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Corresponding Author: Ms. Lee B Corbett,

Corresponding Author's Institution: University of Vermont

First Author: Lee B Corbett

Order of Authors: Lee B Corbett; Paul R Bierman; Jason P Briner; Joseph A Graly; Thomas A Neumann; Dylan H Rood; Robert C Finkel

Abstract: In this study, we use a rare isotope, 10Be, to determine when and how rapidly a sparsely studied region of the northwest Greenland coast was deglaciated. Despite the fact that such information is critical to understanding future behavior of the Greenland Ice Sheet, little is known about the timing or rate of ice loss in northwest Greenland, the region with the most marine-based ice. Here, we report the concentration of cosmogenic 10Be in 12 boulders and show that outlet glaciers likely retreated 100 km in no more than a few hundred years at the end of the Last Glacial Maximum around 11,000 years ago. This abrupt loss of ice was forced by post-glacial warming and sea level rise, which together destabilized fjord-based outlet glaciers. Our results suggest an intimate relationship between warming climate, increasing sea level, and ice loss rate, a positive feedback process that could lead to a significant decrease in global ice cover on human time scales. Our work demonstrates that rapid loss of ice in Greenland has occurred in the past; because anthropogenic warming and associated sea level rise have been widely predicted for the future, it is crucial to understand the rate and distribution of these processes.

Cover Letter

The University of Vermont
DEPARTMENT OF GEOLOGY
DELAHANTY HALL
180 COLCHESTER AVENUE
BURLINGTON, VERMONT 05405-1758
(802) 656-3396
FAX (802) 656-0045

To the Editor:

Please consider the attached manuscript, entitled **Rapid Deglaciation in Northwest Greenland Circa 11 ka BP**, for publication as a Rapid Communication in *Quaternary Science Reviews*.

In this manuscript, we show evidence for extremely rapid deglaciation of northwest Greenland at the end of the Last Glacial Maximum. Our work explores the relationships between temperature, sea level, and ice retreat rate and timing. We use our discovery of rapid deglaciation in Greenland to question assumptions made by the most recent Intergovernmental Panel on Climate Change, and to argue that rapid deglaciation episodes are likely in a warming climate. For these reasons, we are confident that our work will be of interest to a wide audience in the Quaternary Science community.

Our manuscript is 1,874 words and has four figures and 30 references in total. Please note that both Figure 3 and Figure 4 contain information previously published by other authors, along with the data from this study. All authors of our manuscript have read and approved the text, and it has not been submitted to another journal.

We are confident that our work investigating rapid deglaciation in Greenland should be published in *Quaternary Science Reviews* because of its wide readership base. Thank you for considering our manuscript.

Sincerely,

Lee Corbett
Lee B Corbett

Department of Geology, University of Vermont
180 Colchester Ave, Burlington VT 05405
Ashley.Corbett@uvm.edu
(802) 380-2344

RAPID DEGLACIATION IN NORTHWEST GREENLAND CIRCA 11 ka BP

Lee B. Corbett*[1], Paul R. Bierman[1], Jason P. Briner[2], Joseph A. Graly[1], Thomas A. Neumann[3],
Dylan H. Rood[4], and Robert C. Finkel[5]

* Contact Author: Ashley.Corbett@uvm.edu, (802) 380-2344
[1]Department of Geology, University of Vermont, Burlington, VT 05405
[2]Department of Geology, University at Buffalo, Buffalo NY 14260
[3]NASA Goddard Space Flight Center, Greenbelt, MD 20770
[4]Center for Accelerator Mass Spectrometry, Lawrence Livermore National Laboratory, Livermore, CA 94550
[5]Department of Earth and Planetary Science, University of California Berkeley, Berkeley, CA 94720

