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A Younger Dryas re-advance of local glaciers in north Greenland

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ABSTRACT

The Younger Dryas (YD) is a well-constrained cold event from 12,900 to 11,700 years ago but it remains unclear how the cooling and subsequent abrupt warming recorded in ice cores was translated into ice margin fluctuations in Greenland. Here we present ^{10}Be surface exposure ages from three moraines in front of local glaciers on a 50 km stretch along the north coast of Greenland, facing the Arctic Ocean. Ten ages range from 11.6 ± 0.5 to 27.2 ± 0.9 ka with a mean age of 12.5 ± 0.7 ka after exclusion of two outliers. We consider this to be a minimum age for the abandonment of the moraines. The ages of the moraines are furthermore constrained using Optically Stimulated Luminescence (OSL) dating of epishelf sediments, which were deposited prior to the ice advance that formed the moraines, yielding a maximum age of 12.4 ± 0.6 ka, and bracketing the formation and subsequent abandonment of the moraines to within the interval 11.8–13.0 ka ago. This is the first time a synchronous YD glacier advance and subsequent retreat has been recorded for several independent glaciers in Greenland. In most other areas, there is no evidence for re-advance and glaciers were retreating during YD. We explain the different behaviour of the glaciers in northernmost Greenland as a function of their remoteness from the Atlantic Meridional Overturning Circulation (AMOC), which in other areas has been held responsible for modifying the YD drop in temperatures.

1. Introduction

The Younger Dryas (YD) marks a cold period at the end of the last glaciation, from 12.9 to 11.7 ka ago (Rasmussen et al., 2006). In spite of rising insolation during the YD, temperatures dropped, probably because the Atlantic Meridional Overturning Circulation (AMOC) was reduced or even shut down by large amounts of meltwater running off the melting ice sheets (Broecker et al., 1989; Denton et al., 2005; Carlson, 2013). The YD is especially pronounced in areas bordering the North Atlantic, and nowhere is it seen more clearly than in ice cores from the top of the Greenland ice sheet where the oscillation began with a c. 6 °C drop in temperatures over a period of 200 years, and ended with an abrupt rise of c. 10 °C over a period of only 60 years (Steffensen et al., 2008; Buizert et al., 2014). Knowledge about how these abrupt climate changes are translated into ice marginal behaviour along the Greenland ice sheet is of importance for evaluating the impact of future warming on the ice margin.

Here we present new evidence of a YD advance and subsequent retreat by three outlet glaciers from the North Cap, the local ice cap over the North Greenland mountain range (Fig. 1). The maximum positions of this advance in respective valley are marked by prominent terminal moraines, which ages are determined by new and previously published surface exposure ages, combined with previously published Optically Stimulated Luminescence (OSL) ages. We furthermore discuss the implications of our findings in the view of previous studies on the YD ice margin behaviour in other parts of Greenland.

2. Study area

The north coast of Greenland represents the land area closest to

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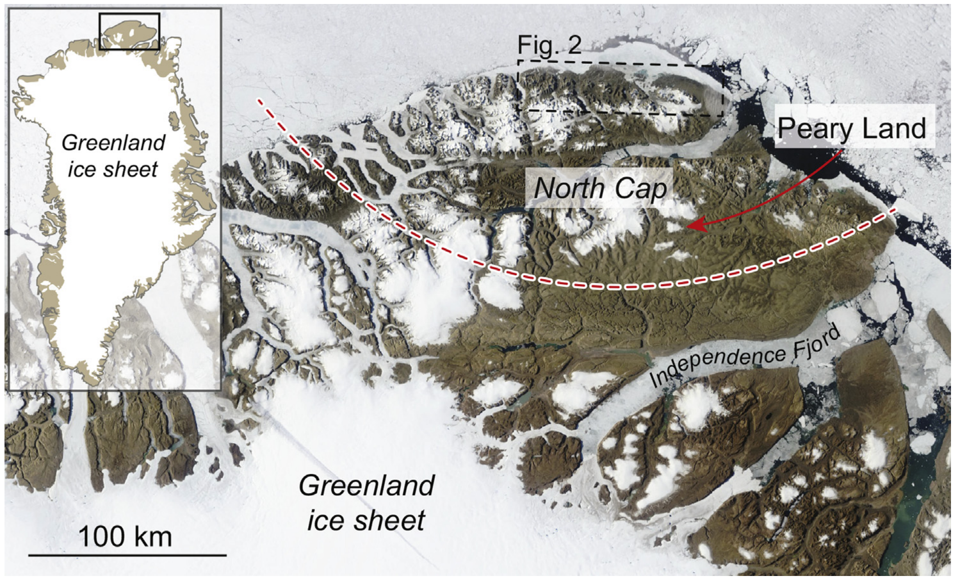

Fig. 1. Overview of North Greenland. Dashed line defines the boundary between the Greenland ice sheet and the independent North Cap (Koch, 1923).

the North Pole. It comprises a 10–15 km wide coastal plain, bordered to the south by 500–1500 m high mountains. The coastal plain and connected valleys impinging into the mountain range southwards, host landforms and sediments recording glacial and marine events since the Last Glacial Maximum (LGM) in Greenland (Larsen et al., 2010). Based on the distribution of erratic boulders it was established that a local ice cap, the North Cap, developed over the mountain range in Peary Land during LGM, which to the south and southeast merged with the Greenland ice sheet (Koch, 1923; Dawes, 1986; Funder, 1989). On the coastal plain, erratics, till fabric measurements, and striations show that the outlet glaciers from the local ice caps merged with the Greenland ice sheet to form shelf-based ice in the Arctic Ocean that was deflected eastwards along the coast (Funder and Larsen, 1982; Dawes, 1986; Larsen et al., 2010; Jakobsson et al., 2014). The deflection of the glaciers was most likely a result of buttressing by thick multiyear (palaeocrystic) sea ice in the Arctic Ocean (Bradley and England, 2008), which forced the local glaciers from Peary Land to flow along the coast (Larsen et al., 2010; Jakobsson et al., 2014). During the initial deglaciation large epishelf lakes were formed between the shelf-based ice and the mountains (Larsen et al., 2010; Möller et al., 2010). In these lakes, thick successions of laminated glaciolacustrine sediments were deposited on the coastal plain and in Sifs valley up to an elevation of 110 m a.s.l. (Figs. 2–3). OSL ages of the epishelf lake sediments ranged from 135 to 12.4 ka and the large spread suggests that they were differently affected by incomplete bleaching, with the youngest age serving as a maximum age for the deposition of the glaciolacustrine sediments (Larsen et al., 2010; Möller et al., 2010). During the final break-up of the shelf-based ice at ~10.1 cal ka BP the coastal plain and the major valleys were inundated and marine sediments were deposited up to 40 m a.s.l. (Möller et al., 2010; Funder et al., 2011a). The isostatic uplift of the coastal plain following the deglaciation left a succession of beach ridges with driftwood that was used to constrain the Holocene sea ice history in the Arctic Ocean (Funder et al., 2011a). Following the deglaciation the local glaciers re-advanced through all major valleys along the coast and formed major terminal moraines on the coastal plain. Previously one of these moraines (Constable Bugt) was dated to between 9.6 and 6.3 cal ka BP and there was further evidence of a second re-advance in Sifs Valley between 5.5 and 5.0 cal ka BP (Möller et al., 2010). The two Holocene re-advances were linked to increased precipitation caused by more open water conditions in the Artic Ocean during the warm Holocene Thermal Maximum. Our new results indicate that the moraine originated earlier, during the YD.

3. Methods

Ten samples from three terminal moraines on the coastal plain at Henson Bugt, Constable Bugt and Bliss Bugt were collected for surface exposure dating in this study (Fig. 2). Eight boulders were sampled using hammer and chisel, as well as a rock drill. The sampled boulder lithologies are meta-sandstone and quartz (Table 1). Two amalgamated pebble samples were collected from the sediment surface; rounded milky quartz pebbles were collected in sample bags in the field and split into uniform size categories (uniform a, b, c axis) before crushing. Sample locations and elevations were recorded in the field with a hand-held GPS. Clinometer measurements were taken for each sample for determination of the site-specific topographic shielding. Sample thickness was noted in the field (checked before crushing), as well as observations with regard to potential weathering loss (e.g. surface roughness, ventifacts, differential weathering, striae) and snow shielding (e.g. geomorphology, snow patch distribution, lichen distribution and type).

