Rapid Communication

Constraining Holocene $^{10}$Be production rates in Greenland

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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 Isbrae, 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 Isbrae forefield, we derive a $^{10}$Be production rate value of $3.98 \pm 0.24$ atoms g$^{-1}$, using the ‘$S$’ 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 $\sim10,500$ 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 $\sim9800$ to $\sim10,000$ 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 ‘Marrat 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 Marrat 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 $8800 \pm 340$, $8750 \pm 220$, $8670 \pm 260$, $8570 \pm 400$ and $7930 \pm 270$ cal a BP, and provide minimum and maximum age constraints for the deposition of the Marrat and Tasiussaq moraines, respectively. The Marrat 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 $\sim1.5$-m-thick sediment layer that was deposited in the lake when the Marrat Moraine was emplaced. Radiocarbon
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 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.

**10Be dating**

10Be 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 10Be 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 10Be 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 10Be 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 10Be dating. Thus, the best candidate for constraining 10Be production rates is to use the radiocarbon ages and 10Be 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 by Tasiussaq outwash constrain the deposition of the Tasiussaq Moraine to after 7650 ± 70 cal a BP (n = 4; Fig. 4). The 10Be 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 10Be age is 7.2 ± 0.1 and 7.4 ± 0.1 ka (X^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 (X^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 10Be 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 10Be 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 10Be measurements (red = beyond Marrait Moraine; green = Tasiussaq Moraine boulders; white = between 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 Isbæ 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 14C chronology. (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 10Be 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.
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 10Be 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 10Be 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 10Be 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 10Be measurements were made from ice-sculpted bedrock between the Marrait and Tasiussaq moraines. (iii) 10Be measurements were made from seven ice-sculpted bedrock samples immediately inboard of the historical moraine. At all of these sites, the average 10Be age calculated using the global production rate calibration data set is inconsistent, and the 10Be ages based on the NENA production rate calibration data set are consistent, with the independent radiocarbon age constraints (Figs 3 and 4).

A 10Be production rate calibration dataset from western Greenland

Combined, the 10Be measurements made from Tasiussaq Moraine boulders and from other surfaces related to the radiocarbon-dated deglaciation history of Jakobshavn Isbrae reveal that the NENA 10Be production rate calibration data set is suitable for west Greenland. Recently, 10Be 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 10Be 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 10Be production rate using the average 10Be 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 10Be 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 10Be calibration data set yields 10Be ages consistently too young compared with robust independent radiocarbon age control in west Greenland. In contrast, 10Be 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 10Be ages that are generally consistent with the 14C 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 10Be production rate can be more precisely constrained on Greenland, we suggest that users of 10Be 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 10Be ages.
- Table S3. 10Be ages with Lal/Stone and Lifton scaling from the Disko Bugt region.
- Table S4. 10Be 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 Kjøve Land and the depth-profile surface ages of the 101 m asl delta at Holger Danskes Briller.

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

References