Abstract

In this study, we use a rare isotope, ^{10}Be, to determine when and how rapidly a sparsely studied region of the northwest Greenland coast was deglaciated. Despite the fact that such information is critical to understanding future behavior of the Greenland Ice Sheet, little is known about the timing or rate of ice loss in northwest Greenland, the region with the most marine-based ice. Here, we report the concentration of cosmogenic ^{10}Be in 12 boulders and show that outlet glaciers likely retreated 100 km in no more than a few hundred years at the end of the Last Glacial Maximum around 11,000 years ago. This abrupt loss of ice was forced by post-glacial warming and sea level rise, which together destabilized fjord-based outlet glaciers. Our results suggest an intimate relationship between warming climate, increasing sea level, and ice loss rate, a positive feedback process that could lead to a significant decrease in global ice cover on human time scales. Our work demonstrates that rapid loss of ice in Greenland has occurred in the past; because anthropogenic warming and associated sea level rise have been widely predicted for the future, it is crucial to understand the rate and distribution of these processes.

1. Introduction

Temperature and sea level have played important roles in controlling the dynamics of the Greenland Ice Sheet in the past, and will continue to do so into the future (Alley et al., 2005; Gregory et al., 2004). Warming Arctic temperatures increase melting rates of ice, changing both the thickness and extent of glaciers (Hanna et al., 2008). As seas rise, water lifts grounded glacial ice off its bed and allows it to retreat from protective terminal moraine complexes. Floating ice loses mass much more rapidly than grounded ice through the process of calving (Kirkbride, 1993), allowing large areas of ice to disappear over time scales of years to decades (Joughin et al., 2004). Since the loss of ice cover impacts surface albedo, and the addition of icebergs from once-grounded ice sheets contributes to further sea level rise, these scenarios represent non-linear ice sheet responses to climate change.

Rapid ice discharge caused by sea level rise is one element of dynamically forced discharge and is not well understood (Alley et al., 2005; Pfeffer et al., 2008), causing the International Panel on Climate Change Fourth Assessment to exclude changes in dynamic effects from its forecasts (IPCC, 2007). However, recent work demonstrates that dynamic loss of ice is indeed an important response to and component of climate change. Rapid loss of ice occurred on the margin of the Laurentide Ice Sheet at the termination of the Last Glacial Maximum about 9,500 years ago (Briner et al., 2009). Since the Greenland Ice Sheet (Fig. 1) currently contains about 7 m of global sea level equivalent (Alley et al., 2005), it is imperative to determine whether such rapid loss of ice is also possible in Greenland.

Northwest Greenland is characterized by abundant fjords and vast amounts of ice adjacent to the present-day coastline; it is, therefore, highly susceptible to rapid ice loss through calving. However, few data are available to constrain the timing of ice loss there at the end of the

Last Glacial Maximum. Only three radiocarbon ages exist from this region, placing deglaciation between about 9 and 10.6 calibrated ka BP (Bennike, 2000, 2008; Fredskild, 1985). Most dating of ice retreat in Greenland has been concentrated in limited geographic areas including Sisimiut Fjord (Rinterknecht et al., 2009; Roberts et al., 2009) and Jakobshavn Icefjord (Long and Roberts, 2002; Weidick and Bennike, 2007) in west Greenland, Scoresby Sund (Kelly et al., 2008) in east Greenland, and the Quassimiut Lobe in south Greenland (Weidick et al., 2004).

2. Experimental Design and Methods

To investigate the rate of ice sheet retreat in northwest Greenland after the Last Glacial Maximum, we collected samples for the analysis of *in situ* cosmogenic ^{10}Be (Gosse and Phillips, 2001) between 72.5 and 72.8°N near the town of Upernavik (Figs. 1 and 2). Post-glacial relative sea level was at most 20 m above present (Funder and Hansen, 1996; Simpson et al., 2009), hence isostatic emergence does not control cosmogenic ages. We sampled 12 glacially-deposited boulders along a 100-km northwest to southeast transect parallel to ice flow near Upernavik (Fig. 1). Samples came from six different locations along this transect, at elevations ranging between 20 and 775 m above sea level (a sampling scheme modeled after Stone et al. (2003)). All sampled boulders lay directly on bare, glacially sculpted bedrock outcrops, unrelated to moraines; hence, the ^{10}Be exposure ages indicate when the landscape was exposed from under ice at the end of the Last Glacial Maximum. Determining exposure ages along a transect parallel to ice flow yields information about the rate at which the ice margin retreated to its present position (Briner et al., 2009; Roberts et al., 2009; Stone et al., 2003).

