JOURNAL OF QUATERNARY SCIENCE (2012) 27(1) 2–6 ISSN 0267-8179. DOI: 10.1002/jqs.1562

Rapid Communication

Constraining Holocene ^{10}Be production rates in Greenland

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Received 18 September 2011; Revised 5 November 2011; Accepted 13 November 2011

ABSTRACT: The absence of a production rate calibration experiment on Greenland has limited the ability to link ^{10}Be exposure dating chronologies of ice-margin change to independent records of rapid climate change. We use radiocarbon age control on Holocene glacial features near Jakobshavn Isbræ, western Greenland, to investigate ^{10}Be production rates. The radiocarbon chronology is inconsistent with the ^{10}Be age calculations based on the current globally averaged ^{10}Be production rate calibration data set, but is consistent with the ^{10}Be production rate calibration data set from north-eastern North America, which includes a calibration site nearby on north-eastern Baffin Island. Based on the best-dated feature available from the Jakobshavn Isbræ forefield, we derive a ^{10}Be production rate value of 3.98 ± 0.24 atoms g a^{-1}, using the 'St' scaling scheme, which overlaps with recently published reference ^{10}Be production rates. We suggest that these ^{10}Be production rate data, or the very similar data from north-eastern North America, are used on Greenland. Copyright © 2011 John Wiley & Sons, Ltd.

KEYWORDS: ^{10}Be production rate; Greenland Ice Sheet; Holocene; Jakobshavn Isbrae.

Introduction

Cosmogenic ^{10}Be exposure dating (^{10}Be dating) has emerged as a premiere tool to date Quaternary fluctuations of glaciers and ice sheets (e.g. Balco, 2011). Since the earliest applications in Greenland (Håkansson *et al.*, 2007a,b; Kelly *et al.*, 2008; Rinterknecht *et al.*, 2008), the use of ^{10}Be dating in Greenland has become widespread and is increasing (Fig. 1 and Supporting information, Fig. S1). However, lingering uncertainties in ^{10}Be production rates hinder applications of ^{10}Be dating that require precise constraints on ice-sheet advance and retreat, and hamper correlations of glacier change to independent millennial-scale records of climate change. Users of ^{10}Be dating currently have several ^{10}Be production rate calibration data sets to choose from, including the globally averaged data set summarized in Balco *et al.* (2008), and more recently deduced calibration data sets from north-eastern North America (NENA; Balco *et al.*, 2009), the southern hemisphere (Putnam *et al.*, 2010; Kaplan *et al.*, 2011) and Norway (Fenton *et al.*, 2011; Goehring *et al.*, 2012). Here, we present ^{10}Be measurements from radiocarbon-dated glacial features formed during the deglaciation of Jakobshavn Isbrae through the early Holocene to constrain the ^{10}Be production rate calibration data set that is most appropriate for ^{10}Be dating in Greenland.

Jakobshavn Isfjord, west Greenland

Radiocarbon dating

Weidick and Bennike (2007) summarize decades of research about the Greenland Ice Sheet (GIS) in the Disko Bugt region, which has resulted in a well-defined radiocarbon dating-based history of deglaciation from ~10 500 cal a BP to the present (Fig. 2); additions to the radiocarbon chronology were made by Briner *et al.* (2010) and Young *et al.* (2011b). Combined, the present radiocarbon-dated constraints on ice-margin change (see supporting Table S1 and Fig. 2) are as follows.

(i) GIS retreat from east-central Disko Bugt took place after $10\,370 \pm 130$ cal a BP based on a basal radiocarbon age from a marine sediment core reported by Lloyd *et al.* (2005). The deglaciation of Disko Bugt around this time is supported by numerous additional studies (Ingólfsson *et al.*, 1990; Bennike *et al.*, 1994; Rasch, 1997; Long *et al.*, 1999; Long and Roberts, 2002; Weidick and Bennike, 2007). The GIS margin first retreated onto land before ~9800 to ~10 000 cal a BP, based on the oldest ^{14}C ages from raised marine deposits along the coast ($n = 3$; Weidick and Bennike, 2007).

