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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; Dylan H Rood

Abstract: Boulders and landscapes preserved beneath cold-based, non-erosive glacial ice violate assumptions associated with simple cosmogenic exposure dating. In such a setting, simple single isotope exposure ages over estimate the latest period of surface exposure; hence, alternate approaches are required to constrain the multi-stage exposure/burial histories of such samples. Here, we report 28 paired analyses of 10Be and 26Al in boulder samples from Thule, northwest Greenland. We use numerical models of exposure and burial as well as Monte Carlo simulations to constrain glacial chronology and infer process in this Arctic region dominated by cold-based ice. We investigate three specific cases that can arise with paired nuclide data: (1) exposure ages that are coeval with deglaciation and 26Al/10Be ratios consistent with constant exposure; (2) exposure ages that pre-date deglaciation and 26Al/10Be ratios consistent with burial following initial exposure; and (3) exposure ages that pre-date deglaciation and 26Al/10Be ratios consistent with constant exposure. Most glacially-transported boulders in Thule have complex histories; some were exposed for tens of thousands of years and buried for at least hundreds of thousands of years, while others underwent only limited burial. These boulders were recycled through different generations of till over multiple glacial/interglacial cycles, likely experiencing partial or complete shielding during interglacial periods due to rotation or shallow burial by sediments. Our work demonstrates that the landscape in Thule, like many high-latitude landscapes, was shaped over long time durations and multiple glacial and interglacial periods throughout the Quaternary.

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

January 28, 2016

To the Editor:

After performing a second set of revisions from two reviewers, we are resubmitting our manuscript, **Constraining Multi-Stage Exposure-Burial Scenarios for Boulders Preserved Beneath Cold-Based Glacial Ice in Thule, Northwest Greenland**, for publication in *Earth and Planetary Science Letters*.

We appreciated the additional comments from the two Reviewers who revisited the manuscript and are glad to hear that our first round of revisions was effective. During this second round, we focused on making the minor wording changes suggested and providing additional information about quantification of Al in samples. Attached, you will find a list of the reviewers' suggestions and details about how we incorporated those suggestions.

We are optimistic that these minor revisions have finished polishing the manuscript to ready it for publication. Thank you in advance for considering our revised draft.

Sincerely,

Lee Corbett (for the author team)

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

Please note: Our responses to the reviewers can be found in red, below.

Comments from Derek Vance, Editor

Ms. Ref. No.: EPSL-D-15-00732R1
Title: Constraining multi-stage exposure-burial scenarios for boulders preserved beneath cold-based glacial ice in Thule, Northwest Greenland
Earth and Planetary Science Letters

Dear Dr. Corbett,

Thank you for the re-submission of this paper and for dealing so thoroughly with the comments of the previous reviewers. As I suggested I would in my decision letter last time, I sent the revision to two of the previous reviewers. Both or these are very happy with the revision and have only minor comments.

Please could you attend to the final points listed below on your revised manuscript, and then I will be able to accept it for publication. Given that the requested revisions are fairly minor the new version is required within 1 month.

We are glad to hear that our treatment of the first round of reviews was satisfactory. We have made the minor changes detailed below and are resubmitting a revised draft for publication. Most of our work focused on adding additional information about quantification of total Al in the samples as suggested by Reviewer #1.

Comments from Reviewer #1

The author's did a good job incorporating the suggestions, the revised manuscript is much improved and I recommend publication in EPSL for the reasons outlined in my first review. The incorporation of section 5.5 is a significant improvement and the 'AMS standard' issue is now well explained.

We thank the Reviewer for making these suggestions in the initial review and are glad to hear the revisions we made, particularly the addition of Section 5.5, improved the manuscript.

One 'misunderstanding' and remaining problem: I was not implying to produce more data, but I still would like to see 27Al raw data and more details about how the ICP-OES based 27Al concentrations and errors are constraint. Still no information about this, so I cannot fully re-calculate the 26Al ages and burial numbers. I actually would again motivate the authors to include these numbers in the supplemental table. Not much work, but important!

We are grateful to the reviewer for clarifying this point and regret the misunderstanding that occurred during the first round of revisions. We agree that ^{27}Al quantification is important and have sought to make this element of the manuscript more accessible. To the text in the methods section, we added information about which ICP-OES emission lines we used as well as statistics about the replication of Al quantification of blanks (whereas before we had reported only data for the samples). To the table in the data supplement, we added two columns that provide ICP-quantified total Al based on each of the two replicates. We think these additions, coupled with the pre-existing text, provide the necessary background for the reader to understand Al quantification and uncertainty.

This paper is going to be very helpful for many future studies. Nice work!

Comments from Reviewer #2

Based on the 'response to reviews' letter and the new manuscript itself, it is clear the authors have made an admirable effort to address and incorporate every comment from all three reviewers. I really like the revised version and find it immediately understandable from both a cosmogenic and a geomorphological point of view. The article will appeal to and be more accessible to a broader audience and be more widely cited. This version presents and reveals some of the interesting details of two nuclide analysis and interpretation in a way that can be understood by non-experts. In detail, for example, the explanation on the bottom of page 16 of the samples whose ratio suggests continuous simple exposure, but whose ages are too old in light of stratigraphic relations, is excellent.

I would like to comment and say the authors are completely correct in their assessment of the 26Al data. None of their 26/10 points is outside the realm of 'natural' 26/10 ratios reported by many other groups. Their data is very robust.

We thank the Reviewer for the positive feedback and are happy to hear that the revisions we performed make the manuscript more accessible and relevant.

Very minor detailed comments:
p. 3 line 46 cosmic rays not cosmogenic rays.
Change made.

p. 6 line 114 I don't think the hyphen is correct here, no hyphen needed : glacially-deposited boulders.
Change made.

p. 7 line 117 ; also p. 17 line 354 I would spell it orthogneisses not orthogneises.
Change made in both locations, plus p. 5 line 85.

p. 15 line 309 I believe it is the change in dominance of obliquity (41 ka) to dominance of eccentricity (100 ka), not change in the obliquity pattern.
We have rewritten the phrase in question to read: "…when the tempo of glacial cycles changed from 41 ka to 100 ka (Raymo et al., 1997)".

