Diachronous retreat of the Greenland ice sheet during the last deglaciation

^{1*}Sinclair, G., ¹Carlson, A.E., ¹Mix, A.C., ²Lecavalier, B.S., ³Milne, G., ¹Mathias,

A., ¹Buizert, C., ⁴DeConto, R.,

¹College of Earth, Ocean, and Atmospheric Sciences, Oregon State University,
USA

²Department of Physics and Physical Oceanography, Memorial University, Canada

³Department of Earth and Environmental Sciences, University of Ottawa, Canada

⁴Department of Geosciences, University of Massachusetts, Amherst, USA

*gsinclair@coas.oregonstate.edu, 607-319-1945

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 673 published ¹⁰Be 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. ¹⁴C 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 ¹⁰Be 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.

Key words: Greenland ice sheet; deglaciation; Holocene; ice-sheet models; model-data comparison; surface exposure dating; radiocarbon dating

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

(Figure 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 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 & Briner, 2015).

2. Methods

2.1 The ^{10}Be Database

An extensive literature review revealed 37 publications (as of May 2016) that include ^{10}Be exposure ages in Greenland (Figure 1, Table 1). A total of 673 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 to 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 2011-2015), 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 been included here to ensure the dataset is complete for future investigations, which may have different research goals from those of the original publications.

A subset of ^{10}Be ages (n=453 samples) was compiled to investigate the main phase of GrIS retreat from the LGM to the middle Holocene. The deglacial interval is defined here as occurring between 21 ka and the onset of Neoglacial cooling around 4 ka (Clark et al., 2009; Lecavalier et al., 2014; Larsen et al., 2015). This data set contains the same information as the main database, but all 159 samples older than 21 ka and all 39 samples younger than 4 ka were excluded from the comparison *a priori*. Seven further samples were excluded from the dataset because while they are older than 4 ka, they are ‘old’ outliers from late-Holocene moraines (Levy et al., 2014; Winsor et al., 2014), likely due to inheritance from earlier exposure histories. All ^{10}Be ages from pebbles on moraines were excluded, to avoid anomalously young ages due to exhumation of small clasts. The only ^{10}Be study in Greenland to rely heavily on amalgamated pebble samples due to a lack of suitable bedrock or boulder samples had widely scattered ages spanning ~8 ka (Alexanderson and Håkansson, 2014). This suggests that the oldest ages could be minimum limiting (i.e., constraining the younger limit of the potential age range of the moraine), because the pebbles have likely experienced significant exhumation since deglaciation (Alexanderson and Håkansson, 2014).

2.2 ¹⁴C Database

In addition to the ¹⁰Be database, a deglacial database of ¹⁴C ages was constructed that builds on the existing database of Dyke (2004) (Figure 2, Table 2). The ¹⁴C database was used to check ¹⁰Be ages, testing the hypothesis that ¹⁰Be ages are on average older than ¹⁴C ages; ¹⁴C ages are by definition minimum limiting because they date death of organic material which grows sometime after retreat of the ice sheet. While this ¹⁴C database can also be used to test ice-sheet model simulations, the comparison was not done here. The ice-sheet model was tuned in part to the ¹⁴C records (Lecavalier et al., 2014), so validating it with the ¹⁴C database would introduce an element of circularity. Like the ¹⁰Be database, the ¹⁴C database was constructed through a detailed literature review. 791 ¹⁴C dates and metadata were pulled from the original publications, and re-calibrated using the IntCal13 calibration dataset in Calib14 (Reimer et al., 2013; <http://calib.qub.ac.uk>). To maintain consistency across calculations from different research groups, all marine ages were corrected for a constant 400-year ¹⁴C reservoir age (i.e., $\Delta R=0$), which is commonly used around Greenland (Dyke, 2004; Carlson et al., 2008; Jennings et al., 2006; 2014). Radiocarbon ages were then calculated as the median between the upper and lower limits of all age distributions for both 1- and 2-sigma uncertainties. The ¹⁴C database is available in .xls, .kmz, and .shp form from the U.S. National Climate Data Center.

2.3 Factor Analysis of Cosmogenic and Radiocarbon Data

Q-mode factor analysis (e.g., Imbrie and Van Andel, 1964) and associated transfer functions have traditionally been applied to ocean sediment data in paleoceanography and paleoclimate. This method is most commonly used with marine biological assemblages to determine past ocean temperatures (e.g., Imbrie and Kipp 1971; Mix et al. 1999). Imbrie and van Andel (1964) established the method for applying Q-mode factor analysis to geochemical data.