(ii) Following deglaciation of the coastal landscapes along eastern Disko Bugt, a widely traceable and prominent moraine complex was deposited (Fig. 2). These 'Fjord Stade' moraines comprise the older 'Marrait Moraine System' and younger 'Tasiussaq Moraine System' (Weidick, 1968; Kelly, 1985; Weidick and Bennike, 2007). In some places, there is wide spatial separation of the two moraines, whereas in other places the two moraines are nested together, and in yet other places the Tasiussaq Moraine is the only moraine present (Fig. 2). Radiocarbon ages that constrain moraine deposition are from bivalves in marine sediments located inland of the older Marrait Moraine and buried by outwash deposited during emplacement of the younger Tasiussaq Moraine (Weidick and Bennike, 2007). The five ages, each from a slightly different location, are 8800 ± 340, 8750 ± 220, 8670 ± 260, 8570 ± 400 and 7930 ± 270 cal a BP, and provide minimum and maximum age constraints for the deposition of the Marrait and Tasiussaq moraines, respectively. The Marrait Moraine is further constrained by radiocarbon ages from a proglacial-threshold lake adjacent to the moraine. Young *et al.* (2011b) dated the lower and upper contacts of a ~1.5-m-thick sediment layer that was deposited in the lake when the Marrait Moraine was emplaced. Radiocarbon

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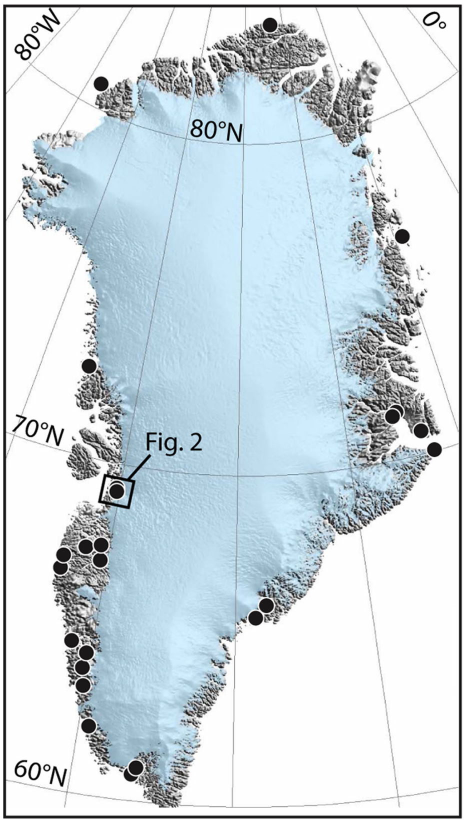

Figure 1. Greenland showing locations of published cosmogenic-nuclide exposure ages (including conference abstracts; see supporting Fig. S1 and Appendix S1 for references). This figure is available in colour online at wileyonlinelibrary.com.

ages from the lower contact are 9190 ± 100 and 9140 ± 110 cal a BP and from the upper contact are 9210 ± 80 and 9150 ± 120 cal a BP, and thus constrain moraine deposition to ~9200 cal a BP.

(iii) Retreat from the Tasiussaq Moraine is constrained by minimum radiocarbon ages ($n = 5$) from basal sediments from four lakes on the ice-proximal side of the Tasiussaq Moraine, which range from 7590 ± 80 to 7740 ± 80 cal a BP, after excluding one old outlier of 8820 ± 180 cal a BP (Long *et al.*, 2006). In addition, radiocarbon ages from basal sediments in lakes near the historical moraine located ~45 km to the east (Fig. 2) are between ~7100 and ~7300 cal a BP ($n = 3$). These ages indicate the time when the GIS retreated past this point to an unknown location further inland from its historical moraine (Weidick and Bennike, 2007; Briner *et al.*, 2010).

