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A ^{10}Be chronology of early Holocene local glacier moraines in central West Greenland

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New cosmogenic ^{10}Be exposure ages constrain Greenland Ice Sheet (GrIS) deglaciation and the culmination of a local glacier advance on the southern shore of Nuussuaq (peninsula) in central West Greenland. Mean ages of GrIS deglaciation and local glacier moraine deposition are 10.5±0.1 ka (n = 2) and 10.4±0.2 ka (n = 5), respectively. The similar ages suggest an advance/stillstand of local glaciers soon after the local retreat of the GrIS. The moraines dated in this study may be correlative to the nearby Disko Stade moraines. Moraine chronologies for both GrIS moraines and our local glacier moraines in central West Greenland correspond to detrital carbonate peaks in a Labrador shelf marine sediment core that records Laurentide Ice Sheet (LIS) discharge from Hudson Strait. Large freshwater discharge events into the North Atlantic sub-polar gyre have been linked to abrupt cooling events in the Northern Hemisphere during the early Holocene. We propose LIS freshwater input to the sub-polar gyre and associated regional cooling as the main driver for advance/stillstand of both local glaciers and the GrIS in central West Greenland during the early Holocene.

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Much of the previous research conducted on glaciers in Greenland has focused on the Greenland Ice Sheet (GrIS), in large part due to its potential for future contribution to sea level rise (~7.4 m; Morice *et al.* 2012). However, a recent study estimated that ~30% of the observed sea level rise between 2003 and 2009 was the result of melt from glaciers and icecaps that are independent of the Greenland and Antarctic Ice Sheets (Gardner *et al.* 2013). Currently, glaciers and icecaps independent of the GrIS (herein referred to as local glaciers) are undergoing net mass loss with the exception of the north-central portion of Greenland (Bolch *et al.* 2013). Glacier length, a proxy for mass loss, on a number of local glaciers in Greenland has also been decreasing since the 1860s (Leclercq *et al.* 2012).

Many studies focusing on local glaciers in Greenland concentrate on the late Holocene, because local glacier moraines dating to the early–middle Holocene are sparse (Kelly & Lowell 2009; we adopt early/middle/late Holocene boundaries from Walker *et al.* 2012). This dearth of information limits our ability to identify specific climatic forcing mechanisms that influenced local glacier behaviour prior to the instrumental record. The early Holocene contains several well-documented abrupt cooling events, posing an ideal time period to test for local glacier sensitivity to abrupt climate change. Significant abrupt cooling events include the Preboreal oscillation (*c.* 11.5–11.4 ka; Björck *et al.* 1997; Rasmussen *et al.* 2007), the 9.3 ka event (Rasmussen *et al.* 2007) and the 8.2 ka event (Kobashi *et al.* 2007; Rasmussen *et al.* 2007). These climate events have been tied to numerous records of glacier expansion and are often cited as potential drivers of early Holocene moraine deposition in Greenland (e.g. Kelly *et al.* 2008; Young *et al.* 2011a; Levy *et al.* 2016). There is increasing evidence that additional early Holocene abrupt climate events occurred (e.g. Geirsdóttir *et al.* 2013; Jennings *et al.* 2015) and it is important to determine whether or not glaciers respond to them because it provides insight into forcing mechanisms of glacier change.

The main goals of this research are threefold: (i) to add to existing early Holocene local glacier reconstructions in West Greenland, (ii) to assess synchronicity in glacier behaviour within a region, and (iii) to explore forcing mechanisms that may have driven early Holocene glacier advance/stillstand and the associated deposition of moraines. In order to fulfil these objectives we date prehistorical local glacier moraines on Nuussuaq in central West Greenland (Fig. 1) using ^{10}Be cosmogenic nuclide exposure dating (herein ^{10}Be dating). We then compare our resulting local glacier chronology with previously dated local glacier advances/stillstands and nearby GrIS moraine chronologies. Lastly, we relate our local glacier record and pre-existing GrIS moraine chronologies from central West Greenland to a high-resolution marine sediment core record from the Labrador shelf (Jennings *et al.* 2015). This marine record contains evidence of large ice discharge events from an outlet glacier of the Laurentide Ice Sheet (LIS) that probably affected ocean circulation. This may have induced abrupt cooling events that affected glacier margin fluctuations in the Baffin Bay region during the early Holocene.

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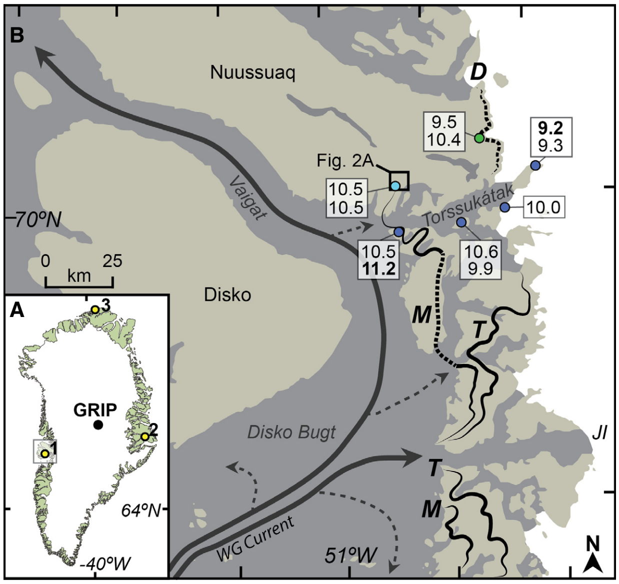

