Quaternary Science Reviews 98 (2014) 135–143

Contents lists available at ScienceDirect

Quaternary Science Reviews

journal homepage: www.elsevier.com/locate/quascirev

^{10}Be dating of the Narsarsuaq moraine in southernmost Greenland: evidence for a late-Holocene ice advance exceeding the Little Ice Age maximum

K. Winsor [a,*], A.E. Carlson [a,b], D.H. Rood [c,d]

[a] Department of Geoscience, University of Wisconsin-Madison, WI, Madison 53706, USA
[b] College of Earth, Ocean, and Atmospheric Sciences, Oregon State University, Corvallis, OR 97331, USA
[c] Scottish Universities Environmental Research Centre (SUERC), University of Glasgow, East Kilbride G75 0QF, UK
[d] Earth Research Institute, University of California-Santa Barbara, Santa Barbara, CA 93106, USA

A R T I C L E I N F O

Article history:
Received 18 January 2014
Received in revised form
25 April 2014
Accepted 28 April 2014
Available online

Keywords:
Cosmogenic surface exposure dating
Greenland ice sheet
Glacial geology

A B S T R A C T

In southernmost Greenland near Narsarsuaq, the terminal Narsarsuaq moraine was deposited well outside of a historical Little Ice Age (LIA) moraine adjacent to the modern ice margin. Using ^{10}Be surface exposure dating, we determine Narsarsuaq moraine abandonment at 1.51 ± 0.11 ka. A second set of ^{10}Be ages from a more ice-proximal position shows that ice has been within or at its historical (i.e., LIA) extent since 1.34 ± 0.15 ka. Notably, Narsarsuaq moraine abandonment was coincident with climate amelioration in southern Greenland. Southern Greenland warming at ~1.5 ka was also concurrent with the end of the Roman Warm Period as climate along the northern North Atlantic sector of Europe cooled into the Dark Ages. The warming of southern Greenland and retreat of ice from the Narsarsuaq moraine is consistent with studies suggesting possible anti-phase centennial-scale climate variability between northwestern Europe and southern Greenland. Other southernmost Greenland ice-margin records do not preclude a pre-LIA ice-margin maximum, potentially concurrent with a Narsarsuaq advance prior to ~1.51 ka, but also lack sufficient ice-margin control to confirm such a correlation. We conclude that there is a clear need to further determine whether a late-Holocene pre-LIA maximum was a local phenomenon or a regional southern Greenland ice maximum, and if this advance and retreat reflects a regional fluctuation in climate.

Published by Elsevier Ltd.

1. Introduction

Over the Holocene, boreal climate generally cooled in response to declining high northern latitude summer insolation, culminating in the Little Ice Age (LIA) of the last several centuries (Kaufman et al., 2009; Marcott et al., 2013). In Greenland, valley glaciers and the Greenland ice sheet advanced across the Neoglacial interval (the last 4 ka), with their maximum extents generally occurring during the LIA (Weidick, 1963; Kelly, 1980; Weidick et al., 2004, 2012; Kelly et al., 2008; Kelly and Lowell, 2009; Alley et al., 2010; Briner et al., 2011; Funder et al., 2011; Levy et al., 2012, 2013; Lowell et al., 2013). The timing and extent of these late-Holocene glacier maxima are often used as baselines for assessing the cause of present and future ice volume changes on the island (Oerlemans, 2005; Jansen et al., 2007). It is therefore societally relevant to determine the timings of Greenland ice margin maximum late-Holocene extents and to constrain the geographic variability of these maxima (Seidenkrantz et al., 2008).

Ice margin records from across Greenland suggest that general global cooling resulted in glacial maxima at different times during the late Holocene. Jakobshavn Isbræ, which is the largest single source of modern ice loss in Greenland, advanced throughout the LIA, surpassing older late Holocene extents (Weidick and Bennike, 2007; Briner et al., 2011). However, just to the south of Jakobshavn, ^{14}C dating of land-terminating ice margins indicates a late-Holocene maximum post-dating the LIA in the last century (Kelley et al., 2012). Ice-marginal records from east Greenland also show a nuanced response to late-Holocene climate change, with one valley glacier reaching its maximum extent early in the LIA (Kelly et al., 2008), while two ice caps neared their late-Holocene maximum prior to the LIA (Levy et al., 2013; Lowell et al., 2013). In southwest and southeast Greenland, ice-marginal records are

* Corresponding author. Tel.: +1 401 451 4037.
E-mail addresses: winsor@wisc.edu, kelsey.winsor@gmail.com (K. Winsor).

http://dx.doi.org/10.1016/j.quascirev.2014.04.026
0277-3791/Published by Elsevier Ltd.

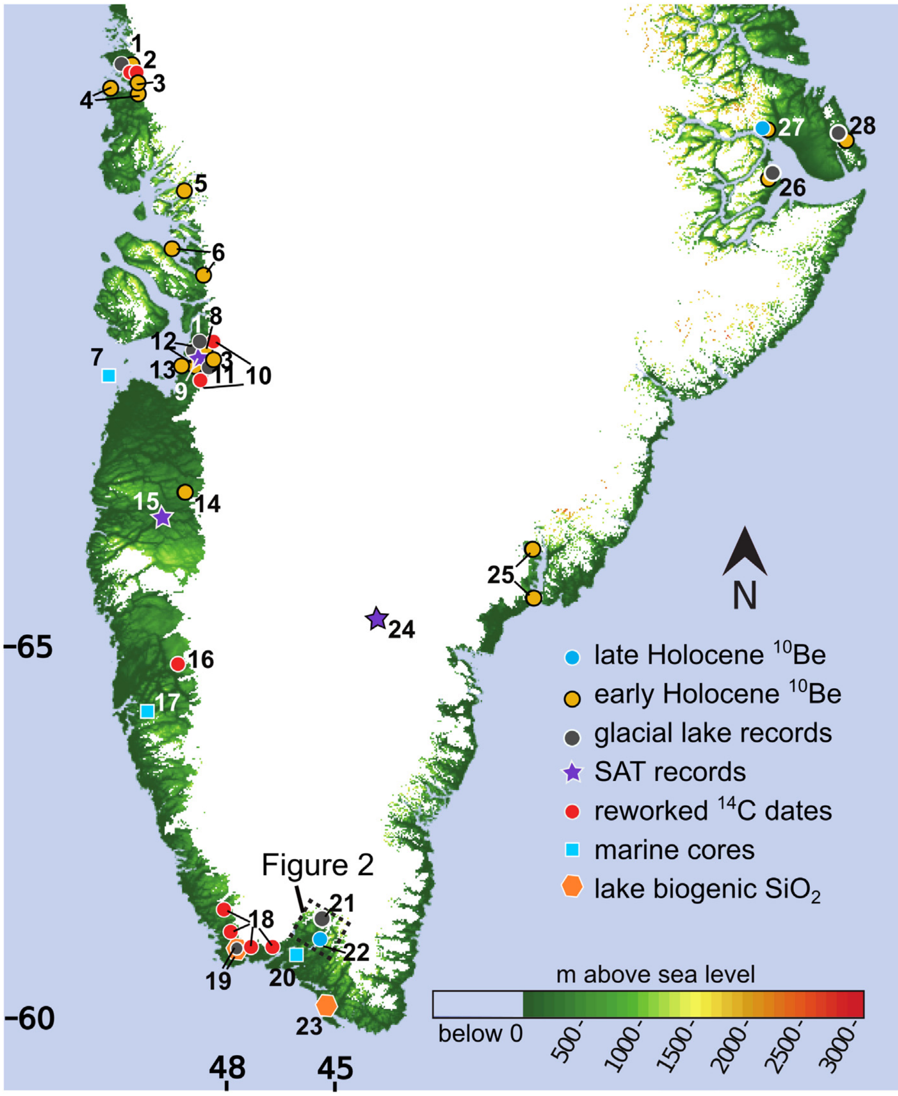

Fig. 1. Location of Holocene records from southern to central Greenland. Fig. 2 location is indicated by the dashed-line box. Also shown are early and late Holocene ^{10}Be dates, ice-marginal lake records, reworked ^{14}C dates in historical moraines, surface-air temperature (SAT) records, lake biogenic silica records, marine ice-rafted debris, and benthic faunal records. In counter-clockwise order around the island are represented sites from [1]Briner et al. (2011), [2]Briner et al. (2014), [3]Briner et al. (2013), [4]Corbett et al. (2013), [5]Lane et al. (2013), [6]Roberts et al. (2013), [7]Perner et al. (2011), [8]Corbett et al. (2011), [9]Axford et al. (2013), [10]Weidick et al. (1990), [11]Briner et al. (2010), [12]Kelley et al. (2012), [13]Young et al. (2011), [14]Levy et al. (2012), [15]D'Andrea et al. (2011), [16]Kelly (1980), [17]Seidenkrantz et al. (2007), [18]Weidick et al. (2004), [19]Kaplan et al. (2002), [20]Nørgaard-Pedersen and Mikkelsen (2009), [21]Larsen et al. (2011), [22]this study, [23]Andresen et al. (2004), [24]Dahl-Jensen et al. (1998), [25]Hughes et al. (2012), [26]Levy et al. (2013), [27]Kelly et al. (2008), and [28]Lowell et al. (2013).