Highlights:

Constraining multi-stage exposure-burial scenarios for boulders preserved beneath cold-based glacial ice in Thule, Northwest Greenland

Lee B. Corbett*[a], Paul R. Bierman[a], and Dylan H. Rood[b]

*Corresponding Author: Ashley.Corbett@uvm.edu, (802) 380-2344
[a]Department of Geology and Rubenstein School of Environment and Natural Resources, University of Vermont, Burlington, VT 05405
[b]Department of Earth Science and Engineering, Imperial College London, South Kensington Campus, London SW7 2AZ, UK & Scottish Universities Environmental Research Centre (SUERC), East Kilbride G75 0QF, UK

- We conducted cosmogenic $^{26}Al/^{10}Be$ analysis of boulders from Thule, NW Greenland
- We utilized numerical models to constrain exposure/burial scenarios and uncertainty
- Most of the boulders have been preserved beneath cold-based, non-erosive ice
- Some boulders were exposed during Marine Isotope Stages 5e and 1
- Other boulders have longer, more complex histories spanning hundreds of ky

*Manuscript
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Revised Submission

CONSTRAINING MULTI-STAGE EXPOSURE-BURIAL SCENARIOS FOR BOULDERS PRESERVED BENEATH COLD-BASED GLACIAL ICE IN THULE, NORTHWEST GREENLAND

Lee B. Corbett*[a], Paul R. Bierman[a], and Dylan H. Rood[b]

*Corresponding Author: Ashley.Corbett@uvm.edu, (802) 380-2344
[a]Department of Geology and Rubenstein School of Environment and Natural Resources, University of Vermont, Burlington, VT 05405
[b]Department of Earth Science and Engineering, Imperial College London, South Kensington Campus, London SW7 2AZ, UK & Scottish Universities Environmental Research Centre (SUERC), East Kilbride G75 0QF, UK

Abstract

Boulders and landscapes preserved beneath cold-based, non-erosive glacial ice violate assumptions associated with simple cosmogenic exposure dating. In such a setting, simple single isotope exposure ages over-estimate the latest period of surface exposure; hence, alternate approaches are required to constrain the multi-stage exposure/burial histories of such samples. Here, we report 28 paired analyses of ^{10}Be and ^{26}Al in boulder samples from Thule, northwest Greenland. We use numerical models of exposure and burial as well as Monte Carlo simulations to constrain glacial chronology and infer process in this Arctic region dominated by cold-based ice. We investigate three specific cases that can arise with paired nuclide data: (1) exposure ages that are coeval with deglaciation and $^{26}Al/^{10}Be$ ratios consistent with constant exposure; (2) exposure ages that pre-date deglaciation and $^{26}Al/^{10}Be$ ratios consistent with burial following initial exposure; and (3) exposure ages that pre-date deglaciation and $^{26}Al/^{10}Be$ ratios consistent with constant exposure. Most glacially-transported boulders in Thule have complex histories; some were exposed for tens of thousands of years and buried for at least hundreds of thousands of years, while others underwent only limited burial. These boulders were recycled through different generations of till over multiple glacial/interglacial cycles, likely experiencing partial or complete shielding during interglacial periods due to rotation or shallow burial by sediments. Our work demonstrates that the landscape in Thule, like many high-latitude landscapes, was shaped over long time durations and multiple glacial and interglacial periods throughout the Quaternary.

Key words: geochronology; cosmogenic nuclides; Polar Regions; cold-based ice; till recycling; Quaternary

1. Introduction

In situ produced cosmogenic nuclides, such as ^{10}Be and ^{26}Al, are widely used to reconstruct glacial histories (Balco, 2011; Fabel and Harbor, 1999). These nuclides, produced predominately by nuclear spallation reactions caused by the bombardment of cosmic rays, build up in rock surfaces at predictable rates over time (Lal, 1988) and can be used to make inferences about surface exposure history (Granger et al., 2013). However, measurement of cosmogenic nuclides in cold, high-latitude areas can yield results that are complex and challenging to interpret (Briner et al., 2005). Both bedrock surfaces and boulders can yield exposure ages that are older than expected, sometimes by hundreds of thousands of years (Bierman et al., 1999). Rather than forming a single, normally distributed population, exposure ages from boulders in polar regions often form multi-modal distributions (Marsella et al., 2000), consistent with exposure during different numbers of interglacial periods as till was repeatedly reworked (Briner et al., 2005; Corbett et al., 2015). When multiple nuclides with different half lives are analyzed in the same sample, they can (but do not always) yield discordant exposure ages and isotopic ratios indicative of at least one period of burial following initial exposure (Bierman et al., 1999). Pre-deglaciation exposure ages, multi-modal age distributions, and discordant ages from different isotopes are all consistent with landscapes preserved for multiple glacial/interglacial cycles beneath cold-based, non-erosive ice.

Non-erosive glacial ice existed widely in high latitude regions in the past, including areas of Greenland (Bierman et al., 2014; Håkansson et al., 2008), Antarctica (Nishiizumi et al., 1991), Arctic Canada (Bierman et al., 1999; Briner et al., 2003), and Scandinavia (Stroeven et al., 2002). Cold-based ice also existed in mid-latitude regions, especially at high elevations (Bierman et al., 2015) and along thin ice sheet margins (Colgan et al., 2002). Since cosmic rays attenuate as they pass through Earth materials at a rate controlled by density, burial by ~10 m of ice causes production of nuclides by spallation to become negligible (Lal, 1988). But because bedrock and boulders buried by cold-based ice are not deeply eroded, they can contain cosmogenic nuclides inherited from previous periods of exposure and thus violate the primary assumption of simple cosmogenic exposure dating: that the sample surface began the exposure period of interest containing no cosmogenic nuclides. Constraining the history of once-glaciated bedrock surfaces and boulders that have been alternately exposed and buried with little erosion requires the use of multiple isotopes including a stable nuclide (^{3}He or ^{21}Ne) and/or radioactive nuclides (e.g. ^{10}Be, ^{26}Al, ^{36}Cl, and ^{14}C) in order to quantify the durations of exposure and burial (Bierman et al., 1999; Briner et al., 2003; Briner et al., 2006; Corbett et al., 2013; Håkansson et al., 2008; Kaplan et al., 2001; Marquette et al., 2004; Stroeven et al., 2002; Sugden et al., 2005).

Measuring at least two radioactive cosmogenic nuclides in a single sample sheds light on multi-stage exposure/burial histories because the nuclides decay at different rates when the sampled surface is shielded from cosmic-ray exposure (but not eroded) and nuclide production ceases (Granger, 2006). Such data are typically plotted on a two-isotope diagram, where samples can either overlap or fall below a pathway consistent with constant surface exposure (Klein et al., 1986). Using two nuclides, a minimum total history (one period of exposure followed by one period of burial) can be calculated (Fabel and Harbor, 1999), providing minimum limits of exposure and burial durations (Bierman et al., 1999). However, limitations still persist even with the multiple-nuclide approach since modeled histories represent non-unique inverse solutions.

Here, we present and analyze measurements of ^{10}Be and ^{26}Al in samples from 28 glacially-deposited boulders collected near Thule, northwest Greenland (Fig. 1), a long-lived landscape preserved beneath non-erosive glacial ice (Corbett et al., 2015). These boulders were sourced from two distinct diamict units that were deposited at different times and by different bodies of ice. Our goal is to make inferences about land surface development, boulder source/transport, and the history of ice cover in this cold-based ice landscape. We seek to provide additional constraints on the non-unique solutions that can arise when using cosmogenic nuclides at high latitude where ice is cold-based and exposure histories are often complex and multi-stage. Utilizing paired cosmogenic nuclides, numerical models, and Monte Carlo simulations, we provide a generalizable approach to understanding the history of cold-based ice landscapes and the sediments that mantle them.