In the field, we collected the top several cm of material from glacially-transported boulders that were not sheltered or small enough to be covered by snow. We isolated quartz through physical and chemical processes. After quartz purification, we added ^{9}Be carrier and isolated Be in the University of Vermont Cosmogenic Laboratory (see Supplementary Information). Isotopic analysis took place at the Center for Accelerator Mass Spectrometry at Lawrence Livermore National Laboratory. We calculated exposure ages with the CRONUS Earth calculator, using a variety of production rate calibrations to understand the range of potential dates represented by the measured ^{10}Be concentrations. The ^{10}Be ages displayed here were calculated using a Northeastern North America production rate (Balco et al., 2009) and a scaling scheme from Desilets and Zreda (2003).

3. Results and Discussion

All samples contained ^{10}Be inventories consistent with Late Pleistocene exposure, ranging between $5x10^{4}$ and $9x10^{5}$ atoms g^{-1} (see Supplementary Information). Internal uncertainties range between 2 and 5%, with an average of 3.3%. Calculated ^{10}Be ages can vary by as much as 5% based on the chosen scaling scheme for spallation, and by as much as 14% based on the chosen ^{10}Be production rate.

Two of the 12 boulder samples returned ages that were appreciably older than the rest (20 and 21 ka). It is possible that these older ages represent thinning of the Greenland Ice Sheet at the end of the Last Glacial Maximum, thereby exposing high-elevation samples before low-elevation samples (Roberts et al., 2009). The older ages may also have been caused by inherited ^{10}Be from previous periods of exposure.

The exposure ages of the remaining 10 boulder samples range from 10.6 to 14.0 ka, exhibiting scatter that is common in cosmogenic data sets, especially those from the Arctic where subglacial erosion rates are low (Bierman et al., 1999) (Figs. 3 and 4). It is likely that the older samples contain inherited ^{10}Be from previous periods of exposure and therefore do not record deglaciation age faithfully. The seven youngest samples, which range in age between 10.6 and 11.7 ka and have overlapping one-sigma uncertainties, are centered on 11.1 ka. We interpret the average age of these young samples (n=7) to be the best estimate for the deglaciation age of the Upernavik coast.

There is little trend in ages along the length of the transect indicating that ice retreated 100 km very rapidly (Fig. 3). To calculate a rate of ice sheet retreat, we systematically simulated potential linear retreat patterns taking into account the location and uncertainty of each age measurement (see Supplementary Information). The maximum likelihood ice retreat rate is 183 m yr^{-1}, with possible rates as low as 109 m yr^{-1} and as high as 599 m yr^{-1} (1σ). The data imply that maximum likelihood duration of ice retreat was 545 years, and may have ranged between 168 and 922 years (1σ). These rates indicate that vast amounts of northwestern Greenland ice were lost over a very short time, perhaps only several human lifetimes.

Rapid deglaciation of the Upernavik coast at 11.1 ka BP was likely caused by warming temperatures and rising sea levels associated with the termination of the Last Glacial Maximum. An increase in sea level may have provided enough leverage to float a significant portion of the low-elevation, marginal ice near Upernavik, leading to accelerated calving and the loss of large volumes of ice on a short time scale. While sediment deposition at a glacier’s terminus can provide sufficient anchoring to allow continued glacier grounding when sea-levels rise slowly (Alley et al., 2007), sea-level rise at the end of the Younger Dryas may have been rapid enough to outpace this stabilizing mechanism. The rapid retreat measured here likely represents a threshold response, during which stable grounded ice became floating ice that was highly susceptible to calving and rapid retreat (Briner et al., 2009).

Our results are consistent with long-term Late Glacial trends in northern hemisphere climate (Fig. 4). Taking uncertainties into consideration, the rapid deglaciation of the Upernavik coast at 11.1 ka BP is consistent with the end of post-Younger Dryas warming (Alley, 2000; Taylor et al., 1997), which coincided with a significant increase in Arctic temperatures. This time period also marked the introduction of large amounts of fresh water to the North Atlantic through Meltwater Pulse 1B, which some think increased global sea level abruptly (Fairbanks, 1989). This combination of warmer temperatures and rising sea level likely represented a “double threat” to the marginal areas of the Greenland Ice Sheet, resulting in the loss of vast amounts of ice in only hundreds of years.