more limited and do not provide a close constraint on late-Holocene Greenland ice sheet and valley glacier behavior (e.g., Roberts et al., 2008; Hughes et al., 2012; Weidick et al., 2012; Larsen et al., 2013).

In southernmost Greenland, the prominent Narsarsuaq moraine was deposited outside of the LIA/historical extent of the outlet glacier Kiagtût sermiat, and is indirectly inferred to be late Holocene in age, although an early or middle Holocene age is also plausible given available chronologic constraints (Weidick, 1963; Kelly, 1980; Dawson, 1983; Bennike and Sparrenbom, 2007). Existing records from other southern Greenland ice margins are somewhat contradictory, and are interpreted to show either ice-margin late-Holocene maxima during the LIA (Kaplan et al., 2002) or an earlier maximum (Larsen et al., 2011). Here, we use ^{10}Be surface exposure ages to directly date ice retreat from the Narsarsuaq moraine and to determine if this moraine represents a pre-LIA late-Holocene maximum ice-margin advance.

2. Kiagtût sermiat setting & methodology

Northeast of Narsarsuaq [61.15°N, 45.43°W] (Fig. 1), the Kiagtût sermiat outlet glacier flows to the southwest. The outlet glacier is sourced from the southern dome of the Greenland ice sheet as part of a larger outlet glacier that splits into Kiagtût sermiat and Qôrqup sermia glaciers (Fig. 2) (Weidick et al., 2004; Larsen et al., 2011). The modern glacier is land-terminating, with the head of Tunugliarfik fjord located ~8 km down valley to the southwest of the present ice margin. Kiagtût sermiat glacier is sometimes referred to as Kiattut sermiat of Kiatuut sermia (e.g., Weidick et al., 2004; Nelson et al., 2014).

The Narsarsuaq moraine of Kiagtût sermiat is clast-supported and consists of a prominent ridge extending from the valley mouth up onto the plateau (Fig. 2) (Weidick, 1963; Larsen et al., 2011). Several recessional moraines are up-valley of the terminal moraine, but these as well as the terminal moraine have been heavily reworked by human activity, particularly during and

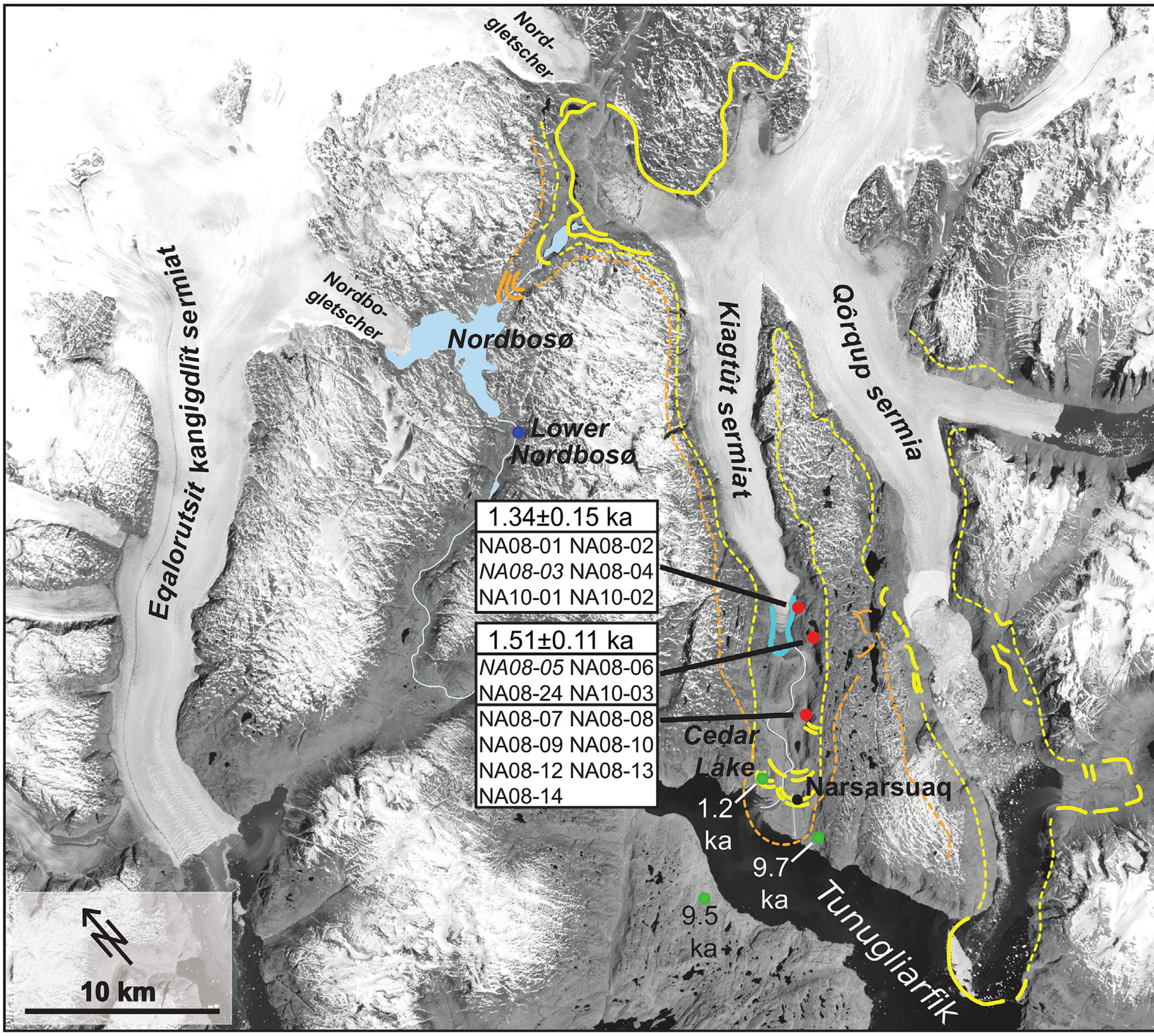

Fig. 2. The Narsarsuaq region, its three main outlet glaciers—Eqalorutsit kangigdlît sermiat, Kiagtût sermiat, and Qôrqup sermia, early Holocene moraines (orange lines), Narsarsuaq moraine (yellow lines), and historical moraine (blue lines) (Modified from Larsen et al., 2011). ^{10}Be sample sites of this study indicated by the red circles, and ^{14}C sample sites of previous studies by the green circles. Note the locations of Nordbo Glacier, Nordbosø, and Lower Nordbosø (the Larsen et al., 2011 study area, with the blue dot indicating the coring sites). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

shortly after World War II. Weidick (1963) first suggested a late-Holocene age for the Narsarsuaq moraine based on its elevation relative to the marine limit, although marine limit deposits also experienced significant human impact from World War II activity. Organic materials recovered from Cedar Lake within the moraine date (calibrated) to ~1.2 ka (Bennike and Sparrenbom, 2007), but these are minimum-limiting radiocarbon dates and therefore do not preclude an age for the moraine ranging from the last deglaciation to the late Holocene. Similarly, lichenometry has been interpreted to suggest a moraine age of ~2.4 ka, but this age is an extrapolation of the lichen growth curve well beyond its calibration period of the last several centuries, and only constrains the moraine as older than the latest-Holocene lichen-calibration period (Dawson, 1983; Loso and Doak, 2006).