2. Study Site, Previous Work, and Data Set

Thule, northwest Greenland (~69°W, 77°N) is located on the coast at the margin of the Greenland Ice Sheet, bordered on the east by TUTO Ice Dome and on the north by the Harald Moltke Bræ outlet glacier (Fig. 1). Little bedrock is exposed in the study area, although Late Proterozoic basin sediments of the Thule Supergroup (including shale and redbeds) crop out in the areas of high topography lying to the north and northeast of Thule Air Base, close to Wolstenholme Fjord (Dawes, 2006). Archaean basement orthogneisses and paragneisses are exposed to the east of the study area between TUTO Ice Dome and Harald Moltke Bræ, as well as across the fjord on the north side of Harald Moltke Bræ (Dawes, 2006). Previous work constrained the timing of the last deglaciation to a minimum of ~10-9 cal ka BP with radiocarbon ages of mollusk shells in raised marine material (Goldthwait, 1960; Morner and Funder, 1990). Mollusk ages and stratigraphic analysis also suggest that Harald Moltke Bræ readvanced more recently than ~10 cal ka BP, possibly in concert with the 8.2 ka cold reversal (Corbett et al., 2015). Ice margins later receded inland of their current position during the mid-Holocene, as constrained by radiocarbon ages of marine shells embedded in glacial shear planes (Goldthwait, 1960; Morner and Funder, 1990).

Additional work investigated the glacial history of Thule with mapping and cosmogenic exposure dating. Corbett et al. (2015) documented two different surface sedimentary units: a clay-rich diamict deposited by the main Greenland Ice Sheet during the last glaciation and a sandy diamict deposited by a subsequent re-advance of the Harald Moltke Bræ outlet glacier immediately north of Thule (Fig. 1). Although simple exposure dating with ^{10}Be was complicated by the presence of nuclides inherited from past periods of exposure, Corbett et al. (2015) inferred the timing of the last deglaciation to be ~11 ka based on the youngest ^{10}Be ages from boulders in the clay-rich diamict, an age estimate supported by previous radiocarbon dating of marine bivalves. The findings of Corbett et al. (2015) strongly suggest that at least some boulders in the Thule area, which preserve tens of thousands of years worth of exposure history and form multi-modal age distributions, contain cosmogenic nuclides inherited from previous exposure due to subglacial landscape preservation beneath cold-based, non-erosive ice. Based on the old simple ^{10}Be exposure ages and small 1σ analytic uncertainties (average of 2.8 ± 0.6 %), the original dataset described in Corbett et al. (2015) is an ideal candidate for analysis of an additional nuclide (^{26}Al), the results of which we present here and assess with numerical modeling approaches.

3. Methods

3.1. Sample Collection, Laboratory Preparation, and Single-Isotope Exposure Ages

Samples were collected in 2011-2013 from 28 glacially deposited boulders, all of which were above the post-glacial marine limit of ~40-50 m (Morner and Funder, 1990). Details of sample collection and processing are presented in Corbett et al. (2015). Boulder lithologies are dominantly granite gneiss, likely derived from outcrops of the Archaean orthogneisses described by Dawes (2006) that are exposed to the north and east of the study area. Thirteen boulders were located in the clay-rich diamict unit and 15 were located in the sandy diamict unit (Table 1, Fig. 1).

We added ~250 μg of ^{9}Be to each sample using in-house-made beryl carrier. If needed, we added ^{27}Al using 1000 μg mL^{-1} SPEX Al standard. Additions of ^{27}Al carrier were optimized to reach a total of ~2500 μg Al in each sample based upon quantification of native ^{27}Al in purified quartz. We then quantified total ^{27}Al in the samples via inductively-coupled plasma optical emission spectrometry (ICP-OES) analysis of replicate aliquots removed from the samples immediately following digestion (see supplemental data); these aliquots represent ~2% and 4% of the sample mass, respectively. We used two emission lines for each element (Be, 234.861 and 249.473 nm; and Al, 308.215 and 309.271 nm) and two internal standards (Ga and Y) for all analyses. The agreement between Al estimates for the replicate analyses of process blanks is 0.4 ± 0.4 % (average, 1SD, n = 4 sets of replicates) while the agreement between Al estimates for the replicate analyses of samples is 1.1 ± 2.9 % (average, 1SD, n = 28 sets of replicates). We use the ICP-quantified total ^{27}Al (1824-4028 μg; see supplemental data) of all samples and blanks for further calculations. Since the uncertainty of our ^{27}Al quantification is less than the analytic uncertainty of the AMS measurements, we did not propagate the ^{27}Al quantification uncertainty into our calculation of sample ^{26}Al concentrations.

Isotopic ratios were measured by Accelerator Mass Spectrometry (AMS) at the Scottish Universities Environmental Research Centre (Xu et al., 2015). Measured sample ratios for $^{10}Be/^{9}Be$ (see supplemental data) are $6.6 \cdot 10^{-14}$ to $5.6 \cdot 10^{-13}$ (average analytic uncertainty 2.8 ±

0.5%, 1SD, n = 28). Ratios were normalized to the NIST standard, with an assumed $^{10}Be/^{9}Be$ ratio of $2.79 \cdot 10^{-11}$. We used a $^{10}Be/^{9}Be$ background ratio of $2.7 \pm 0.2 \cdot 10^{-15}$ (average, 1SD, n = 3), which equates to $4.1 \pm 0.4 \cdot 10^{4}$ atoms of ^{10}Be, representing a 2.0 ± 0.8 % blank correction for the samples (average, 1SD, n = 28). Measured sample ratios for $^{26}Al/^{27}Al$ (see supplemental data) are $1.1 \cdot 10^{-13}$ to $8.8 \cdot 10^{-13}$ (average analytic uncertainty 3.5 ± 0.8%, 1SD, n = 28). Ratios were normalized to standard Z92-0222 with an assumed $^{26}Al/^{27}Al$ ratio of $4.11 \cdot 10^{-11}$, which is closely inter-calibrated with standard KNSTD (Xu et al., 2015). We used a $^{26}Al/^{27}Al$ background ratio of $8.7 \pm 3.9 \cdot 10^{-16}$ (average, 1SD, n = 4), which equates to $4.8 \pm 2.2 \cdot 10^{4}$ atoms of ^{26}Al, representing a 0.3 ± 0.1 % blank correction for the samples (average, 1SD, n = 28). We subtracted background ratios from sample ratios and propagated uncertainties in quadrature.