This method takes a set of samples characterized by multiple variables, and extracts a set of factors representing theoretical end member assemblages that can be combined in different proportions to recreate the sample set. Q-mode analysis should be used with most geochemical data, as opposed to R-mode analysis, because its factors represent end-member samples instead of variables (ibid, Pias et al. 2013). Q-mode factor analysis weights the relationships between all variables and all samples equally, and therefore does not rely on *a priori* assignment of groups based on perceived similarities and/or geographic location. This analysis will therefore provide objective estimates of (1) the number of end-member assemblages explaining the majority of variance within the samples; (2) the composition of these assemblages; and (3) the contributions of these end members to each individual sample (Imbrie and van Andel 1964). Here, ^{10}Be and ^{14}C ages are evaluated using factor analysis to determine if a spatial pattern can be objectively identified, and if this pattern can be related to paleoclimate records.

We performed the Q-mode analysis on normalized grid cell probability density functions (PDFs). Figure 3 shows a schematic illustration of the process for assigning samples to grid cells and building PDFs for the ^{10}Be factor analysis. First, ^{10}Be samples are sorted into grid cells. For simplicity and to facilitate later data-model comparison, we have used the Huy3 20 km model grid cell to sort the samples (Lecavalier et al., 2014). We assigned ^{10}Be samples to their grid cells by calculating the distance from the sample to the midpoint of each grid cell. The sample was then placed into the nearest grid cell (1). Between 1 and 27 samples were located in each grid cell. Next, a Gaussian distribution was calculated at 10-year intervals from 0 ka to the maximum possible age of the sample (4-sigma greater than the re-calculated age, using the internal analytical uncertainty as the 1-sigma uncertainty) (2). The Gaussians for all samples in a grid cell are then summed to create a grid cell PDF (3). To avoid weighting the analysis to those grid cells

with many samples, each grid cell PDF is normalized to an area under the curve of 1 (4). These normalized grid cell PDFs are then used for Q-mode factor analysis following Pias et al. (2013). A final varimax factor matrix is achieved by rotating a preliminary matrix calculated with the retained significant orthogonal factors to maximize positive loadings of all factors. This results in the retained factors explaining approximately equal amounts of variance (Imbrie and van Andel, 1964).

The process for calculating factors for the ^{14}C database is identical to that for the ^{10}Be database, with the exception that instead of using all data points in a given grid cell, we calculate the normalized PDF for only the oldest ^{14}C age in a grid cell. This controls for the fact that many of the ^{14}C ages come from lake or marine cores, where only the oldest age is relevant for determining minimum ice-retreat ages, and is also a way to identify the oldest minimum-limiting ^{14}C age in a given 20 km area.

2.4 Data-Model Comparison

Our ^{10}Be database represents the most complete record of terrestrial GrIS retreat currently available and can therefore be used as an independent validation tool for ice-sheet models. This data set provides a framework to test the Huy3 reconstruction of GrIS retreat from ~19 ka to the present (Lecavalier et al., 2014). The ice-sheet reconstruction is based on a thermodynamic ice-sheet model used in series with a glacial isostatic adjustment model of sea-level change. The ice model was run at 20 km grid resolution. For this analysis, we considered model output of ice extent at 1 ka intervals. The model was forced from 19 ka to the late Holocene using atmospheric temperatures extrapolated from the GRIP $\delta^{18}\text{O}$ temperature reconstruction. Certain model aspects and parameters were varied to seek an optimal fit to both ice-extent data from the LGM through to the present as well as a regional relative sea-level database (see Lecavalier et al. (2014) for

detailed descriptions of model forcing and physics).

To facilitate comparison with the ice-sheet model reconstruction, each ^{10}Be sample from the deglacial dataset was associated with a model grid cell as described in Section 2.2. Where more than three samples were present in an individual grid cell, Chauvenet's criterion was used to test for outliers (Balco, 2011). This is a gentle test for anomalous data, which compares each ^{10}Be age to the mean and standard deviation of the samples in a grid cell. If the sample deviation exceeds the maximum assigned for a given number of samples, the sample is excluded from the analysis. This method led to the exclusion of ten ^{10}Be ages. In an effort to maintain objectivity in the data-model comparison, no further ^{10}Be ages were excluded from the comparison, even when they were excluded from analysis in the original publications.

After removal of samples with Chauvenet's criterion, 453 samples remained for comparison within 102 model grid cells. To compare these ages with the model grid cells, all the normalized grid cell PDFs in each of the 14 regions around the island were summed (Figure 3, 4), and the resulting PDF was compared to a histogram of model ice-retreat ages from that region (Figure 4).

