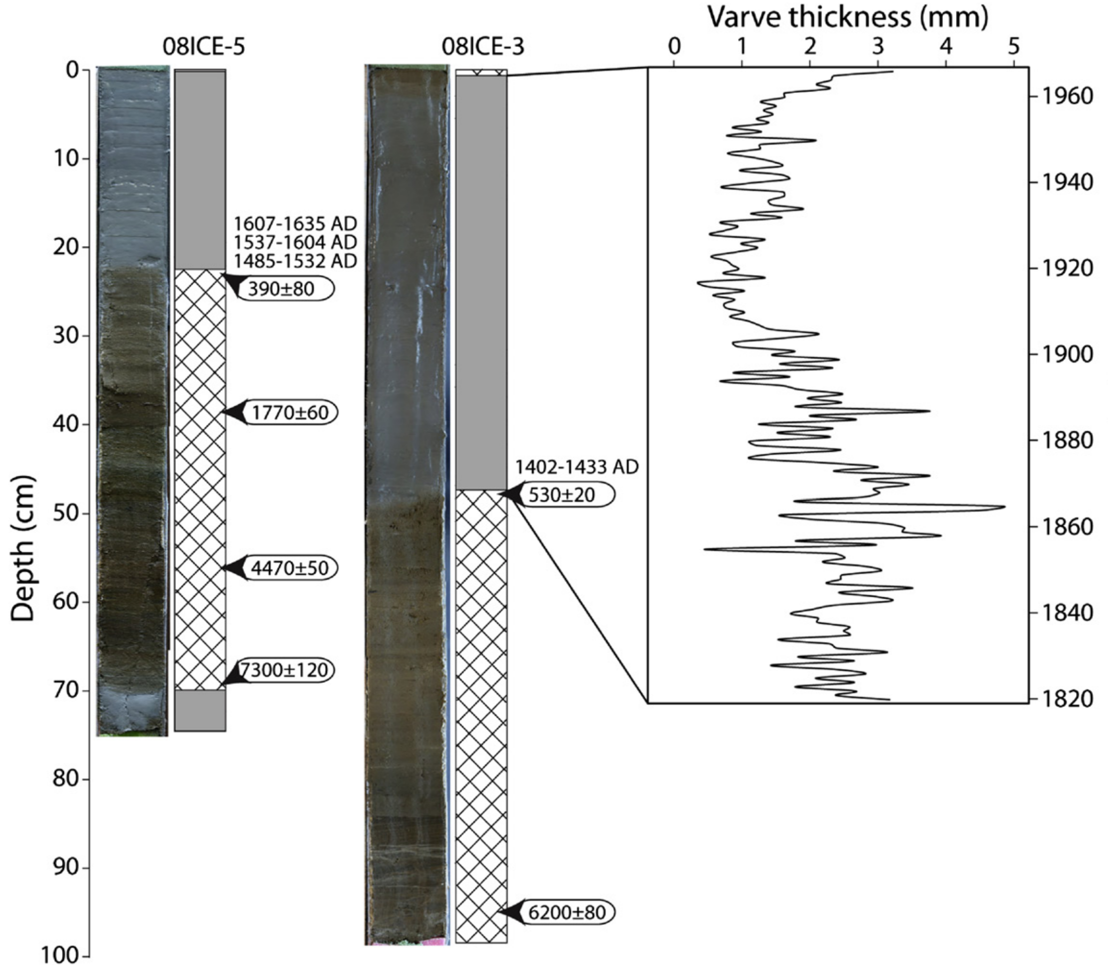

Fig. 5. Sediment stratigraphy captured in two cores from Iceboom Lake (gray = glaciolacustrine sediment; hachured = organic-rich sediment); also shows are radiocarbon ages in cal yr BP (the uppermost age from each core is also shown with their 2-sigma calibrated age solutions in AD). At right is varve thickness versus age for the glaciolacustrine section from 08ICE-3, compiled using sediment thin sections.

glaciolacustrine sediments at site 3, the single site that we investigated in the shallow, southern part of the lake basin (Fig. 3). The uppermost age (08GLM3-3) is from 3 cm beneath the surface and immediately beneath the contact between peat and the overlying glaciolacustrine sediments (Fig. 4b). The sample yielded a radiocarbon age of 520 $\pm$ 15 ^{14}C yr BP and a 2-sigma calibrated age solution of 516–544 cal yr BP. A second sample from site 3 is from the deepest portion of the peat deposit that we could access (08GLM3-119; 119 cm below the surface), which yielded a radiocarbon age of 4665 $\pm$ 20 ^{14}C yr BP and 2-sigma calibrated age solutions of 5320–5330 and 5350–5470 cal yr BP. There are no minerogenic sediment layers visible between the top and bottom of the peat deposit. The remaining three radiocarbon ages are from uppermost tundra plants in growth position that lie beneath thick successions of glaciolacustrine sediments (Fig. 4d). The ages are 160 $\pm$ 20 ^{14}C yr BP from site 2 (2-sigma calibrated solutions of 0–30, 70–80, 80–100, 140–150, 170–220 and 260–280 cal yr BP), 210 $\pm$ 15 ^{14}C yr BP from site B (2-sigma calibrated solutions of 0–10, 150–170, 180–190 and 270–300 cal yr BP), and 180 $\pm$ 15 ^{14}C yr BP from site C (2-sigma calibrated solutions of 0–20, 140–160, 170–220 and 270–280 cal yr BP).