We calculated simple exposure ages using the CRONUS Earth calculator (Balco et al., 2008) with calculator version 2.2 and constants version 2.2.1. We employed the northeastern North American sea-level production rates of 3.93 ± 0.19 atoms g^{-1} yr^{-1} for ^{10}Be and 26.54 ± 1.35 atoms g^{-1} yr^{-1} for ^{26}Al (Balco et al., 2009) and the Lal/Stone constant production rate model and scaling scheme (Lal, 1991; Stone, 2000).

3.2. Two-Isotope Exposure and Burial Durations

To perform two-isotope exposure/burial calculations, we normalized nuclide concentrations to sea level using the CRONUS-determined production rates (Table 1). We assume a $^{26}Al/^{10}Be$ production ratio of 6.75 (Balco et al., 2009), a ^{10}Be half-life of $1.36 \cdot 10^{6}$ yr (Nishiizumi et al., 2007), and a ^{26}Al half-life of $7.05 \cdot 10^{5}$ yr (Nishiizumi, 2004). We assume no nuclide production during burial by ice. Before two-isotope calculations were performed, sample nuclide concentrations were corrected for the most recent period of continuous exposure (Table

1) based on the average ^{10}Be exposure age of the three youngest samples from this data set (10.7 ka; GT022, GT023, and GT055; Table 1). To perform this correction, we subtracted 10.7 ky worth of surface nuclide production from each sample's ^{10}Be and ^{26}Al concentrations; this correction shifts sample points downward and leftward on the two-isotope diagram, yielding shorter minimum limiting exposure durations and longer minimum burial durations than if the data had not been corrected. Using the corrected $^{26}Al/^{10}Be$ ratio as a filter, we modeled two-isotope histories only for samples that had corrected $^{26}Al/^{10}Be$ ratios indicative of burial beyond 1σ analytic uncertainties (n = 8) and report isotopic concentrations corrected for the most recent period of exposure only for these eight samples.

We conducted Monte Carlo simulations (10,000 models, varying ^{26}Al and ^{10}Be independently and assuming a normal uncertainty distribution for each isotope concentration) for the eight samples (GT014, GT015, GT016, GT019, GT021, GT036, GT054, and GT058) that had $^{26}Al/^{10}Be$ ratios indicative of burial after initial exposure. For each randomly selected pair of independent $^{26}Al/^{10}Be$ concentrations, we calculated minimum limiting exposure and burial durations as described in Bierman et al. (1999), solving iteratively to determine the simplest numerical solution (one period of exposure followed by one period of burial, Fig. 2). We then used these 10,000 simulations to create probability density functions for the exposure and burial duration populations (Fig. 3) and calculated a mean and a standard deviation in order to assign a central tendency and an uncertainty for each sample's modeled exposure and burial durations. For these eight samples, we report (Table 2) the mean exposure and burial durations, their 1σ uncertainties, and the minimum total history (the sum of the initial exposure duration, the burial duration, and the assumed most recent exposure duration of 10.7 ky).

3.3. Forward Exposure/Burial Scenario Models

We utilize multi-stage forward exposure/burial models to constrain possible boulder histories, assuming the same production rates and half-lives described above. In these models, we assume that boulders may have been exposed during one or multiple interglacial periods with the low global ice volume: marine isotope stages (MIS) 15, 11, 9, and 5e (Lisiecki and Raymo, 2005). In scenarios involving numerous periods of exposure, we utilize incrementally increasing exposure durations (2 ky increments up to 10 ky for the last period of exposure) to simulate the boulder slowly making its way toward the coast via glacial transport and experiencing longer ice-free periods. We use burial durations of 200 ky during MIS 14-12, 75 ky during MIS 10, 225 ky during MIS 8-6, and 100 ky during MIS 4-2, based on the timing described in Lisiecki and Raymo (2005). We do not include the most recent period of exposure (~10.7 ky) in these models so that the modeled isotopic concentrations (at the end of MIS 2) are comparable to the corrected isotopic concentrations in Thule samples for which minimum limiting exposure and burial durations were calculated.

We also use forward models to simulate cases in which boulders experience partial shielding during interglacial periods due to cover by overlying material, either because the boulder was rotated (thus placing the sample surface on the bottom during prior exposure) or was covered by till. For these models, we use 10 ky exposure periods alternating with 100 ky burial periods. During exposure, we utilize varying nuclide production scenarios that are based on portions of surface production, where 100% corresponds to no burial and full surface production. Our first modeled case (60% of surface production rates) equates to burial by ~35 cm of overlying rock or ~55 cm of overlying till. Our second modeled case (30% of surface production rates) equates to burial by ~70 cm of rock or ~110 cm of till. The above assume a cosmic ray attenuation length of 160 g cm^{-2}, a rock density of 2.7 g cm^{-3}, and a till density of 1.8 g cm^{-3}.

4. Results

For the 28 glacially-deposited boulders we sampled in the Thule area, ^{10}Be concentrations are $5.2 \cdot 10^4$ to $4.3 \cdot 10^5$ atoms g^{-1}, yielding simple exposure ages of 10.6 to 77.5 ka; ^{26}Al concentrations are $3.7 \cdot 10^5$ to $2.2 \cdot 10^6$ atoms g^{-1}, yielding simple exposure ages of 10.7 to 59.0 ka (Tables 1 and 2). Exposure ages calculated with ^{10}Be and ^{26}Al are well correlated (R^2 = 0.95, $p<0.01$), although ^{10}Be ages are systematically greater than ^{26}Al ages (regression slope = 0.72). Exposure ages from both isotopes form multi-modal age distributions with a distinct young peak ~11 ka, numerous overlapping peaks ~15-30 ka, and a single older outlier (Fig. 4). Measured ^{26}Al/^{10}Be ratios are 5.13 ± 0.14 to 8.50 ± 0.49 (average 6.85 ± 0.65, n = 28, 1SD), and ^{26}Al/^{10}Be ratios corrected for the most recent period of exposure (reported only for the eight samples with ^{26}Al/^{10}Be ratios indicative of complex histories) are as low as 4.88 (Table 1, Fig. 5).

There is no relationship between simple exposure age and the sedimentary unit from which the boulder was sourced (Table 2). Simple ^{10}Be boulder exposure ages from the clay-rich diamict are 25.5 ± 17.0 ka (average, 1SD, n = 13) while those from the sandy diamict are 21.2 ± 5.0 ka (average, 1SD, n = 15), representing two populations that are not statistically distinguishable (p = 0.40 for an unequal variance two-tailed Student's T-test). There is, however, a relationship between boulder history (as reflected by the ^{26}Al/^{10}Be ratio) and sedimentary unit (Table 1). Uncorrected boulder ^{26}Al/^{10}Be ratios from the clay-rich diamict are 6.55 ± 0.66 (average, 1SD, n = 13) while those from the sandy diamict are 7.11 ± 0.54 (average, 1SD, n =

15), representing two distinguishable populations ($p = 0.02$ for an unequal variance two-tailed Student's T-test).