3. Results

3.1 Factor Analysis

Results of the factor analysis are shown in Figures 5 and 6c. Note that 49 ages from Upernavik, Thule, Johannes V. Jensen Land, and Store Koldewey were excluded from the analysis. We excluded these ages from the factor analysis because these areas have a very high proportion of inherited ^{10}Be , and have widely scattered ages (Larsen et al., 2016; Corbett et al., 2013; 2015; Möller et al., 2010; Håkansson et al., 2007b). Factor analysis including all ages is not significantly different from that presented here, but the factors explain a smaller proportion

of the total variance. Six factors were required to explain ~82% of the variance in the data, but only four were retained to calculate orthogonal factors. These explain ~72% of total variance (Table3) and simplify the final analysis. The final factors are named from the age of maximum probability, although it is important to note that each factor plot has significant structure beyond the peak. In particular, the 12 ka factor includes elevated values from ~20 ka to 11.5 ka. The 12 ka factor has its highest loadings in east Greenland (Figure 5a), with scattered grid cells in south and west Greenland, most notably a cluster of grid cells on the west coast of the Sisimiut-Kangerlussuaq region. In contrast, the 7.5 ka grid cell is almost exclusively concentrated in west Greenland, particularly in the eastern part of Sisimiut-Kangerlussuaq, Disko Bugt, and Uummannaq. Both the 10 ka and 11 ka factors are relatively high across the island, although the 10 ka factor is notably diminished in east Greenland.

The map of dominant factors shows a similar spatial pattern to the maps of individual factors (Figure5b). The dominant factor is defined here as the factor that explains the plurality of variance in a grid cell. In east Greenland, the 12 ka and 11 ka factors dominate. West Greenland is the only place where the 7.5 ka is dominant. The 10 ka factor is dominant in south Greenland, in addition to scattered grid cells where the 11 ka and 12 ka ages are dominant. The average communality of factors in all gridcells is 0.72; Figure 5c shows how this is distributed around the island.

In contrast to the ^{10}Be ages, factor analysis of ^{14}C ages does not reveal a significant spatial pattern. Figures 7 and 8 show the results of the factor analysis of ^{14}C ages. Ten factors were required to explain ~80% of the variance in the data (Table 4); we retained four factors for the final analysis, which explain ~62% of the total variance in the ^{14}C ages. The four factors each have sharply defined peaks at 11.2 ka, 10.2 ka, 9.5 ka, and 8.3 ka (Figure 7). However, none of

the factors are heavily concentrated in any given region (Figure 8a), and there are no distinctive patterns in the map of dominant factors (Figure 8b). In addition, communality in the factors is significantly lower in the ^{14}C analysis (Figure 8c), with average communality of 0.61.

3.2 Model-Data Comparisons

Figure 4 shows that model-data fits vary between different regions in Greenland. The closest match between the Huy3 model and ^{10}Be ages is in west Greenland, where model retreat ages overlap with ^{10}Be PDFs in Upernavik, Uummannaq, Disko Bugt, Sisimiut-Kangerlussuaq, and Nuuk. In contrast, ^{10}Be PDFs consistently peak between 1 and 4 ka before modeled ice retreat occurs in north, east, and south Greenland, including Scoresby Sund, Kangerdlussuaq, Sermilik, and Paamiut. In Bernstorffs and Narsarsuaq, the majority of modeled ice retreat occurs after the main peak in the ^{10}Be ages, although the lead in ^{10}Be ages is less pronounced than in the rest of east and south Greenland.

4. Discussion

The ^{10}Be factor analysis results differ significantly from the deglacial GrIS retreat scenario outlined by Funder et al. (2011), which shows deglaciation from the outer coast after ~ 11.7 ka in all locations except Scoresby Sund (deglaciated before ~ 12.4 ka) and Kap Farvel at the southern tip of Greenland (deglaciated by ~ 14 ka). In our analysis, significant terrestrial ice retreat occurred before ~ 11.7 ka at Scoresby Sund, Kangerdlussuaq, Sermilik, Nuuk, and Sisimiut-Kangerlussuaq (Figure 5, 6c) (also further north at Johannes V. Jensen Land, and Store Koldewey; Figure 4). Several studies from east Greenland investigated the behavior of local glaciers and ice caps after the retreat of the ice sheet (Kelly et al., 2008; Levy et al., 2014; Lowell et al., 2013); these minimum-limiting ages may suggest even earlier ice retreat of the GrIS from the region, consistent with the overall spatial pattern observed here. This difference is

expected as the Funder et al. (2011) reconstruction relied largely on minimum-limiting ^{14}C ages that reflect the first establishment of soils, marine life and vegetation, which has an unknown lag time behind ice-margin retreat.