3.1. ^{10}Be sample preparation and ^{10}Be age calculation

All rock samples were crushed at the Swedish Museum of Natural History (Stockholm), and processed at the School of Geographical and Earth Sciences (University of Glasgow). The 0.25–0.5 mm fraction from crushing and pulverizing was enriched with respect to quartz by treatment with HCl/HNO_3, magnetic separation, and H_3PO_4. Purification of the quartz fraction was done by successive HF/HNO_3 leaches, and purity (i.e. [Al] < 100 μg/g) was assessed by measuring the Al concentration using flame atomic absorption spectrometry (AAS) and inductively coupled plasma optical emission spectrometry (ICP-OES).

Preparation of samples for Be measurement was done at the Glasgow University – Scottish Universities Environmental Research Centre (GU – SUERC) Cosmogenic Isotope Laboratory, following procedures modified from Child et al. (2000). After carrier addition (see Table 1 for amounts and concentrations), clean quartz

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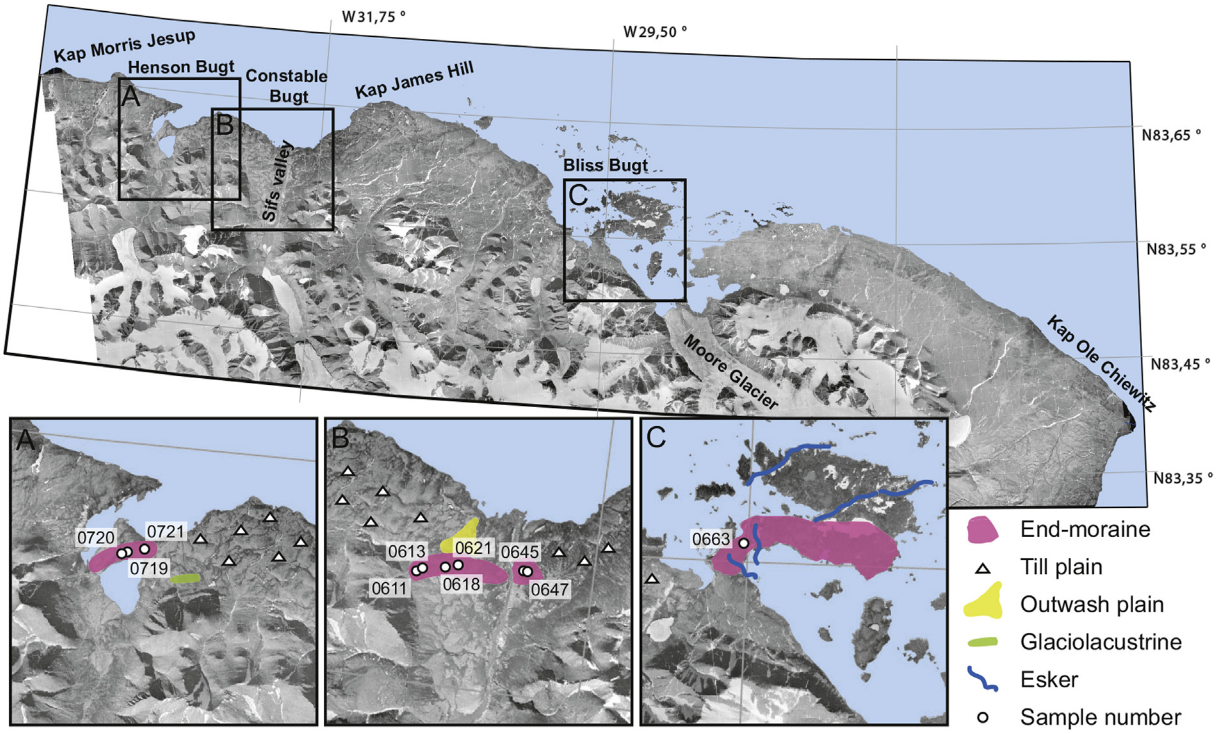

Fig. 2. North coast of Greenland with location names mentioned in the text. The inset geomorphological maps show the ^{10}Be sample sites on the moraines at A) Henson Bugt, B) Constable Bugt and C) Bliss Bugt (modified from Larsen et al., 2010).

(11–27 g) was dissolved in 40% HF. Be was extracted from solution by anion and cation exchange, precipitated as $Be(OH)_2$, dried and oxidized to BeO. AMS targets were made by mixing BeO and Nb (1:6) and pressing this into cathodes. The ^{10}Be/^{9}Be of these targets were measured at the SUERC AMS facility (Xu et al., 2010), and normalised to a nominal value of NIST SRM 4325 of 3.06×10^{-11}. Samples were prepared and measured between 2007 and 2013. Corresponding process blanks gave ^{10}Be/^{9}Be ratios between 1.7 and 6.1×10^{-15} (see Table 1 for sample/blank ratios and uncertainties). The calculated ^{10}Be concentrations have 1σ analytical errors between 3.4 and 6.0%.

The CRONUS-Earth online calculator was used to estimate surface exposure ages from the calculated ^{10}Be concentrations (Balco et al., 2008). We report exposure ages ($\pm 1\sigma$, Table 1) calculated according to the St scaling scheme using the Arctic ^{10}Be production rate from Young et al. (2013b) (spallation-induced production rate of 3.93 ± 0.15 atoms g^{-1} a^{-1}, CRONUS-Earth; Alternate calibration data sets, Wrapper script 2.2, Main calculator 2.1, constants 2.2.1, muons 1.1) (Balco et al., 2008). The Arctic production rate is appropriate because of its geographic coverage and because the calibration data set extends back to ca. 16 ka. The analytical uncertainties are used when comparing results internally (i.e. ^{10}Be data only), whereas the systematic uncertainty (parentheses, last column, Table 1) should be used when comparing the results with ages obtained using different cosmogenic nuclides or independent dating methods.

No correction for erosion, snow cover or landform degradation has been applied, but this does not mean that these factors are irrelevant – just hard to constrain. Erosion is very lithology specific, ranging from close to zero (amorphous quartz pebbles), granular weathering (meta-sandstones), to random loss of pieces (quartz veins/lenses). Snow cover can potentially be present most of the year, but no data on duration, thickness and density is available. Landform degradation encompasses several processes, such as wind deflation (evident from pebble lags) and freeze–thaw activity (polygonal cracking patterns, ice-wedge polygons and patterned ground), transforming the ridges from their initial unknown geometry to the present-day gently sloping features.

4. Results

4.1. Henson Bugt

In Henson Bugt, a large terminal moraine is located ~10 km from the present ice margin of a local glacier draining a small ice cap (Fig. 2). The ~30–40 m high and ~600 m wide moraine displays occasional large boulders of which three were sampled for surface exposure dating (Fig. 4). The small diameter of lichens on the boulder surfaces suggests an age of only 100 years (E.S. Hansen, pers.com.). However, the 'lichen-kill' effect of semi-permanent snowbeds in the recent past (Lévesque and Svoboda, 1999; Matthews, 2005) would hamper the applicability of lichenometric dating. Three boulder samples (PEA 0719, 0720, 0721) yield ^{10}Be surface exposure ages of 12.5 ± 0.6, 13.5 ± 0.7, and 12.4 ± 0.6 ka (Table 1, Fig. 3), revealing statistically indistinguishable ages, allowing a mean arithmetic age of 12.8 ± 0.8 ka to be calculated.