Fig. 1. A. Greenland and the Greenland Ice Sheet (white) modified from Cronauer *et al.* (2016). Yellow circles are general locations of published absolute age chronologies for Lateglacial to early Holocene local glaciers in Greenland. The numbers denote research areas from (1) Ingólfsson *et al.* (1990); Jomelli *et al.* (2016); (2) Kelly *et al.* (2008), Alexanderson & Håkansson (2014), Levy *et al.* (2016) and (3) Möller *et al.* (2010), Larsen *et al.* (2016). B. Regional map showing locations of ^{10}Be constraints on GrIS retreat in our study area, the West Greenland (WG) Current (grey solid and dashed lines; modified from Perner *et al.* (2013)), and ice-sheet moraines (modified with elements from Weidick & Bennike (2007)). Ice-sheet moraine extents (black solid (mapped) and dashed (inferred) lines) are based on Weidick & Bennike (2007). These ice-sheet moraines include the Drygalski Moraines (*D*) and the Fjord Stade Moraines: the Marrait (*M*, *c.* 9.3 ka) and Tasiussaq (*T*, *c.* 8.2 ka) Moraines (Young *et al.* 2013a; Cronauer *et al.* 2016). The location of this study is indicated by the black box (labelled Fig. 2A) on southeastern Nuussuaq. Locations of ^{10}Be ages of erratic boulders and bedrock samples that constrain GrIS deglaciation near our study area are displayed with dark blue (Kelley *et al.* 2015), green (Cronauer *et al.* 2016) and light blue dots (this study). Individual ^{10}Be ages are shown in thousands of years (ka) and all have internal (1σ) errors of 0.5 ka or less. Bold numbers are ages from bedrock samples and normal text denotes ages from erratic boulder samples. [Colour figure can be viewed at www.boreas.dk]

Background

Previous Lateglacial to early Holocene Greenland local glacier chronologies

Only three regions in Greenland contain previous absolute age chronologies for local glaciers in the early Holocene (Fig. 1A; Kelly & Lowell 2009; Möller *et al.* 2010; Alexanderson & Håkansson 2014; Larsen *et al.* 2016; Levy *et al.* 2016). In order to accurately compare ^{10}Be ages between studies, we calculate all ^{10}Be ages using a local production rate for the Arctic (Young *et al.* 2013b) and the Lal (1991)/Stone (2000) spallation scaling scheme. Relevant ages from Kelly *et al.* (2008) and Möller *et al.* (2010) were already recalculated using the above production rate and scaling scheme by Levy *et al.* (2016) and Larsen *et al.* (2016), respectively, so we cite the ^{10}Be ages reported therein. The ^{10}Be ages from Alexanderson & Håkansson (2014) and 10 additional ^{10}Be ages from Möller *et al.* (2010) were recalculated for this study using the CRONUS-Earth online exposure age calculator (Balco *et al.* 2008, version 2.2.1, http://hess.ess.washington.edu/).

West Greenland

In West Greenland, moraines with early Holocene age constraints are located on Disko Island. These moraines are attributed to the Disko Stade re-advance (Fig. 1; Ingólfsson *et al.* 1990). Age constraints from eastern Disko near Mudderbugt consist of two uncalibrated minimum-limiting radiocarbon (^{14}C) ages from inboard of a set of Disko Stade moraines in Kvandalen (Ingólfsson *et al.* 1990). The first ^{14}C age is from basal gyttja of a lake sediment core (8950±125 ^{14}C a BP) and the second ^{14}C age is from a mollusc shell associated with a 45 m a.s.l. marine limit (8700±120 ^{14}C a BP; Ingólfsson *et al.* 1990). These ages have been recalibrated (IntCal13, MARINE13, and CALIB v. 7.1; Reimer *et al.* 2013; Stuiver *et al.* 2013) and the mollusc age was reservoir corrected (−400 years; Stuiver & Braziunas 1993). Recalibration resulted in ages of 10 065±175 cal. a BP (gyttja) and 9845±190 cal. a BP (mollusc); thus, deposition of the Disko Stade Moraines is interpreted as a short-lived re-advance prior to *c.* 10.1 ka (Ingólfsson *et al.* 1990). Additional age constraints of the Disko Stade Moraines consist of three ^{36}Cl exposure ages from moraine boulders (10.5±1.3, 12.0±1.5 and 13.4±1.6 ka) from the Lyngmarksbræen icecap in southern Disko (Jomelli *et al.* 2016). The average age of the moraine boulders (11.9±1.7 ka) suggests moraine stabilization during the transition from Lateglacial to the early Holocene.

East Greenland

In East Greenland, moraines constrained to the early Holocene are found in the Scoresby Sund region. This area contains the most absolute age constraints on early–middle Holocene moraines and has been the subject of multiple studies (Hall *et al.* 2008, 2010; Kelly *et al.* 2008; Alexanderson & Håkansson 2014; Levy *et al.* 2014, 2016). One data set in this area consists of 38 ^{10}Be ages collected across three local glacier moraines from Gurreholm Dal in the Stauning Alper (Kelly *et al.* 2008). However, the early Holocene ages do not cluster tightly and appear to be affected by inheritance. Based on their chronology, Kelly *et al.* (2008) suggest moraine abandonment during the Lateglacial from 13.6 to 12.4 ka (G-III moraine, n = 4) and during the end of the Younger Dryas or beginning of the Preboreal from 12.1 to 11.1 ka (G-II moraine, n = 11). In both cases, the lower bounds for moraine abandonment are the youngest ages in each sample population and the upper bounds are derived from the average of ^{10}Be ages determined by Kelly *et al.* (2008) to best represent moraine age. Milne Land Stade GrIS margin moraines mapped as equivalents of the G-II moraine are well constrained to be *c.* 11.3 to 11.0 ka based on both a local relative sea-level curve and an additional radiocarbon age (Hall *et al.* 2008), and are believed to act as independent constraints on the G-II moraines (Kelly *et al.* 2008). A relative sea-level curve based on radiocarbon ages of shells collected from marine sediments in nearby Schuchert Dal revealed a similar marine limit age used to estimate the age of an adjacent set of moraines to be older than *c.* 11.9 to 13.0 cal. a BP (Hall *et al.* 2010).

An additional local glacier chronology from nearby Milne Land in East Greenland contains eight ^{10}Be ages from a right-lateral moraine deposited by the Vinkeldal Glacier (Levy *et al.* 2016). After excluding an outlier (9.8±0.4 ka), the ages range from 11.1±0.3 to 12.1±0.3 ka with an average of 11.4±0.6 ka. Levy *et al.* (2016) also dated correlative GrIS moraines in this area (Inner Milne Land Stade) and found a similar average ^{10}Be age of 11.4±0.8 ka, suggesting that the ice sheet and nearby icecap behaved synchronously at this time. These ages are consistent with the Gurreholm Dal chronology and suggest that the Vinkeldal Glacier moraines may be correlative to the G-II moraines discussed above (Kelly *et al.* 2008).

