Quaternary Science Reviews 145 (2016) 243–258

Contents lists available at ScienceDirect

Quaternary Science Reviews

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

Diachronous retreat of the Greenland ice sheet during the last deglaciation

G. Sinclair [a, *], A.E. Carlson [a], A.C. Mix [a], B.S. Lecavalier [b], G. Milne [c], A. Mathias [a], C. Buizert [a], R. DeConto [d]

[a] *College of Earth, Ocean, and Atmospheric Sciences, Oregon State University, USA*
[b] *Department of Physics and Physical Oceanography, Memorial University, Canada*
[c] *Department of Earth and Environmental Sciences, University of Ottawa, Canada*
[d] *Department of Geosciences, University of Massachusetts, Amherst, USA*

ARTICLE INFO

Article history:
Received 12 February 2016
Received in revised form
24 May 2016
Accepted 27 May 2016

Keywords:
Greenland ice sheet
Deglaciation
Holocene
Ice-sheet models
Model-data comparison
Surface exposure dating
Radiocarbon dating

ABSTRACT

The last deglaciation is the most recent interval of large-scale climate change that drove the Greenland ice sheet from continental shelf to within its present extent. Here, we use a database of 645 published ^{10}Be ages from Greenland to document the spatial and temporal patterns of retreat of the Greenland ice sheet during the last deglaciation. Following initial retreat of its marine margins, most land-based deglaciation occurred in Greenland following the end of the Younger Dryas cold period (12.9–11.7 ka). However, deglaciation in east Greenland peaked significantly earlier (13.0–11.5 ka) than that in south Greenland (11.0–10 ka) or west Greenland (10.5–7.0 ka). The terrestrial deglaciation of east and south Greenland coincide with adjacent ocean warming. ^{14}C ages and a recent ice-sheet model reconstruction do not capture this progression of terrestrial deglacial ages from east to west Greenland, showing deglaciation occurring later than observed in ^{10}Be ages. This model-data misfit likely reflects the absence of realistic ice-ocean interactions. We suggest that oceanic changes may have played an important role in driving the spatial-temporal ice-retreat pattern evident in the ^{10}Be data.

1. Introduction

During the global Last Glacial Maximum (LGM, 19–26 ka; Clark et al., 2009), the Greenland ice sheet (GrIS) covered ~65% more area than its present extent and in many places extended to the continental shelf-slope break (Funder et al., 2011). Over the next ~15 ka as temperatures increased, the GrIS retreated, reaching a smaller-than-present extent in the early to middle Holocene (e.g., Carlson et al., 2014; Larsen et al., 2015; Young and Briner, 2015). Superimposed on the general warming trend from the LGM to the middle Holocene were several rapid climate fluctuations in the North Atlantic region. Abrupt warming initiated the Bølling Interstadial period at ~14.6 ka. Regional cooling initiated the Younger Dryas Stadial at ~12.9 ka, and abrupt warming defines the onset of the Holocene at ~11.7 ka (Shakun and Carlson, 2010; Clark et al., 2012; Buizert et al., 2014). While the GrIS retreated in response to this most recent interval of large-scale climate change, questions remain as to potential differences in how particular regions behaved and whether retreat was synchronous across the island.

Several studies have examined regional to continental-scale deglaciation of Greenland, using both proxy data and model results (e.g., Bennike and Björck, 2002; Dyke, 2004; Simpson et al., 2009; Funder et al., 2011; Lecavalier et al., 2014; Young and Briner, 2015), with the emergence of ^{10}Be surface exposure dating enabling increasingly detailed and precise geochronological studies, improving our understanding of the patterns of ice retreat. Thirty-seven studies using ^{10}Be ages to date ice-marginal systems around Greenland have been published since 2007, addressing land-based retreat from the outer coast to the present margin (Fig. 1). This rapidly growing dataset documents spatial and temporal information of GrIS responses to deglacial climate change, and can be used to independently validate ice-sheet models.

Here, we assemble a complete database of all published ^{10}Be ages from Greenland. All ages are recalculated with the most up-to-date production rate (Young et al., 2013a) and scaling schemes, and are therefore internally consistent. We use this compilation and factor analysis to investigate the spatial-temporal patterns of GrIS

---

* Corresponding author.
E-mail address: gsinclair@coas.oregonstate.edu (G. Sinclair).

http://dx.doi.org/10.1016/j.quascirev.2016.05.040
0277-3791/

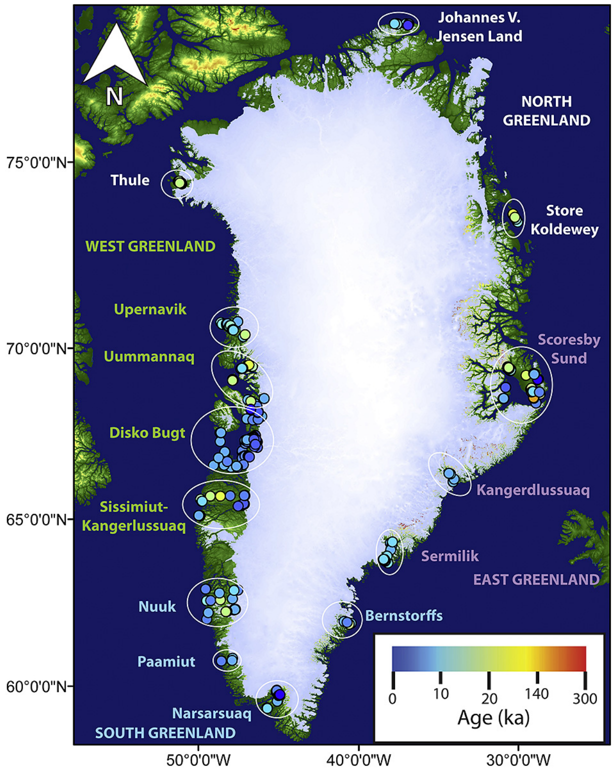

Fig. 1. Map of all published ^{10}Be ages from Greenland. Individual ^{10}Be ages are represented by dots, with colors corresponding to the age of the sample. Text colors correspond to the broader region (identified in all capitals) each individual location is assigned to by factor analysis.