4.2. Constable Bugt

In Constable Bugt, a ~60–100 m high and ~1 km wide terminal moraine blocks the entrance to Sifs Valley (Figs. 2 and 5). The moraine, located ~17 km from the present valley glacier margin, has a core composed of diamict and, in addition to this, glaciotectonically up-thrusted fine-grained glaciolacustrine sediments on its proximal part (Möller et al., 2010). Six processed samples (PEA 0611, 0613, 0618, 0621, 0645, 0647) range from 11.6 ± 0.5 to 27.2 ± 0.9 ka (Table 1, Fig. 3). From its stable setting, cobble on bedrock, sample PEA 0647 is expected to provide the most reliable ^{10}Be surface

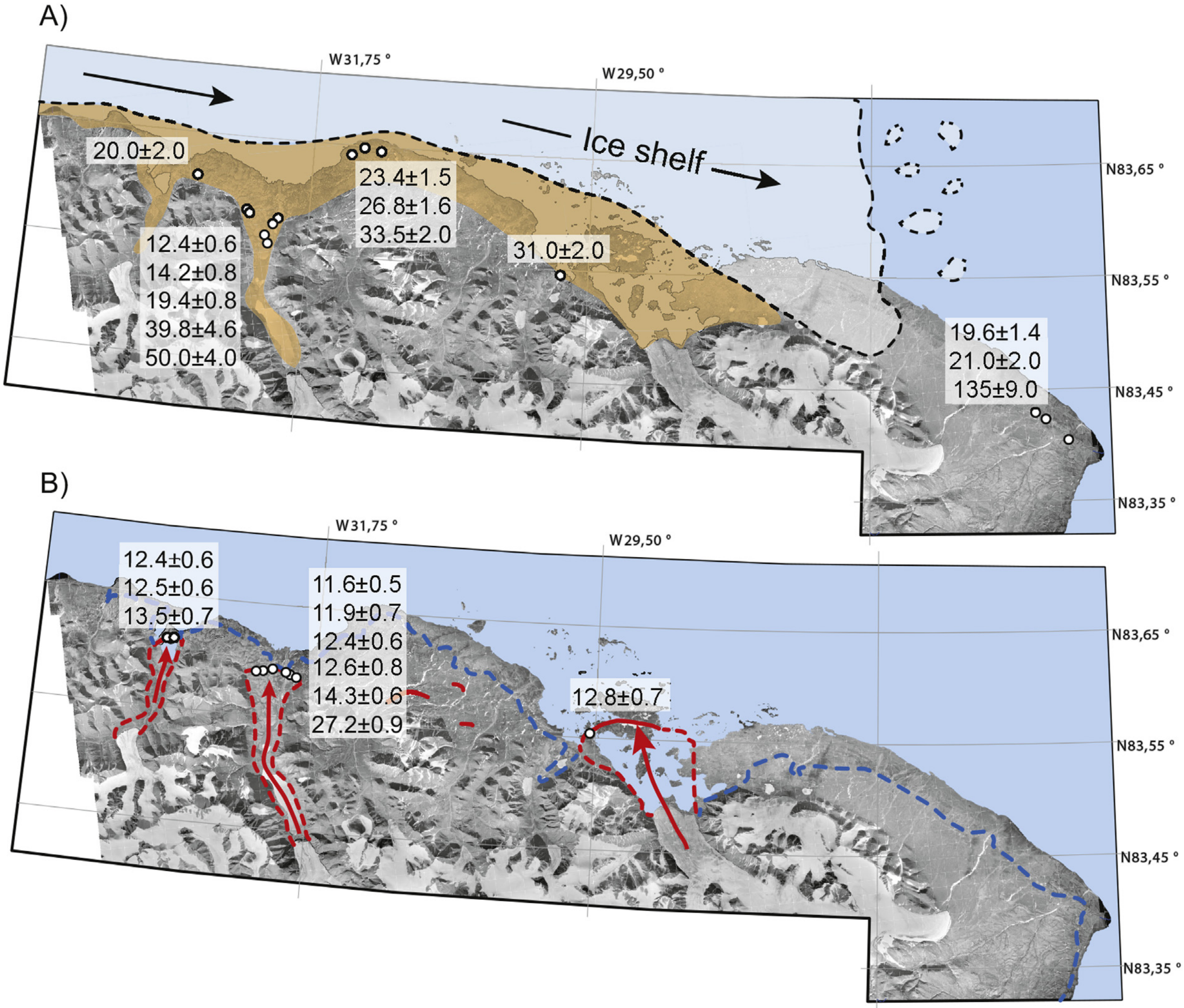

Fig. 3. (A) OSL ages (ka) of glaciolacustrine sediments (orange) deposited in late glacial epishelf lakes between the shelf-based ice (hatched) and the mountains (Larsen et al., 2010; Möller et al., 2010). Note incomplete bleaching causes the large spread of ages and the youngest age is likely the most reliable. (B) ^{10}Be surface exposure ages (ka) of boulders on terminal moraines in Henson Bugt, Constable Bugt and Bliss Bugt (red). Blue stippled line marks the highest marine level on the north coast, c. 40 m a.s.l. (Möller et al., 2010). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

exposure age (assuming no inheritance), and this cobble gives 12.6 ± 0.7 ka. Samples PEA 0613, 0618, 0645 and 0647 yield statistically indistinguishable ages, resulting in an arithmetic mean age of 12.1 ± 0.6 ka for the moraine ridge. The two older ^{10}Be surface exposure ages can likely be explained by inheritance. Occasional boulders showing inheritance are to be expected, however, the amalgamated pebble sample (PEA 0611) yields the oldest age, suggesting that the re-worked material comprising the moraine has a complex exposure history prior to moraine ridge formation.

4.3. Bliss Bugt

In Bliss Bugt a ~10–30 m high moraine is located ~8 km from the present ice margin of Moore Glacier (Fig. 2). The surface consists of sorted coarse-grained sediments with few scattered boulders (Fig. 6). One amalgamated sample of surface pebbles from the sediment ridge gives a ^{10}Be surface exposure age of 12.8 ± 0.7 ka (Table 1, Fig. 3). This sample was included in the study by Möller et al. (2010), but because its ^{10}Be surface exposure age was considered to be an outlier (significantly older than the data set from Bliss Bugt at that time), no conclusions were drawn. However, since the age overlaps with the new ^{10}Be data from the moraine ridges at Constable Bugt and Henson Bugt we find it to be reliable.

5. Discussion

5.1. Younger Dryas moraines in north Greenland

In total, we dated eight boulders and two amalgamated pebble samples from the moraines on the north coast of Greenland. Two samples are significantly older than the rest and considered as outliers, suffering from inheritance. However, the consistent ages of the majority of samples suggest that inheritance is not a significant problem; otherwise a more scattered age distribution would have been expected, such as noted for erratics on moraines in Scoresby Sund (Kelly et al., 2008). We attempted to minimize the post-depositional effects by sampling the largest boulders on the flat surface of the moraine crests at Henson Bugt and Constable Bugt. Long-term moraine degradation also plays an insignificant role in West Greenland where the Fjord Stade moraines were precisely dated to 9.3 and 8.2 ka by ^{10}Be measurements, controlled by threshold lake records (Young et al., 2011, 2013a). These

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Table 1
Summary of ^{10}Be sample information for rock samples from northernmost Greenland (bold numbers indicate assumed reliable ages, numbers in italics indicate mean ages).