The rapid deglaciation of the Upernavik coast exhibits a pattern similar to the rapid deglaciation of Sam Ford Fjord on the east coast of Baffin Island (Briner et al., 2009) (Fig. 3). Both datasets indicate that significant ice retreat (100 km in Upernavik and 80 km in Baffin) occurred in a very short time. These events, however, do not correspond temporally. When the data from Briner et al. (2009) are reprocessed using the same production rate and scaling factors as the data in this study, the rapid deglaciation in Baffin appears to be about 1.5 ka younger than the rapid deglaciation in Greenland. Perhaps this offset is due to fjord geometry. The shallow shelf at the end of the Sam Ford Fjord in Baffin (Briner et al., 2009) may have helped to stabilize the outlet glacier and therefore allowed it to persist in an enlarged form for longer than the outlet glaciers in Upernavik. Regardless, these two events, at the same latitude and on opposite sides of Baffin Bay, are likely responses to the same climate forcing filtered through local effects such as fjord geometry.

4. Conclusions

This study demonstrates that glacial ice in Upernavik disappeared on a human time scale, likely due to increasing temperatures and rising seas during the rapid post-Younger Dryas warming. Positive feedback loops involving surface albedo and freshwater additions to the sea would have allowed this system to respond non-linearly to the initial forcings. It is widely accepted that humans have altered Earth's climate causing measurable changes in atmospheric chemistry, global temperatures, and sea level (IPCC, 2007). In this study, we infer that rising temperature and sea-level forcings led to rapid loss of Greenland's ice in the past; thus, it is prudent to consider the probability of rapid ice loss from Greenland in the future.

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Figure Legends

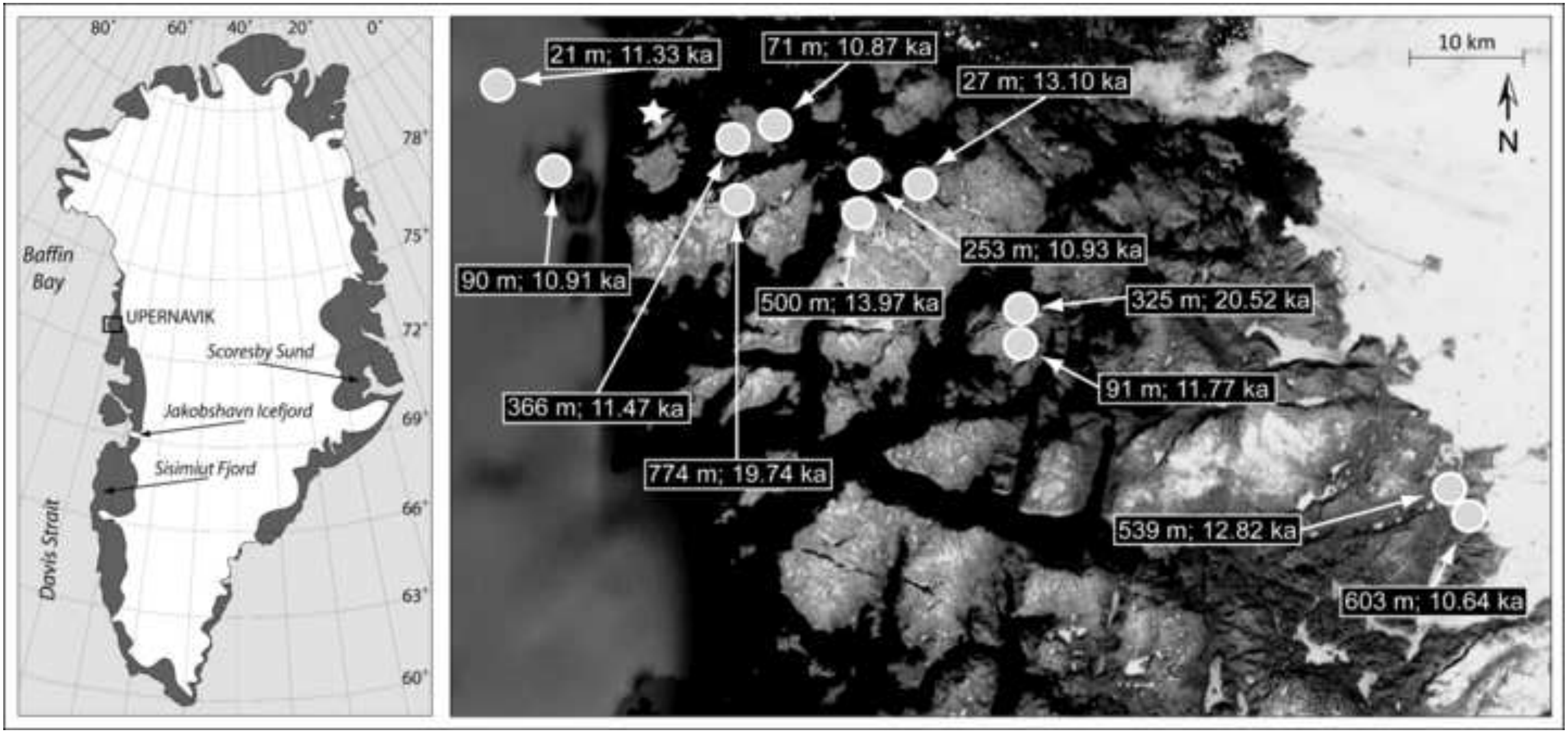
Figure 1: Upernavik (72°N, 56°W), Northwest Greenland. Left Panel: Upernavik is located in northwest Greenland, where the ice sheet extends almost to the coastline. The black rectangle representing Upernavik corresponds to the enlarged satellite image (Google Earth) to the right. Other location names refer to those mentioned in the text. Right Panel: Boulder samples were collected along a 100-km northwest-southeast transect. The elevation and model exposure age are shown for each sample. The white star shows the location of the town of Upernavik.