In addition, ^{10}Be and Optically Stimulated Luminescence (OSL) ages constrain deposition of moraines from the nearby Liverpool Land icecap to *c.* 13–11 ka, also suggesting a potential glacial advance during the early Holocene in the Scoresby Sund area (Alexanderson & Håkansson 2014). Five ^{10}Be ages were obtained from moraines in the Lejrelv (6.7±0.4 ka), Umingmak (10.5±1.2 ka) and Gåseelv (13.4±3.6, 9.5±1.3 and 4.8±0.6 ka) valleys. Four of the ^{10}Be ages were from samples consisting of pebbles and one was from a single cobble. The oldest age on each moraine is interpreted by Alexanderson & Håkansson (2014) as a minimum constraining age for moraine formation. In the Lejrelv area, OSL ages from lacustrine sediments inboard of the moraines suggest that moraines must be at least as old as 13±2 ka and that the ^{10}Be age from that moraine (6.7±0.4 ka) was probably affected by prior shielding of the surface. In the Umingmak area, the youngest OSL age from lacustrine sediments outboard of the moraines was interpreted as a maximum constraining age (10.0±0.6 ka). In the Gåseelv area, OSL ages of a delta associated with the marine limit of this area (12±2 and 11±1.3 ka) were within error of the ^{10}Be moraine age minimum constraint (13.4±3.6 ka). In addition, OSL ages from lacustrine sediments in the nearby Nathorst valley (12–13±2 ka) suggest that an ice-damned lake existed to the north of the ice lobe that deposited the Gåseelv moraines (Alexanderson & Håkansson 2014).

Other early Holocene ^{10}Be moraine boulder ages exist in the Scoresby Sund area for the Datum moraine (informal name) of the Bregne icecap (Levy *et al.* 2014). However, these ages were regarded as outliers affected by inherited nuclides due to the large spread within the ^{10}Be moraine boulder age population, independent constraints from a nearby lake sediment record and observations of the fresh, unvegetated moraine boulder surfaces that all support late Holocene deposition of the Datum moraine (Levy *et al.* 2014).

North Greenland

In North Greenland, early Holocene moraines are found in Johannes V. Jensen Land. Data from an initial study at this site consist of both radiocarbon and ^{10}Be ages from two valleys (Möller *et al.* 2010). A local glacier advance in the Sifs valley was constrained to 9.6–6.3 ka based on radiocarbon dating of geomorphic features with relative ages older and younger than the moraine succession. Three ^{10}Be ages on the Sifs valley moraine ranged from 11.9 to 12.6 ka and were regarded as unreliable age constraints by Möller *et al.* (2010). Seven samples from boulders collected inboard of the nearby Moore Glacier moraine were directly dated with ^{10}Be, yielding a mean age of 9.0±1.2 ka. Three younger ages located close to the current ice margin (average age of 6.0±1.2 ka) were excluded from the sample population used to calculate the *c.* 9 ka average maximum age constraint. One age derived from pebbles collected from the end moraine (12.8±0.7 ka) was assumed by Möller *et al.* (2010) to be erroneous.

Larsen *et al.* (2016) revisited the Möller *et al.* (2010) chronology and added six ^{10}Be ages from the Sifs valley (n = 3) and nearby Henson Bugt (n = 3). Their data set, including three ages from Möller *et al.* (2010), suggests that moraine deposition in the Sifs valley and Henson Bugt occurred at 12.1±0.6 and 12.8±0.8 ka, respectively. The reinterpretation places the Moore Glacier moraine ^{10}Be age (12.8±0.7 ka) as the correct minimum age constraint for moraine formation as opposed to the previous Möller *et al.* (2010) estimate based on radiocarbon ages. The 9.6–6.3 ka radiocarbon-based constraint from Möller *et al.* (2010) is proposed by Larsen *et al.* (2016) to be the result of a younger event where material was thrust up onto the older moraine during a subsequent re-advance. The average age of the three moraines is 12.5±0.7 ka. With this updated chronology, Larsen *et al.* (2016) suggest that the moraines document unprecedented evidence of local ice re-advances associated with cooling during the Younger Dryas. This age overlaps with a maximum limiting OSL age of nearby glaciolacustrine sediments deposited prior to moraine formation (12.4±0.6 ka; Larsen *et al.* 2010) and suggests moraine deposition between 11.8 and 13.0 ka (Larsen *et al.* 2016). These ages are similar to the youngest of the G-III moraine ages from Gurreholm Dal in East Greenland (Kelly *et al.* 2008). However, it is difficult to determine if the two sets of moraines are correlative due to the potential nuclide inheritance in the East Greenland data set.

Early Holocene ice-sheet moraine chronologies in Disko Bugt region

There have been numerous studies dating ice-sheet moraines around Greenland (see Young & Briner (2015) and Sinclair *et al.* (2016) for recent reviews), and we mention the most relevant chronologies in our study area in the Disko Bugt region. The Fjord Stade Moraines were deposited in West Greenland by the GrIS during the early Holocene, thought to be in response to the 8.2 and 9.3 ka abrupt cold events because GrIS moraines have been dated to 9.2 and 8.2 ka (Young *et al.* 2011b, 2013a). ^{10}Be reconstructions of the Fjord Stade Moraines suggest significant ice-sheet advances at the marine-terminating outlet glacier Jakobshavn Isbræ. Stillstands indicative of a diminished response, still in phase with the cold events, were also reconstructed along a land-terminating margin to the south of Jakobshavn Isbræ (Young *et al.* 2013a). Another set of ice-sheet moraines, the Drygalski Moraines, were deposited by a high-elevation, land-terminating ice-sheet margin located on Nuussuaq ~40 km west of our study site. These moraines are also early Holocene in age (Cronauer *et al.* 2016). Unlike the Fjord Stade Moraines, however, the Drygalski Moraines have mean moraine ages of *c.* 8.6, 8.5 and 7.6 ka suggesting a lack of, or complex, response to the 8.2 or 9.3 ka climate events.