The sediment fill in the Glacial Lake Morten basin is composed of laminated couplets of alternating sand and silt (Fig. 4). The base of each couplet is composed of medium to coarse sand, whereas the top of each couplet is composed of fine sand and silt. The couplets

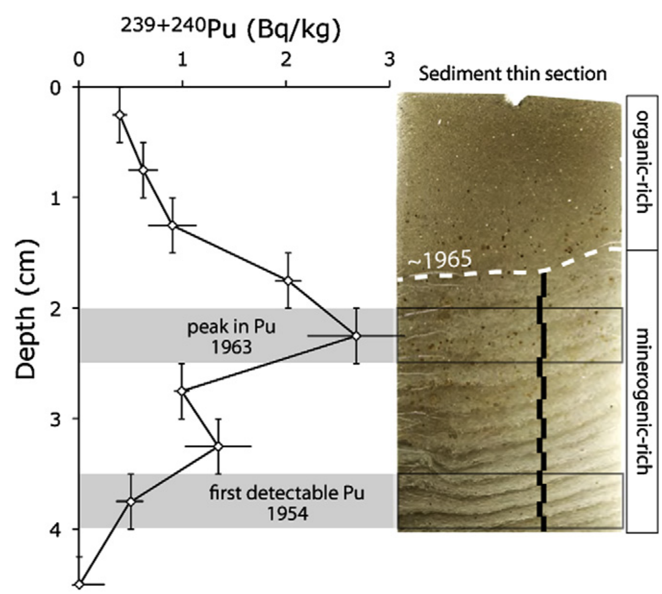

Fig. 6. Plot of $^{239+240}$Pu versus depth for the top of 08ICE-3. Adjacent to the plot is the uppermost thin section, which illustrates the contact between the varved glaciolacustrine sediments and the overlying organic-rich sediments.

range in thickness from 1.0 to 118.6 mm, and with few exceptions couplet thickness is relatively uniform across the excavation faces (Fig. 4c). The six stratigraphic logs compiled from field measurements, later refined with the high-resolution digital photo logs, reveal a combined total of 191 couplets (Fig. 7). There is not a single site that contains the entire sequence of couplets; for example, sites A and B contain the first couplets deposited above the pre-lake tundra surface, and only sites D and F contain the uppermost couplets up to the paleo-lake floor. The six sites each have different average thicknesses, ranging from 8.8 mm (site D) to 19.5 mm (site A). The couplets are thinnest at the bottom and top of the sediment fill (Fig. 7). The upper sediments exposed at site A contain cross-bedded sand and gravel that unconformably overlies the package of laminated sediments.

5. Interpretation

5.1. Ice sheet history at Iceboom Lake

Our first objective regarding the laminated minerogenic unit preserved in Iceboom Lake sediments is to determine if the laminations are annual couplets (ie, varves). The Pu analysis reveals that 1963 AD occurs in the 2.0–2.5 cm sample and encompasses lamination #2 and #3 (counted from top), and that 1954 AD occurs in the 3.4–4.0 cm sample and encompasses lamination #10 through #12 (Fig. 6). Because the number of couplets and years between the two samples has a solution, and because the couplets have characteristics common to varves (Lamoureux and Gilbert, 2004; Thomas and Briner, 2009), we conclude that the couplets in Iceboom Lake are varves. We thus assign the uppermost varve at ~1.5 cm depth to have been deposited in 1964 or 1965 AD, compatible with the 1964 AD aerial photograph depicting the lake as glacier-fed. Finally, we assign the lowermost varve to have been deposited ~1820 AD. Assigning uncertainty to this value is difficult. Although there are no anomalously thick layers that may have been associated with erosion or any obvious appearance of unconformable couplets, there are places where it is difficult to distinguish varve boundaries from sub-laminations. We replicated varve counts and estimate an uncertainty of ~3%; however, sub-laminations incorrectly identified as varves have an unknown impact on the varve chronology. To summarize, the varve-counting exercise suggests that Iceboom Lake was receiving meltwater from the GIS between 1820 ± 5 AD and 1964–1965 AD.

The two radiocarbon ages from the uppermost organic sediments pre-date the varve-based age assignment of 1820 ± 5 AD. The uppermost ages from 08ICE-3 and 08ICE-5 have 2-sigma age ranges of 1400–1430 AD and 1490–1530, 1540–1600, and 1610–1640 AD, respectively. Thus, the even the youngest radiocarbon age solution is ~200 years older than the varve-based age. This discrepancy could be due to either (1) incorrect varve counting, or (2) the fact that the uppermost radiocarbon-dated macrofossils provide maximum age constraints only.

We discuss these possibilities further below.

5.2. Ice sheet history at Glacial Lake Morten

Unlike at Iceboom Lake, we did not date the surface sediments in the Glacial Lake Morten basin with Pu. Available imagery shows Glacial Lake Morten present in 1985 AD and partially drained in 1992 AD (Fig. 1). The 1992 AD image shows a lake of smaller extent that still covers the site of our lowest stratigraphic section (site A); evidence of this shoreline is recognized in the field as a faint beach and as cross-bedded sand overlying the laminations at section A. Therefore, our measurements of the laminations from site A only extend from the base of the sediment fill to the presence of sediments associated with this lower lake stand. Sites B–F are located above this lake level. The sediments from Site A contain no additional sediment facies similar in character to the 1992 AD shoreline deposits, nor do the other sites. Thus, unlike some lakes known to repeatedly fill and drain via their ice dams (e.g., Thomsen, 1984; Anderson et al., 2003), there is no stratigraphic evidence that Glacial Lake Morten ever did so. Rather, our best estimate is that GLM drained once since it formed sometime between 1986 and 1991 AD.