In our factor analysis of ^{14}C ages, there is no evidence of the spatial pattern clearly expressed in the ^{10}Be data. A direct comparison of the average ^{10}Be age and the oldest ^{14}C age in the 27 gridcells containing both types of data shows that in most cases ^{14}C ages lag ^{10}Be ages, but that the offset is not constant (Figure 9). ^{10}Be ages should directly date ice-margin retreat in most cases (if inheritance, erosion, or later exhumation are not an issue), so the offset is likely explained by the minimum-limiting nature of ^{14}C ages and an unknown time between ice retreat and migration of vegetation to the site.

In contrast to the spatial Greenland deglaciation pattern identified by factor analysis, the Huy3 model shows homogenous terrestrial ice-margin retreat. At a local scale, ^{10}Be ages generally lead the Huy3 model results (Figure 4), with the exceptions of Uummannaq, Disko Bugt, Nuuk and Sisimiut-Kangerlussuaq regions. This pattern is particularly pronounced in east Greenland, where there is generally little to no overlap of ^{10}Be PDFs and model histograms. The majority of data used to calibrate the Huy3 model comes from west Greenland, particularly from near Disko Bugt, so it is perhaps not surprising that this region shows the best data-model fit. Discrepancies in other regions suggest some combination of model limitations (e.g., inaccurate or missing forcings), bias in the data used to tune the model (e.g., use of ^{14}C ages), or systematic biases in the ^{10}Be database. We note that the Huy3 model does have earlier periods of GrIS retreat, as early as ~ 16 ka (Lecavalier et al., 2014), but this retreat is on the continental shelf and not in regions constrained by ^{10}Be data. In the following sub-sections, we discuss three hypotheses that could explain the spatial variability of terrestrial deglaciation and the data-model

misfit.

4.1 Elevation signal in ^{10}Be ages

It is possible that the asynchronous retreat of the GrIS observed here is due to different elevations of samples. East Greenland has higher mountains in general than south and west Greenland, so the earlier deglaciation observed there could be a result of ice thinning, if the samples were taken at higher elevations. However, there is no relationship between elevation and ^{10}Be ages in most parts of the ice sheet (Table 5); the only two regions with an age-elevation relationship significant at $p < 0.05$ are Disko Bugt and Johannes V. Jensen Land. The correlation coefficient for Disko Bugt is negative, suggesting older ages are at lower elevations, and therefore do not represent thinning of the ice sheet. There may be some thinning of the ice recorded in cosmogenic ages in Johannes V. Jensen Land, however these were excluded from the factor analysis and therefore cannot bias the analysis to thinning of the ice. We therefore believe that most to all of the cosmogenic ages from the island record retreat of the ice margin, not the GrIS thinning history.

4.2 ^{10}Be inheritance and post-exposure erosion

Systematic inheritance of ^{10}Be may account for the older ^{10}Be ages in some regions. Fast-flowing, warm-based ice may remove at least 2 m of bedrock over a glacial cycle, removing most inherited nuclides, but glacial erosivity is highly variable (e.g., Koppes and Montgomery, 2009), and surfaces beneath cold-based ice may be preserved for several glacial cycles (e.g., Davis et al., 2006; Stroeven et al., 2002; Corbett et al., 2011; 2013). Inheritance of ^{10}Be can be identified in individual studies if sufficient samples are analyzed. Ideally, anomalous ^{10}Be ages would be identified at the landform scale (e.g., at individual moraines), using quantitative statistics with more than seven samples per landform collected (Putkonen and Swanson, 2003).

Unfortunately, in most Greenland locations where ^{10}Be ages have been collected, too few samples were collected to quantitatively identify outliers. Only 28 grid cells (27%) have five or more ^{10}Be samples, and only six grid cells (6%) have 10 or more samples (Figure 10). This presents a significant limitation for objectively identifying outliers. However, *a priori* exclusion should remove most old outliers; in the original literature, 54 samples (out of 673) were identified as old outliers younger than 21 ka, while 159 samples are older than 21 ka. In this study, Chauvenet's criterion was applied at the model grid-cell scale where three or more samples are present, which led to the exclusion of ten ages. This approach therefore leads to the inclusion of ages that may have been excluded from original publications as outliers, but it also represents an objective method for excluding outliers and forcing ^{10}Be data to match model outputs.