Sample[a]	Elevation (m asl)	Sample type	Lithology	Latitude (°N)	Longitude (°W)	Shielding factor[b]	Thickness[c] (cm) (factor)	Quartz[d] (g)	Be carrier[e] (g)	^{10}Be/^{9}Be[f,g] ($\times10^{-15}$)	^{10}Be/^{9}Be blanks[h] ($\times10^{-15}$)	^{10}Be conc.[i] (10^4 at g^{-1} SiO_2)	^{10}Be age[j,k] (ka)
Constable Bugt − terminal moraine ridge													
PEA 0611	130	pebbles (n = 20)	quartz	83.5877	32.2603	0.9963	2.0 (0.9836)	23.303	0.1264*1	231.16 ± 6.16	1.71 ± 0.70	13.84 ± 0.47	27.16 ± 0.93 (1.40)
PEA 0613	123	boulder	meta-sandstone	83.5879	32.2360	0.9975	3.0 (0.9756)	17.200	0.2256*2	73.90 ± 2.30	6.10 ± 0.84	5.83 ± 0.27	**11.56 ± 0.53 (0.69)**
PEA 0618#	86	boulder	meta-sandstone	83.5880	32.1679	0.9986	3.8 (0.9696)	16.499	0.8722*3	60.51 ± 2.14	4.50 ± 0.79	5.94 ± 0.30	**12.35 ± 0.63 (0.79)**
PEA 0621	82	boulder	quartz	83.5890	32.1396	0.9993	3.5 (0.9716)	27.288	0.1273*1	133.65 ± 4.77	1.71 ± 0.70	6.84 ± 0.29	14.27 ± 0.61 (0.82)
PEA 0645#	112	boulder	meta-sandstone	83.5945	31.8538	0.9996	3.5 (0.9716)	22.843	0.8262*3	86.35 ± 4.13	4.50 ± 0.79	5.93 ± 0.34	**11.94 ± 0.69 (0.83)**
PEA 0647#	112	cobble on bedrock	meta-sandstone	83.5944	31.8555	0.9996	6.0 (0.9519)	10.762	0.8250*3	44.45 ± 1.70	4.50 ± 0.79	6.14 ± 0.37	**12.60 ± 0.76 (0.90)**
												arithmetic mean (n = 4):	***12.11 ± 0.64***
Henson Bugt - terminal moraine ridge													
PEA 0719	34	boulder	quartz	83.6142	32.9454	0.9989	5.0 (0.9597)	22.517	0.1272*1	90.61 ± 3.69	1.71 ± 0.70	5.58 ± 0.27	**12.46 ± 0.61 (0.77)**
PEA 0720	34	boulder	quartz	83.6136	32.9428	0.9988	2.0 (0.9836)	23.239	0.1272*1	103.40 ± 4.40	1.71 ± 0.70	6.19 ± 0.31	**13.50 ± 0.67 (0.85)**
PEA 0721	37	boulder	quartz	83.6135	32.9113	0.9986	4.0 (0.9676)	22.227	0.1273*1	90.12 ± 3.74	1.71 ± 0.70	5.63 ± 0.28	**12.43 ± 0.62 (0.78)**
												arithmetic mean (n = 3):	***12.80 ± 0.77***
Bliss Bugt - terminal moraine ridge													
PEA 0663#	23	pebbles (n = 20)	quartz	83.5617	29.4832	0.9999	1.0 (0.9918)	18.655	0.8309*4	70.40 ± 3.03	4.66 ± 0.90	5.85 ± 0.33	**12.80 ± 0.72 (0.87)**
All moraines												***arithmetic mean (n = 8):***	***12.46 ± 0.73***

[#] Samples included in Möller et al. (2010) and recalculated in this study.
[a] All samples processed and measured at SUERC.
[b] Geometric shielding correction was computed after Dunne et al. (1999).
[c] Sample thickness measured from the surface, correction factor calculated assuming an exponential reduction in ^{10}Be production rate with depth (Gosse and Phillips, 2001; Balco et al., 2008).
[d] All samples use a density value of 2.65 g cm^{-3}.
[e] Carrier concentrations:*1(1664.175 mg g^{-1}),*2 (980.39 mg g^{-1}),*3 (300.0 mg g^{-1}),*4 (299.0 mg g^{-1}).
[f] Isotope rations normalised to the NIST SRM 4325 ^{10}Be standard with a nominal value of ^{10}Be/^{9}Be = 3.06×10^{-11}.
[g] Uncertainties are reported at the 1σ confidence level.
[h] Procedural blank values used to correct for background.
[i] Propagated uncertainties include error in the blank and counting statistics.
[j] 10Be surface exposure ages and corresponding analytical uncertainties calculated using the CRONUS-Earth online calculator (Balco et al., 2008) version 2.2, assuming no atmospheric pressure anomalies (std model), no significant denudation during exposure (e = 0 mm a-1), no prior exposure, and no temporal shielding (snow, sediment, vegetation).
[k] Ages calculated using the Arctic ^{10}Be production rate of Young et al. (2013b). Propagated errors in the calculated ages include uncertainties of the ^{10}Be production rate and of the ^{10}Be decay constant. Errors in parenthesis are the systematic uncertainties.

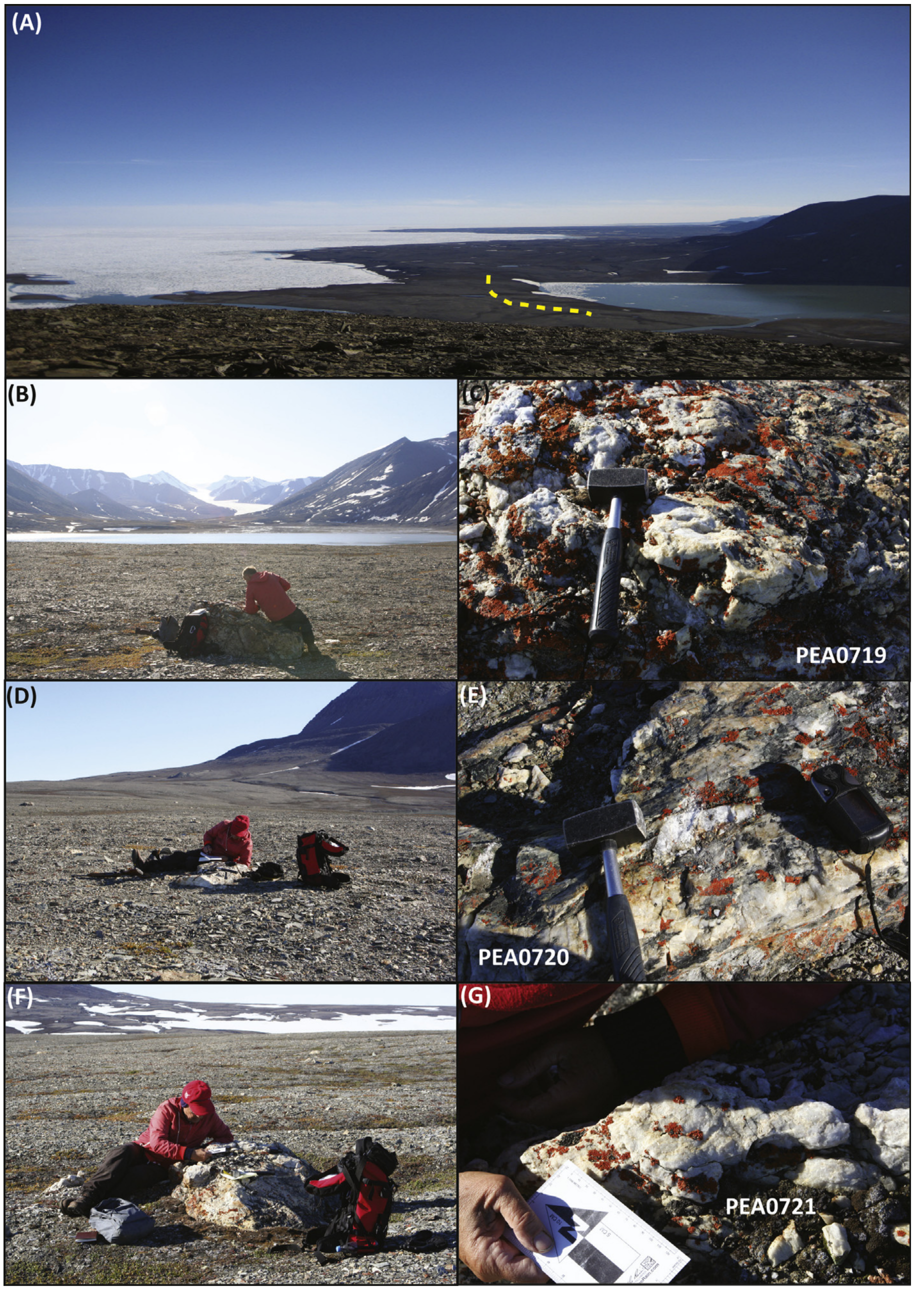

Fig. 4. (A) View from the west of the terminal moraine in Henson Bugt. Dashed yellow line indicates the location of the sampled boulders. (B) Setting of boulder and (C) surface of boulder from which sample PEA 0719 was collected. (D) Setting of boulder and (E) surface of boulder from which sample PEA0720 was collected. (F) Setting of boulder and (G) surface of boulder from which sample PEA 0721 was collected. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

uncertainties, in addition to other processes such as shielding by long lasting snow cover, moraine degradation where boulders are slowly exhumed until the moraine stabilizes, or because of dead-ice melting (Heyman et al., 2011; Houmark-Nielsen et al., 2012), have the potentials of making the ages too young. We therefore treat all ages as minimum ages. Accordingly, we calculate an arithmetic mean minimum age of 12.5 ± 0.7 ka (n = 8), excluding the two outliers mentioned above (Fig. 7).