Next, we aim to determine when Glacial Lake Morten first formed. First, we discuss the radiocarbon ages. Of the five ages, three are considered to be from material that was in growth position at the time of lake formation. Although the radiocarbon ages from the top and bottom of the peat section at site 3 reveal that the

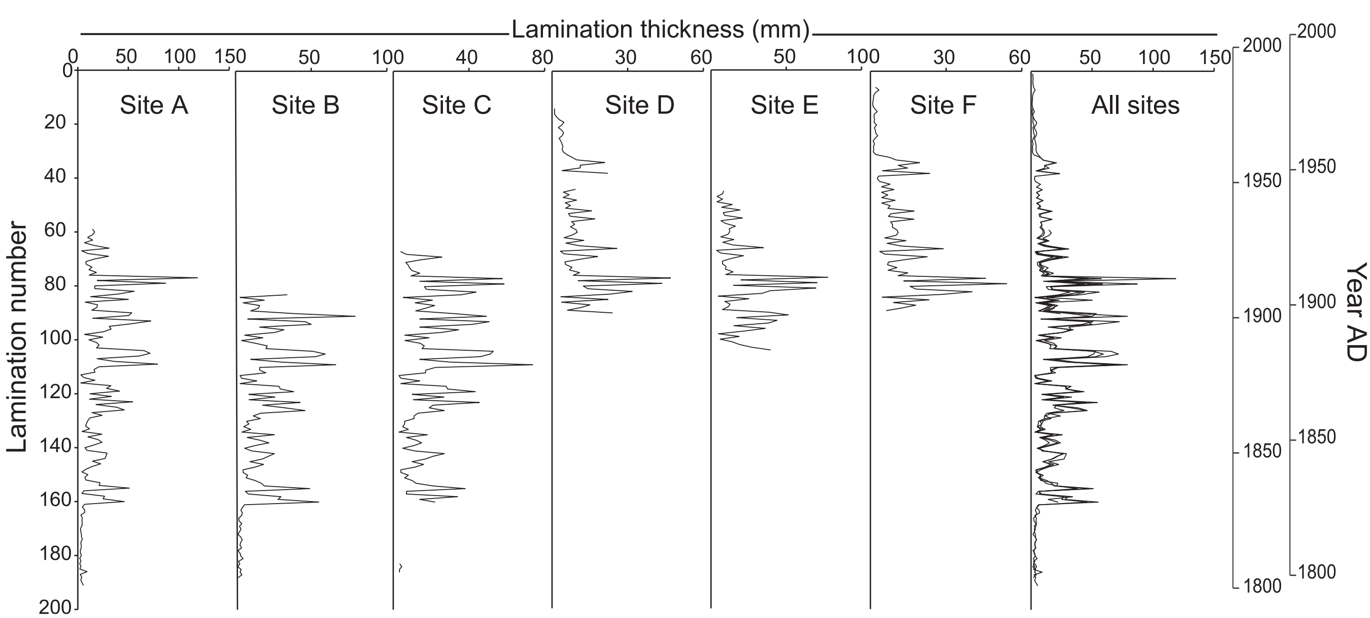

Fig. 7. Lamination thickness versus number from six sites investigated in the Glacial Lake Morten basin; site locations shown in Fig. 2. All six plots are overlaid on each other at right. Far right shows two age models that assume that the laminations are varves and the uppermost varve is either 1991 (left axis) or 1986 (right axis).

valley remained free of an ice-dammed lake throughout the middle Holocene until the LIA, the uppermost radiocarbon age is not interpreted to be a close maximum age because the macrofossils dated were not in growth position. On the other hand, the three samples from beneath thicker sequences of the glaciolacustrine sediment at sites B, C, and 2 were in growth position. Thus, their radiocarbon ages are considered to be close maximum ages for the formation of Glacial Lake Morten. All three ages have 2-sigma calibrated solutions that overlap with each other (Fig. 8). Based on their similar stratigraphic context, we consider the samples to have died simultaneously, and thus consider the ages as a single population and sum their calibrated age solutions (Fig. 8). The summed probability yields three prominent solutions: (1) ~1650 to ~1690 AD, (2) ~1730 to ~1810 AD, and (3) modern. We rule out the modern solution because there is ample historic evidence to suggest that the lake existed during the 20th century (Fig. 2), which leaves the first two modes as possibilities for time periods when Glacial Lake Morten first formed.

Second, we consider the possibility that the Glacial Lake Morten laminations are varves. Although we do not have chronology to evaluate the couplets as potential varves, the nature of the sediments and the environment are consistent with varve formation (e.g., Lamoureux and Gilbert, 2004; Hodder et al., 2007). The laminations are normally-graded couplets with distinct coarse bases and finer-grained caps and a sharp upper contact (Fig. 4). Whereas only a thin drape of sediment exists in the distal portion of the lake, a much thicker (>10 m) and coarser sediment package exists adjacent to the moraine. The sections that we measured, which consist of 1–3 m of laminated sediments, are near the center of the basin. Very few dropstones throughout the investigated sections suggest a mostly grounded ice margin with few icebergs, which likely aided