For this study, we sampled 17 boulders for ^{10}Be surface exposure dating from within the innermost recessional segments of the Narsarsuaq moraine (Fig. 2). Eleven samples were from just within the last recessional moraine segment and thus date the onset of Kiagtût sermiat retreat from the Narsarsuaq moraine. Another six samples are just ice-distal of the historical ice limit—which also is the LIA ice limit—and therefore constrain the last time Kiagtût sermiat was more advanced than its 20th century extent (Weidick, 1963). We chose large (>1 m tall) granitoid or gneissic boulders with relatively even and horizontal tops. Samples showed no sign of post-depositional rolling or of being reworked, and their topographic shielding was recorded. We avoided boulders on the moraine itself because of human impact on the end-moraine segments and clear evidence for downhill deflation of the lateral moraines. We note that our samples are likely not noticeably impacted by inheritance, as evidenced by low concentrations of ^{10}Be found in sediments released from the GIS in this region (Nelson et al., 2014).

Laboratory preparation of ^{10}Be targets was performed in the University of Wisconsin-Madison Cosmogenic Nuclide Laboratory. Processing included the isolation of pure quartz and removal of meteoric ^{10}Be using successive HF/HNO_3 acid leaches, chemical separation and purification of $Be(OH)_2$ via anion and cation chromatography and selective hydroxide precipitation, ignition to BeO, and mixture with Nb powder prior to loading into cathodes (Nishiizumi et al., 1984; Kohl and Nishiizumi, 1992). Samples were analyzed by Accelerator Mass Spectrometry (AMS) for $^{10}Be/^{9}Be$ (online data repository) at Lawrence Livermore National Laboratory (LLNL) and the Scottish Universities Environmental Research Centre (SUERC) (Rood et al., 2010, 2013; Xu et al., 2010). At LLNL, samples were normalized to standard 07KNSTD3110 with a reported ratio of 2.85×10^{-12} (Nishiizumi et al., 2007). At SUERC, samples were normalized to the NIST standard with an assumed ratio of 2.79×10^{-11}. All samples were blank corrected (online data repository).

We calculated surface exposure ages with the CRONUS online calculator (version 2.2, with constants version 2.2) using the Arctic reference sea-level high-latitude production rate due to spallation of 3.96 ± 0.15 ^{10}Be atoms g^{-1} yr^{-1} (Young et al., 2013), the muonogenic production rate from Heisinger et al. (2002a,b), and the time-dependent Lal/Stone scaling scheme (Table 1 and online data repository) (Lal, 1991; Stone, 2000; Balco et al., 2008). Use of other scaling schemes provided by the CRONUS calculator yield maximum age differences of 4–7% (online data repository). No corrections were made for snow cover or erosion, considering the height of the boulders and their young age, respectively.

3. Results

The five samples from just ice-distal of the historical extent of Kiagtût sermiat yield exposure ages between 0.91 ± 0.06 ka and 1.82 ± 0.09 ka, after excluding one outlier based on Chauvenet's criterion (NA08-03; 3.49 ± 0.34 ka) (Table 1, Figs. 2, 3). Because the five ages are normally distributed, as determined by a Shapiro–Wilk normality test, we calculate an arithmetic mean of 1.34 ± 0.15 ka (all ages are presented with one standard error uncertainty). After excluding one outlier based on Chauvenet's criterion (NA08-05; 4.85 ± 0.39 ka), the remaining ten samples from just within the Narsarsuaq moraine are normally distributed according to a Shapiro–Wilk test and have exposure ages between 1.04 ± 0.26 and 2.12 ± 0.18 ka (Table 1, Figs. 2, 3), with an arithmetic mean of 1.51 ± 0.11 ka for ice retreat from the Narsarsuaq moraine. Our mean ages for the two sample locations overlap within the standard errors of the sample sets, but due to their different geographic settings are separate glacial deposits from Kiagtût sermiat retreat.

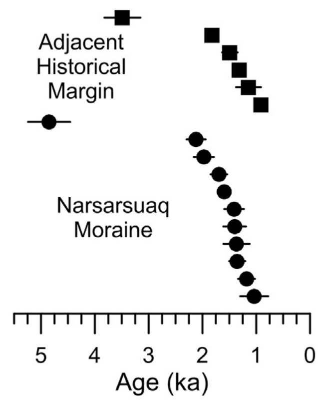

Fig. 3. ^{10}Be exposure ages and standard error from this study for historic-marginal ages (top) and Narsarsuaq moraine ages (bottom). One older statistical outlier for each group is observable.

4. Discussion

Our new ^{10}Be exposure ages suggest that the Narsarsuaq moraine is from a pre-LIA, late-Holocene advance of Kiagtût

Table 1
^{10}Be sample data and exposure ages.

Sample[a]	Latitude (°N)	Longitude (°E)	Elevation (m asl)	Thickness (cm)	Shielding factor	^{10}Be (atoms g^{-1})[c]	Uncertainty (atoms g^{-1})[d]	Age (ka)[e]	Internal uncertainty (ka)[d]
Just within the Narsarsuaq moraine									
NA08-05	*61.2061*	*−45.3153*	*285*	*2.0*	*1.000*	*27,861*	*2252*	*4.85*	*0.39*
NA08-06	61.2061	−45.3153	285	4.0	1.000	6683	890	1.18	0.16
NA08-24	61.2061	−45.3119	305	1.5	0.999	9966	907	1.70	0.15
NA10-03	61.2063	−45.3150	289	2.5	0.999	11,338	1073	1.98	0.19
NA08-07	61.1856	−45.3618	68	1.5	0.973	7199	451	1.60	0.10
NA08-08	61.1856	−45.3618	68	1.5	0.973	9550	801	2.12	0.18
NA08-09[b]	61.1856	−45.3618	67	2.5	0.960	6232	805	1.41	0.18
NA08-10[b]	61.1851	−45.3632	76	2.0	0.980	6389	962	1.40	0.21
NA08-12	61.1847	−45.3635	59	2.5	0.965	6002	1072	1.37	0.24
NA08-13[b]	61.1886	−45.3590	153	1.5	1.000	6845	760	1.35	0.15
NA08-14[b]	61.1889	−45.3602	159	2.0	1.000	5262	1323	1.04	0.26
Ice-distal of the historical extent of Kiagtût sermiat									
NA08-01	61.2153	−45.3045	180	2.0	0.992	9354	453	1.82	0.09
NA08-02	61.2153	−45.3050	180	1.5	0.995	7706	742	1.49	0.14
NA08-03[b]	*61.2158*	*−45.3042*	*179*	*3.0*	*0.990*	*17,712*	*1701*	*3.49*	*0.34*
NA08-04	61.2149	−45.3043	171	2.5	0.989	5784	1173	1.14	0.23
NA10-01	61.2159	−45.3041	185	2.0	0.994	4707	289	0.91	0.06
NA10-02	61.2159	−45.3034	181	2.0	0.991	6757	343	1.32	0.07

[a] Italics indicates sample with inheritance that were excluded as outliers.
[b] Data measured at SUERC.
[c] ^{10}Be concentrations are blank corrected (LLNL: average blank $^{10}Be/^{9}Be$ of $8.8 \pm 1.5 \times 10^{-16}$, $n = 6$; SUERC: average blank $^{10}Be/^{9}Be$ of $6.1 \pm 0.7 \times 10^{-16}$, $n = 3$) and normalized to standards 07KNSTD3110 with a reported ratio of 2.85×10^{-12} (Nishiizumi et al., 2007) at LLNL or NIST_27900 with an assumed ratio of 2.79×10^{-11} at SUERC.
[d] Uncertainties are 1σ AMS uncertainties propagated in quadrature with associated blank uncertainties.
[e] Calculations use standard atmosphere, density of 2.65 g cm^{-3}, zero erosion, and no inheritance in the CRONUS online calculator (Balco et al., 2008) (version 2.2, with constants version 2.2) using the Arctic reference sea-level high-latitude spallogenic production rate 3.96 ± 0.15 ($\pm 1\sigma$) ^{10}Be atoms g^{-1} yr^{-1} (Young et al., 2013), muonogenic production after Heisinger et al. (2002a,b), and the time-dependent Lal/Stone scaling scheme.