margin retreat. We also compare our results against an updated ^{14}C database and a recent ice-sheet model simulation of the last deglaciation (Lecavalier et al., 2014) to test whether the simulated GrIS response to deglacial climate change agrees with observations, building on recent model-data comparisons for the Holocene when the GrIS was smaller than its present extent (Larsen et al., 2015; Young and Briner, 2015).

2. Methods

2.1. The ^{10}Be database

An extensive literature review revealed 36 publications (as of May 2016) that include ^{10}Be exposure ages in Greenland (Fig. 1, Table 1). A total of 645 ages have been published, with between two and 47 ages per publication. Most studies focused on constructing a local to regional ice-retreat chronology, although some use ^{10}Be ages to evaluate response of parts of the GrIS to climatic events like the Younger Dryas, 9.3 ka and 8.2 ka events (Young et al., 2013b; Larsen et al., 2016) or to constrain the thickness and extent of the GrIS during the LGM (e.g., Håkansson et al., 2007a). Several papers also investigated the behavior of local ice caps and mountain glaciers separate from the main ice sheet (e.g., Kelly et al., 2008; Möller et al., 2010; Levy et al., 2014; Lowell et al., 2013; Young et al., 2015; Larsen et al., 2016). All ages are included in our database.

All the data necessary to calculate ^{10}Be ages using the CRONUS-Earth online calculator (Balco et al., 2008; hereafter the CRONUS calculator) were extracted from the original publications. In case of ambiguity or missing data, corresponding authors were contacted to provide original data. If ^{26}Al measurements were performed in the original study, ^{26}Al concentrations, uncertainties, and standards were included in the database to facilitate calculation of ^{26}Al exposure ages. However, ^{26}Al ages were excluded from the data-model comparison presented below, because only 90 samples included ^{26}Al ages in addition to ^{10}Be ages, and ^{26}Al ages were used in the original studies primarily to supplement ^{10}Be ages and test for inheritance.

In the original publications, slightly different standards were used for several fields in the CRONUS calculator. To account for this, the following minor modifications were performed with the original data to ensure the dataset is internally consistent. All granitic and gneissic samples were assigned a density of 2.65 g cm^{-3}, and all sandstone samples were assigned a density of 2.38 g cm^{-3}. Densities of granite/gneissic samples, where reported, ranged between 2.56 and 2.81 g cm^{-3}; however, these were generally inferred instead of directly measured, so a constant density assigned here is equally plausible and is internally consistent. In addition, all samples were assigned zero post-exposure erosion. Some evidence of erosion was observed in original studies, particularly in east Greenland (Levy et al., 2014; Håkansson et al., 2007b). However, in most regions little to no post-exposure erosion was observed, and small-scale glacial erosional features, such as polish and striae, were often observed, indicating the surfaces are well preserved since deglaciation. The database includes both the assigned densities and erosion rates and the original reported values for reference, although they are not included in our analyses.

No correction for isostatic uplift was included in the re-calculated ages for two reasons. First, only three of the original studies included an isostatic uplift correction for ^{10}Be ages (Kelly et al., 2008; Young et al., 2011a; Rinterknecht et al., 2014). Including isostatic uplift in these two studies changed ages by 2–9%. Second, estimating the precise amount of isostatic uplift is difficult, because local relative sea-level change near ice sheets is influenced by isostatic adjustment of the solid Earth as well as changes in ocean surface height due to global meltwater influx and local gravity changes associated with surface (ice-ocean) and internal (Earth deformation) mass redistribution (Farrell and Clark, 1976; Milne and Shennan, 2013). Therefore, estimating the amount of atmospheric depth change requires the use of an isostatic sea-level model, which in turn requires estimating the position of the glacier margin, leading to somewhat circular reasoning and calculations.

Once the database of published information was compiled, all ^{10}Be ages were re-calculated using the CRONUS calculator, version 2.2 (http://hess.ess.washington.edu/). Calculations using both the Northeast North American (Balco et al., 2009) and Arctic (Young et al., 2013a) production rates were performed. Results from all five scaling schemes calculated on the CRONUS calculator are reported in the database, along with information from the publications necessary to reproduce these calculations or re-calculate ages with any future changes to regional production rates and/or scaling schemes. In our analysis, we use ^{10}Be ages calculated using the Arctic production rate (Young et al., 2013a) and the Lal/Stone time-varying scaling scheme, with internal uncertainties. Use of alternate scaling schemes does not significantly impact results; the internal uncertainty calculated with CRONUS for a given sample is on average 6.1 times greater than the difference between the oldest and youngest ages calculated from the different scaling schemes. The difference between re-calculated ages and reported ages is negligible for most recent publications (from 2011 to 2015), but is significant for the 148 ages published between 2007 and 2010, where the median difference between reported and re-calculated ages is 1.7 ka. The database is available in .xls, .kmz, and .shp form from the U.S. National Climate Data Center. No published samples are excluded from this database; even where ^{10}Be ages were excluded from analysis in the original publications they have