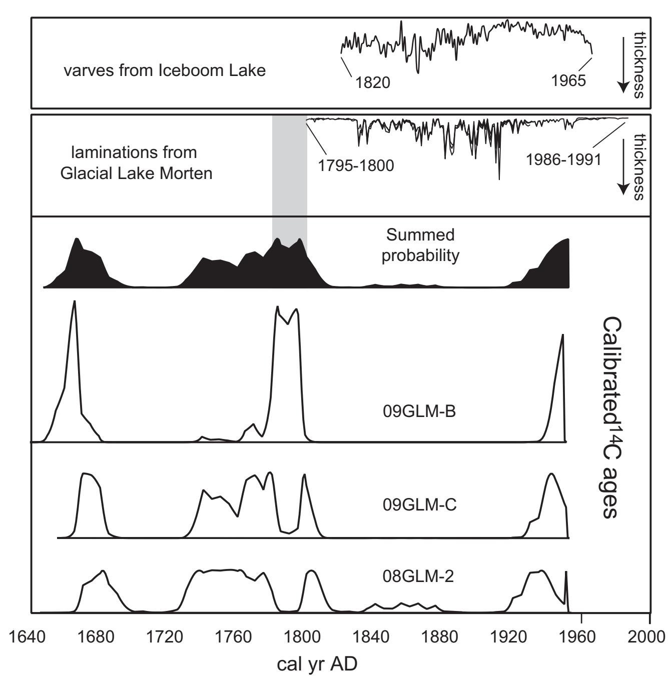

Fig. 8. Composite of data regarding the age of the glaciolacustrine sediments in the Glacial Lake Morten basin. Bottom panel shows the individual (white) and summed (black) probability distribution functions of the calibrated radiocarbon ages from the in-situ tundra fragments buried beneath the glaciolacustine sediments. The upper portion of the lower panel shows the laminations (from Fig. 7) of Glacial Lake Morten sediments plotted against time. Combined, the data suggest that Glacial Lake Morten was impounded in the late 1700s AD. The upper panel shows varve thickness versus age from Iceboom Lake core 08ICE-3, and reveals that Iceboom Lake first received meltwater from the ice margin around 1820 AD.

uniform sediment deposition and its subsequent preservation. Assuming that the couplets are varves would mean that the sediment package spans at least 191 years. Unlike the varves from Iceboom Lake, which were counted in one core, we have multiple sites containing Glacial Lake Morten sediments, which reveal highly consistent sequences of lamination thickness, supporting the total number of couplets counted (Fig. 7). However, we are less certain about where to pin these couplets into absolute time for two reasons. First, we have only constrained the draining of the lake to a six-year window between 1986 and 1991. Second, we are not sure that the uppermost varves are preserved on the lake floor. We visited the basin ~20 years after it drained and therefore encountered a modest amount of incision. Despite this, we selected two sites where we could excavate a stratigraphic section into what appeared to be the primary lake floor (sites D and F). Indeed, when these sites were linked into the others sites using marker horizons, both sites yielded the uppermost laminations. However, it still is possible that wind deflation or sheetwash has removed some laminations. Nonetheless, assuming the 191 laminations are varves and the lake drained between 1986 and 1991 AD, we suggest that Glacial Lake Morten formed sometime around or prior to 1795–1800 AD.

Taken together, the radiocarbon age assignment, and the age we derive if we assume the couplets are varves, are compatible. If our lamination chronology is missing no upper layers, the estimated age for lake initiation would be 1795–1800 AD, which overlaps with the middle calibrated radiocarbon age solution (~1730 to ~1810 AD). However, if there has been a few cm of erosion, which could correspond to a couple decades based on the sedimentation rate at the top of the section, then the basal age of the lamination chronology could be older, but probably would still correspond to the 1730–1810 AD age solution. In the most conservative interpretation, that the laminations either are not varves or that the section is missing >100 couplets, then the oldest radiocarbon age solution of ~1650 to ~1690 AD could be the timing of lake initiation (Fig. 9).

5.3. Ice margin history north of Jakobshavn Isbræ

The age control from each of the two lake sites is generally consistent. Our best estimate for when Iceboom Lake first received meltwater based on the varve chronology is 1820 ± 5 AD. Given this age and the proximity of the two lake sites, we favor a latest 1700s AD age assignment for the initial impoundment of Glacial Lake Morten. This would mean that Glacial Lake Morten was impounded ~20–25 years prior to when the ice margin reached Iceboom Lake. We note that this is roughly the same duration separating ice margin retreat from Iceboom Lake's catchment (~1965 AD) and when Glacial Lake Morten drained (1986–1991 AD). This implies that the relative position of the ice margin during the advance phase was similar to its position during the retreat phase. The ice margin had retreated ~1.5 and ~1.1 km behind its historical moraine when Iceboom Lake returned to non-glacial conditions and when Glacial Lake Morten drained, respectively. By inference, we suggest that the ice margin had advanced to approximately these same distances of the lakes when they each were first influenced by the ice margin.

6. Discussion

6.1. The Little Ice Age advance of Jakobshavn Isbræ

The evidence from our two study lakes indicates that the land-based ice margin north of Jakobshavn Isbræ was advancing toward its late Holocene maximum position late during the LIA, likely around 1800 AD (Fig. 9). Using the land-based ice margin studied here as a proxy for the location of the Jakobshavn Isbræ terminus