Figure 2: Upernavik Topography. The Upernavik area is characterized by heavily dissected flat-lying uplands, steep and rugged topography, and deep fjords. No marine sediments are visible and till is sparse.

Figure 3: Boulder Exposure Ages and Distance Along Transect. Ten of the 12 Upernavik boulder samples have exposure ages between 10.6 to 14.0 ka (circles). The 7 youngest samples (filled circles) are centered on 11.1 ka, providing the best estimate for the deglaciation age of the Upernavik area (trend line shows best linear fit). Samples with older exposure ages (open circles) likely contain ^{10}Be inherited from previous periods of exposure. Simulations suggest that deglaciation occurred over only hundreds of years. A similar study on the east coast of Baffin Island (Briner et al., 2009) found that the same trend occurred at the same latitude (grey squares), but 1.5 ka later.

Figure 4: Rapid Deglaciation of Upernavik and Regional/Global Trends. A.) Nominal eustatic sea level from multiple sites around the world, showing rapid sea level rise during deglaciation and after the Younger Dryas (Fleming et al., 1998). B.) Oxygen isotope ratios from the GISP2 ice core, showing pronounced warming after the Younger Dryas (Stuiver and Grootes, 2000). C.) Summed probability analysis of Upernavik boulder exposure ages. The small peaks (thin lines) represent individual samples and their uncertainties, while the large peaks (thick line) represent the cumulative probability of the data set. The wide, light gray bar represents the timing of the Younger Dryas (Alley, 2000) and the narrow, dark gray bar represents the timing of Meltwater Pulse 1B (Fairbanks, 1989).