Clearly, our new ^{10}Be results yielding a YD age of the moraines seems incompatible with our previous interpretation which suggests an age between 9.6 and 6.3 cal ka BP (Möller et al., 2010). However, the two interpretations are not necessarily mutually exclusive. The consistency of ^{10}Be ages on three independent moraines along 50 km of coast is very compelling. So is also the radiocarbon age (~10.3 cal ka BP) of the glaciotectonically up-thrusted sediments on the proximal side of the moraine in Constable Bugt (site CB0705; Fig. 5 in Möller et al., 2010), suggesting a younger age for this part of the moraine. With the new ^{10}Be ages along the major part of the Constable Bugt moraine, we suggest that its core was formed during the YD advance, while the up-thrusted sediments on its proximal side are related to a younger re-advance between 9.6 and 6.3 cal ka BP (Fig. 8). Given that the coastal plain was inundated 10.1 cal ka BP, following the break-up of the ice on the shelf, marine sediments were deposited on the distal part of the moraine up to 40 m a.s.l. in Constable Bugt. Thus, the surficial diamict with molluscs (~10.1 and 9.6 cal ka BP) located

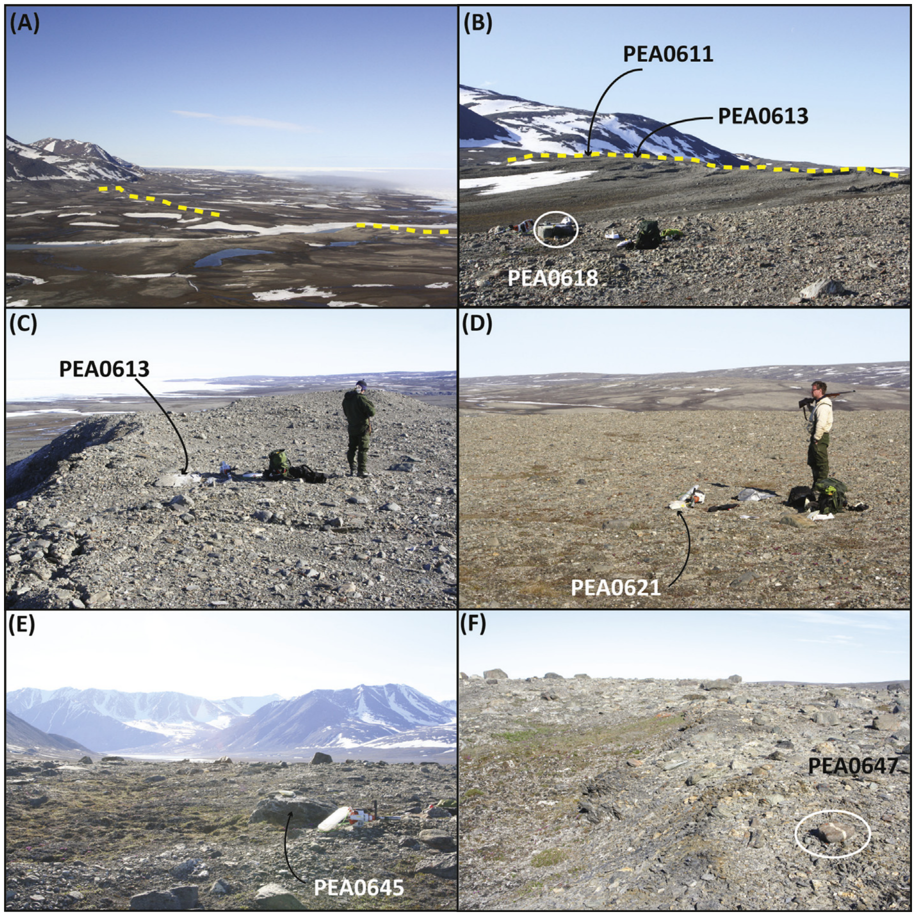

Fig. 5. (A) View from the east of the terminal moraine at Constable Bugt. Dashed yellow line follows the crest of main ridge west and east of Sifs River. (B) Boulder on the proximal slope of the western part of the moraine ridge from which sample PEA0618 was collected. Rock drill to the left of the boulder is for scale. Approximate locations of samples PEA 0611 and PEA 0613 are indicated. (C) Close-up of the location of the low and flat boulder surface from which sample PEA 0613 was collected. (D) Wide, flat part of the terminal moraine with a small quartz boulder from which sample PEA 0621 was collected. (E) Sample PEA0645 was collected from a boulder protruding from the till on the eastern part of the moraine ridge, rock drill for scale. (F) Flat cobble (6 cm thick) on exposed bedrock on the eastern part of the moraine ridge, collected and processed as sample PEA 0647. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

below the marine limit (site CB0706; Fig. 5 in Möller et al., 2010) is re-interpreted. We thus suggest it represents a marine drop till or, more likely, a young solifluction lobe with diamictized marine sediment on the distal part of the moraine, rather than being glacially remoulded marine sediment from the interior of Sifs valley at terminal moraine formation, as suggested by Möller et al. (2010).

We can furthermore constrain the age of moraines by re-evaluating the retrieved OSL ages of the epishelf sediments, deposited during the break-up of the LGM shelf-based ice and before the moraines were formed (Larsen et al., 2010; Möller et al., 2010). The large spread of older OSL ages, from 135 to as young as 12.4 ka, with the youngest ages likely a maximum age interval for the formation of the moraines as discussed above (Figs. 3 and 7). Besides giving a lower age constrain for the moraine, the presence of epishelf sediments in Sifs valley furthermore demonstrates that the glacier advanced to the moraine from up-valley, *i.e.* the moraine was not formed by still-stand during stepwise deglaciation.

In summary, the age of the moraines are bracketed by the minimum limiting ^{10}Be surface exposure ages of 12.5 ± 0.7 and the maximum limiting OSL age of 12.4 ± 0.6 ka, implying that the moraines were formed and abandoned within an age interval of 11.8–13.0 ka. The ^{10}Be surface exposure ages are derived from three terminal moraines formed by independent glaciers over a distance of 50 km. This indicates that the glaciers advanced as a response to external climate forcing rather than local topography or surging, and we conclude that the moraines formed during an advance in response to the YD cooling. However, the large uncertainties both in surface exposure and OSL ages preclude an assessment of the duration of moraine formation, and its more precise age within the YD.

5.2. *Younger Dryas ice margin fluctuations in Greenland*

In other parts of Greenland the ice margin response to the YD cooling is more ambiguous. This is seen from recent ^{10}Be surface exposure dating of moraines and detailed seismic studies on the shelf, accompanied by AMS ^{14}C-dated marine cores (Fig. 9). Below is a brief review of the evidence and the climatic background given by the authors.