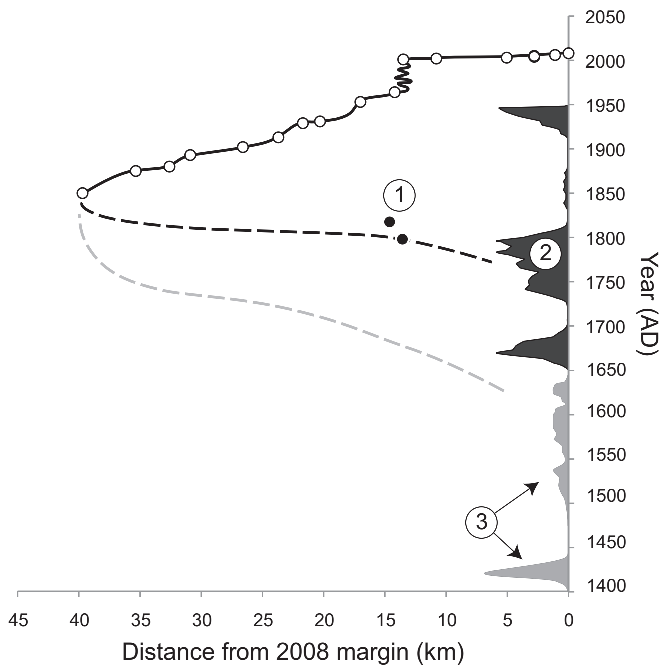

Fig. 9. Time-distance diagram of the Jakobshavn Isbræ marine terminus and the age control presented here from its adjacent land-based ice margin to the north. 1: Black dots represent best estimate ages for when the two study sites were first influenced by the ice margin; distance assumes that the position of the Jakobshavn Isbræ terminus at this time was roughly where it was when the lake sites ceased to be influenced by the ice margin. This age would imply an ice advance depicted by the black dashed line. 2: Summed calibrated radiocarbon age solution (black) of the three in-situ tundra fragments from the Glacial Lake Morten basin. The youngest solution is incompatible with historical evidence (white dots on time–distance diagram), the middle solution coincides with the age information shown by (1), the oldest solution is also a possibility, and would imply an ice advance depicted by the gray dashed line. 3: Calibrated age solutions (gray) of the uppermost radiocarbon ages ($n = 2$) from the sediment cores from Iceboom Lake, considered as maximum ages of Jakobshavn Isbræ advance.

implies that it too was likely advancing through the Isfjord at this time. We extrapolate with caution, however, as the position of the Jakobshavn Isbræ terminus through time is heavily influenced by non-climatic dynamic factors, and its behavior can differ markedly from its adjacent land-based margins (e.g., Sohn et al., 1998; Joughin et al., 2004; Csatho et al., 2008). As one example, while the marine terminus retreated ~10 km between ~1850 and ~1900 AD, nearby land-based margins remained near the historical moraine (Weidick, 1968; Csatho et al., 2008). Part of the difference likely arises because the terminus of Jakobshavn Isbræ was a floating tongue, the position of which is less comparable to land-based margins than its grounding line. Unfortunately, however, the position of the grounding line through time is unconstrained. As another example, whereas the land-based ice margin north of the Isfjord continuously retreated during the second half of the 20th century, the calving front of Jakobshavn Isbræ remained within a 2–3 km zone within the Isfjord (Sohn et al., 1998; Csatho et al., 2008). Despite that Jakobshavn Isbræ may not behave in concert with its adjacent land-based margins on these relatively short timescales, Jakobshavn Isbræ and its immediately adjacent land-based ice margins appear to generally behave similarly on decadal to centennial timescales (Csatho et al., 2008; Stewart, 2009). We note that the land-based ice margin immediately adjacent to Jakobshavn Isbræ, including the study sites, has retreated much more during the 20th century than ice margins farther from Jakobshavn Isbræ (Csatho et al., 2005). This implies that the behavior of Jakobshavn Isbræ and the ice margin near our study lakes are indeed linked. We find it difficult to envision that the Jakobshavn Isbræ terminus could have sustained its maximum position for long before the adjacent land-based ice margin advanced near our study lakes. Thus, we use the history of the ice margin in the study area as a proxy for the position of the Jakobshavn Isbræ terminus during its advance phase (Fig. 9).

Next, we compare our reconstruction of the Neoglacial history of Jakobshavn Isbræ to results from prior research. Weidick and Bennike (2007) review the glacial history of the Jakobshavn Isbræ region. Radiocarbon ages from marine fauna reworked into the historical moraine reveal that Jakobshavn Isbræ and surrounding outlets advanced through unglaciated fjords during the late Holocene (Weidick et al., 1990; Weidick, 1992; Weidick and Bennike, 2007). However, the maximum ages for the deposition of the historical moraine are only as young as ~2000 yr old, and based on our results, only provide a broad maximum constraint on Jakobshavn Isbræ's advance during the LIA. Similarly, relative sea level data show submergence of coastlines initiating ~3000 yr ago, generally regarded as the timing of significant Neoglaciation (Long et al., 1999, 2006); however, these data bear less directly on the LIA advance. Increasing sedimentation rates from marine sediment cores from Disko Bugt near the mouth of Jakobshavn Isfjord are interpreted to indicate an advance of Jakobshavn Isbræ after 1440–1530 AD (Lloyd, 2006). Reeh (1983) took a modeling approach to reconstruct ice margin change north of Jakobshavn Isbræ. Driven with isotope data from Dye-3, a model of ice margin change north of Jakobshavn Isbræ reconstructs advances of about equal magnitude ~700–900 and ~1600–1800 AD. Although the timing of the latter advance agrees with our reconstruction, we find no evidence that the earlier advance, if it took place, was of equal magnitude due to the lack of sediments in our study lakes. Finally, local knowledge suggests that Jakobshavn Isbræ may have been advancing through an unoccupied Isfjord during the 1700s AD (Weidick and Bennike, 2007). Taken together, our results and prior findings provide little doubt that Jakobshavn Isbræ advanced to its Neoglacial maximum position late during the LIA.