Figure 1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Baffin Bay
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Sisimiut Fjord
Davis Strait
21 m; 11.33 ka
71 m; 10.87 ka
27 m; 13.10 ka
10 km
N
90 m; 10.91 ka
253 m; 10.93 ka
500 m; 13.97 ka
325 m; 20.52 ka
91 m; 11.77 ka
366 m; 11.47 ka
774 m; 19.74 ka
539 m; 12.82 ka
603 m; 10.64 ka

Figure 2

Figure 3

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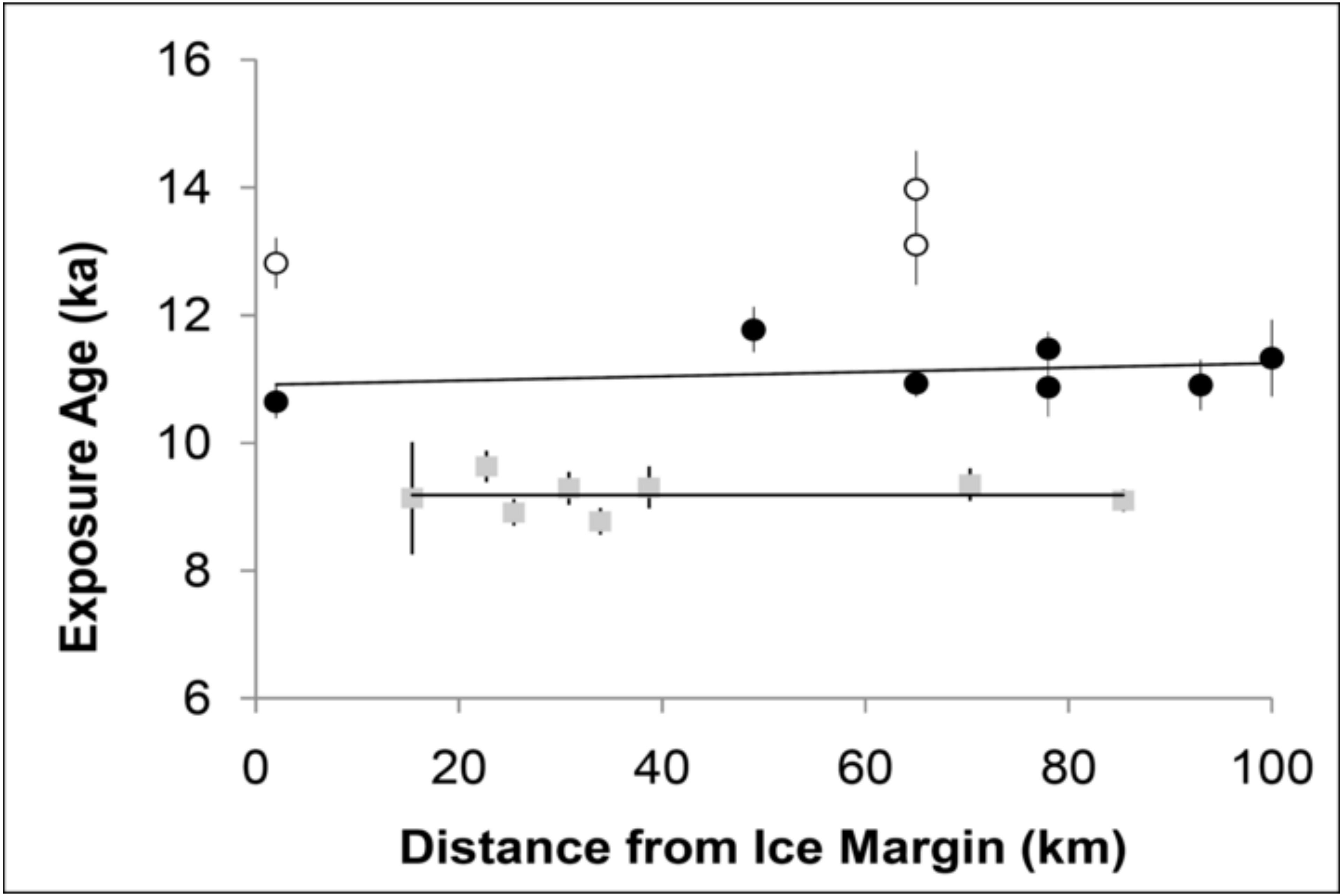