sermiat. It is unlikely that the moraine is a recessional deposit from an early to middle Holocene ice advance, as abundant evidence points to a smaller-than-present early- to mid-Holocene ice margin extent (e.g., Weidick et al., 2004; Sparrenbom et al., 2006a,b; Long et al., 2011), with Neoglacial advance occurring after ~3 ka (e.g., Weidick et al., 2004; Larsen et al., 2011). Additionally, the only moraine that lies in front of these ^{10}Be sample locations is the Narsarsuaq moraine, thus suggesting that they provide a close age constraint on ice retreat after moraine deposition. Our data is in agreement with previous inferences from the marine limit, minimum-limiting ^{14}C dates, and new ^{10}Be data (Weidick, 1963; Kelly, 1980; Bennike and Sparrenbom, 2007; Nelson et al., 2014). We now precisely date moraine abandonment at 1.51 ± 0.11 ka, several hundred years earlier than the oldest minimum-limiting AMS ^{14}C date from within the moraine (Bennike and Sparrenbom, 2007). Our ice-proximal ^{10}Be ages show that up-valley retreat to near the present ice margin occurred by 1.34 ± 0.15 ka, and that ice did not subsequently exceed its historical extent. These ^{10}Be ages suggest that Kiagtût sermiat retreated from the Narsarsuaq moraine to its historical/LIA extent at a rate of greater than 15 m yr^{-1} (maximum age difference between the two sampling sites).

4.1. Comparison to other Greenland ice margins

Our results raise the question as to whether the Narsarsuaq moraine maximum prior to the LIA was a local phenomenon or part of a more regional-scale ice-margin fluctuation. We therefore compare our Narsarsuaq ^{10}Be ages against other Greenland ice-margin constraints on when glaciers and the ice-sheet margin reached their late-Holocene maximum extent (Fig. 4).

No direct ages or indirect ^{14}C dates confirm correlative mapping of the Narsarsuaq moraine outside the terminal region of Kiagtût sermiat (Fig. 2) (Weidick, 1963; Weidick et al., 2004; Larsen et al., 2011). However, Larsen et al. (2011) used a sediment sequence from a nearby threshold lake of Nordbo Glacier (Figs. 1, 2), Lower Nordbosø, to constrain Nordbo Glacier behavior during the Holocene. Larsen et al. (2011) documented minerogenic sedimentation at ~3 to 2.8 ka and in the last ~0.5 ka, probably resulting from ice-margin advance into the catchment. We show in Fig. 4A the ^{14}C dates from Lower Nordbosø that are unambiguously from intervals of organic deposition in the lake and firmly constrain a retracted ice margin. Like Larsen et al. (2011), we suggest that the Nordbo Glacier margin was at least near its late Holocene maximum by ~3 ka. We note, however, that Nordbosø Lake lies above Lower Nordbosø and could buffer the Lower Nordbosø sediment sequence from recording more subtle changes in the sediment discharge from Nordbo Glacier (Fig. 2).

Another sediment record from Qipisarqo Lake may constrain the behavior of the Qassimiut lobe in southern Greenland (Fig. 1). Kaplan et al. (2002) interpreted the sediment record as indicating maximum extent of the Qassimiut lobe during the LIA. However, multiple radiocarbon date reversals occur in the upper 50 cm (late Holocene) portion of the core, particularly in the sequence attributed to the LIA period (Kaplan et al., 2002). Because these are ^{14}C dates on humic acid extractions, not macrofossils, the cause of the reversals is not unequivocally reworking of plant remains. We thus only show the ^{14}C dates from portions of the lake record that are clearly intervals of organic sedimentation >2 ka (Fig. 4A), which document the Qassimiut lobe as being smaller than present prior to the Neoglacial advance. It is therefore unclear from the Qipisarqo Lake record as to when the Qassimiut lobe reached its maximum late-Holocene extent, which could have occurred prior to the LIA. In agreement with our interpretation of the Qipisarqo Lake record, ^{14}C dates on samples reworked in historical moraines of southern

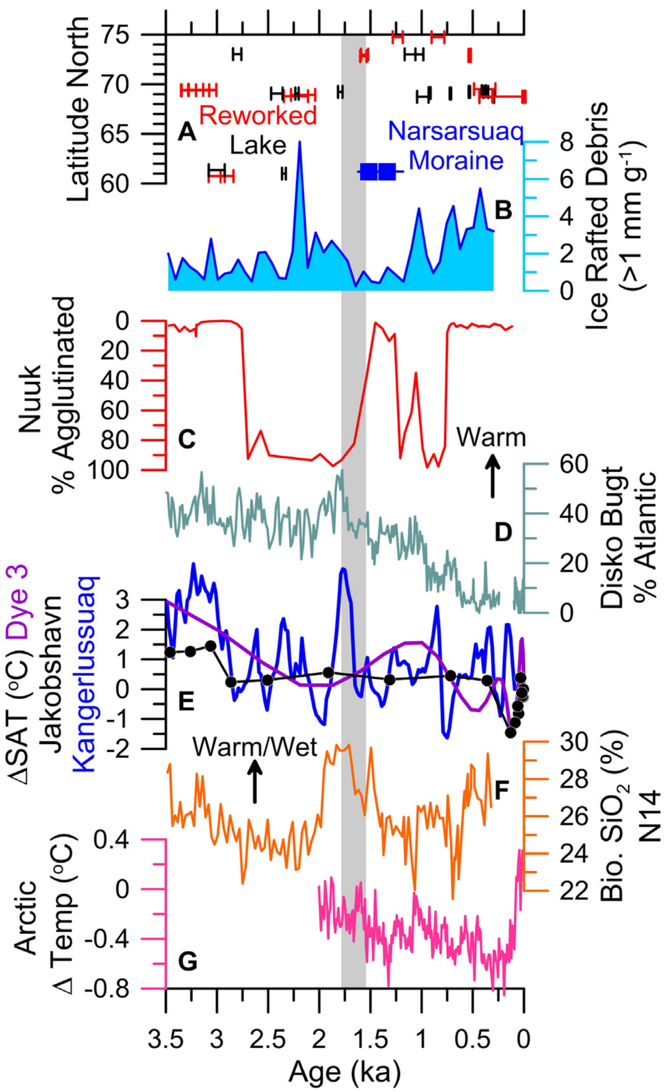

Fig. 4. Late-Holocene records from southern to western Greenland (Fig. 1). To facilitate comparison between figures, each relevant reference below is given with the corresponding number shown in Fig. 1. (A) ^{14}C dates from intervals of organic deposition in threshold lakes (black bars) ([20]Kaplan et al., 2002; [1,3,11]Briner et al., 2010, 2011; 2013; [21]Larsen et al., 2011; [12]Kelley et al., 2012), and from reworked material in historical moraines that clearly document as ice being less far-reaching than its late-Holocene extent (red bars) ([16]Kelly, 1980; [10,18]Weidick et al., 1990, 2004; [2]Briner et al., 2014), and Narsarsuaq ^{10}Be dates (blue squares; this study), (B) ice rafted debris from Ga3-2 ([20]Nørgaard-Pedersen & Mikkelsen, 2009), (C) percent agglutinated/Arctic benthic foraminifera from 248260-2 ([17]Seidenkrantz et al., 2007), (D) percent Atlantic foraminifera from 344310 ([7]Perner et al., 2011), (E) change in surface air temperature (SAT) at Dye 3 (purple, [24]Dahl-Jensen et al., 1998), Jakobshavn (black, [9]Axford et al., 2013), and Kangerlussuaq (blue, [15]D'Andrea et al., 2011), (F) percent biogenic silica in Lake N14 sediment ([23]Andresen et al., 2004), and (G) compilation of relative changes in Arctic temperatures (Kaufman et al., 2009). Vertical gray bar shows timing of maximum Kiagtût sermiat extent at the Narsarsuaq moraine. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Greenland outlet glaciers and the Qassimiut lobe have yet to be found younger than ~3 ka (Figs. 1, 4A) (Weidick et al., 2004, 2012). These maximum-limiting, indirect ^{14}C dates on ice-margin advance in southern Greenland are consistent with our direct ^{10}Be ages on Kiagtût sermiat retreat.