Combined, the radiocarbon ages constrain the time–distance history of the ice margin from Disko Bugt to the present ice margin between ~10 000 and ~7000 cal a BP (Figs 2 and 3). The land surface between Disko Bugt and the Fjord Stade moraines was deglaciated at or slightly before 9800–10 000 cal a BP. The Marrait Moraine was deposited ~9200 cal a BP. The Tasiussaq Moraine was deposited between ~8500 and ~7700 cal a BP. The land surface immediately distal to the historical moraine became ice free at or slightly before ~7300 cal a BP.

^{10}Be dating

^{10}Be measurements from 25 samples from the landscape between Disko Bugt and the historical moraine near Jakobshavn Isbræ are reported by Young *et al.* (2011b; Figs 2 and 3; supporting Tables S2 and S3). The samples are from glacially sculpted bedrock, erratic boulders perched atop glacially sculpted bedrock and moraine boulders. The sample locations include: (i) surfaces outboard of the Fjord Stade moraines, (ii) the landscape between the two Fjord Stade moraines, (iii) boulders from the Tasiussaq Moraine and (iv) surfaces between the Tasiussaq Moraine and the historical moraine. There is no evidence for widespread inheritance in the abraded and plucked bedrock outcrops in the region (Young *et al.*, 2011b), which the geomorphology of the bedforms and the nature of reconstructed ice flow support (Roberts and Long, 2005). All samples are above local marine limits and sample elevations are corrected for isostatic rebound following Young *et al.* (2011a). We do not make any corrections for erosion, snow cover or sediment shielding, because the samples are from: (i) areas higher than locally surrounding terrain and are likely to be windswept of snow, and (ii) resistant lithologies that in most locations contain primary glacial surfaces.

We calculate ^{10}Be ages (supporting Table S3) using the global and NENA production rate calibration data sets and the 'St' and 'Li' scaling schemes of Balco *et al.* (2008) (see supporting Fig. S4 and Table S4). We report the ages using St because it is most commonly used, and with Li because it is representative of the other neutron-monitor-based scaling models (e.g. De, Du; Balco *et al.*, 2008) and incorporates solar modulation of isotope production (Lifton *et al.*, 2009), which is especially important at high latitudes. We use the NENA ^{10}Be production rate calibration data set (Balco *et al.*, 2009) because its calibration sites are most proximal to west Greenland. We note that the NENA calibration data set is similar to other recently published datasets (Putnam *et al.*, 2010; Fenton *et al.*, 2011; Kaplan *et al.*, 2011; Goehring *et al.*, 2012).

Our ^{10}Be measurements are from glacial features that apply to several components of the radiocarbon-based time–distance history described above. The portion of the deglaciation history of Jakobshavn Isbræ best constrained by radiocarbon dating is the deposition of the Fjord Stade Moraines. Unlike other portions of deglaciation that are constrained with minimum limiting radiocarbon ages, the two Fjord Stade Moraines have both minimum and maximum limiting ages. Young *et al.* (2011b) found no boulders on the Marrait Moraine suitable for ^{10}Be dating. Thus, the best candidate for constraining ^{10}Be production rates is to use the radiocarbon ages and ^{10}Be measurements relating to the Tasiussaq Moraine. As described above, radiocarbon ages from marine sediments overlain by Tasiussaq outwash constrain the deposition of the Tasiussaq Moraine to after 8700 ± 100 cal a BP ($n = 4$), after omitting the youngest age, which is probably an outlier (Fig. 4). Also, radiocarbon ages from basal lake sediments inboard of the moraine constrain moraine abandonment to before 7650 ± 70 cal a BP ($n = 4$; Fig. 4). The ^{10}Be measurements from six Tasiussaq Moraine boulders from both the north and the south sides of Jakobshavn Isfjord (Fig. 2) are indistinguishable from each other (supporting Table S2). The average ^{10}Be age is 7.2 ± 0.1 and 7.4 ± 0.1 ka ($\chi^2_{reduced} = 0.46$ and 0.52) using the global production rate calibration data set and the St and Li scaling schemes, respectively, and 8.2 ± 0.1 and 7.9 ± 0.1 ka ($\chi^2_{reduced} = 0.86$ and 0.55) using the NENA production rate calibration data set and the St and Li scaling schemes, respectively. Thus, the average ^{10}Be age is consistent only with the independent radiocarbon chronology and geomorphic evidence when using the NENA production rate calibration data set (Fig. 4).