Study area

This paper focuses on the Nákâgajoq mountain moraines (informal name) located in southern Nuussuaq ~36 km to the west of the current GrIS margin in central West Greenland (Fig. 1B). The Nákâgajoq mountain region is dominated by Archean gneiss that experienced granulite facies metamorphism during the Proterozoic (Henriksen *et al.* 2000). Much of the bedrock in the uplands of our study area has undergone extensive frost shattering and there is evidence of solifluction along the lower slopes of the Nákâgajoq mountain massif. Currently, very little ice cover remains on the summit of the Nákâgajoq mountain (~0.15 km^2); however, a small north-facing glacier still exists on the northwest side of the massif (~0.28 km^2). Nearby mountains to the west and northeast currently maintain local glaciers and icecaps.

The Nákâgajoq mountain moraines were deposited along two valleys on the southeastern facing side of the Nákâgajoq massif (peak elevation ~960 m a.s.l., Fig. 2). Both of these lateral moraine sets are mapped on the Geological Survey of Greenland regional Quaternary map (1:500 000 scale; Weidick 1974). Lateral moraines are SSE trending and are well defined, whereas terminal moraines have been breached by stream channels and are not well expressed in the landscape. The lateral moraines are ~3–10 m high, ~500–800 m long, matrix supported, and span elevations between 222 (lowest) and 611 (highest) m a.s.l. These moraines have ample lichen and tundra cover, exhibit flat to rounded crests and are located far below the present-day regional snowline, suggesting that they pre-date Neoglaciation.

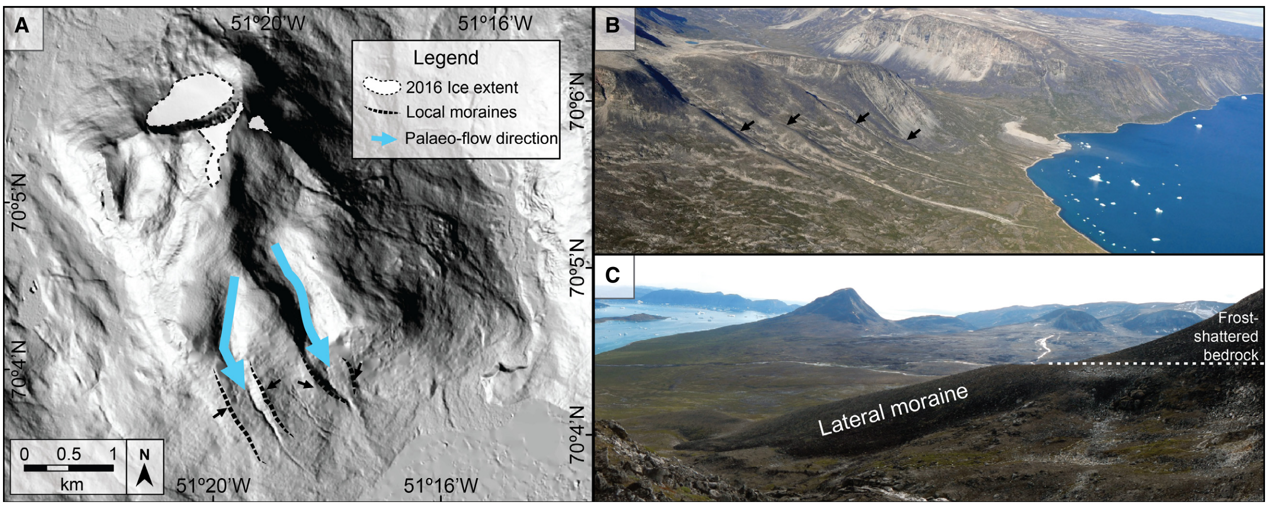

Fig. 2. A. Hillshade map of the area produced from a digital surface model (http://www.pgc.umn.edu/elevation/stereo/setsm) with 2× vertical exaggeration to highlight moraines (SSE linear features pointed to by black arrows). B. Oblique aerial view of the study area. Moraine crests (black arrows) are visible. C. Photograph taken from the eastern side of the western valley looking toward the right lateral moraine of the western valley from which 13GRO-Q3 and 13GRO-Q4 were sampled. The moraine ends at a break in slope denoted by the white dotted line (maximum lateral moraine elevation). [Colour figure can be viewed at www.boreas.dk]

The region was completely occupied by the GrIS during the Last Glacial Maximum (Funder *et al.* 2011; Ó Cofaigh *et al.* 2013). The moraines demarcating former glacier extents on Nákâgajoq mountain indicate that they were deposited following GrIS retreat from the area. We interpret erratic boulders strewn across the landscape beyond the Nákâgajoq mountain moraines as being deposited by the GrIS during its eastward retreat from the Nákâgajoq mountain area. Based on previous ^{10}Be dating along Torssukátak Fjord, we interpret this to have taken place *c.* 10.5 ka (Kelley *et al.* 2015), although this is only our best estimate based on available data. Estimated marine limit elevation in this area is between 40 and 80 m a.s.l. (Weidick 1968; Weidick & Bennike 2007).

Material and methods

^{10}*Be dating*

In the summer of 2013, the Nákâgajoq mountain moraines were mapped in the field using a handheld Garmin GPS unit. Rock samples were collected for ^{10}Be dating from surfaces of moraine boulders and erratics perched on bedrock outboard of the moraines. Samples were collected using a hand sledge and chisel from the top (<3 cm) of boulder surfaces, avoiding collection from more easily eroded corners and edges. Relatively tall, subangular boulders in high topographical positions or close to moraine crests with stable appearances were preferentially sampled to minimize the chances of postdepositional modification or snow and sediment shielding that would result in an artificially young age (Fig. 3).

Latitude, longitude and elevation were acquired for each sample location with a handheld Garmin GPS unit. Sample elevations range from 271 to 450 m a.s.l., well above the estimated 40–80 m a.s.l. marine limit for this area (Weidick & Bennike 2007). The average thickness was obtained for each sample in order to account for reduced ^{10}Be production with depth (Gosse & Phillips 2001). Topographical shielding was measured for each sample location using a compass and clinometer. Shielding values were calculated using the CRONUS-Earth geometric shielding calculator (version 1.1.; http://hess.ess.washington.edu).