One method for testing inheritance in ^{10}Be ages is to compare boulder and bedrock ^{10}Be ages, because erratic boulders are less likely to show significant inheritance (e.g., Briner et al., 2006). Figure 11 shows that the majority of regions with both boulder and bedrock ages have older bedrock ages than boulder ages. However, the Wilcoxon signed rank test for different distributions shows significantly different ages ($p < 0.05$) for only three regions: Sermilik, Sisimiut-Kangerlussuaq, and Scoresby Sund (Table 5). All of the coastal ages from Sermilik are from bedrock with no adjacent boulder samples; the boulder samples come from further inland. The "outliers" in the Sisimiut-Kangerlussuaq boulder distribution overlapping the bedrock ages come from the coast. It is therefore difficult to ascertain if the older bedrock ages are a result of systematic inheritance or geographic location in these cases. In the case of Scoresby Sund, it is possible that the bedrock samples are influenced by inheritance. However, these bedrock ages compose only 15% of all deglacial samples from Scoresby Sund, and therefore

cannot account for the trends observed across the island.

Post-exposure erosion removes ^{10}Be -rich surface layers, thereby biasing the samples towards younger ages. There is some evidence of erosion in east Greenland (Håkansson et al., 2011), although it has not been directly measured. If significant post-exposure erosion indeed occurred in east Greenland, it could not account for the older exposure ages found there; on the contrary, it would make the lead of east GrIS deglaciation even more pronounced.

4.3 Model resolution and approximations

A third hypothesis for the ^{10}Be data-model mismatch is that the ice-sheet model in its present form is unable to capture high-resolution changes in the ice-margin reconstructed by ^{10}Be studies. Young and Briner (2015) noted such deficiencies in their review of Disko Bugt deglaciation relative to the simulated deglaciation. ^{10}Be ages in Greenland are largely collected from within and near fjord systems. These fjords are generally 3-5 km wide and rarely wider than 10 km, and therefore cannot be fully resolved in a model that runs at 20 km resolution. So, while small-scale topographical features may significantly impact ice-margin behavior and be recorded in the ^{10}Be record (e.g., Lane et al., 2013), this behavior will not be captured in a model that does not resolve these topographic features.

The Huy3 model uses the shallow-ice approximation (Hutter, 1983; Simpson et al., 2009; Lecavalier et al., 2014). This means that longitudinal stresses are ignored in the model, and basal traction provides the only resistance to ice flow. This approximation works well for ice-sheet interiors where longitudinal stresses are minimal, but breaks down at ice-sheet margins. In particular, the approximation does not simulate marine-terminating outlet glaciers well (e.g., Dupont and Alley, 2005). ^{10}Be ages may therefore detect more rapid and earlier deglaciation in fjords, while the model will reconstruct slower and therefore later deglaciation.

Disko Bugt, Sisimiut-Kangerlussuaq and Nuuk are the only regions where ^{10}Be ages do not significantly lead model deglaciation ages (Figure 4). The Sisimiut-Kangerlussuaq and Nuuk ^{10}Be ages mostly measure terrestrial deglaciation in regions with more limited fjord systems, so model resolution is less of an issue (Larsen et al., 2013; Winsor et al., 2015a). For Disko Bugt, the data-model agreement likely also reflects the wealth of high precision relative sea-level data from this locality (Simpson et al., 2009; Lecavalier et al., 2014).

Several further model limitations may explain the model-data discrepancies. When comparing the modelled and observed present-day ice thickness distribution, the model overpredicts ice thickness at the margin, which is also likely true for past GrIS geometries. Due to the steep horizontal gradient in ice thickness at the margin, a small change in extent quickly propagates to large ice thickness changes. Additionally, the adopted grid spacing poorly resolves ice streams and outlet glaciers, which leads to an under-estimated discharge of ice at the margins, thereby overestimating ice thickness at the margins. This highlights the need to improve the model resolution, particularly in marginal areas with more complex topography. The Huy3 model is at present the highest resolution model reconstruction of the last Greenland deglaciation, but the comparison discussed above indicates that there are still limitations within this model that should be addressed in the future.

4.4 Climatic forcing

The largest source of uncertainty in the modeled ice-retreat reconstruction is the climate forcing (e.g., Zweck and Huybrechts, 2005). The Huy3 model uses a climate forcing based on the GRIP $\delta^{18}\text{O}$ record scaled to temperature, which differs significantly from more accurate recent temperature reconstructions of the deglacial interval using nitrogen isotopes (Figure 6b)

(Buizert et al., 2014). Such differences between the estimated and actual climate forcing could contribute to the data-model mismatch.