A single marine ice-rafted debris (IRD) record from a southern Greenland fjord near Kiagtût sermiat (Figs. 1, 2) shows a peak in iceberg sedimentation 2.3–1.8 ka, with a decrease at ~1.5 ka

(Fig. 4B) (Nørgaard-Pedersen and Mikkelsen, 2009). Increased IRD deposition is, however, ambiguous with respect to ice-margin position. This late Holocene peak and subsequent diminution at ~1.5 ka could reflect either an ice-margin maximum (more icebergs and IRD from closer ice proximity) and later retreat at ~1.5 ka (fewer icebergs/IRD), or ice retreat 2.3–1.8 ka (more icebergs/IRD from increased calving) and subsequent advance at ~1.5 ka (reduced calving/IRD) (Nørgaard-Pedersen and Mikkelsen, 2009).

In southwest Greenland, there are fewer chronologic constraints on when ice margins reached their late-Holocene maxima (Figs. 1, 4A) (Weidick et al., 1990, 2012; Larsen et al., 2013). Radiocarbon dates on marine shells underlying late-Holocene glacial outwash from inland of Nuuk document local outlet glacier advance after ~4.7 ka (Fig. 1) (Weidick et al., 1990, 2012). Larsen et al. (2013) produced ^{10}Be boulder and bedrock surface exposure ages outside of the historical extent of the southwest Greenland ice-sheet margin (Fig. 1). These ^{10}Be samples date to the early Holocene and thus preclude a late-Holocene advance of the ice margin to their position, consistent with continuous organic sedimentation in a lake ~4 km from the ice margin since ~8.7 ka (Larsen et al., 2013). Nevertheless, they are >500 m above the present historical ice limit, or ~1 km in front of the historical ice limit, and therefore do not provide a constraint on margin behavior within this distance. Indeed, Weidick et al. (2012) noted that the late-Holocene history of this portion of Greenland was not well constrained before ~0.3 ka.

Southwest and west Greenland ice margins near Kangerlussuaq and in the Disko Bugt, Uummannaq Fjord, and Upernavik regions are well-constrained by ^{10}Be ages, reworked ^{14}C dates in historically deposited moraines, and ice-marginal lake records. Most of these records show that ice margins reached their maximum extent during the LIA (Figs. 1, 4A) (Briner et al., 2010, 2011, 2013, 2014; Corbett et al., 2011, 2013; Young et al., 2011, 2013; Kelley et al., 2012).

The timings of southeast Greenland late-Holocene ice maxima are poorly constrained. ^{10}Be ages from Sermilik Fjord only constrain the Helheim Glacier Holocene history to within ~40 km of its present calving margin (Hughes et al., 2012). Roberts et al. (2008) produced bedrock ^{10}Be and ^{26}Al ages that constrain the Greenland ice-sheet margin just south of Sermilik Fjord to have not advanced beyond its LIA extent since ~11–12.5 ka (we recalculate this published data on samples Tl1 and Tl5 using the new Arctic ^{10}Be production rate and updated CRONUS versions; Young et al., 2013). However, these concordant ^{10}Be–^{26}Al bedrock ages do not necessarily rule out brief periods of ice cover given the uncertainties in both measurements.

Ice-sheet margins have not been directly dated in east Greenland, but four ^{10}Be dates on a moraine in the Scoresby Sund region have two different populations (ages calculated with the Arctic ^{10}Be production rate; Young et al., 2013). One population suggests moraine deposition during the LIA, the other several hundred years prior to the LIA (Kelly et al., 2008). Threshold lake records for two other ice caps in the Scoresby Sund region show that these ice margins neared their maximum late-Holocene extents prior to the LIA, but do not constrain precisely when this maximum occurred (Levy et al., 2013; Lowell et al., 2013).

We have summarized an emerging picture of Greenland ice-sheet and glacier margin advance in the late Holocene. In west and east Greenland, it is clear that most ice margins were at their maximum extents during the LIA, although in east Greenland the advance to this maximum could have occurred prior to the LIA. In southwest and southeast Greenland, records are more tentative, and in only one location in southeast Greenland is the ice-margin maximum confirmed as likely occurring during the LIA (Roberts et al., 2008). In contrast, in south Greenland, the only record that suggests an LIA maximum, the Qipisarqo Lake sediment sequence (Kaplan et al., 2002), has issues with age reversals during the most critical part of the record.

Other south Greenland ice-margin constraints from reworked ^{14}C dates and IRD, as well as a more conservative interpretation of the Qipisarqo Lake record, are not inconsistent with our Narsarsuaq ^{10}Be ages for a pre-LIA maximum that terminated at ~1.5 ka. The Larsen et al. (2011) Lower Nordbosø sediment record does suggest an earlier timing for the end of the first late-Holocene maximum extent of Nordbo Glacier, but the onset of this maximum still could have been coincident with the advance of Kiagtût sermiat. The role of upstream Nordbosø in buffering the Lower Nordbosø sediment record has also yet to be resolved. We suggest that direct dating of Nordbo Glacier margin deposits and coring of Nordbosø would help to determine if Nordbo Glacier behaved differently than the adjacent Kiagtût sermiat. This comparison of records across the southern half of Greenland implies that southern Greenland ice margins may have behaved differently from their northern counterparts. Therefore, an inspection of regional climate (and the forcings behind this climate) is warranted to help understand potential spatial variability in late-Holocene Greenland ice margins.

4.2. Late Holocene Greenland climate change

We now assess the records of climate change across the southern half of Greenland to determine if a climatic forcing underlies Kiagtût sermiat advance to and later abandonment of the Narsarsuaq moraine, and if spatially variable climate change could explain ice-margin variability. We note that observations and glacier modeling suggests that marine-terminating ice margins can respond to climate change within a decade while land-terminating ice margins can respond to climate change within a century (Andresen et al., 2012; Kelley et al., 2012; Nick et al., 2013). As such, we limit our discussion of paleoclimate records to the century or longer time scale to reduce the potential for associating climate variations to local non-climatic ice-margin variations. There is no evidence for centennial scale variations in snow accumulation over Greenland during the late Holocene (Cuffey and Clow, 1997), implying that temperature was the primary forcing of late-Holocene Greenland glacier variations. A climatically driven pre-LIA maximum in southern Greenland is conceivable, as the Mann et al. (2009) hemispheric climate reconstruction for the last 1.5 ka shows southern Greenland to be anomalously warm during both the LIA and the preceding Medieval Climate Anomaly, relative to the mid-last century and the general Arctic temperature pattern (Fig. 4G) (Kaufman et al., 2009; PAGES 2k Network, 2013).

One pollen-based record exists from Qipisarqo Lake in southern Greenland (Fréchette & de Vernal, 2009), but its interpreted surface air temperature (SAT) record has uncertainties large enough to preclude any assessment of relative temperature change within the late Holocene. The aforementioned humic ^{14}C age reversals from the same core question its late-Holocene stratigraphic integrity. The SAT estimate of the Qipisarqo Lake pollen record may also have biases introduced from far traveled pollen sourced from Canada (Jessen et al., 2011).

Two biogenic silica records, which are proxies of lake biological productivity potentially related to temperature and/or precipitation, exist in south Greenland but are in disagreement. The record from Lake N14 (Fig. 1) suggests cooler/drier conditions during the Narsarsuaq ice maximum and warmer/wetter conditions around the time of ice retreat (Fig. 4F) (Andresen et al., 2004). The Lake N14 record ends at ~0.5 ka, precluding an assessment of whether the LIA was actually a cool/dry period in southern Greenland. The other record is from Qipisarqo Lake (Fig. 1) (Kaplan et al., 2002) and has the aforementioned issues with humic acid ^{14}C date reversals that question the stratigraphic integrity of the record.

Southern Greenland's fjord benthic faunal records do show consistent late-Holocene subsurface water source variability (Arctic vs. Atlantic, i.e., temperature). The best-resolved and dated record, however, comes from southern southwest Greenland. Core 248260-2 in Amerilik Fjord near Nuuk documents the first late-Holocene arrival of cold Arctic waters at ~2.8 ka and the return of warm Atlantic waters at ~1.5 ka (Fig. 4C) (Møller et al., 2006; Seidenkrantz et al., 2007), which also occurred in southernmost Greenland fjords near Narsarsuaq (Jensen et al., 2004; Lassen et al., 2004). The return of warm Atlantic waters at ~1.5 ka is concurrent with Kiagtût sermiat retreat from the Narsarsuaq moraine (Fig. 4A).