The lack of high-resolution climate data from the Disko Bugt region makes linkages between ice margin change and climate change challenging. Borehole (mean annual) temperature data from both Dye-3 and GRIP reveal a cold period centered ~1500 AD and a sharper and colder period ~1800–1900 AD (Dahl-Jensen et al., 1998). Foraminifera data from Disko Bugt reveal an increased influence of arctic water after 1440–1530 AD (Lloyd, 2006), which implies some oceanographic forcing of ice margin advance (Holland et al., 2008). Both the instrumental record from Ilulissat (Vinther et al., 2006) and the Arctic-wide reconstruction (Kaufman et al., 2009), reveal summer temperatures in the 19th century ~1 °C cooler than in the 20th century. The record of Kaufman et al. (2009) also reveals that the coolest temperatures of the last two millennia occurred between ~1650 and ~1900 AD. A millennial-scale chironomid-inferred summer temperature reconstruction from a lake near Jakobshavn Isbræ supports a local LIA summer temperature depression of ~1 °C (Young et al., 2011). Despite the lack of high-resolution, quantitative temperature reconstructions from coastal west Greenland, the available evidence suggests that the coldest part of the last millennium occurred in the 18th and 19th centuries with summers about ~1 °C cooler than the 20th century. We suggest that the drop in summer temperature at this time drove the rapid advance of Jakobshavn Isbræ (Fig. 9).

6.2. Implications for outlet glacier response to climate forcing

Comparing the timing of Jakobshavn Isbræ advance to its post-1850 retreat indicates an average advance rate as high as its average rate of retreat (Fig. 9). Such a rapid advance of calving ice margins compared to their rates of retreat is surprising given the general theories of calving glacier behavior (e.g., Clarke, 1987; Hughes, 2002; Pfeffer, 2007); however, empirical data on the advance phase of marine glaciers are rare. The response of Jakobshavn Isbræ to what was likely ~1 °C of summer cooling was not only rapid, but was almost certainly large in magnitude (tens of kilometers) as well. This significant advance and retreat of Jakobshavn Isbræ may be due partly to the sensitivity of this sector of the GIS to climate change, which is routinely depicted in ice sheet models as experiencing much more change than elsewhere around the GIS (Tarasov and Peltier, 2003; Alley et al., 2005; Simpson et al., 2009). Furthermore, we speculate that even subtle changes in atmospheric temperature or oceanographic conditions may result in a significant response of very high-flux outlet glaciers like Jakobshavn Isbræ (Rignot and Kanagaratnam, 2006). As one example, Joughin et al. (2008) suggest that the buttressing effect of sea ice on the calving front partly controls terminus position, at least on seasonal and annual timescales. The notion that periods of increased sea ice can lead to terminus advance is intriguing, and may be one mechanism that promoted a rapid and large advance of Jakobshavn Isbræ during the cold 18th and 19th centuries.

In any case, it appears that Jakobshavn Isbræ may have advanced rapidly, suggesting that it has the ability not only to respond quickly to warming events, but also to cooling events. This may be especially important for predicting the behavior of major ice streams during future climate change, but is also relevant for ice margin reconstructions during brief episodes of Holocene cooling like the 8.2 ka event (e.g., Young et al., 2011). Ultimately, with more detailed records of ice sheet advance such as those presented here, coupled with additional high-resolution paleoclimate proxy records (e.g., sea ice formation; Krawczyk et al., 2010), we will have a more complete understanding of ice sheet response to climate perturbations.

7. Conclusion

The use of lake sediments to constrain late Holocene fluctuations of the GIS so far has been limited, but given the number of lakes near late Holocene ice margins, the approach could be used much more widely. Creating varve chronologies can be challenging, but we demonstrate that they provide more precise age control for an ice advance into a proglacial-threshold lake than radiocarbon dating. In particular, on decadal timescales radiocarbon dating is hampered by several factors: (1) broad solutions when calibrating radiocarbon years to calendar years, (2) an unknown transport time of macrofossils to core sites, and (3) the ability to find datable macrofossils precisely at key stratigraphic contacts in lakes with relatively low sedimentation rates (e.g., ~cm/century). We demonstrate that radiocarbon dating in-situ tundra fragments alleviates some of these uncertainties, but is still hampered by radiocarbon calibration. Despite these challenges, more data like these would improve our understanding of the GIS's response to LIA climate change.

The rapid and large response of Greenland outlet glaciers like Jakobshavn Isbræ to LIA climate forcing needs to be further pursued. With additional high-resolution climate reconstructions, such as paleoceanographic data from Disko Bugt or temperature inferences made from lacustrine proxies from the Jakobshavn region, we will be able to better assess regional climate and oceanographic history of the region. And, in turn, data like these will increase our understanding about causal mechanisms of ice sheet change on decadal to centennial timescales. However, even the available data suggest that Jakobshavn Isbræ experienced a large response to a relatively subtle cooling event. Our finding that the advance rates of Jakobshavn Isbræ were similar to its average post-1850 retreat is surprising given theories of calving glacier behavior, but may be unique to high-flux glaciers like Jakobshavn Isbræ. Field reconstructions like these will be useful for those who model ice sheet response to climate change.

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References

Abdalati, W., Krabill, W., Frederick, E., Manizade, S., Martin, C., Sonntag, J., Swift, R., Thomas, R., Wright, W., Yungel, J., 2001. Outlet glacier and margin elevation changes: near-coastal thinning of the Greenland Ice Sheet. Journal of Geophysical Research 106, 33729–33741.

Alley, R.B., Clark, P.U., Huybrechts, P., Joughin, I., 2005. Ice-sheet and sea-level changes. Science 310, 456–460.

Alley, R.B., Andrews, J.T., Brigham-Grette, J., Clarke, G.K.C., Cuffey, K.M., Fitzpatrick, J.J., Funder, S., Marshall, S.J., Miller, G.H., Mitrovica, J.X., Muhs, D.R., Otto-Bliesner, B.L., Polyak, L., White, J.W.C., 2010. History of the Greenland ice sheet: paleoclimatic insights. Quaternary Science Reviews 29, 1728–1756.