5.2.1. *East Greenland*

In the East Greenland Fjord Zone, between 70° and 77°N, a belt of moraines - the Milne Land moraines - were formed by outlet glaciers from the ice sheet at the mouths of all major fjords (Fig. 9). The moraines occur in swarms forming a generally 5–10 km but up to 25 km wide belt. Distinct weathering limits between the outer moraines and the terrain distal to them and also their impressive dimensions – probably the highest and longest moraine ridges in Greenland – suggest that the moraine formation began with a re-advance after a period when the glaciers had been farther back in

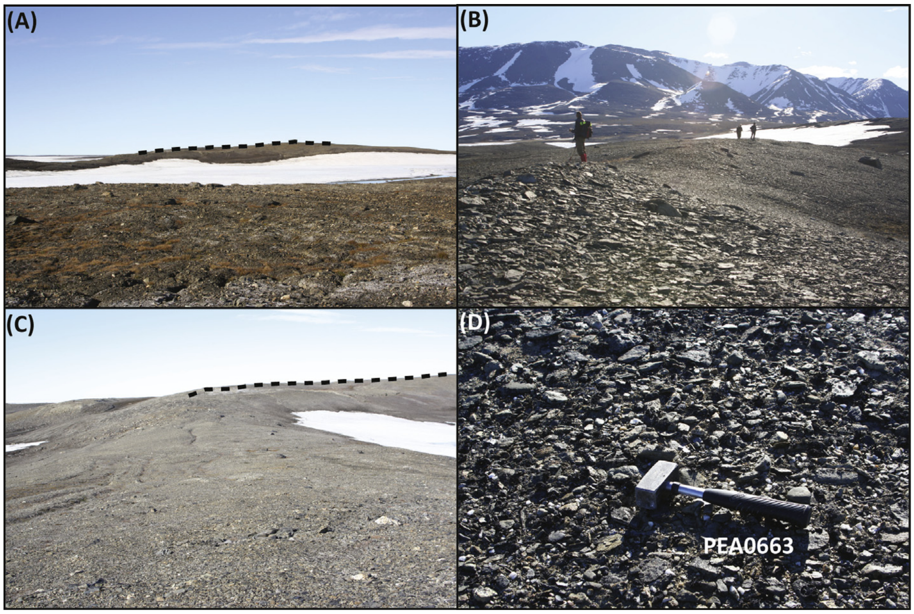

Fig. 6. (A) View from the southeast of the western part of the terminal moraine ridge at outer Bliss Bugt. Dashed black line follows the crest of the ridge. (B) View to the south along the ridge. (C) View to the north along the ridge. The dashed line outlines the same part of the ridge as (A). (D) Sample PEA0663 consisted of 20 quartz pebbles collected around the hammer.

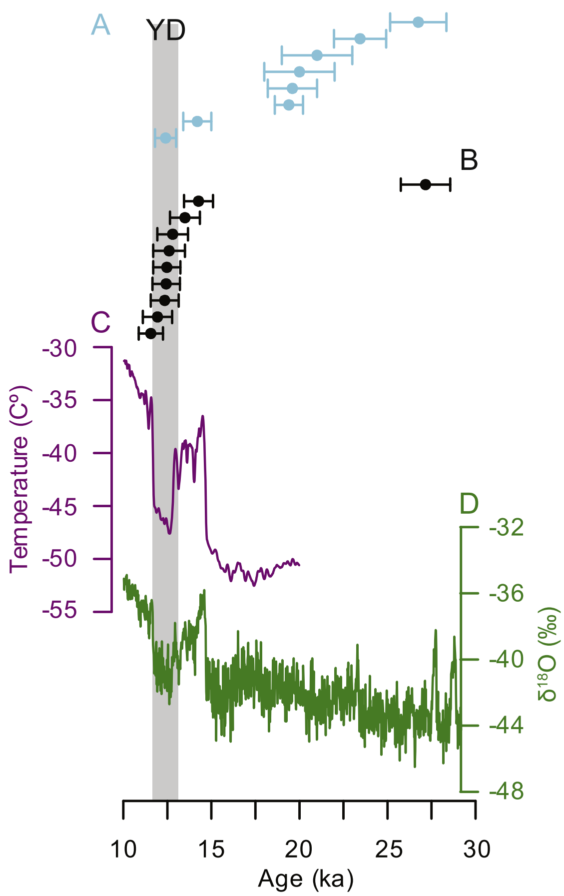

Fig. 7. Comparison of the moraine ages with Greenland ice core climate records. The age of the moraines are bracketed by the (A) maximum limiting OSL ages and (B) minimum limiting ^{10}Be ages. Note that the three oldest OSL have not been plotted. (C) δ^{15}N based temperature reconstruction (average of NEEM, GISP2 and NGRIP reconstructions) (Buizert et al., 2014) and (D) δ^{18}O record from NGRIP showing an abrupt onset and termination of the Younger Dryas (Steffensen et al., 2008).

the fjords (Hjort, 1981; Funder, 1989; Landvik, 1994). In support of this, marine cores from the outer fjord area of Scoresby Sund may indicate that, this part of the fjord was deglaciated already during the Allerød (Marienfeld, 1992; Dowdeswell et al., 1994; Funder et al., 1998). Cessation of ice rafted debris (IRD) deposition on the shelf along the fjord zone during the Bølling (c. 13.8 ka cal. BP), suggests that, by this time, the major outlet glaciers had retreated from the inner shelf and terminated in the fjords where a large part of their IRD was trapped (Stein et al., 1993; Funder et al., 1998). Concordantly, this evidence suggests that the outer Milne Land moraines were formed during re-advance or a long lasting still stand, and not as a step during deglaciation.

Results from radiocarbon dating of marine shells associated with the Milne Land moraines indicate that, in the entire region, the belt of moraines was abandoned and rapid deglaciation begun by the end of the Preboreal Oscillation (11.3–11.15 ka cal. BP) (Björck et al., 1997). Both in Scoresby Sund and on Hochstetter Forland, 500 km to the north, the moraine formation was accompanied by a fall of 30–40 m in relative sea level from the outer to the inner moraine, suggesting that they were formed during a protracted period of time (Funder, 1978; Hjort and Björck, 1984; Hall et al.,

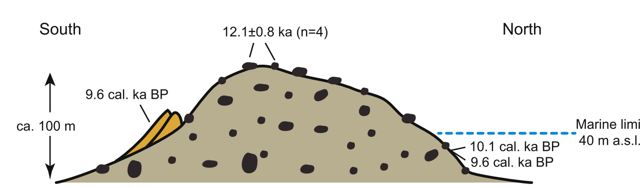

Fig. 8. The terminal moraine in Constable Bugt and the associated reworked organic remains in the up-thrusted glaciolacustrine silt (orange) on the proximal side and marine molluscs in diamict on the distal side of the moraine, used to constrain the age of the moraine. On top of the moraine are the new cosmogenic exposure ages from Constable Bugt. In the present interpretation the moraine was formed during the Younger Dryas and the up-thrusted sediment on the distal side are related to a younger re-advance 9.6 to 6.3 cal ka BP. The marine molluscs in the surfical diamict are interpreted as, by solifluction processes, redeposited marine sediments (see text for further discussion). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