^{10}Be was isolated from acid-cleaned quartz samples at the University at Buffalo Cosmogenic Nuclide Laboratory following methods outlined in Kelley *et al.* (2012). The concentration of ^{9}Be carrier used during sample preparation was 372.5 ppm. Sample ^{10}Be/^{9}Be ratios were measured at the Lawrence Livermore National Laboratory (LLNL) Center for Accelerator Mass Spectrometry (CAMS) using the standard 07KNSTD3110. The ^{10}Be ages were calculated via the CRONUS-Earth online exposure age calculator (Balco *et al.* 2008, version 2.2.1, http://hess.ess.washington.edu/) using a production rate for the Arctic (Young *et al.* 2013b) and the Lal/Stone constant-production scaling scheme (Lal 1991; Stone 2000). The individual ^{10}Be ages are reported in Table 1 with age uncertainties associated only with measurement of ^{10}Be atoms (internal). Total uncertainties (external) include the internal uncertainty as well as production rate and scaling uncertainties (Table 2). Average ages of GrIS deglaciation and local glacier moraine abandonment are reported below as the mean of the ^{10}Be age population ±one standard deviation of the ^{10}Be age population (1σ).

Results and discussion

^{10}*Be chronology*

Two samples processed from erratics perched on bedrock outboard of the moraines returned ^{10}Be ages of 10.5±0.3 and 10.5±0.5 ka, with a resulting mean age of 10.5±0.1 ka (Fig. 4, Table 1). Six samples from lateral Nákâgajoq mountain moraine boulders collected from two adjacent alpine valleys returned ^{10}Be ages ranging from 6.9±0.2 to 10.7±0.3 ka (n = 6), with a mean age of 9.9±1.4 ka (Fig. 5, Table 1). However, we consider the ^{10}Be age of 6.9±0.2 ka an outlier after testing the sample population via the mean square of weighted deviates (MSWD) statistic and χ^2 statistical probability limits. The MSWD and probability limits were calculated with a Microsoft Excel add-in program (Ludwig 2012) following the suggested methods of interpretation outlined in Douglass *et al.* (2006). Calculating the MSWD (15.5) and χ^2 probability limit (<0.000) for the moraine boulder population before removal of the outlier resulted in an interpretation that either the analytical uncertainty was underestimated or that geological processes significantly affected the ages within our sample population. Removal of the outlier significantly reduced the MSWD from 15.5 to 0.24, resulting in an interpretation that the analytical uncertainty for our updated age population may now be overestimated. With removal of the outlier, the probability limit for the χ^2 statistic increased from well below (<0.000) the recommended limit of 0.05 from Douglass *et al.* (2006) to well above it (0.92). A probability limit above 0.05 indicates that the distribution of ages can be explained by analytical error and that geological uncertainty is no longer necessary to explain age variations. Without the outlier, the mean age of Nákâgajoq mountain moraine boulders becomes 10.4±0.2 ka (Table 1). Ages calculated with alternative scaling schemes are similar to the ages reported here (percentage difference ≤1%) and are shown in Table 2 (Lal 1991; Stone 2000; Dunai 2001; Desilets & Zreda 2003; Lifton *et al.* 2005; Desilets *et al.* 2006).

Fig. 3. Photographs of samples collected during the summer of 2013. Samples 13GRO-Q3 and Q4 were collected from the right lateral moraine of the western valley, and 13GRO-Q5 was collected from the left lateral moraine. 13GRO-Q6, Q8 and Q9 were sampled from the right lateral moraine of the eastern valley. No samples were collected on the left lateral moraine of the eastern valley due to a lack of boulders suitable for ^{10}Be dating and concerns about rock fall and colluvium. Samples 13GRO-Q12 and Q13 were sampled outboard of the moraines from erratics perched on bedrock surfaces. [Colour figure can be viewed at www.boreas.dk]

Interpretation

Two of the eight new ^{10}Be ages presented in this study constrain the timing of GrIS deglaciation of the study area to *c.* 10.5 ka. This result is consistent with previously published ^{10}Be deglaciation ages including two ages from outboard of the Drygalski Moraines at the base of the Nuussuaq peninsula (Fig. 1; Cronauer *et al.* 2016) and a transect of seven ages along the adjacent Torssukátak Fjord (~14 km) to the south (Fig. 1; Kelley *et al.* 2015). The ^{10}Be ages closest to our study location from the Torssukátak Fjord deglaciation transect are an erratic boulder and bedrock pair with ages of 10.5±0.4 and 11.2±0.3 ka, respectively (Fig. 1; Kelley *et al.* 2015). An older bedrock sample age relative to a younger erratic boulder age for the same location

Table 1. ^{10}Be ages for perched erratics and moraine boulders. Density value used for CRONUS input was 2.65 g cm^{-3} and erosion rate used was 0 cm a^{-1}. Sample elevations were not corrected for rebound.

Sample name	Sample type	Latitude (°N)	Longitude (°E)	Elevation (m a.s.l.)[1]	Sample height (m)[2]	Thickness (cm)[3]	Topographical shielding correction[4]	Quartz (g)	^{9}Be carrier added (g)[5]	^{10}Be/^{9}Be Ratio[6]	Ratio uncertainty[6]	^{10}Be (atoms g^{-1})	Uncertainty (atoms g^{-1})	Exposure age (ka)[7]
Outboard														
13GRO-Q12	Erratic	70.04464	−51.3718	310	0.8	3	0.9984	11.9293	0.6068	4.763E-14	1.56E-15	6.03E+04	1.98E+03	10.5±0.3
13GRO-Q13	Erratic	70.04685	−51.3672	321	0.7	1	0.9985	22.9236	0.6060	9.504E-14	4.24E-15	6.25E+04	2.79E+03	10.5±0.5
													Average ±1σ:	10.5±0.1
Moraines														
13GRO-Q3	M. Boulder	70.06549	−51.3309	354	1.0	2	0.9955	17.4566	0.6111	7.08E-14	1.88E-15	6.16E+04	1.64E+03	10.2±0.3
13GRO-Q4	M. Boulder	70.06806	−51.3343	450	1.5	1	0.9919	22.0955	0.6059	6.794E-14	1.90E-15	4.64E+04	1.30E+03	6.9±0.2
13GRO-Q5	M. Boulder	70.06555	−51.3189	271	1.2	2	0.9951	22.6447	0.6061	8.543E-14	2.60E-15	5.69E+04	1.73E+03	10.2±0.3
13GRO-Q6	M. Boulder	70.07003	−51.3103	391	2.4	2	0.9935	29.7618	0.6116	1.267E-13	2.91E-15	6.48E+04	1.49E+03	10.3±0.2
13GRO-Q8	M. Boulder	70.07077	−51.3112	417	2.4	2	0.9956	28.1655	0.6061	1.272E-13	4.41E-15	6.82E+04	2.36E+03	10.6±0.4
13GRO-Q9	M. Boulder	70.07047	−51.3111	420	1.2	1	0.9850	36.1541	0.6031	1.661E-13	5.18E-15	6.90E+04	2.15E+03	10.7±0.3
												Average ±1σ without outlier:		10.4±0.2