This conclusion is further bolstered when considering six ^{10}Be measurements from three bedrock and three erratic

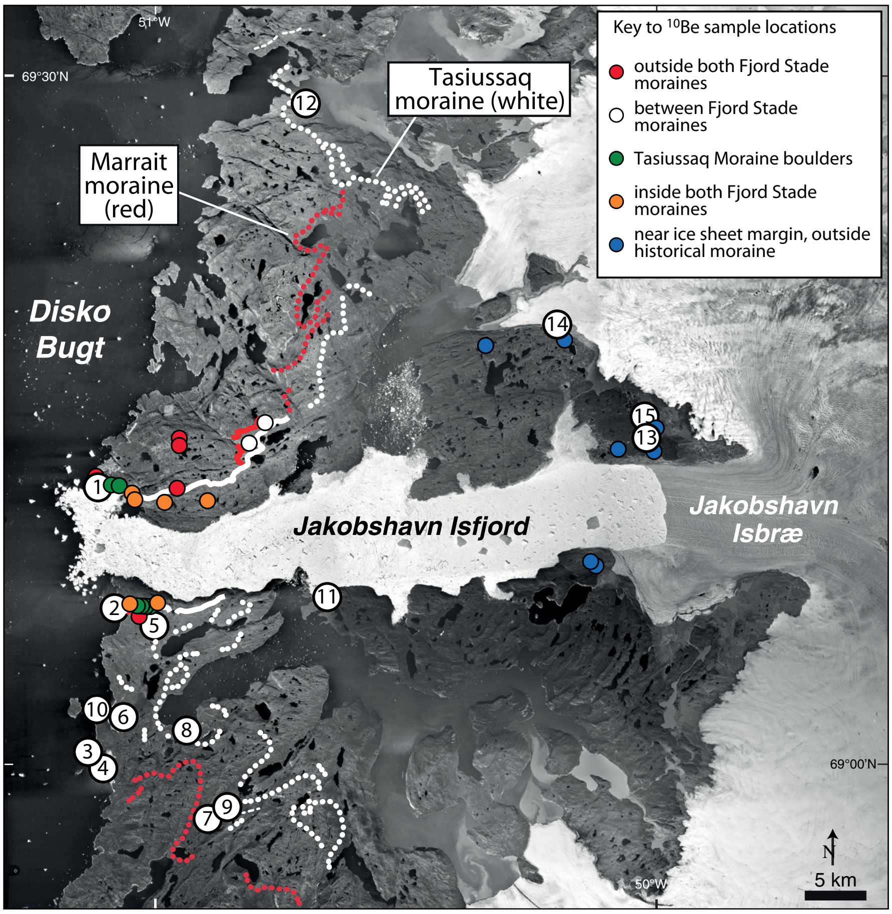

Figure 2. Jakobshavn region showing locations of radiocarbon age control (numbered locations refer to radiocarbon ages in supporting Table S1) and ^{10}Be measurements [red = beyond Marrait Moraine; green = Tasiussaq Moraine boulders; white = between q moraines; orange = inboard of Tasiussaq Moraine; blue = outboard of historical moraine; reported in Young *et al.* 2011b)]. Red and white lines represent Marrait and Tasiussaq moraines, respectively [solid lines from Young *et al.* (2011b), dotted lines from Weidick (1968)].