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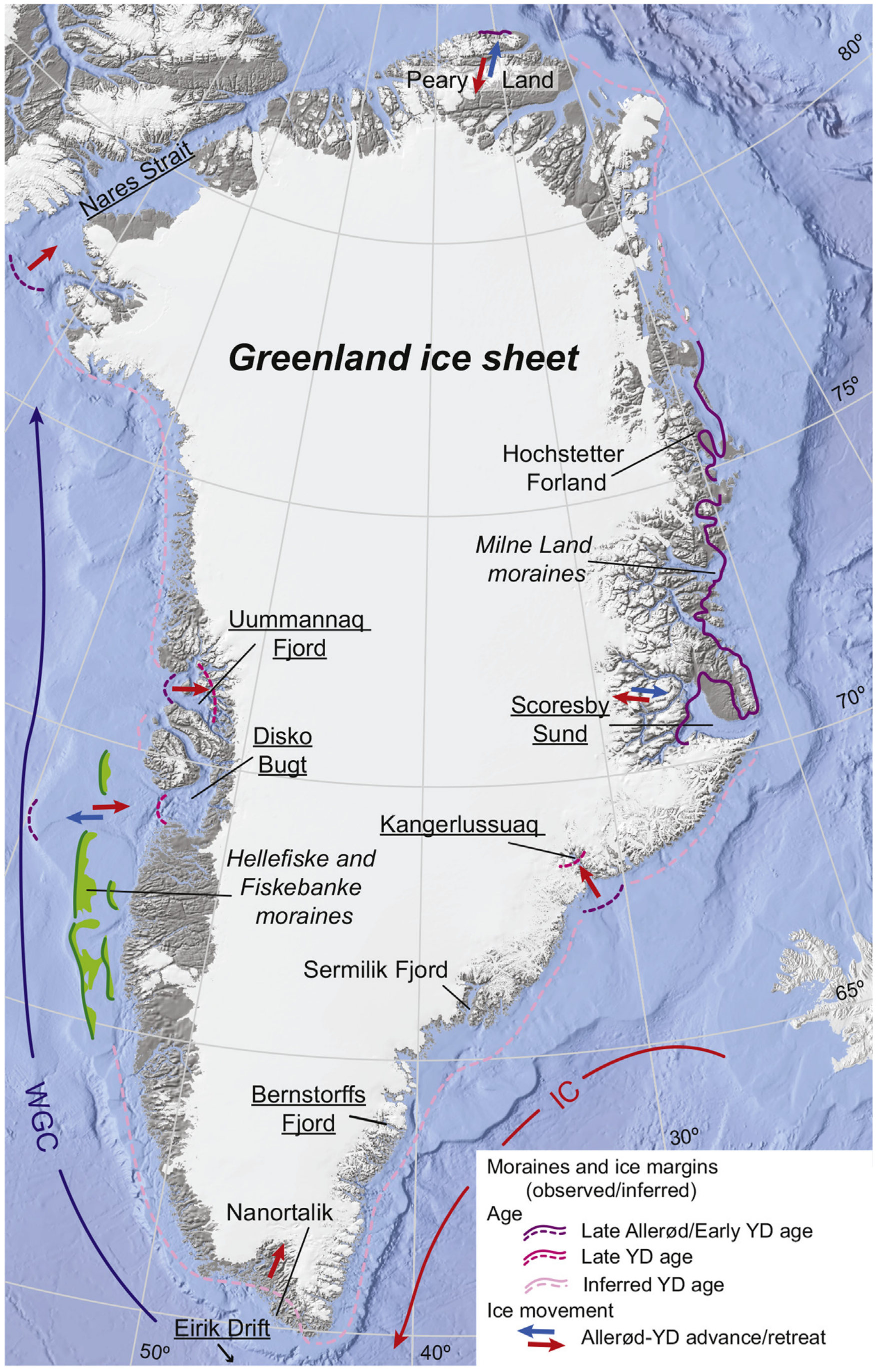

Fig. 9. Compilation of observed and inferred Younger Dryas ice marginal positions in Greenland (see main text for data source). Underlined place names refer to the marine coring sites mentioned in the text.

2010). This has later been confirmed by an extensive data set comprising both ^{10}Be exposure and AMS ^{14}C ages from the moraines in Scoresby Sund. These data indicate that the advance of the region's largest outlet glacier most likely culminated in late Allerød times (>12.9 ka cal. BP), and that moraine formation ceased at 11–11.2 ka cal. BP (Hall et al., 2008). ^{10}Be surface exposure dating of erratic boulders on moraines from a local ice cap, correlated with the Milne Land moraines, gives a slightly older age for the period, from 13 to 11.6 ka (Kelly et al., 2008).

Unfortunately the time resolution of the dating prevents conclusions about the character of the retreat from the oldest moraines - whether it was gradual or punctuated by significant re-advance, or possibly even consisted of only two distinct re-advances – one in late Allerød times and the other in the late Preboreal, because no moraines have been directly dated to YD, neither in Scoresby Sund, nor in more northerly areas. Hjort and Björck (1984) suggested that the moraines on Hochstetter Forland were separated by an ice free interval, followed by a re-advance, and Denton et al. (2005) and Hall et al. (2010) suggested that the Preboreal re-advance could have obliterated the missing moraines from late YD. Still, even though no moraines have been dated to the YD, it is a reasonable assumption that the glacier fronts were located within the zone of the Milne Land moraines during the YD, and could be represented by undated moraines between the outer and inner Milne Land moraines. This would imply that the YD here was a period of oscillatory retreat within a narrow a zone.

Denton et al. (2005) noticed a mismatch between the YD temperatures deduced from moraine altitudes and those derived from borehole temperatures in nearby ice cores. It was suggested that while the borehole temperatures record mean annual temperature, the equilibrium-line altitudes deduced from moraines, mainly reflect summer temperatures. This implies that the YD temperature drop was mainly a winter phenomenon with little effect on the ice margin. This increase in seasonality was seen as a result of a reduction in the AMOC, which led to increased sea ice and reduced inflow of advective heat to the North Atlantic (Denton et al., 2005).

In contrast to this, in the Kangerlussuaq area to the south (c. 67°N), both shelf and fjord experienced large-scale retreat of the ice sheet margin in the YD (Fig. 9). This was shown by the occurrence of light isotopes in foraminifer shells from marine sediments on the shelf, as well as onset of IRD deposition during YD, which indicate a large supply of meltwater and break-up of the ice sheet margin (Jennings et al., 2006). A “major construction feature” c. 50 km off the coast could be a YD terminal moraine (Andrews et al., 1997), and is the only possible indication of re-advance during or before YD. It was suggested that the massive retreat was caused by advection of warm Atlantic intermediate water through the Irminger Current, which overruled the climatic cooling. This should also have persisted when the ice margin retreated into the long and deep fjord, which was almost completely deglaciated during late YD, as shown recently by ^{10}Be surface exposure ages (Dyke et al., 2014).

5.2.2. Southeast Greenland

Farther to the south, at Sermilik (66°N) and Bernstorffs Fjord (64°N) (Fig. 9), ^{10}Be surface exposure ages and ^{14}C ages lake sediments show that large outlet glaciers here remained on the inner shelf until c. 11 ka (Long et al., 2008; Roberts et al., 2008; Dyke et al., 2014; Larsen et al., 2015). Apparently the warm Irminger Current water did not reach this coast and ice margin, in spite of its appearance at the shelf break outside Bernstorffs Fjord, as shown by sea-bed and core data (Kuijpers et al., 2003). Here, the warm Irminger Current water appeared already at 14.5 cal ka BP, continuing through the YD with no apparent increase in sea ice or reduction in AMOC (Kuijpers et al., 2003; Knutz et al., 2011). It is difficult to reconcile the land and marine records from this area, especially since the shelf here has a width of only 50 km, but the ice sheet margin apparently stayed on the inner shelf during the YD.

5.2.3. South Greenland

In a marine sediment core from the Eirik Drift to the south of Greenland's southern tip (c. 58°N) Carlson et al. (2008) found an increase in Greenland detritus during YD, implying increased runoff from the ice sheet (Fig. 9). This is in agreement with evidence from isolation lakes in the Nanortalik district in southernmost Greenland, indicating rapid uplift, i.e. ice thinning retreat, especially during the late YD (Sparrenbom et al., 2006). In a lake core near the southern tip of Greenland (c. 60°N) - the only lake sediment record in Greenland reaching beyond YD - the Allerød/YD transition is characterized by an increase in lake productivity and occurrence of a warmth demanding diatom, indicating that YD was warmer than Allerød (Björck et al., 2002). This “anomalous” warming was explained as a result of reduced AMOC and increased sea ice and seasonality (Björck et al., 2002). This is the same mechanism that was proposed to afford the glacier advance in Scoresby Sund, but here in the south the increased seasonality resulted in summer temperatures that were high enough to promote melting. It is notable that the beginning of the Holocene in this lake is marked by a sharp transition from minerogenic to organic sediment – akin to the boundary seen in NW European lakes, and so far the only evidence of the abrupt warming at the end of the YD found in ice-free Greenland.