[1]Recorded from a handheld Garmin GPS unit in metres above sea level (m a.s.l.) with ±5–10 m accuracy.
[2]Boulder sample surface elevation with respect to ground/supporting material.
[3]Average thickness of each sample.
[4]Amount of topographical shielding. Value of 1 is equivalent to no effect from surrounding topography on ^{10}Be accumulation.
[5]^{9}Be carrier concentration was 372.5±3.5 ppm.
[6]The ^{9}Be/^{10}Be ratios were measured at Lawrence Livermore National Laboratory and were blank corrected with a blank ratio of 1.96E-15±1.28E-15 for 12GRO-Q3 and -Q6 and 1.9E-15±3.4E-16 for all other samples. AMS standard was 07KNSTD3110.
[7]Calculated using the CRONUS-Earth online exposure age calculator (Balco *et al.* 2008; version 2.2.1; http://hess.ess.washington.edu/), a locally constrained production rate (Young *et al.* 2013b) and the Lal/Stone constant-production scaling scheme (Lal 1991; Stone 2000).

Table 2. Alternative ^{10}Be scaling schemes.

Scaling scheme for spallation:	Desilets & Zreda (2003)/ (Desilets *et al.* 2006)		Dunai (2001)		Lifton *et al.* (2005)		Time-dependent Lal (1991)/ Stone (2000)	
Sample name	Exposure age (ka)	External uncertainty (ka)	Exposure age (ka)	External uncertainty (ka)	Exposure age (ka)	External uncertainty (ka)	Exposure age (ka)	External uncertainty (ka)
Outboard								
13GRO-Q12	10.5	0.6	10.5	0.6	10.5	0.6	10.5	0.5
13GRO-Q13	10.6	0.6	10.6	0.7	10.6	0.7	10.5	0.6
Moraine								
13GRO-Q3	10.2	0.5	10.2	0.5	10.3	0.5	10.2	0.5
13GRO-Q4	7.0	0.4	7.0	0.4	7.0	0.4	7.0	0.3
13GRO-Q5	10.2	0.5	10.2	0.6	10.3	0.5	10.2	0.5
13GRO-Q6	10.4	0.5	10.4	0.5	10.4	0.5	10.3	0.5
13GRO-Q8	10.7	0.6	10.7	0.6	10.7	0.6	10.6	0.5
13GRO-Q9	10.8	0.6	10.8	0.6	10.8	0.6	10.7	0.5

suggests that nuclides may be inherited from previous exposure of the bedrock surface and that the boulder age may be a more reliable constraint for deglaciation.

Five moraine boulder ages constrain Nákâgajoq mountain moraine abandonment to *c.* 10.4 ka. Although this age statistically overlaps with the timing of GrIS deglaciation from the region, the Nákâgajoq mountain moraines must have been deposited following regional deglaciation, but the timing of the two events occurred within the resolution of the ^{10}Be chronologies. One ^{10}Be age was determined to be a statistical outlier and was removed from the data set prior to calculating the average age. The outlier was collected from a boulder on a steep section of the moraine and was most likely affected by postdepositional modification (i.e. exhumation), or may have been sourced from the frost-shattered bedrock above (Fig. 2B, C). With removal of the outlier, the moraine age overlaps with the age of the erratics, suggesting that the Nákâgajoq mountain glaciers deposited and

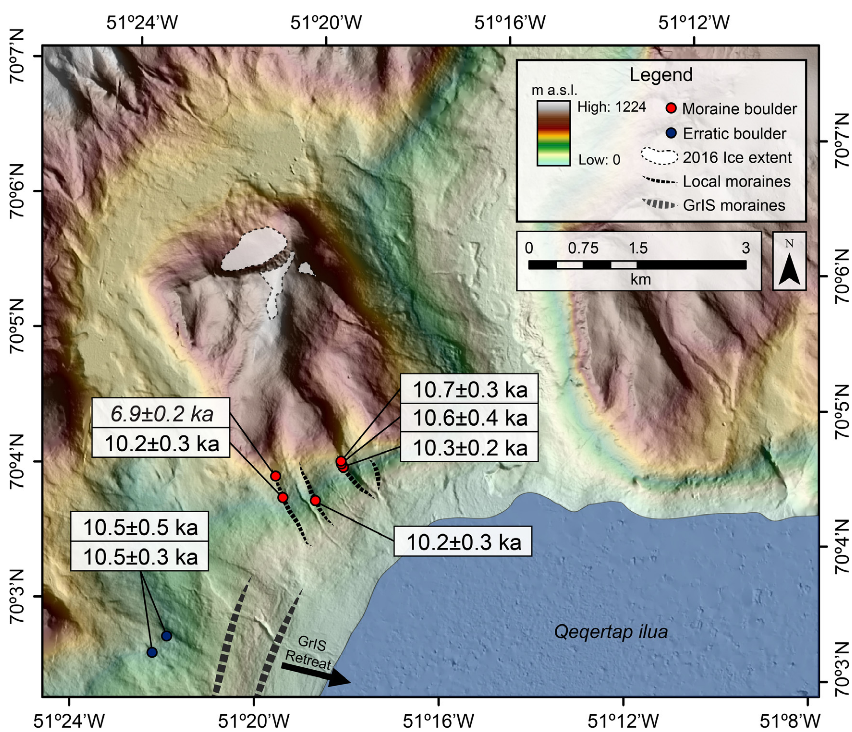

Fig. 4. Map of the study area that displays sample locations and ^{10}Be ages. Erratic boulder (blue) and moraine boulder (red) sample locations are denoted by coloured circles. Italic font is used for the age outlier identified using the MSWD statistic and χ^2 statistical probability limits. Thin, dotted black lines denote local glacier moraines and thick, grey lines are GrIS moraines as mapped by Weidick (1974). The map image is a hillshade produced from a digital surface model (http://www.pgc.umn.edu/elevation/stereo/setsm) with 2× vertical relief. A transparent colour overlay of the original surface model is superimposed over the hillshade to display elevation. [Colour figure can be viewed at www.boreas.dk]