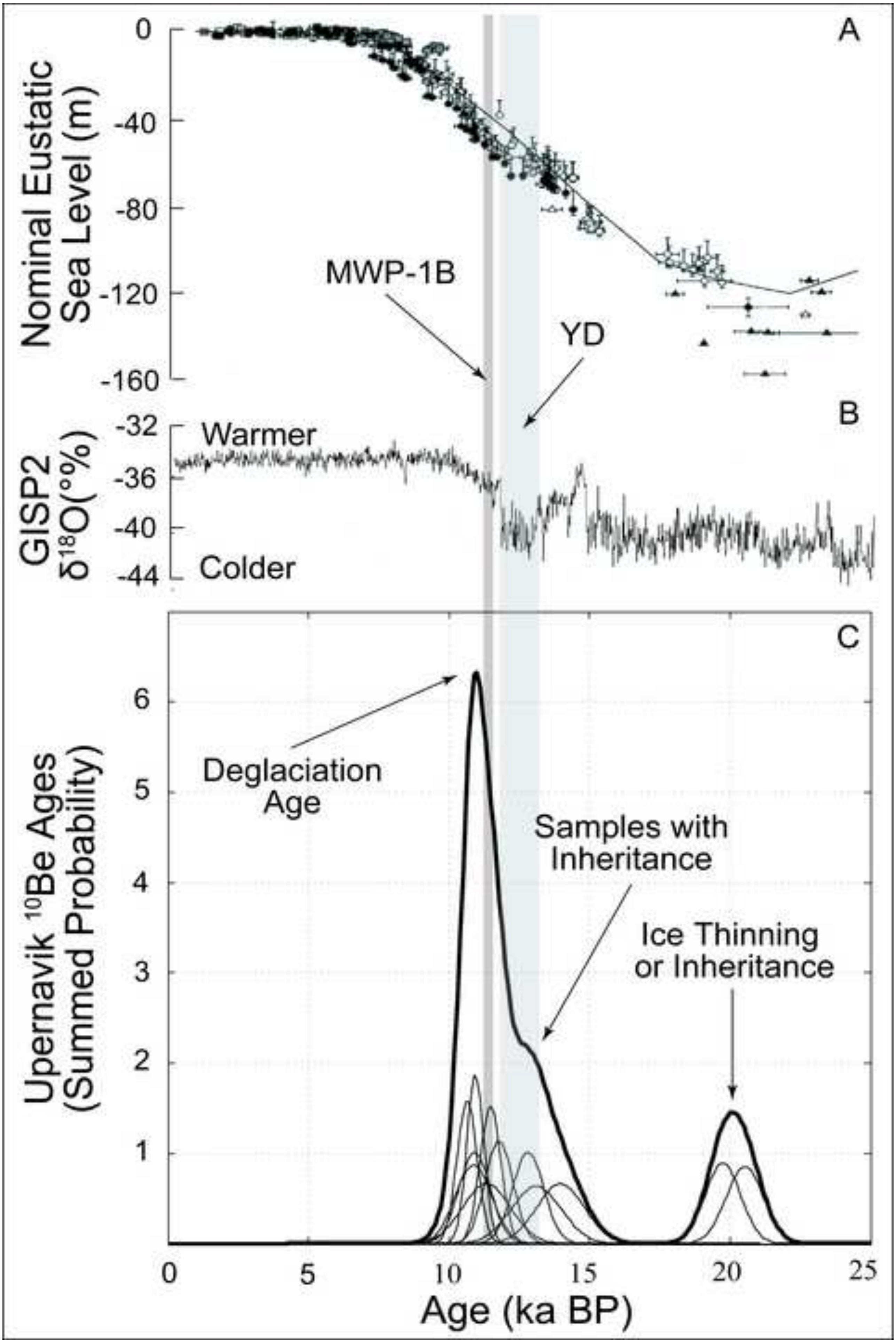


Figure 4


A
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-36
-40
-44
Warmer
Colder
C
Upernavik 10Be Ages (Summed Probability)
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4
3
2
1
Deglaciation Age
Samples with Inheritance
Ice Thinning or Inheritance
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5
10
15
20
25
Age (ka BP)

Supplementary Information