5.2.4. West Greenland

In West Greenland, outlet glaciers in all major fjords coalesced on the shelf. Here, two large moraine systems, the Hellefiske and Fiskebanke moraines were traced for c. 500 km during oil-prospecting in the 1970's (Kelly, 1985; Funder et al., 2011b) (Fig. 9). The Hellefiske moraine follows the shelf edge, while the Fiskebanke moraine reflects a lobate ice sheet margin on the inner shelf and in the shelf troughs. These moraines have alternatively been referred to as Saalian/LGM or LGM/YD in their formation (Funder et al., 2011). Recent results from Disko Bugt show that a large outlet glacier reached the shelf edge, more than 200 km off the coast, at the LGM (see below), suggesting that the ice sheet margin also reached the much narrower shelf edge farther south, and that the oldest of the moraines were not older than the LGM. However, as none of the moraines have yet been dated, and as no YD moraines have so far been observed elsewhere in West Greenland, it remains an open question if either the Hellefiske or Fiskebanke moraines were formed during the YD, but recent ^{10}Be surface exposure ages from coastal areas show that the ice sheet margin remained on the shelf in this part of Greenland up until shortly before 11 or even 10 ka ago (Roberts et al., 2009; Larsen et al., 2014).

In Disko Bugt, the largest drainage trough in western Greenland (c. 70°N), ^{14}C ages of shells from marine cores show that the large ice stream, which occupied the trough outside Disko Bugt, may have begun its retreat at 13.8 cal ka BP (Fig. 9) (O'Cofaigh et al., 2012). However, by c. 12.2 cal ka BP, in mid-YD times, the retreat was interrupted by a short-lived re-advance almost to the shelf edge, followed by "instantaneous" collapse (O'Cofaigh et al., 2012; Kelley et al., 2013; Jennings et al., 2014; Rinterknecht et al., 2014). The re-advance amounted to almost 100 km along a c. 50 km wide front. This is seen from ^{14}C ages of shells from marine cores, both incorporated in till and *in situ* in the overlying marine mud on the inner shelf (O'Cofaigh et al., 2012; Rinterknecht et al., 2014). The collapse brought the ice margin back from the shelf-edge c. 200 km to the mouth of Disko Bugt (Fig. 9). The short duration of this re-advance/retreat suggests that it could represent a surge of a thin glacier lodged in the trough and controlled by subglacial topography and ice thickness, and not directly by the YD cooling (O'Cofaigh et al., 2012). Both before and especially after the re-advance, the Disko Bugt glacier retreated rapidly over the shelf through large-scale calving (Jennings et al., 2014). ^{10}Be surface exposure ages from the coastal area at the mouth of Disko Bugt show that deglaciation of the bay began between 12.2 and 11.6 ka ago (Kelley et al., 2013; Rinterknecht et al., 2014). According to Rinterknecht et al. (2014) the collapse of the shelf-bound part of the Disko Bugt ice stream was triggered by the arrival of warm sub-surface water as a result of a reduced AMOC.

5.2.5. Northwest Greenland

Farther north, in the Uummannaq Trough (c. 71°N), ^{14}C dated marine cores show that deglaciation from the outer shelf began c. 14.8 cal ka BP, and ^{10}Be surface exposure ages from coastal mountains show that by 12.4 ka ago the outer and mid shelf, as well as the mountains, were cleared of ice (Fig. 9). After this, the recession picked up speed, and in the following millennium 100 km of the fjords were deglaciated (Roberts et al., 2013). Accordingly, the YD, and especially its mid and late parts, appears to be a period of retreat.

Along the northwest coast of Greenland, the YD ice sheet margin was also located on the shelf. A marine core from the entrance to Nares Strait between Canada and Greenland (c. 77°N) shows that the cored site was deglaciated before 12.5 cal ka BP and that meltwater sediments dominated for some centuries (Knudsen et al., 2008).

5.3. Synthesis of the Greenland ice sheet's response to the YD cooling

As noted above, the circumstance that three major glaciers over a distance of 50 km from east to west advanced and retreated synchronously imply that this advance was not caused by local forcing, such as the short-lived re-advance on the shelf off Disko Bugt, but by external, climatic factors. Surprisingly, the survey of ice margin behaviour in other parts of Greenland shows that no other moraines have been dated to the YD, although some moraines are under discussion (Fig. 9). The Milne Land moraines, the only other evidence in Greenland for significant late glacial ice margin re-advance, apparently culminated in late Allerød times, but smaller re-advances of the outlet glaciers may have occurred during YD, represented by undated moraines in the area. In more southerly areas, wherever a record is available, the ice margins seem to have retreated from the shelf and in the fjords as shown by the records from Kangerlussuaq, Nanortalik, Uumannaq Fjord and especially Disko Bugt, where the retreat in late YD amounted to large scale collapse (Jennings et al., 2006; Sparrenbom et al., 2006; Carlson et al., 2008; O'Cofaigh et al., 2012; Roberts et al., 2013; Dyke et al., 2014; Jennings et al., 2014; Rinterknecht et al., 2014).

There is therefore a striking mismatch between the dramatic cooling and later abrupt warming seen in ice cores, and the retreat of the ice margins at most sites where a record is available. This has generally been explained as a result of a reduction in AMOC and accompanying increase of seasonality (Björck et al., 2002; Denton et al., 2005; Carlson et al., 2008; Hall et al., 2008; Kelly et al., 2008; Rinterknecht et al., 2014). The reduced AMOC is thought to have been caused by a large supply of meltwater to the North Atlantic from melting ice sheets, which freshened the sea surface and reduced the advection of heat into the North Atlantic. This in turn increased sea ice extent, which sealed the ocean from exchange with the atmosphere, resulting in higher seasonality in Greenland. In addition, reduction in the AMOC may also have increased production of warm subsurface water at low latitudes, which advected northwards and promoted melting of shelf-bound ice margins (Marcott et al., 2011), as noted for the shelf-bound ice margins at Kangerlussuaq and Disko Bugt (Jennings et al., 2006; Rinterknecht et al., 2014).

These mechanisms may explain why the cold oscillation seen in ice cores did not lead to significant re-advance, and all processes are tied up to oceanographic perturbations originating in the North Atlantic. It is therefore noteworthy that areas with significant YD ice margin retreat in Greenland all are located in areas which today lie alongside the warm Irminger and Greenland Currents, which transport warm Atlantic water to the coasts of Southeast and West Greenland, while the areas with advance or sluggish retreat – Peary Land and the East Greenland Fjord Zone – are outside this realm (Fig. 9). This underlines Carlson et al.'s (2008) contention that ice sheets responded differently to cooling, depending on their geographic distribution relative to heat transport. In concert with this, Buizert et al. (2014) from analyses of ice cores showed that YD seasonality, a measure of the AMOC intensity, decreases from south to north, away from the influence of warm Atlantic water. We suggest that the reason for the YD glacier advance/retreat in Peary Land, at a time when ice margins generally retreated, may lie in the respective distances of these areas from North Atlantic advective heat, with Greenland's north coast being the farthest away. However, the coupling between the YD cooling and the subsequent glacier response remains enigmatic, in part because there are very few well-dated sites from this period in Greenland.

6. Conclusion

We have constrained the age of three terminal moraines in front of local glaciers along a 50 km stretch on the north coast of Greenland, using OSL and surface exposure dating techniques. The minimum limiting ^{10}Be surface exposure ages on erratics on the moraines show a mean age of 12.5 ± 0.7 ka and the maximum limiting OSL age for epishelf-lake sediments immediately preceding moraine formation give an age of 12.4 ± 0.6 ka. These ages bracket the formation and subsequent abandonment of the moraines to within the interval 11.8–13.0 ka. The synchronous advance of independent glaciers suggests that they responded to external climate forcing rather than being controlled by topography or being the result of glacier surging. Occurrence of older glaciolacustrine sediments up valley from one of the moraines shows that this valley was ice free before the advance, and this is the first record of YD glacier re-advance/retreat in Greenland. In all other studied areas of Greenland the ice margins were retreating at this time, probably sluggishly in northern East Greenland, but rapidly in more southerly areas. The difference in ice margin response to the YD cooling may be explained by distance to the AMOC, with East and North Greenland being the farthest away. Where data are available, the retreat began before YD, and there is so far none, or little, evidence of a direct ice margin response, neither to the early YD cooling nor to the subsequent rapid Preboreal warming. This may to some extent owe to the limits of the available dating techniques and inaccessibility of critical sites, but in the light of the ongoing warming and its dramatic effect on the Greenland ice sheet, the problem deserves more attention.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.quascirev.2015.10.036.

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