Anderson, S.P., Walder, J.S., Anderson, R.S., Kraal, E.R., Cunico, M., Fountain, A.G., Trabant, D.C., 2003. Integrated hydrologic and hydrochemical observations of Hidden Creek Lake jökulhlaups, Kennicott glacier, Alaska. Journal of Geophysical Research 108 (F1), 6003. doi: 10.1029/2002JF000004.

Bamber, J.L., Alley, R.B., Joughin, I., 2007. Rapid response of modern day ice sheets to external forcing. Earth and Planetary Science Letters 257, 1–13.

Briner, J.P., Stewart, H.A.M., Young, N.E., Philipps, W., Losee, S., 2010. Using proglacial-threshold lakes to constrain fluctuations of the Jakobshavn Isbrae ice margin, western Greenland, during the Holocene. Quaternary Science Reviews 29, 3861–3874.

Clarke, G.K.C., 1987. Fast glacier flow: Ice streams, surging, and tidewater glaciers. Journal of Geophysical Research 92, 8835–8841.

Csatho, B., van der Veen, C.J., Tremper, C., 2005. Trimline mapping from multispectral Landsat ETM+ imagery. Geographie et Physique Quaternaire 59, 49–62.

Csatho, B., Schenk, T., van der Veen, C.J., Krabill, W., 2008. Intermittent thinning of Jakobshavn Isbræ, west Greenland, since the Little Ice Age. Journal of Glaciology 54, 131–144.

Dahl-Jensen, D., Mosegaard, K., Gundestrup, N., Clow, G.D., Johnsen, S.J., Hansen, A.W., Balling, N., 1998. Past temperatures directly from the Greenland Ice Sheet. Science 282, 268–271.

Engell, M.C., 1904. Undersøgelser og Opmaalinger ved Jakobshavn Isfjord og i Orpigsuit i Sommeren 1902. Meddelelsser om Grønland 26(1).

Francus, P., Asikainen, C., 2001. Sub-sampling unconsolidated sediments: a solution for the preparation of undisturbed thin-sections from clay-rich sediments. Journal of Paleolimnology 26, 323–326.

Grove, J.M., 2001. The initiation of the "Little Ice Age" in regions around the North Atlantic. Climatic Change 48, 53–82.

Hodder, K.R., Gilbert, R., Desloges, J.R., 2007. Glaciolacustrine varved sediment as an alpine hydroclimate proxy. Journal of Paleolimnology 38, 365–394.

Holland, D.M., Thomas, R.H., de Young, B., Ribergaard, M.H., Lyberth, B., 2008. Acceleration of Jakobshavn Isbrae triggered by warm subsurface ocean waters. Nature Geoscience 1, 659–664.

Howat, I.M., Joughin, I., Scambos, T.A., 2007. Rapid changes in ice discharge from Greenland outlet glaciers. Science 315, 1559–1561.

Hughes, T., 2002. Calving bays. Quaternary Science Reviews 21, 267–282.

Joughin, I., Abdalati, W., Fahnestock, M., 2004. Large fluctuations in speed on Greenland's Jakobshavn Isbrae glacier. Nature 432, 608–610.

Joughin, I., Howat, I.M., Fahnestock, M., Smith, B., Krabill, W., Alley, R.B., Stern, H., Truffer, M., 2008. Continued evolution of Jakobshavn Isbrae following its rapid speedup. Journal of Geophysical Research 113, F04006.

Kaplan, M.R., Wolfe, A.P., Miller, G.H., 2002. Holocene environmental variability in southern Greenland inferred from lake sediments. Quaternary Research 58, 149–159.

Kaufman, D.S., Schneider, D.P., McKay, N.P., Ammann, C.M., Bradley, R.S., Briffa, K.R., Miller, G.H., Otto-Bliesner, B.L., Overpeck, J.T., Vinther, B.M., Lakes, Arctic, 2k