In addition, the ice-sheet model was not forced with regionally constrained temperatures, which are especially necessary given the significance of surface mass balance in governing ice-sheet extent. Marginal lakes have been recently used for climate reconstructions, which could constrain the climate forcing at the ice margin (e.g., D'Andrea et al., 2011; Young et al., 2011a; Axford et al., 2013; Carlson et al., 2014, Larsen et al., 2015), but these records do not extend back into the deglacial period. These model weaknesses are outstanding issues in most standard glacial cycle simulations (Huybrechts, 2002; Tarasov and Peltier, 2002; Simpson et al., 2009; Tarasov et al., 2012) and have ramifications on the ice-sheet model reconstruction and on the quality of the fit to the ^{10}Be ages.

The model does not explicitly incorporate the direct effects of ocean temperatures on ice-sheet mass loss (Rignot et al., 2010). Where the glacier terminus is grounded below sealevel, enhanced melting by warmer oceans can undercut the ice cliff, accelerating calving and ice retreat (Kirkbride and Warren, 1997; van der Veen, 2002), in addition to direct melting. If a floating ice shelf is present, warming ocean waters can lead to enhanced basal melting of the shelf, reducing buttressing effects and permitting faster flow and thinning of the ice (Schoof, 2007; Dupont and Alley, 2005; Shepherd et al., 2004). In addition, collapse of floating ice shelves can cause rapid acceleration and retreat of outlet glaciers feeding into the former ice shelf (e.g., Scambos et al., 2004; Marcott et al., 2011).

The lack of an ocean forcing can explain the discrepancy in areas such as southeast and south Greenland, where marine records show a general warming trend from ~15 ka to peak warmth ~10 ka (Figure 6a) (Williams, 1993; Solignac et al., 2004; Jennings et al., 2006; Winsor

et al., 2012). This warming continues through the Younger Dryas cold period, and is concurrent with increased sediment discharge from southeast Greenland (Carlson et al., 2008; Colville et al., 2011) and southern Greenland (Winsor et al., 2015b). The warming trend is also concurrent with the increase in the varimax factor scores for the 12 ka factor, which is most concentrated in east Greenland and northern southeast Greenland (Figure 6b). Peak ocean warmth occurs between approximately 12 ka and 9.5 ka, encompassing the maximum values of all factors except the 7.5 ka factor (Figure 6c). We therefore hypothesize that south and east GrIS margin retreat from the shelf and into fjords prior to modeled margin retreat could reflect this additional climate forcing that was excluded in the Huy3 model. Marine records from west Greenland show cold glacial conditions persisting until 7-8 ka near the end of west GrIS retreat and the peak in the 7.5 ka factor (Figure 6a, 6c)(Jennings et al., 2014), possibly explaining the agreement between ice-sheet-modeled deglaciation and ^{10}Be -observed deglaciation as the main climate forcing would be atmospheric changes that were included in the ice-sheet model.

5. Conclusions

Our analyses of the ^{10}Be database highlights several important deglacial features of the GrIS. While the majority of terrestrial ice retreat likely occurred following the Younger Dryas in the early Holocene, it was spatially variable, with factor analysis indicating it can be explained by the combination of 4 orthogonal factors. In general, east Greenland is best explained by the 12 ka and 11 ka factors, south Greenland is best explained by the 11 ka and 10 ka factors, and west Greenland is best explained by the 10 ka and 7.5 ka factors. These factors define a progression of GrIS retreat from east to south to west Greenland. This pattern is not observed in a similar analysis of ^{14}C ages, and the Huy3 ice sheet model reconstruction does not simulate the earlier onset of GrIS retreat in east and south Greenland, where it lags the ^{10}Be ages. This could be

partly due to the minimum-limiting nature of ^{14}C ages and the resolution of the model, which is too coarse to resolve the many fjord systems in these regions, limiting ice-ocean interactions. Also, the Huy3 model does not include any direct influence of ocean warming on mass loss, and east to south GrIS retreat is concurrent with general surface and subsurface ocean warming suggesting a potential causal linkage. Conversely, the model captures the deglacial pattern of west GrIS retreat, where fjord systems are more limited (with the exception of Disko Bugt) and where ocean temperatures did not begin to warm until near the end of the deglaciation. As such, the simpler atmospheric model forcing and ice-sheet model resolution were sufficient to simulate deglaciation in this region.

Future ice-sheet modeling efforts should focus on improving model resolution to resolve the complex topography of Greenland and include interaction with ocean waters. Specifically, the model would benefit from increased resolution, dynamics derived from geophysical processes, and the inclusion of ice-ocean interactions using ocean temperature forcing informed by ocean proxy records. As advances in modeling techniques and resolution continue, the ^{10}Be database presented here will continue to be a useful tool for developing and validating models, particularly as new data continue to be collected and published.