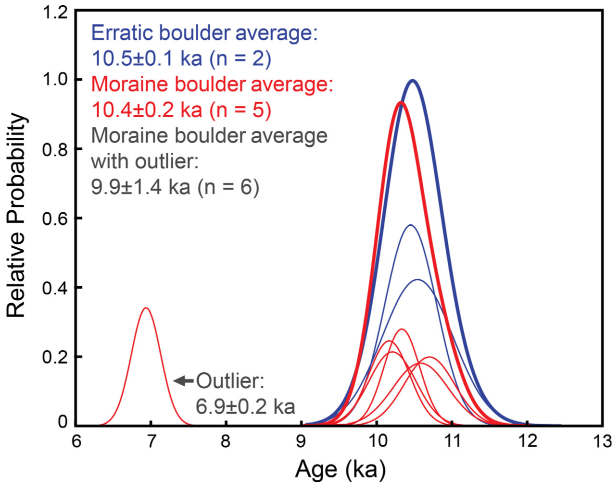

Fig. 5. Camel plot displaying individual (thin lines) and summed (thick lines) probability distributions for erratic ages (blue) and moraine ages with (grey) and without (red) outliers. The age distributions of moraines and erratics are statistically indistinguishable and suggest that deglaciation and local glacier moraine deposition occurred simultaneously within the resolution of our chronology. Distributions were calculated with free MATLAB code from Greg Balco at the University at Washington Cosmogenic Isotope Lab available from http://depts.washington.edu/cosmolab/pubs/gb_pubs/camelplot.m. [Colour figure can be viewed at www.boreas.dk]

abandoned moraines very soon after GrIS retreat from the area.

Discussion

Here we compare our ages of the Nákâgajoq mountain moraines with moraine ages from elsewhere around Greenland. It is difficult to assess whether or not the moraine dated by Alexanderson & Håkansson (2014) in the Umingmak area of East Greenland is correlative to our moraine due to relatively large analytical errors and additional potential geological uncertainty for the samples within their data set. It is possible that the Nákâgajoq mountain moraines are correlative to the nearby Disko Stade moraines in central West Greenland (Ingólfsson *et al.* 1990), but these moraines have yet to be tightly constrained and are currently considered to be 11.9±1.7 ka (Jomelli *et al.* 2016). The average Nákâgajoq mountain moraine age, however, does not appear to correspond to average moraine ages from previous local glacier studies in North or East Greenland (Kelly *et al.* 2008; Möller *et al.* 2010; Alexanderson & Håkansson 2014; Larsen *et al.* 2016; Levy *et al.* 2016).

Similarly, the Nákâgajoq mountain moraine age does not appear to correlate with nearby GrIS moraine chronologies (Young *et al.* 2013a; Cronauer *et al.* 2016). This lack of correlation differs from locations in East Greenland (Levy *et al.* 2016) and Baffin Island (Young *et al.* 2012) where ice-sheet margins and nearby local glaciers appear to have responded synchronously to abrupt climate events in the early Holocene. Potential explanations for a lack of synchronicity in our study area may be that, unlike the Nákâgajoq mountain glaciers, the GrIS retreated without advances/stillstands sufficient to deposit distinct moraine crests throughout much of the Disko Bugt region, with the exception of the Marrait, Tasiussaq and Drygalski moraines. In addition, Disko Bugt was being abandoned around *c.* 10.5 ka (Kelley *et al.* 2013) and thus dynamically modulated ice collapse there may have precluded moraine deposition. It is also possible that ice-sheet moraines mapped in the Torssukátak area are of similar age, but they remain undated. The GrIS Marrait moraine (dated to *c.* 9.3 ka; Young *et al.* 2013a) is mapped near our study area (Fig. 1), but our erratic boulder ^{10}Be ages suggest that the area was ice free a thousand years prior to this time.

Due to peak values in summer insolation during the early Holocene, we do not consider orbital climatic forcing mechanisms as a likely explanation for glacial advance/stillstand of the Nákâgajoq massif glaciers (Fig. 6; Berger & Loutre 1991). Ingólfsson *et al.* (1990) attributed the nearby Disko Stade advance to increased snow drift (i.e. accumulation) on glaciers with eastern aspects on Disko during the early Holocene. Increased accumulation on eastern Disko glaciers was thought to be the result of an upper-air flow regime from the west (as opposed to the modern dominant direction from the south). This change in local climatic conditions was proposed instead of a regional forcing mechanism because of the difference between the large Disko Stade advance in eastern Disko and the lack of a significant advance in western Disko. The Nákâgajoq mountain glaciers would have faced the southeast and, similar to eastern Disko, are located to the east of high topographical areas (>1000 m a.s.l.) that could be affected by changes in upper-air wind conditions. Thus, the Nákâgajoq mountain glaciers may also have experienced increased snow drift (i.e. accumulation) under a westerly dominant air flow and we do not rule this out as an explanation for the advance/stillstand. Another alternative explanation for advance/stillstand at 10.4 ka is increased moisture availability due to lessening sea ice. This potential forcing mechanism is supported by the dinocyst assemblages of a marine core record from the outer Disko Trough, which shows an overall decrease in sea-ice duration from *c.* 11.5 to *c.* 10.5 cal. ka BP (Jennings *et al.* 2014).