Project Members, 2009. Recent warming reverses long-term arctic cooling. Science 325, 1236–1239.
Ketterer, M.E., Hafer, K.M., Jones, V.J., Appleby, P.G., 2004a. Rapid dating of recent sediments in Lock Ness: inductively coupled plasma mass spectrometric measurements of global fallout plutonium. Science of the Total Environment 322, 221–229.
Ketterer, M.E., Hafer, K.M., Link, C.L., Kolwaite, D., Wilson, J., Mietelski, J.W., 2004b. Resolving global versus local/regional Pu sources in the environment using sector ICP-MS. Journal of Analytical Atomic Spectrometry 19, 241–245.
Krawczyk, D., Witkowski, A., Moros, M., Lloyd, J., Kuijpers, A., Kierzek, A., 2010. Late-Holocene diatom-inferred reconstruction of temperature variations of the West Greenland current from Disko Bugt, central West Greenland. The Holocene 20, 659–666.
Lamoureux, S.F., 1994. Embedding unfrozen lake sediments for thin section preparation. Journal of Paleolimnology 10, 141–146.
Lamoureux, S.F., Gilbert, R., 2004. Physical and chemical properties of high latitude lake sediments. In: Pienitz, R., Douglas, M., Smol, J. (Eds.), Long-term Environmental Change in Arctic and Antarctic Lakes. Springer, Dordrecht, The Netherlands.
Lloyd, J.M., 2006. Late Holocene environmental change in Disko Bugt, west Greenland: interaction between climate, ocean circulation and Jakobshavn Isbrae. Boreas 35, 35–49.
Long, A.J., Roberts, D.H., Wright, M.R., 1999. Isolation basin stratigraphy and Holocene relative sea level change on Arveprinsen Ejland, Disko Bugt, west Greenland. Journal of Quaternary Science 14, 323–345.
Long, A.J., Roberts, D.H., Dawson, S., 2006. Early Holocene history of the west Greenland Ice Sheet and the GH-8.2 event. Quaternary Science Reviews 25, 904–922.
Loso, M.G., Anderson, R.S., Anderson, S.P., 2004. Post-Little Ice Age record of coarse and fine clastic sedimentation in an Alaskan proglacial lake. Geology 32, 1065–1068.
Loso, M.G., Anderson, R.S., Anderson, S.P., Reimer, P.J., 2006. A 1500-year record of temperature and glacial response inferred from varved Iceberg Lake, south-central Alaska. Quaternary Research 66, 12–24.
Nick, F.M., Vieli, A., Howat, I.M., Joughin, I., 2009. Large-scale changes in Greenland outlet glacier dynamics triggered at the terminus. Nature Geoscience 2, 110–114.
Pfeffer, W.T., 2007. A simple mechanism for irreversible tidewater glacier retreat. Journal of Geophysical Research 112 (F3), F03S25. doi:10.1029/2006JF000590.
Reeh, N., 1983. Ikke-stationær beregningsmodel for Indlandsisens randzone. Gletscher-hydrologiske Meddelelser Grønlands Geologiske Undersøgelse, 83/7, p. 81.
Rignot, E., Thomas, R.H., 2002. Mass balance of polar ice sheets. Science 297, 1502–1506.
Rignot, E., Kanagaratnam, P., 2006. Changes in the velocity structure of the Greenland ice sheet. Science 311, 986–990.
Simpson, M.J.R., Milne, G.A., Huybrechts, P., Long, A.J., 2009. Calibrating a glaciological model of the Greenland Ice Sheet from the Last Glacial Maximum to present-day using field observations of relative sea level and ice extent. Quaternary Science Reviews 28, 1631–1657.
Sohn, H.-G., Jezek, K.C., van der Veen, C.J., 1998. Jakobshavn Glacier, west Greenland: 20 years of spaceborne observations. Geophysical Research Letters 25, 2699–2702.
Stewart, H.A.M., 2009. Climate vs. dynamic forcing of Greenland's largest glacier: a study of Jakobshavn Isbrae's response to the Little Ice Age. MS thesis, Department of Geology, University at Buffalo, p. 109.
Straneo, F., Hamilton, G.S., Sutherland, D.A., Sterns, L.A., Davidson, F., Hammill, M.O., Stenson, G.B., Rosing-Asvid, A., 2010. Rapid circulation of warm subtropical waters in a major glacial fjord in east Greenland. Nature Geoscience 3, 182–186.
Stuiver, M., Reimer, P.J., Reimer, R.W., 2005. CALIB 5.0. http://calib.qub.ac.uk/calib/.
Tarasov, L., Peltier, W.R., 2003. Greenland glacial history, borehole constraints, and Eemian extent. Journal of Geophysical Research 108, 2143. doi: 10.1029/2001JB001731.
Thomas, E.K., Briner, J.P., 2009. Climate of the past millennium inferred from varved proglacial lake sediments on northeast Baffin Island, Arctic Canada. Journal of Paleolimnology 41, 209–224.
Thomas, R.H., Abdalati, W., Frederick, E., Krabill, W.B., Manizade, S., Steffen, K., 2003. Investigation of surface melting and dynamic thinning on Jakobshavn Isbræ, Greenland. Journal of Glaciology 49, 231–239.
Thomas, R.H., Frederick, E., Krabill, W., Manizade, S., Martin, C., 2009. Recent changes on Greenland outlet glaciers. Journal of Glaciology 55, 147–162.
Thomsen, H.H., 1984. Glaciologiske undersøgelser I Disko Bugt området 1983. Gletcher-hydrologiske Meddelelser, 84/1. p. 35.
Vinther, B.M., Andersen, K.K., Jones, P.D., Briffa, K.R., Cappelen, J., 2006. Extending Greenland temperature records into the late eighteenth century. Journal of Geophysical Research 111, D11105. doi: 10.1029/2005JD006810.
Weidick, A., 1968. Observations on some Holocene glacier fluctuations in west Greenland. Meddelelsser om Grønland 165, 202.
Weidick, A., 1992. Jakobshavn Isbræ area during the climatic optimum. Grønlands Geologiske Undersøgelse Rapport, 155, pp. 67–72.
Weidick, A., Bennike, O., 2007. Quaternary glaciation history and glaciology of Jakobshavn Isbræ and the Disko Bugt region, west Greenland: a review. Geological Survey of Denmark and Greenland Bulletin 14, 78.
Weidick, A., Oerter, H., Reeh, N., Thomsen, H.H., Thorning, L., 1990. The recession of the Inland ice margin during the Holocene climatic optimum in the Jakobshavn-Isfjord area of West Greenland. Global and Planetary Change 82, 389–399.
Weidick, A., Kelly, M., Bennike, O., 2004. Late Quaternary development of the southern sector of the Greenland Ice Sheet, with particular reference to the Qassimiut lobe. Boreas 33, 284–299.
Wolfe, A.P., Miller, G.H., Olsen, C.A., Forman, S.L., Doran, P.T., Holmgren, S.U., 2004. Geochronology of High Latitude Lake Sediments. In: Pienitz, R., Douglas, M., Smol, J. (Eds.), Long-term Environmental Change in Arctic and Antarctic Lakes. Springer, Dordrecht, The Netherlands.
Young, N.E., Briner, J.P., Stewart, H.A.M., Axford, Y., Csatho, B., Rood, D.H., Finkel, R.C., 2011. The response of Jakobshavn Isbrae to Holocene climate change. Geology 39, 131–134.