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Table Captions

Table 1: Description of all published papers with ^{10}Be ages in Greenland, with region of publication and number of ^{10}Be samples. Full references in reference list.

Table 2: Description of all published papers with ^{14}C ages in Greenland, with number of ^{14}C samples. Full references in reference list.

Table 3: Eigenvalues for initial factors in ^{10}Be Q-mode analysis.

Table 4: Eigenvalues for initial factors in ^{14}C Q-mode analysis.

Table 5: Pearson's correlation coefficient and p values for ^{10}Be age-elevation relationships for the different regions of Greenland.

Table 6: Results of Wilcoxon signed-rank test for bedrock and boulder ages.

Figure Captions

Figure 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.

Figure 2: Map of all published ^{14}C ages from Greenland. Individual ^{14}C ages are represented by diamonds, with colors corresponding to the age of the sample (note the scale in this color bar is different from Figure 1).

Figure 3: Schematic diagram showing method for calculating normalized grid cell PDFs for factor analysis, and regional PDFs for comparison with the Huy3 ice sheet model reconstruction. The reader is referred to the text for a full description of the Figure.

Figure 4: Summed grid cell PDFs of deglacial ^{10}Be ages in Greenland, compared with deglacial ages in the Huy3 model. Each region is labeled with the number of samples indicated. Gray shading is the PDF while the green bars are the model results.

Figure 5: ^{10}Be Factor Analysis (a) Factor loadings in individual grid cells with the factors noted by the peak of that factor; height of the bar denotes the strength of each factor in that cell. (b) Dominant factor in each grid cell, defined as the factor with the highest loading in that cell; colors correspond to (a). (c) Communalities of factors for each grid cell, which indicates how much of the variance of each grid cell is explained by the sum of the four factors.

Figure 6: Comparison of ^{10}Be factors with climatic forcings. (a) Mg/Ca-derived subsurface water temperatures at Eirik Drift, south Greenland (points), with 3-point running average (line) (MD99-2227, Winsor et al., 2012) and percentage of warm-water foraminifera in Disko Bugt (orange) (HU2008029-070CC, Jennings et al., 2014); (b) Huy3 temperature forcing (red; GRIP ice core, Lecavalier et al., 2014) and reconstructed central Greenland air surface temperatures (blue; GISP2 ice core, Buizert et al., 2014); (c) ^{10}Be varimax factor loadings (this study), with colors representing different factors labeled by their peak value. Inset map shows approximate locations of ice and ocean core records.

Figure 7: ^{14}C varimax factor loadings, with colors representing different factors labeled by their peak value.

Figure 8: ^{14}C Factor Analysis (a) Factor loadings in individual grid cells with the factors noted by the peak of that factor; height of the bar denotes the strength of each factor in that cell. (b) Dominant factor in each grid cell, defined as the factor with the highest loading in that cell; colors correspond to (a). (c) Communalities of factors for each grid cell, which indicates how much of the variance of each grid cell is explained by the sum of the four factors.

Figure 9: Comparison of average ^{10}Be and oldest ^{14}C ages in the same grid cell. Uncertainty bars for ^{14}C ages reflect 1-sigma uncertainty for the sample; uncertainty bars for ^{10}Be ages reflect standard error of ^{10}Be ages in the grid cell (if 3 or more samples are present) or average analytical uncertainty of ages (if fewer than 3 samples are present).

Figure 10: Histogram showing the number of model grid cells with a given number of ^{10}Be samples.

Figure 11: Comparison via whisker plots of bedrock (blue) and boulder (red) ages for all regions in Greenland (labeled) with both bedrock and boulder ages. The box shows the one sigma range with the bar in the middle being the median age while the lines (whiskers) denote the two sigma range of the samples.