Two lake alkenone-SAT records from near Kangerlussuaq in southwest Greenland also show a decrease to generally colder temperatures between ~2.8 and 1.8 ka, with rapid warming centered at ~1.6 ka followed by cooling to a non-trending but variable SAT (Fig. 4E) (D'Andrea et al., 2011). No SAT proxy records exist at present from southeast or east Greenland ice margins. Although the Dye 3 mean-annual borehole SAT records the coldest late-Holocene interval as occurring during the LIA (Fig. 4E) (Dahl-Jensen et al., 1998), such high-elevation observations should not necessarily be extrapolated to Greenland ice-sheet margins due to the thermal inversion over the Greenland ice sheet (e.g., Cuffey and Clow, 1997; Severinghaus et al., 1998).

In west Greenland's Disko Bugt, lake and marine records show that the LIA interval was the coldest period of the late Holocene on land and in the adjacent fjords (Fig. 4D, E) (Seidenkrantz et al., 2008; Briner et al., 2011; Perner et al., 2011; Axford et al., 2013). Most of the existing ice-marginal constraints document that the west Greenland ice margin maximum extent occurred during this late-Holocene temperature minimum (Briner et al., 2011, 2013; Kelley et al., 2012).

The paleoclimate records from southern Greenland could therefore suggest an underlying climate forcing of the Kiagtût sermiat advance to and retreat from the Narsarsuaq moraine. Cold/dry atmospheric conditions existed in southernmost Greenland and Arctic-sourced waters occupied its fjords when Kiagtût sermiat was presumably advancing to the Narsarsuaq maximum. Likewise, abandonment of the Narsarsuaq moraine corresponds with warm/wet conditions in southernmost Greenland and the arrival of warm Atlantic-sourced waters in its fjords. Similarly, the LIA maximum in west Greenland is concurrent with the coldest late-Holocene temperatures. This spatially variable Greenland climate could be the underlying cause of the different timing of ice-margin maximum extent between south and west Greenland.

Andresen et al. (2004) and Seidenkrantz et al. (2007) both noted that the period of relatively cold conditions in southern Greenland prior to 1.5–1.6 ka corresponded with the Roman Warm Period in northwestern Europe, while the return to relatively warm conditions in southern Greenland corresponded with cooling of northwestern Europe into the Dark Ages. Glacier records from northern Europe are consistent with this regional pattern of climate change as they show retracted ice during the Roman Warm Period with ice advance during the Dark Ages (Denton and Karlen, 1973; Nesje, 2009). The contrast between southern Greenland and northwestern European climate fits with the analogy that late-Holocene centennial-scale climate variability in the North Atlantic region had a footprint similar to the modern North Atlantic Oscillation (Keigwin and Pickart, 1999; Andresen et al., 2004; Seidenkrantz et al., 2007; Mann et al., 2009; Trouet et al., 2009; D'Andrea et al., 2011; Ribeiro et al., 2011). The North Atlantic Oscillation is defined as the pressure difference between the Azores high and the Icelandic low over the last century (Marshall et al., 2001), and the resulting climate pattern shows an anti-phase behavior between southern Greenland SAT and northwestern European SAT (Hanna and Cappelen, 2003).

This North Atlantic Oscillation analogy has usually been made when comparing the Medieval Climate Anomaly to the LIA (e.g., Keigwin and Pickart, 1999; Mann et al., 2009; Trouet et al., 2009), but it may also have extended to earlier centennial climate events like the Roman Warm Period and the Dark Ages (e.g., Keigwin, 1996; Keigwin and Pickart, 1999; Andresen et al., 2004; Seidenkrantz et al., 2007; D'Andrea et al., 2011; Ribeiro et al., 2011). If this is the case, the Narsarsuaq moraine could indicate that at least one southern Greenland ice margin responded to late-Holocene century-scale climate variability. This speculation does, however, require further dating of other southern Greenland ice margins, because a regional advance would be predicted if southern Greenland was generally cooler during the Roman Warm Period relative to the LIA.

5. Conclusions

We have used ^{10}Be surface exposure ages to date the retreat of Kiagtût sermiat from the Narsarsuaq moraine in southernmost Greenland at 1.51 ± 0.11 ka, and determined that ice reached its historical/LIA position at 1.34 ± 0.15 ka. Thus, high-precision dating confirms a pre-LIA late-Holocene glacier maximum extent in southernmost Greenland. We show that the Kiagtût sermiat occupied the Narsarsuaq moraine during cool/dry climate conditions in southern Greenland when cold Arctic waters filled nearby fjords, with retreat of Kiagtût sermiat from the moraine coincident with warming of southern Greenland. This transition from colder to warmer conditions in southern Greenland and the contemporary retreat of ice from the Narsarsuaq moraine are concurrent with northwestern European cooling from the Roman Warm Period into the Dark Ages, which would lend support to the hypothesis that late Holocene climate variability in southern Greenland did not necessarily track that of northwestern Europe (Andresen et al., 2004; Seidenkrantz et al., 2007; Mann et al., 2009; D'Andrea et al., 2011). At present, records for other southern Greenland ice margins are not necessarily inconsistent with the Narsarsuaq advance being regional in extent, but they also do not confirm such a correlation. We conclude that future research should focus on directly dating the late-Holocene extent of southern Greenland ice margins and quantitatively reconstructing the parallel climate conditions.

Acknowledgments

We thank E. Colville, E. Obbink, M. Reusche, E. Siewert, and D. Ullman for assistance in the field and the laboratory. G. Sinclair provided our base map of Greenland. N. Larsen, N. Glasser, and an anonymous reviewer provided valuable suggestions on an early version of this manuscript. The National Geographic Society (8687-09), University of Wisconsin Climate, People and Environment Program and Wisconsin Alumni Research Foundation (AEC), and National Science Foundation Graduate Fellowship Program (KW) supported this research.

Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.quascirev.2014.04.026.