For the eight samples with corrected $^{26}Al/^{10}Be$ ratios indicative of burial following initial exposure, we modeled exposure/burial durations and the associated uncertainties (Table 2). Modeled minimum limiting exposure durations prior to burial are 11 to 96 ky (not including the most recent period of exposure) and modeled minimum limiting burial durations are 88 to 627 ky. Minimum total histories (the sum of initial exposure duration, burial duration, and the most recent exposure duration) are 111 to 734 ky. Exposure duration uncertainties as constrained by Monte Carlo simulations are 1 to 4 ky, or 4 to 8% (average of 7%, 1SD) while burial duration uncertainties are 55 to 112 ky, or 9 to 105% (average of 37%, 1SD). Uncertainties scale inversely with modeled duration (see supplemental data).

5. Discussion

Cosmogenic data from boulders in cold-based ice regions generally fall into three different categories. 1.) Samples have simple exposure ages coincident with independent estimates of local deglaciation and $^{26}Al/^{10}Be$ ratios indistinguishable from continuous exposure within 1σ analytic uncertainties; these samples are likely free of cosmogenic nuclides from previous periods of exposure and record the timing of deglaciation. 2.) Samples have pre-deglaciation simple exposure ages and $^{26}Al/^{10}Be$ ratios that fall below the constant exposure pathway beyond 1σ analytic uncertainties; these samples likely experienced long durations of burial (hundreds of ky) by non-erosive or weakly-erosive ice and short durations of interglacial exposure. 3.) Samples have pre-deglaciation simple exposure ages but $^{26}Al/^{10}Be$ ratios that are consistent with constant exposure within 1σ analytic uncertainties; these samples may have experienced limited burial, but burial durations were not long enough to cause a detectable change in the $^{26}Al/^{10}Be$ ratio and/or the samples were re-exposed after burial long enough to increase the $^{26}Al/^{10}Be$ ratio so that it is not distinguishable from the production ratio (Bierman et al., 2015). We investigate these three different cases here, all of which are represented by the boulders from Thule.

5.1. Young Exposure Ages and $^{26}Al/^{10}Be$ Ratios Indicative of Constant Exposure

Deep subglacial erosion (at least several meters) can occur even in cold, high-latitude areas, especially in fjord bottoms where the ice is thick and the flow is channelized (Briner et al., 2009; Corbett et al., 2011; Davis et al., 1999; Hughes et al., 2012; Kaplan et al., 2001; Young et al., 2011). In these areas, boulders freshly quarried from eroded bedrock surfaces yield simple exposure ages that record the timing of deglaciation and $^{26}Al/^{10}Be$ ratios that overlap the constant exposure pathway within 1σ analytic uncertainties.

In Thule, only three of the 28 samples (GT022, GT023, and GT055, all from the clay-rich diamict) appear to have simple exposure ages that record the timing of deglaciation (Table 2). We make this inference because these samples form their own distinct population of ages (Fig. 4) and their ages agree closely with independent minimum deglaciation limits of ~10-9 cal ka BP developed using radiocarbon dating of marine bivalves in the same location (Corbett et al., 2015; Goldthwait, 1960; Morner and Funder, 1990). This implies that although deep glacial erosion can occur on this landscape, it is spatially restricted. These three boulders suggest deglaciation at 10.7 ± 0.1 ka (average, 1SD, taking into account only the ^{10}Be ages) or 11.0 ± 0.5 ka (average, 1SD, taking into account both ^{10}Be and ^{26}Al ages).

5.2. Old Exposure Ages and $^{26}Al/^{10}Be$ Ratios Indicative of Burial

Long durations of burial by cold-based, non-erosive glacial ice cause samples to have pre-deglaciation simple exposure ages and ^{26}Al/^{10}Be ratios inconsistent with constant exposure beyond 1σ analytic uncertainties. In cold-based environments, subglacial erosion is minimal, thereby preserving nuclides from previous periods of exposure and leading to surfaces that reflect at least hundreds of thousands of years worth of history (Bierman et al., 1999; Corbett et al., 2013). In these areas, modern landscapes are a product of development over numerous glacial/interglacial cycles (Kleman and Borgstrom, 1994; Sugden and Watts, 1977).

In Thule, eight of the 28 samples (GT014, GT015, GT016, GT019, GT021, GT036, GT054, and GT058) have old ages and ^{26}Al/^{10}Be ratios lower than production (assuming a production ratio of 6.75; Table 2). Seven of these eight are from the clay-rich diamict, while only one (GT036) is from the sandy diamict. Modeled minimum limiting exposure durations are tens of ky while modeled minimum limiting burial durations are hundreds of ky (Table 2). Exposure durations (including the most recent period of exposure) represent on average only ~11% (range of 4-21%) of the total history of these samples; the small proportion of exposure is suggestive of boulders that spend most of their history buried beneath non-erosive glacial ice and possibly also by till during interglacial periods, experiencing only relatively brief periods of subaerial exposure.

Results from forward models (not including the most recent period of exposure) demonstrate that these eight samples preserve a range of histories. Samples GT014 and GT058, which have ^{26}Al/^{10}Be ratios of 6.45 and 6.29, respectively, are well explained by initial exposure during MIS 9 and re-exposure during MIS5e (Fig. 6). Samples GT015 and GT016 have lower ^{26}Al/^{10}Be ratios, necessitating more burial and hence a scenario including more glacial/interglacial cycles: possibly exposure during MIS 15, 11, 9, and 5e, with burial between (Fig. 6). Samples GT019, GT036, and GT054 have low $^{26}Al/^{10}Be$ ratios but also low concentrations of both isotopes, measurements not well explained by scenarios involving cyclic exposure and burial. Rather, these samples may be explained by a scenario in which the boulders were initially exposed during an early interglacial period (e.g., MIS 11) and then remained completely buried (by ice during glacial periods and till during interglacial periods) until the Holocene (Fig. 6). Significantly longer-duration scenarios (at least a total of 734 ky, but likely much greater) are needed to explain the data from sample GT021, which has a low $^{26}Al/^{10}Be$ ratio and high isotopic concentrations; this boulder could have been repeatedly exposed and buried many times over much of the Quaternary period. Because there is less constraint on the behavior of the Greenland Ice Sheet during the earlier part of the Quaternary, and because so many possible scenarios could explain the location of sample GT021 on the two-isotope diagram, we do not attempt to fit this data point with a specific forward model. Rather, we suggest that this boulder likely preserves inherited nuclides from before the mid-Pleistocene transition, when the tempo of glacial cycles changed from 41 ka to 100 ka (Raymo et al., 1997).