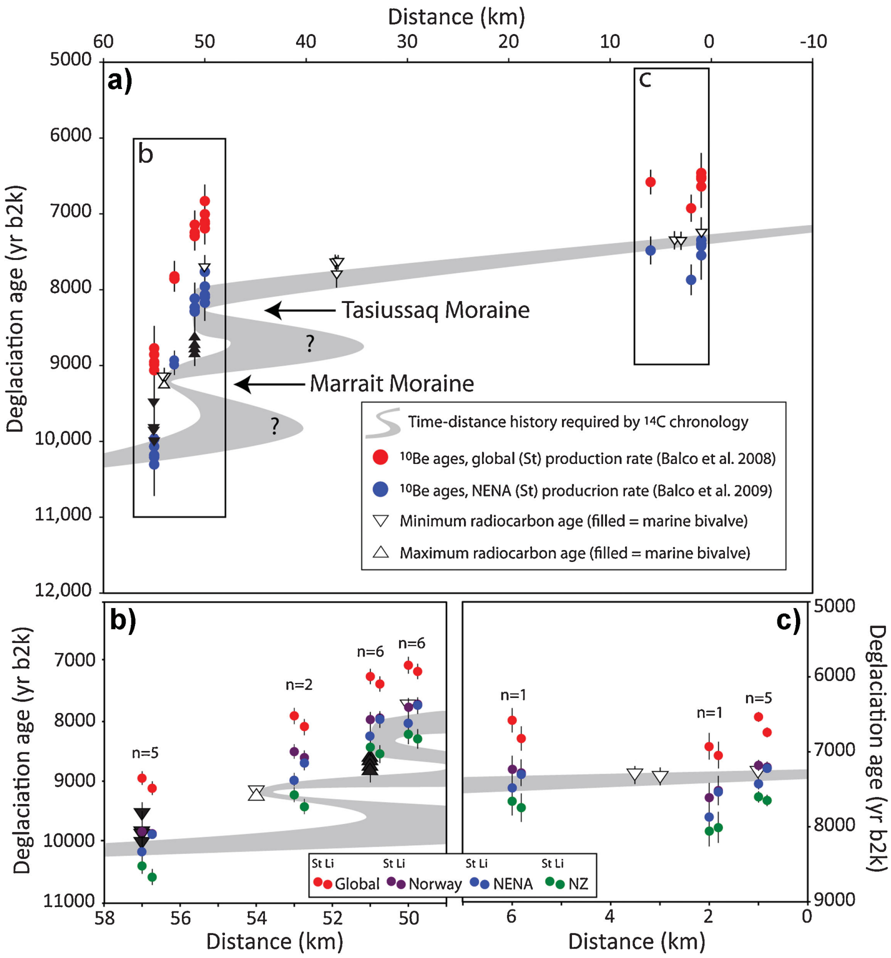

Figure 3. (a) Time–distance history of Jakobshavn Isbræ between the coast of Disko Bugt and the present ice margin. Distance is simplified; the broader area north and south of Jakobshavn Isfjord is condensed into a single distance profile through the Isfjord. Grey shaded line is the time–distance history required by the radiocarbon ages. (b,c) Enlarged portions of the diagram in (a), showing only the average age per ice margin position. Two adjacent symbols represent the Lal/Stone (St) and Lifton (Li) scaling schemes; the two adjacent symbols are measurements from the same ice margin position. We add the age solutions using the ^{10}Be production rates from New Zealand (Putnam *et al.*, 2010) and southern Norway (Goehring *et al.*, 2012); see supporting Table S3. Sample error bars include one-sigma analytical uncertainty.