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Table 1

Study Title	Region	Number of Samples
Håkanson et al. 2007a	Scoresby Sund	4
Håkanson et al. 2007b	Store Koldewey	7
Kelly et al. 2008	Scoresby Sund	38
Roberts et al. 2008	Sermilik	12
Håkanson et al. 2009	Scoresby Sund	43
Rinterknecht et al. 2009	Sissimiut-Kangerlussuaq	12
Roberts et al. 2009	Sissimiut-Kangerlussuaq	16
Moller et al. 2010	Johannes V. Jensen Land	16
Corbett et al. 2011	Disko Bugt	30
Håkanson et al. 2011	Scoresby Sund	14
Young et al. 2011a	Disko Bugt	18
Young et al. 2011b	Disko Bugt	8
Hughes et al. 2012	Sermilik	12
Levy et al. 2012	Sissimiut-Kangerlussuaq	9
Briner et al. 2013	Disko Bugt	2
Corbett et al. 2013	Upernavik	33
Kelley et al. 2013	Disko Bugt	12
Lane et al. 2013	Uummannaq	15
Larsen et al. 2013	Nuuk	47
Levy et al. 2014	Scoresby Sund	12
Lowell et al. 2013	Scoresby Sund	6
Roberts et al. 2013	Uummannaq	17
Young et al. 2013	Disko Bugt	21
Alexanderson and Håkansson 2014	Scoresby Sund	8
	Disko Bugt, Paamiut, Sissimiut-	
Carlson et al. 2014	Kangerlussuaq, Narsarsuaq	29
Dyke et al. 2014	Sermilik	23
Nelson et al. 2014	Narsarsuaq	11
Rinterknecht et al. 2014	Disko Bugt	7
Winsor et al. 2014	Narsarsuaq	17
Corbett et al. 2015	Thule	28
	Narsarsuaq, Paamiut, Sissimiut-	
Winsor et al. 2015	Kangerlussuaq, Nuuk	47
Kelley et al. 2015	Disko Bugt	18
Cronauer et al. 2015	Disko Bugt	11
Young et al. 2015	Disko Bugt	9
Larsen et al. 2016	Johannes V. Jensen	6
Corbett et al. 2016	Thule	28
Levy et al. 2016	Scoresby Sund	27

Table 2

Study	Number of Samples
Fredskild 1973	2
Kelly 1974	1
Kelly 1975	1
Weidick 1975	2
Funder 1979	1
Bennike et al. 2002	6
Kuijpers et al. 2003	16
Weidick et al. 2004	12
Dyke 2004 (and references therein)	235
Lloyd et al. 2005	7
Jennings et al. 2006	41
Sparrenbom et al. 2006a	30
Sparrenbom et al. 2006b	38
Bennike 2007	1
Bennike and Sparrenbom 2007	3
Long et al. 2008	6
Long et al. 2009	9
Nørgaard-Pedersen and Mikkelsen 2009	8
Briner et al. 2010	18
Bennike et al. 2011	9
Jennings et al. 2011	9
Larsen et al. 2011	10
Lloyd et al. 2011	1
Olsen et al. 2011	24
Young et al. 2011a	3
Young et al. 2011b	7
Bennike and Wagner 2012	5
Kelley et al. 2012	6
Massa et al. 2012	28
Storms et al. 2012	17
Briner et al. 2013	15
Lane et al. 2013	2
Levy et al. 2013	20
Lowell et al. 2013	55
Ó Cofaigh et al. 2013	19
Perner et al. 2013	16
Sparrenbom et al. 2013	15
Young et al. 2013	3
Briner et al. 2014	22
Håkansson et al. 2014	11

Larsen et al. 2014	15
Corbett et al. 2015	4
Cronauer et al. 2015	6
Sheldon et al. 2016	2
Hogan et al. 2016	6

Table 3

Factor number	Eigenvalues	Percent variance explained	Cumulative percent variance explained
1	33.8	39.3	39.3
2	11.9	13.8	53.1
3	9.5	11.0	64.1
4	7.0	8.1	72.3
5	4.6	5.4	77.6
6	4.3	5.0	82.7

Table 4

Factor number	Eigenvalues	Percent variance explained	Cumulative percent variance explained
1	60.6801	28.6227	28.6227
2	33.562	15.8311	44.4538
3	20.9421	9.8783	54.3322
4	14.6875	6.9281	61.2602
5	12.1803	5.7454	67.0057
6	8.7107	4.1088	71.1145
7	6.6403	3.1322	74.2467
8	5.3779	2.5367	76.7834
9	4.4372	2.093	78.8764
10	3.9669	1.8712	80.7476

Table 5

Region	Pearson's Correlation Coefficient	P-value
Thule	-0.323	0.177
Upernavik	0.108	0.643
Uummannaq	-0.323	0.177
Disko Bugt	-0.202	0.022
Sissimiut-Kangerlussuaq	0.103	0.529
Nuuk	0.160	0.310
Paamiut	0.057	0.806
Narsarsuaq	0.155	0.441
Bernstorffs	-0.105	0.720
Sermilik	0.095	0.660
Kangerdlussuaq	-0.596	0.158
Scoresby Sund	-0.014	0.912
Store Koldewey	0.224	0.857
Johannes V. Jensen Land	0.576	0.008

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

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Figure 10

Figure 11