5.3. Old Exposure Ages and $^{26}Al/^{10}Be$ Ratios Indicative of Constant Exposure

Different scenarios can lead to samples that have pre-deglaciation simple exposure ages and $^{26}Al/^{10}Be$ ratios consistent with constant exposure within 1σ analytic uncertainties. One possibility is that the land surface on which the boulder resides has been constantly exposed as a nunatak and never buried (Roberts et al., 2009; Stone et al., 1998). A second possibility is that the landscape was buried by ice in the past following initial exposure, but burial was short enough to not cause a detectable decrease in the $^{26}Al/^{10}Be$ ratio (Bierman et al., 2015).

Numerical models demonstrate that relatively short durations of burial, especially when followed by re-exposure, are insufficient to result in a $^{26}Al/^{10}Be$ ratio distinguishable from the constant exposure case at 1σ. Assuming a 10 ky period of exposure is followed by a 100 ky period of burial and subsequent Holocene exposure, a history consistent with exposure during MIS 5e and 1 and burial between, the resulting $^{26}Al/^{10}Be$ ratio is 6.59. Applying an uncertainty of 4.5% to the $^{26}Al/^{10}Be$ ratio (the average ratio uncertainty of the Thule data set), the resulting ratio of 6.59 is indistinguishable from 6.75 even though the surface spent over 80% of its history buried. In this case, the $^{26}Al/^{10}Be$ system is unable to distinguish boulders that experienced exposure during both MIS 5e and 1 from those that only experienced exposure during MIS 1. The inability to detect relatively short periods of burial is partly because the $^{26}Al/^{10}Be$ ratio uncertainty is greater than either of the single-isotope uncertainties (Gillespie and Bierman, 1995) and partly because isotopic concentrations (and hence the $^{26}Al/^{10}Be$ ratio) are more sensitive to exposure than burial due to the long half lives of these nuclides in comparison to the burial times. The relatively low concentrations of nuclides investigated in this study may represent an additional challenge for discerning short burial durations since the analytic uncertainty is more likely to overshadow small changes in nuclide concentrations caused by limited burial duration.

In Thule, 17 of the 28 samples have simple exposure ages older than expected, but $^{26}Al/^{10}Be$ ratios consistent with constant surface exposure. Only three of these 17 are from the clay-rich diamict; the remaining 14 are from the sandy diamict. Based on several lines of evidence, we conclude that these boulders are not indicative of constant exposure despite what their $^{26}Al/^{10}Be$ ratios suggest. Because the sandy diamict stratigraphically overlies both the clay-rich diamict (deposited ~10.7 ka based on the three youngest boulders) and marine sediments (dated to ~10 cal ka BP with radiocarbon, Corbett et al. (2015)), it cannot have been deposited prior to the earliest Holocene. Rather, the boulders that record pre-deglaciation exposure ages, but have $^{26}Al/^{10}Be$ ratios indicative of constant exposure, were likely exposed during MIS 5e, when global ice volume was low (Lisiecki and Raymo, 2005) and Greenland's coastal areas were ice-free (Otto-Bliesner et al., 2006), then buried and minimally eroded until the onset of MIS 1 when they were re-exposed.

5.4. Till Recycling

Because our data indicate that most of the Thule boulders have been preserved subglacially, it is likely that the boulders we sampled are part of till units that have been repeatedly reworked and recycled. These boulders (primarily gneiss), which do not match the local bedrock (weakly metamorphosed basin sediments), were likely sourced to the east of the study area where Archaean basement orthogneisses are exposed (Dawes, 2006), although we are unable to constrain the transport distance since the subglacial extent of these basement rocks is unknown. These boulders may have been incorporated into till during one or numerous previous interglacial periods, slowly progressing coastward in flowing ice over time.

If the boulders in Thule have indeed been assimilated into different generations of till, it is likely that the surfaces we sampled were partially shielded during previous interglacial periods, either because they were buried beneath other sediments or because the boulders rotated and the surfaces we sampled were on the side or bottom during the past. In the case of partial shielding during periods of exposure, the path taken through the two-isotope diagram compresses leftward since cosmogenic nuclides form at lesser rates than in the absence of shielding (Fig. 7). This overall leftward compression allows a larger number of exposure/burial cycles to occur before a given ^{10}Be concentration is reached than in the absence of shielding. Hence, if multiple samples have similar ^{10}Be concentrations, those that experienced partial shielding during periods of exposure have also experienced a larger total number of exposure/burial cycles, leading to longer burial durations and lower $^{26}Al/^{10}Be$ ratios than those that experienced no shielding (Fig. 7). Therefore, variable levels of shielding reflecting rotated or partially buried boulders in reworked till may at least partially explain the range of observed $^{26}Al/^{10}Be$ ratios.

The extent and patterns of till recycling (as recorded by $^{26}Al/^{10}Be$ ratio) appear to be related to the sedimentary unit from which the boulders were sourced, with the clay-rich diamict having been deposited by the main Greenland Ice Sheet during the last glaciation and the sandy diamict having been deposited by an early Holocene re-advance of Harald Moltke Bræ (Corbett et al., 2015). The population of 13 boulders from the clay-rich diamict includes three boulders with young ages and continuous exposure, seven boulders with old ages and complex history, and only one boulder with an old age but a $^{26}Al/^{10}Be$ ratio indistinguishable from constant exposure. Therefore, this unit appears to contain boulders recording heterogeneous processes, representing either no or significant recycling with little middle ground, possibly reflecting a wider source area and less erosive ice. Conversely, the population of 15 boulders from the sandy diamict includes one boulder with an old age and complex history and 14 boulders with old ages but $^{26}Al/^{10}Be$ ratios indistinguishable from constant exposure. Therefore, this unit appears more homogeneous and the boulders record shorter total near-surface histories and less burial, possibly reflecting more erosive ice in the outlet glacier.

5.5. $^{26}Al/^{10}Be$ Production Ratio

A significant limitation in the ability to understand complex exposure histories with a multi-isotope approach lies in the uncertainty of how the ^{26}Al/^{10}Be production ratio varies over space. Although a production ratio of 6.75 is used in most calculations (Balco et al., 2008), recent work suggests that the production ratio is itself dependent on latitude and elevation. Actual ^{26}Al/^{10}Be production ratios may be greater than 6.75, with hypothesized values ranging as high as ~7.3, because each isotope's production rate scales differently with altitude and latitude (Argento et al., 2013; Argento et al., 2015; Borchers et al., 2015).