Discrete episodes of freshwater input from the melting Laurentide and Eurasian ice sheets has been suggested by numerous studies as a forcing mechanism for regional abrupt climate events in the early Holocene (e.g. Clarke *et al.* 2003; Nesje *et al.* 2004; Alley & Agustsdottir 2005). Specific instances of meltwater-induced cooling events in the early Holocene include

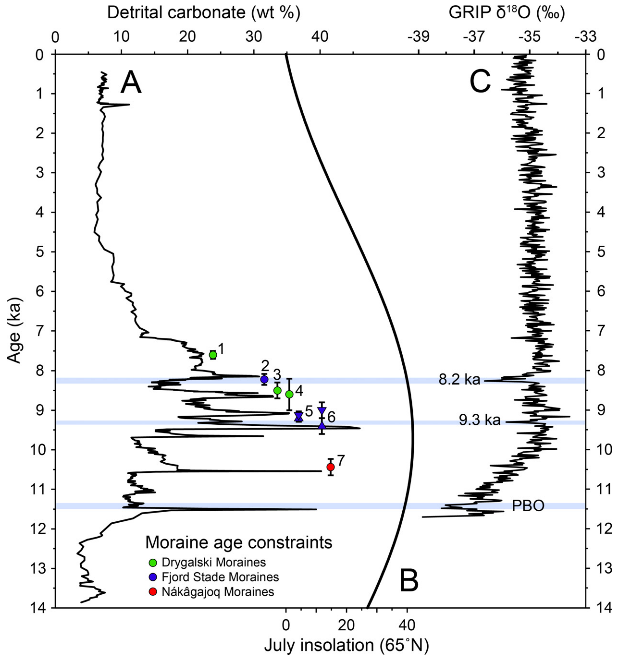

Fig. 6. A. Detrital carbonate record from Jennings *et al.* (2015) with carbonate peaks recording LIS discharge events that may have affected the strength of the sub-polar gyre and be linked to abrupt cooling events in the Northern Hemisphere during the early Holocene. Constraints on moraine records from central West Greenland: 1 = Drygalski Moraine, inner (Cronauer *et al.* 2016); 2 = Tasiussaq Moraine (Young *et al.* 2011a); 3 = Drygalski Moraine, middle (Cronauer *et al.* 2016); 4 = Drygalski Moraine, outer (Cronauer *et al.* 2016); 5 = Marrait Moraine (near Jakobshavn Isbræ; Young *et al.* 2011a); 6 = Marrait Moraine (in southeast Disko Bugt; Young *et al.* 2013a); 7 = Nákâgajoq moraines (this study). B. Northern Hemisphere July insolation values for 65°N (Berger & Loutre 1991). C. $\delta^{18}O$ values from the GRIP core (Fig. 1) with shaded regions denoting the Preboreal Oscillation (PBO), 8.2 ka and 9.3 ka events (Rasmussen *et al.* 2006; Vinther *et al.* 2006). [Colour figure can be viewed at www.boreas.dk]

the Preboreal oscillation (e.g. Fisher *et al.* 2002), the 9.3 ka event (e.g. Fleitmann *et al.* 2008) and the 8.2 ka event (e.g. Alley & Agustsdottir 2005). A number of abrupt peaks in the detrital carbonate content of a recent, high-resolution Labrador shelf marine sediment core are thought to indicate releases of significant volumes of freshwater into the sub-polar gyre from the LIS (Fig. 6; Jennings *et al.* 2015). Hence, it is clear that there have been many early Holocene freshwater events in addition to the ones associated with the previously discussed climate events. The existence of additional early Holocene meltwater pulses is supported by a study that proposed a minimum of 18 Glacial Lake Agassiz flood events during Lateglacial and early Holocene times (Teller & Leverington 2004).

Solomina *et al.* (2015) noted a potential relationship between glacial advances/stillstands and meltwater pulses during the early Holocene. One of the meltwater events (i.e. detrital carbonate peaks) inferred from Jennings *et al.* (2015) is dated to 10.5 cal. ka BP and occurred within error of the Nákâgajoq mountain moraine age (Fig. 6). This connection suggests that the ice advance/stillstand of Nákâgajoq mountain glaciers may be associated with an abrupt cool period triggered by a freshwater pulse at *c.* 10.5 ka. This idea is bolstered by GrIS moraine ages in central West Greenland that also appear to correlate with significant LIS meltwater events (Fig. 6). We speculate that weakening of the sub-polar gyre led to weakening West Greenland Current strength and cooling Baffin Bay due to freshwater events from the LIS. Thus it seems plausible that LIS meltwater events were the main forcing mechanism behind advance/stillstand of ice sheet and local glacier margins in central West Greenland during the early Holocene. Although supported by existing moraine ages in West Greenland and limited early Holocene moraine chronologies from eastern Baffin Island (Young *et al.* 2012), this idea should be tested further with additional moraine chronologies from the Baffin Bay region.

Conclusions

Based on eight new ^{10}Be ages, we conclude that local glaciers of the Nákâgajoq massif deposited moraines at *c.* 10.4 ka, immediately following deglaciation of the GrIS at *c.* 10.5 ka. The Nákâgajoq mountain moraines may be coeval with the nearby Disko Stade moraines, but do not appear to correlate with other local glacier or GrIS fluctuations elsewhere in Greenland. The Nákâgajoq mountain moraine age is consistent with one of a number of proposed LIS discharge events during the early Holocene. This relationship holds for other moraine ages in central West Greenland, supporting speculation that LIS meltwater and associated changes in oceanic circulation acted as the main forcing mechanism behind early Holocene moraine deposition in this area.

We note that additional glacier and palaeoclimate reconstructions are necessary to thoroughly assess potential ice sheet and local glacier synchronicity, as well as the relationship between moraine deposition and LIS freshwater events. GrIS moraine records in central West Greenland reveal ice-sheet margin response to climate excursions like the 9.3 and 8.2 ka events (Young *et al.* 2013a). However, well-constrained local glacier chronologies remain limited in central West Greenland making it difficult to evaluate early Holocene synchronicity between the GrIS and independent local glaciers. In addition, the GrIS deglaciation age suggests that undated GrIS moraines near our study area (currently mapped as the Marrait moraine) are older than previously believed and could be correlative to the Nákâgajoq mountain moraines. Therefore, additional age constraints for both ice sheet and local glacier moraines in central West Greenland will be necessary to (i) assess the potential for ice sheet and local glacier synchronicity, and (ii) further test the link between moraine ages and LIS meltwater events, and thus inform predictions of the future response of local glaciers and the GrIS to climate change.

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