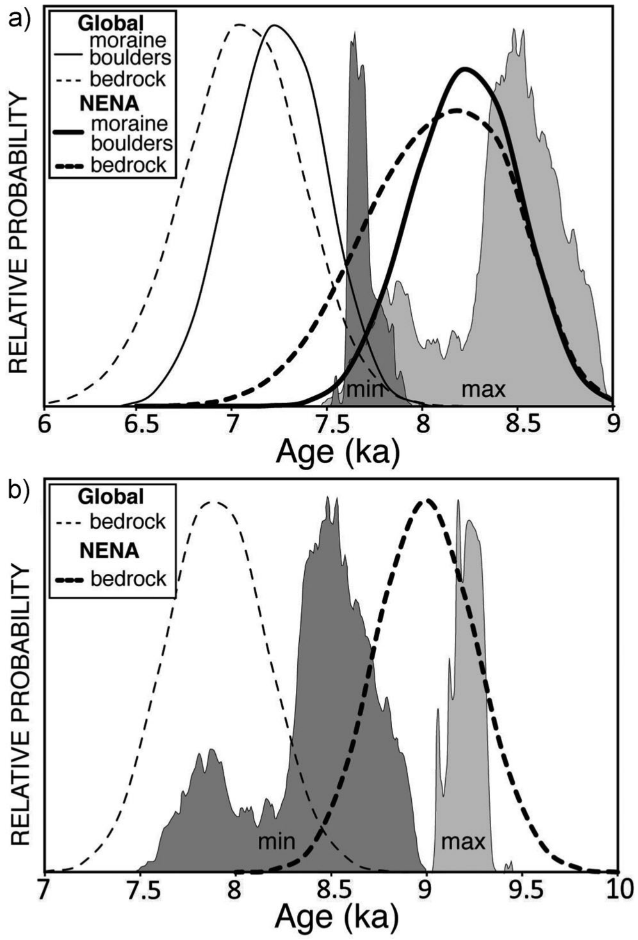

Figure 4. Normal kernel density estimates of ^{10}Be ages of (a) boulders from the Tasiussaq Moraine ($n=6$) and ice-sculpted bedrock inboard of the Tasiussaq Moraine, and (b) ice-sculpted bedrock ($n=2$) between the Tasiussaq and Marrait moraines, calculated with the global ^{10}Be production rate and the north-eastern North America value. Also shown are summed calibration solutions of maximum and minimum radiocarbon age constraints for the age of the Tasiussaq Moraine, and of the bedrock surface between the two Fjord Stade moraines.

samples immediately inboard of the Tasiussaq Moraine. This surface should essentially be the same age or slightly younger than boulders atop the Tasiussaq Moraine, and older than the average radiocarbon age of 7650 ± 70 cal a BP from the basal lake sediments inboard of the Tasiussaq Moraine. The average ^{10}Be age is 7.1 ± 0.1 (St) and 7.1 ± 0.1 (Li) ka using the global production rate calibration data set, and 8.0 ± 0.2 (St) and 7.7 ± 0.1 (Li) ka using the NENA production rate calibration data set. Again, the average ^{10}Be age is consistent only with the independent radiocarbon chronology and geomorphic evidence when using the NENA production rate calibration dataset (Fig. 4).

These findings from the Tasiussaq Moraine are consistent with radiocarbon constraints on the broader time–distance history. (i) Five additional ^{10}Be measurements are from the land surface between Disko Bugt and the Fjord State moraines; four of the samples are from ice-sculpted bedrock, one sample is from an erratic. (ii) Two ^{10}Be measurements were made from ice-sculpted bedrock between the Marrait and Tasiussaq moraines. (iii) ^{10}Be measurements were made from seven ice-sculpted bedrock samples immediately outboard of the historical moraine. At all of these sites, the average ^{10}Be age calculated using the global production rate calibration data set is inconsistent, and the ^{10}Be ages based on the NENA production rate calibration data set are consistent, with the independent radiocarbon age constraints (Figs 3 and 4).