The ^{26}Al/^{10}Be ratios we report from Thule could be consistent with a higher than currently accepted production ratio. Eleven of the 28 measured ^{26}Al/^{10}Be ratios exceed 6.75 by more than 1σ (Table 1), compared to the four samples (16% of the population) we would expect based on measurement uncertainty. If we instead assume a production ratio of 7.16 (the median value of high latitude, low elevation CRONUS calibration samples reported in Argento et al. (2013)), only three of our 28 samples exceed the production ratio by more than 1σ and one (GT039) exceeds it by more than 2σ (Table 1), similar to what would be expected given the analytic precision of our data. Although systematic measurement error could also contribute to high ^{26}Al/^{10}Be ratios, with ICP-OES quantification of total Al being the most likely source (Bierman and Caffee, 2002; Fujioka et al., 2015), we think this is unlikely since we do not see this trend for lower-latitude samples processed in our laboratory.

The assumed ^{26}Al/^{10}Be production ratio has important implications for determining which samples experienced a multi-stage history and for modeling those histories. Assuming a higher ^{26}Al/^{10}Be production ratio results in fewer samples with simple exposure histories and a greater number of samples with histories indicative of burial (Fig. 8). Although the ^{26}Al/^{10}Be production ratio has little impact on modeled minimum limiting exposure duration, it has a pronounced impact on modeled minimum limiting burial duration (Fig. 8). Sensitivity analysis for a representative sample in our dataset (GT016) demonstrates that modeled minimum limiting burial duration increases linearly with $^{26}Al/^{10}Be$ production ratio, with an additional 29 ky of burial added for each 0.1 increment of $^{26}Al/^{10}Be$ production ratio. More closely constraining the variability of the $^{26}Al/^{10}Be$ production ratio over space is an important direction for future work since it has significant implications for detecting and quantifying burial with the two-isotope approach.

6. Conclusions

The landscape in Thule, northwest Greenland, preserves a long record of heterogeneous subglacial processes. A small number of the boulders we sampled (three of 28) were sourced from areas deeply eroded during the last glacial period and their simple exposure ages suggest deglaciation of the landscape ~10.7 ka, consistent with radiocarbon age control. Other boulders (eight of 28) are indicative of ineffective subglacial erosion, yielding old simple exposure ages, $^{26}Al/^{10}Be$ ratios indicative of burial following initial exposure, and modeled total histories of hundreds of ky. These boulders likely experienced initial exposure during MIS9 or an earlier interglacial period and record an exposure/burial history spanning at least several interglacial/glacial cycles. Finally, most boulders (17 of 28) have old simple exposure ages that pre-date deglaciation and $^{26}Al/^{10}Be$ ratios indistinguishable from constant exposure. These boulders have only experienced limited burial, suggesting that they were initially exposed during MIS 5e and re-exposed during MIS 1. Boulders from the clay-rich diamict unit deposited by the main Greenland Ice Sheet have nuclide concentrations indicative of either no or significant burial, whereas boulders from the sandy diamict unit deposited by a subsequent outlet glacier re-advance have nuclide concentrations largely suggestive of limited burial durations. The boulders we sampled come from till units that have likely been recycled but not deeply eroded several or many times over the Quaternary, with boulders sometimes experiencing partial or complete shielding during interglacial periods, leading to the range in exposure/burial scenarios we infer. Together these data reinforce the heterogeneity of subglacial processes and support the use of multi-nuclide approaches for studying glacial history in cold-based ice environments.

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Table Captions

Table 1. Sample collection information and isotopic data from 28 glacially-deposited boulders.

Table 2. Age data from 28 glacially-deposited boulders.

Figure Captions

Figure 1. Location of the study site. Panel A shows the location of Thule in northwest Greenland. Panel B shows the Thule region with places described in the text. Panel C shows the location of the 28 boulder samples collected for analysis of cosmogenic $^{26}Al/^{10}Be$, with the white dashed line denoting the contact between the two diamict units described in the text.

Figure 2. Example of Monte Carlo simulations for sample GT016. Each of the 10,000 simulations (black dots) indicates an iterative numerical solution of one period of exposure followed by one period of burial that explains the observed isotopic concentrations.

Figure 3. Example probability density functions of 10,000 exposure durations and 10,000 burial durations for sample GT016. We used these populations to calculate the mean and standard deviation of simulated exposure and burial durations for each sample.

Figure 4. Probability density functions for ^{10}Be (top panel) and ^{26}Al (bottom panel) simple exposure ages of 28 boulder samples. Thin gray lines indicate the probability of each individual sample; thick black line indicates the summed probability for all samples.

Figure 5. Measured $^{26}Al/^{10}Be$ ratios plotted against ^{10}Be concentrations for sea level normalized values. Top panel shows all samples, with one sample (GT039) omitted for visibility because of its high ratio (n = 27, 1σ error bars). Bottom panel shows only the samples that have been numerically modeled for exposure/burial (n = 8), with concentrations and ratios that have been corrected for the most recent period of exposure (black dots, 1σ error bars) and original uncorrected values (gray dots); see Figures 6 and 7 for sample names. Thick black line shows the constant exposure pathway. Dotted lines show erosion pathways of 25, 10, 5, 2, 1, 0.5, 0.2, and 0.1 m Ma^{-1}, from left to right. Black triangles show secular equilibrium endpoints for erosion scenarios as well as the constant exposure scenario. Burial paths are shown with thin lines, and burial isochrones (0.5, 1.0, and 1.5 Ma, from top to bottom) are shown with thin dashed lines.

Figure 6. Two-isotope diagram as described in Fig. 5. Thick colored lines show isotopic evolution resulting from various exposure/burial scenarios. We assume that exposure durations increase incrementally with each subsequent period of exposure and we utilize burial durations that reflect the chronology described in Lisiecki and Raymo (2005). Black dots show the Thule samples that have been corrected for the most recent period of exposure; numbers indicate the sample number, error bars are 1σ.

Figure 7. Two-isotope diagram as described in Fig. 5. Thick colored lines show isotopic evolution over alternate periods of exposure (10 ky) and burial (100 ky), with various levels of shielding during periods of exposure to simulate till cover or boulder rotation. Black dots show the Thule samples that have been corrected for the most recent period of exposure; numbers indicate the sample number, error bars are 1σ.

Figure 8. Sensitivity analysis investigating the effect of $^{26}Al/^{10}Be$ production ratio on inferred boulder histories using seven different production ratios: 6.75, 6.85, 6.95, 7.05, 7.15, 7.25, and 7.35. Top two panels show modeled minimum limiting exposure and burial durations for a representative sample in the dataset (GT016), with error bars showing +/- 1σ as derived by Monte Carlo analysis. Bottom panel shows the dataset as a whole and inferences regarding how many samples are above, indistinguishable from, or below the production ratio based on 1σ $^{26}Al/^{10}Be$ analytic uncertainties. Gray bars show possible $^{26}Al/^{10}Be$ production ratios from recent studies.