References

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. Quat. Sci. Rev. 29, 1728–1756.
Andresen, C.S., Björck, S., Bennike, O., Bond, G., 2004. Holocene climate changes in southern Greenland. J. Quat. Sci. 18, 783–795.
Andresen, C.S., Straneo, F., Ribergaard, M.H., Bjørk, A.A., Andersen, T.J., Kuijpers, A., Nørgaard-Pedersen, N., Kjær, K.H., Schjøth, F., Weckström, K., Ahlstrom, A.P., 2012. Rapid response of Helheim Glacier in Greenland to climate variability over the past century. Nat. Geosci. 5, 37–41.
Axford, Y., Lose, S., Briner, J.P., Francis, D.R., Langdon, P.G., Walker, I.R., 2013. Holocene temperature history at the western Greenland Ice Sheet margin. Quat. Sci. Rev. 59, 87–100.
Balco, G., Stone, J.O., Lifton, N.A., Dunai, T.J., 2008. A complete and easily accessible means of calculating surface exposure ages or erosion rates from ^{10}Be and ^{26}Al measurements. Quat. Geochronol. 3, 174–195.
Bennike, O., Sparrenbom, C.J., 2007. Dating of the Narssarssuaq stade in southern Greenland. Holocene 17, 279–282.
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. Quat. Sci. Rev. 29, 3861–3874.
Briner, J.P., Young, N.E., Thomas, E.K., Stewart, H.A.M., Losee, S., Truex, S., 2011. Varve and radiocarbon dating support the rapid advance of Jakobshavn Isbrae during the Little Ice Age. Quat. Sci. Rev. 30, 2476–2486.
Briner, J.P., Håkansson, L., Bennike, O., 2013. The deglaciation and Neoglaciation of Upernavik Isstrøm, Greenland. Quat. Res. 80, 459–467.
Briner, J.P., Kaufman, D.S., Bennike, O., Kosnik, M.A., 2014. Amino acid ratios in reworked marine bivalve shells constrain Greenland Ice Sheet history during the Holocene. Geology 42, 75–78.
Corbett, L.B., Young, N.E., Bierman, P.R., Briner, J.P., Neumann, T.A., Rood, D.H., Graly, J.A., 2011. Paired bedrock and boulder ^{10}Be concentrations resulting from early Holocene ice retreat near Jakobshavn Isfjord, western Greenland. Quat. Sci. Rev. 30, 1739–1749.
Corbett, L.B., Bierman, P.R., Graly, J.A., Neumann, T.A., Rood, D.H., 2013. Constraining landscape history and glacial erosivity using paired cosmogenic nuclides in Upernavik, northwest Greenland. Geol. Soc. Am. Bull. http://dx.doi.org/10.1130/B30813.1.
Cuffey, K.M., Clow, G.D., 1997. Temperature, accumulation, and ice sheet elevation in central Greenland through the last deglacial transition. J. Geophys. Res. 102, 26,383–26,396.
D'Andrea, W.J., Huang, Y., Fritz, C.S., Anderson, N.J., 2011. Abrupt Holocene climate change as an important factor for human migration in West Greenland. Proc. Natl. Acad. Sci. 108, 9765–9769.
Dahl-Jensen, D., Mosegaard, K., Gundestrup, N., Clew, G.D., Johnsen, S.J., Hansen, A.W., Balling, N., 1998. Past temperatures directly from the Greenland ice sheet. Science 282, 268–271.
Dawson, A.G., 1983. Glacier-dammed lake investigations in the Hullet lake area, South Greenland. Meddelelser om Grønland. Geoscience 11, 24.
Denton, G.H., Karlen, W., 1973. Holocene climate variations—their pattern and possible cause. Quat. Res. 3, 155–205.
Fréchette, B., de Vernal, A., 2009. Relationship between Holocene climate variations over southern Greenland and eastern Baffin Island and synoptic circulation pattern. Clim. Past 5, 347–359.
Funder, S., Kjeldsen, K.K., Kjær, Ó Cofaigh, C., 2011. The Greenland Ice Sheet during the past 300,000 years: a review. In: Ehlers, J., Gibbard, P.L., Hughes, P.D. (Eds.), Developments in Quaternary Science, vol. 15, pp. 699–713. Amsterdam, The Netherlands.
Hanna, E., Cappelen, J., 2003. Recent cooling in coastal southern Greenland and relation with the North Atlantic Oscillation. Geophys. Res. Lett. 30, 1132 http://dx.doi.org/10.1029/2002GL015797.
Heisinger, B., Lal, D., Jull, A.J.T., Kubuk, P., Ivy-Ochs, S., Neumaier, S., Knie, K., Lazarev, V., Nolte, E., 2002a. Production of selected cosmogenic radionuclides by muons: 1. Fast muons. Earth Planet. Sci. Lett. 200, 345–355.
Heisinger, B., Lal, D., Jull, A.J.T., Kubik, P., Ivy-Ochs, S., Knie, K., Nolte, E., 2002b. Production of selected cosmogenic radionuclides by muons: 2. Capture of negative muons. Earth Planet. Sci. Lett. 200, 357–369.
Hughes, A.L.C., Rainsley, E., Murray, T., Fogwill, C.J., Schnabel, C., Xu, S., 2012. Rapid response of Helheim Glacier, southeast Greenland, to early Holocene climate warming. Geology 40, 427–430.
Jansen, E., Overpeck, J., Briffa, K.R., Duplessy, J.-C., Joos, F., Masson-Delmotte, V., Olago, D., Otto-Bliesner, B., Peltier, W.R., Rahmstorf, S., Ramesh, R., Raynaud, D., Rind, D., Solomina, O., Villalba, R., Zhange, D., 2007. Paleoclimate. In: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M., Miller, H.L. (Eds.), Climate Change 2007: the Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
Jensen, K.G., Kuijpers, A., Koç, N., Heinemeier, J., 2004. Diatom evidence of hydrographic changes and ice conditions in Igaliku Fjord, South Greenland, during the past 1500 years. Holocene 14, 152–164.
Jessen, C.A., Solignac, S., Nørgaard-Pedersen, N., Mikkelsen, N., Kuijpers, A., Seidenkrantz, M.-S., 2011. Exotic pollen as an indicator of variable atmospheric circulation over the Labrador Sea region during the mid to late Holocene. J. Quat. Sci. 26, 286–296.
Kaplan, M.R., Wolfe, A.P., Miller, G.H., 2002. Holocene environmental variability in southern Greenland inferred from lake sediments. Quat. Res. 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., Arctic Lakes 2k Project Members, 2009. Recent warming reverses long-term Arctic cooling. Science 325, 1236–1239.
Keigwin, L.D., 1996. The Little Ice Age and medieval warm period in the Sargasso Sea. Science 274, 1504–1508.
Keigwin, L.D., Pickart, R.S., 1999. Slope water current over the Laurentian Fan on interannual to millennial time scales. Science 286, 520–523.
Kelley, S.E., Briner, J.P., Young, N.E., Babonis, G.S., Csatho, B., 2012. Maximum late Holocene extent of the western Greenland Ice Sheet during the late 20th century. Quat. Sci. Rev. 56, 89–98.
Kelly, M., 1980. The status of the Quaternary geology of western Greenland. Rapport Grønlands Geologiske Undersøgelse, 96, 24 pp.
Kelly, M.A., Lowell, T.V., 2009. Fluctuations of local glaciers in Greenland during latest Pleistocene and Holocene time. Quat. Sci. Rev. 28, 2088–2106.
Kelly, M.A., Lowell, T.V., Hall, B.L., Schaefer, J.M., Finkel, R.C., Goehring, B.M., Alley, R.B., Denton, G.H., 2008. A ^{10}Be chronology of lateglacial and Holocene mountain glaciation in the Scoresby Sund region, east Greenland: implication for seasonality during lateglacial time. Quat. Sci. Rev. 27, 2273–2282.
Kohl, C.P., Nishiizumi, K., 1992. Chemical isolation of quartz measurement of *in-situ*-produced cosmogenic nuclides. Geochim. Cosmochim. Acta 56, 3583–3587.
Lal, D., 1991. Cosmic ray labeling of erosion surfaces: *in situ* nuclide production rates and erosion models. Earth Planet. Sci. Lett. 104, 424–439.
Lane, T.P., Roberts, D.H., Rea, B.R., Ó Cofaigh, C., Vieli, A., Ródes, A., 2014. Controls upon the Last Glacial Maximum deglaciation of the northern Uummannaq Ice Stream System, West Greenland. Quat. Sci. Rev. (in press) http://dx.doi.org/10.1016/j.quascirev.2013.09.013.
Larsen, N.K., Kjær, K.H., Olsen, J., Funder, S., Kjeldsen, K.K., Nørgaard-Pedersen, N., 2011. Restricted impact of Holocene climate variations on the southern Greenland Ice Sheet. Quat. Sci. Rev. 30, 3171–3180.
Larsen, N.K., Funder, S., Kjær, K.H., Kjeldsen, K.K., Knudsen, M.F., Linge, H., 2013. Rapid early Holocene ice retreat in West Greenland. Quat. Sci. Rev. (in press) http://dx.doi.org/10.1016/j.quascirev.2013.05.027.
Lassen, S.J., Kuijpers, A., Kunzendorf, H., Hoffmann-Wieck, G., Mikkelsen, N., Konradi, P., 2004. Late-Holocene Atlantic bottom-water variability in Igaliku Fjord, South Greenland, reconstructed from foraminifera faunas. Holocene 14, 165–171.
Levy, L.B., Kelly, M.A., Howley, J.A., Virginia, R.A., 2012. Age of the Ørkendalen moraines, Kangerlussuaq, Greenland: constraints on the extent of the southwestern margin of the Greenland Ice Sheet during the Holocene. Quat. Sci. Rev. 52, 1–5.
Levy, L.B., Kelly, M.A., Lowell, T.V., Hall, B.L., Hempel, L.A., Honsaker, W.M., Lusas, A.R., Howley, J.A., Axford, Y.L., 2013. Holocene fluctuations of Bregne ice cap, Scoresby Sund, east Greenland: a proxy for climate along the Greenland Ice Sheet margin. Quat. Sci. Rev. (in press).
Long, A.J., Woodroffe, S.A., Roberts, D.H., Dawson, S., 2011. Isolation basins, sea-level changes and the Holocene history of the Greenland Ice Sheet. Quat. Sci. Rev. 30, 3748–3768.
Loso, M.G., Doak, D.F., 2006. The biology behind lichenometric dating curves. Oecologia 147, 223–229.
Lowell, T.V., Hall, B.L., Kelly, M.A., Bennike, O., Lusas, A.R., Honsaker, W., Smith, C.A., Levy, L.B., Travis, S., Denton, G.H., 2013. Late Holocene expansion of Istovet ice cap, Liverpool Land, east Greenland. Quat. Sci. Rev. 63, 128–140.
Mann, M.E., Zhang, Z., Rutherford, S., Bradley, R.S., Hughes, M.K., Shindell, D., Ammann, C., Faluvegi, G., Ni, F., 2009. Global signatures and dynamical origins of the Little Ice Age and Medieval Climate Anomaly. Science 326, 1256–1260.
Marcott, S.A., Shakun, J.D., Clark, P.U., Mix, A.C., 2013. A reconstruction of regional and global temperature for the past 11,300 years. Science 339, 1198–1201.
Marshall, J., Johnson, H., Goodman, J., 2001. A study of the interaction of the North Atlantic Oscillation with ocean circulation. J. Clim. 14, 1399–1421.
Møller, H.S., Jensen, K.G., Kuijpers, A., Aagaard-Sørensen, S., Seidenkrantz, M.-S., Prins, M., Endler, R., Mikkelsen, N., 2006. Late-Holocene environment and climatic changes in Ameralik Fjord, southwest Greenland: evidence from the sedimentary record. Holocene 16, 685–695.
Nelson, A.H., Bierman, P.R., Shakun, J.D., Rood, D.H., 2014. Using *in situ* cosmogenic ^{10}Be to identify the source of sediment leaving Greenland. Earth Surf. Process. Landf. http://dx.doi.org/10.1002/esp.3565 (in press).
Nesje, A., 2009. Latest Pleistocene and Holocene alpine glacier fluctuations in Scandinavia. Quat. Sci. Rev. 28, 2119–2136.
Nick, F.M., Vieli, A., Andersen, M.L., Joughin, I., Payne, A., Edwards, T.L., Pattyn, F., van de Wal, R.S.W., 2013. Future sea-level rise from Greenland's main outlet glaciers in a warming climate. Nature 497, 235–238.
Nishiizumi, K., Elmore, D., Ma, X.Z., Arnold, J.R., 1984. ^{10}Be and ^{36}Cl profiles in an Apollo 15 drill core. Earth Planet. Sci. Lett. 70, 157–163.
Nishiizumi, K., Imamura, M., Caffee, M., Southon, J.R., Finkel, R.C., McAninch, J., 2007. Absolute calibration of ^{10}Be AMS standards. Nucl. Instrum. Methods Phys. Res. Sect. B Bean Interact. Mater. Atoms 258, 403–413.
Nørgaard-Pedersen, N., Mikkelsen, 2009. 8000 year record of climate variability and fjord dynamics from Southern Greenland. Mar. Geol. 264, 177–189.
Oerlemans, J., 2005. Extracting a climate signal from 169 glacier records. Science 308, 675–677.
PAGES 2k Network, 2013. Continental-scale temperature variability during the past two millennia. Nat. Geosci. 6, 339–346.
Perner, K., Moros, M., Lloyd, J.M., Kuijpers, A., Telford, R.J., Harff, J., 2011. Centennial scale benthic foraminiferal record of late Holocene oceanographic variability in Disko Bugt, West Greenland. Quat. Sci. Rev. 30, 2815–2826.