A ^{10}Be production rate calibration dataset from western Greenland

Combined, the ^{10}Be measurements made from Tasiussaq Moraine boulders and from other surfaces related to the radiocarbon-dated deglaciation history of Jakobshavn Isbræ reveal that the NENA ^{10}Be production rate calibration data set is suitable for west Greenland. Recently, ^{10}Be production rate calibration data similar to the NENA rates have become available from calibration sites in the southern hemisphere (Putnam *et al.*, 2010; Kaplan *et al.*, 2011) and Norway (Fenton *et al.*, 2011; Goehring *et al.*, 2012). The Disko Bugt ^{10}Be ages calculated using these data sets are also, within errors, consistent with the independent radiocarbon chronology (Fig. 3). Using the maximum and minimum radiocarbon ages for the Tasiussaq Moraine and solving for a ^{10}Be production rate using the average ^{10}Be concentration of the six Tasiussaq Moraine boulders (supporting Fig. S2) yields a range from 3.74 to 4.21 atoms g a^{-1} and a mid-point and half of the range of 3.98 ± 0.24 atoms g a^{-1} (St scaling). This mid-point value is similar to the NENA value of 3.91 ± 0.19 atoms g a^{-1} (St scaling; supporting Fig. S3). The value is supported further when considering the two bedrock samples inboard of the Marrait moraine, which can be younger, but not older, than 9.2 ka. Using these two samples, we derive a minimum ^{10}Be production rate of 3.83 atoms g a^{-1} (St scaling), and a tentatively narrower range of 3.83–4.21 atoms g a^{-1}.

Conclusions

The current global ^{10}Be calibration data set yields ^{10}Be ages consistently too young compared with robust independent radiocarbon age control in west Greenland. In contrast, ^{10}Be ages based on the NENA production rate calibration data set are consistent with the independent age control. Recent production rates calibrated in Norway (Fenton *et al.*, 2011; Goehring *et al.*, 2012) and the southern hemisphere (Putnam *et al.*, 2009; Kaplan *et al.*, 2011) also yield ^{10}Be ages that are generally consistent with the ^{14}C chronology. It is difficult to know which production rate calibration data set/scaling scheme combination yields the most consistent match with the independent age control with current uncertainties. Until the ^{10}Be production rate can be more precisely constrained on Greenland, we suggest that users of ^{10}Be dating on Greenland use the production rate calibration data reported here or the NENA production rate calibration data set, which includes a calibration site on north-eastern Baffin Island.

Supporting information

Additional supporting information can be found in the online version of this article:

Appendix S1. Comments on chronology.

Table S1. Radiocarbon ages that constrain the ice margin position in the Jakobshavn Isbrae region, western Greenland.

Table S2. Background data from the Disko Bugt region for calculation of ^{10}Be ages.

Table S3. ^{10}Be ages with Lal/Stone and Lifton scaling from the Disko Bugt region.

Table S4. ^{10}Be production rates with the 101 m asl delta at Holger Danskes Briller).

Fig. S1. Greenland with positions of previous and ongoing cosmogenic nuclide exposure dating studies.

Fig. S2. Photographs showing the six moraine boulders from the Tasiussaq Moraine.

Fig. S3. A comparison of spallation-based reference ^{10}Be production rates with the St scaling scheme, normalized to sea level high latitude.

Fig. S4. Relative sea level curve for Kjove Land and the depth-profile surface ages of the 101 m asl delta at Holger Danskes Briller.

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Acknowledgements. This work benefited from high-precision ^{10}Be analyses from Lawrence Livermore National Laboratory; in particular we thank Dylan Rood and Robert Finkel. We greatly appreciate very helpful reviews by Greg Balco and Cassie Fenton. This research was supported by the US National Science Foundation Geography and Spatial Sciences Program, NSF-BCS-0752848 and -1002597.

Abbreviations. GIS, Greenland Ice Sheet; NENA, north-eastern North America.

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