Ribeiro, S., Moros, M., Ellegaard, M., Kuijpers, A., 2011. Climate variability in West Greenland during the past 1500 years: evidence from a high-resolution marine palynological record from Disko Bay. Boreas. http://dx.doi.org/10.111/j.1502–3885.2011.00216.x.

Roberts, D.H., Long, A.J., Schnabel, C., Freeman, S., Simpson, M.J.R., 2008. The deglacial history of southeast sector of the Greenland Ice Sheet during the Last Glacial Maximum. Quat. Sci. Rev. 27, 1505–1516.

Roberts, D.H., Rea, B.R., Lane, T.P., Schnabel, C., Rodés, 2013. New constraints on Greenland ice sheet dynamics during the last glacial cycle: evidence from the Uummannaq ice stream system. J. Geophys. Res. Earth Surf. 118, 1–23 http://dx.doi.org/10.1002/jgrf.20032.

Rood, D.H., Hall, S., Guilderson, T.P., Finkel, R.C., Brown, T.A., 2010. Challenges and opportunities in high-precision Be-10 measurements at CAMS. Nucl. Instrum. Methods B Beam Interact. Mater. Atoms 268, 730–732.

Rood, D.H., Brown, T.A., Finkel, R.C., Guilderson, T.P., 2013. Poisson and non-Poisson uncertainty estimations of $^{10}Be/^{9}Be$ measurements at LLNL-CAMS. Nuclear Instrum. and Methods B Beam Interact. Mater. Atoms 294, 426–429.

Seidenkrantz, M.-S., Aagaard-Sørensen, S., Sulsbrück, H., Kuijpers, A., Jensen, K.G., Kunzendorf, H., 2007. Hydrography and climate of the last 4400 years in a SW Greenland fjord: implications for Labrador Sea palaeoceanography. Holocene 17, 387–401.

Seidenkrantz, M.-S., Roncaglia, L., Fischel, A., Heilmann-Clausen, C., Kuijpers, A., Moros, M., 2008. Variable North Atlantic climate seesaw patterns documented by a late Holocene marine record from Disko Bugt, West Greenland. Mar. Micropaleontol. 68, 66–83.

Severinghaus, J.P., Sowers, T., Brook, E.J., Alley, R.B., Benders, M.L., 1998. Timing of abrupt climate change at the end of the Younger Dryas interval from thermally fractionated gases in polar ice. Nature 39, 141–146.

Sparrenbom, C.J., Bennike, O., Björck, S., Lambeck, K., 2006a. Relative sea-level changes since 15 000 cal. yr BP in the Nanortalik area, southern Greenland. J. Quat. Sci. 21, 29–48.

Sparrenbom, C.J., Bennike, O., Björck, S., Lambeck, K., 2006b. Holocene relative sea-level changes in the Qaqortoq area, southern Greenland. Boreas 35, 171–187.

Stone, J.O., 2000. Air pressure and cosmogenic isotope production. J. Geophys. Res. 105, 23,753–23,759.

Trouet, V., Esper, J., Graham, N.E., Baker, A., Scourse, J.D., Frank, D.C., 2009. Persistent positive North Atlantic oscillation mode dominated the medieval climate anomaly. Science 324, 78–80.

Weidick, A., 1963. Ice margin features in the Julianehåb district, South Greenland. In: Meddelelser om Grønland, vol. 165, 133 pp.

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. Palaeoceanogr. Palaeoclimatol. Palaeoecol. 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.

Weidick, A., Bennike, O., 2007. Quaternary glaciation history of Jakobshavn Isbræ and the Disko Bugt region, west Greenland: a review. Geol. Surv. Den. Greenl. Bull. 14, 78.

Weidick, A., Bennike, O., Citterio, M., Nørgaard-Pedersen, 2012. Neoglacial and historical glacier changes around Kangersuneq fjord in southern West Greenland. Geol. Surv. Den. Greenl. Bull. 27, 68.

Xu, S., Dougnas, A.B., Freeman, S.P.H.T., Schnabel, C., Wilcken, K.M., 2010. Improved ^{10}Be and $^{26}A1$-AMS with a 5 M V spectrometer. Nucl. Instrum. Methods Phys. Res. B 268, 736–738.

Young, N.E., Briner, J.P., Stewart, H.A.M., Axford, Y., Csatho, B., Rood, D.H., Finkel, R.C., 2011. Response of jakobshavn isbræ, Greenland, to holocene climate change. Geology 39, 131–134.

Young, N.E., Schaefer, J., Briner, J.P., Goehring, B., 2013. A ^{10}Be production-rate calibration for the Arctic. J. Quat. Sci. 28, 515–526.