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Corbett_Table1

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Sample Name[a]	Sed. Unit[b]	Latitud (°N)	Longitud (°E)	Elevatio (m a.s.l.)	Measured Values[c]					Correc
					^{10}Be (atoms g^{-}	1σ ^{10}Be Unc. (atoms g^{-1})	^{26}Al (atoms g^{-}	1σ ^{26}Al (atoms g^{-1})	^{26}Al/^{10}Be Ratio (1σ)	^{10}Be (atoms g^{-}
GT014	C	76.54578	-68.15783	350	1.33 x 10^{5}	4.22 x 10^{3}	8.78 x 10^{5}	2.84 x 10^{4}	6.58 ± 0.30	4.84 x 10^{4}
GT015	C	76.55843	-68.64975	276	1.60 x 10^{5}	4.01 x 10^{3}	9.95 x 10^{5}	4.81 x 10^{4}	6.20 ± 0.34	7.67 x 10^{4}
GT016	C	76.55745	-68.71192	252	1.48 x 10^{5}	3.87 x 10^{3}	8.94 x 10^{5}	2.53 x 10^{4}	6.04 ± 0.23	6.84 x 10^{4}
GT018	C	76.54552	-68.61322	251	1.54 x 10^{5}	4.67 x 10^{3}	1.03 x 10^{6}	2.74 x 10^{4}	6.64 ± 0.27	---
GT019	C	76.55382	-68.54360	178	1.12 x 10^{5}	2.44 x 10^{3}	6.72 x 10^{5}	1.99 x 10^{4}	6.01 ± 0.22	5.00 x 10^{4}
GT021	C	76.54702	-68.07298	314	4.33 x 10^{5}	8.20 x 10^{3}	2.22 x 10^{6}	4.38 x 10^{4}	5.13 ± 0.14	2.68 x 10^{5}
GT022$^{(R)}$	C	76.55833	-68.19445	358	6.45 x 10^{4}	1.99 x 10^{3}	4.39 x 10^{5}	1.75 x 10^{4}	6.79 ± 0.34	---
GT023$^{(R)}$	C	76.56945	-68.24887	346	6.30 x 10^{4}	2.15 x 10^{3}	4.71 x 10^{5}	1.94 x 10^{4}	7.47 ± 0.40	---
GT027	S	76.55336	-68.39177	175	1.37 x 10^{5}	3.45 x 10^{3}	9.80 x 10^{5}	2.80 x 10^{4}	7.16 ± 0.27	---
GT030	S	76.55168	-68.39473	171	1.13 x 10^{5}	2.79 x 10^{3}	7.81 x 10^{5}	2.24 x 10^{4}	6.89 ± 0.26	---
GT035	S	76.55843	-68.45382	71	1.03 x 10^{5}	2.36 x 10^{3}	7.30 x 10^{5}	2.19 x 10^{4}	7.08 ± 0.27	---
GT036	S	76.55791	-68.44873	77	1.06 x 10^{5}	3.10 x 10^{3}	6.32 x 10^{5}	1.93 x 10^{4}	5.94 ± 0.25	5.45 x 10^{4}
GT038	S	76.55983	-68.42910	67	5.35 x 10^{4}	1.65 x 10^{3}	3.72 x 10^{5}	1.66 x 10^{4}	6.95 ± 0.38	---
GT039	S	76.56069	-68.42268	74	5.22 x 10^{4}	1.66 x 10^{3}	4.44 x 10^{5}	2.14 x 10^{4}	8.50 ± 0.49	---
GT040	S	76.56132	-68.42116	62	8.93 x 10^{4}	4.24 x 10^{3}	6.85 x 10^{5}	2.32 x 10^{4}	7.67 ± 0.45	---
GT042	S	76.55457	-68.38605	138	1.21 x 10^{5}	2.78 x 10^{3}	8.47 x 10^{5}	2.46 x 10^{4}	7.02 ± 0.26	---
GT043	S	76.55338	-68.39169	175	1.33 x 10^{5}	3.55 x 10^{3}	9.25 x 10^{5}	4.36 x 10^{4}	6.95 ± 0.38	---
GT044	S	76.55151	-68.39625	185	8.31 x 10^{4}	2.08 x 10^{3}	5.91 x 10^{5}	2.17 x 10^{4}	7.11 ± 0.32	---
GT049	S	76.57150	-68.52433	198	1.28 x 10^{5}	3.19 x 10^{3}	9.16 x 10^{5}	3.72 x 10^{4}	7.13 ± 0.34	---
GT050	S	76.57030	-68.51962	198	9.08 x 10^{4}	2.40 x 10^{3}	6.27 x 10^{5}	2.60 x 10^{4}	6.90 ± 0.34	---
GT051	S	76.56734	-68.51293	195	1.08 x 10^{5}	2.56 x 10^{3}	8.09 x 10^{5}	2.30 x 10^{4}	7.49 ± 0.28	---
GT052	S	76.56478	-68.50867	187	1.17 x 10^{5}	2.92 x 10^{3}	8.34 x 10^{5}	3.77 x 10^{4}	7.10 ± 0.37	---
GT053	S	76.56400	-68.50716	180	9.51 x 10^{4}	2.15 x 10^{3}	6.37 x 10^{5}	1.95 x 10^{4}	6.70 ± 0.26	---
GT054	C	76.55590	-68.57046	183	9.27 x 10^{4}	3.10 x 10^{3}	5.66 x 10^{5}	2.11 x 10^{4}	6.11 ± 0.31	3.30 x 10^{4}
GT055$^{(R)}$	C	76.56046	-68.54910	201	5.49 x 10^{4}	2.05 x 10^{3}	4.09 x 10^{5}	1.74 x 10^{4}	7.46 ± 0.42	---
GT056	C	76.58178	-68.58881	324	1.29 x 10^{5}	3.50 x 10^{3}	9.09 x 10^{5}	2.95 x 10^{4}	7.05 ± 0.30	---
GT057	C	76.53712	-68.41935	143	1.29 x 10^{5}	4.16 x 10^{3}	9.22 x 10^{5}	2.64 x 10^{4}	7.14 ± 0.31	---
GT058	C	76.53816	-68.39758	158	1.15 x 10^{5}	3.78 x 10^{3}	7.45 x 10^{5}	2.13 x 10^{4}	6.48 ± 0.28	5.45 x 10^{4}

[a]Sample names followed by (R) are those interpreted to have only experienced the most recent period of exposure; these ages w

[b]Describes the sedimentary unit from which the boulder was collected (C = clay-rich diamict, S = sandy diamict, see Fig. 1)

[c]Ratios and ratio uncertainties for ^{10}Be/^{9}Be and ^{26}Al/^{27}Al are included in the data repository.

[d]The correction for the most recent period of exposure is the average ^{10}Be apparent exposure age of the three youngest samples samples whose corrected ratios are consistent with burial; these are the samples for which exposure/burial modelling was condu

Corbett_Table2

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		Single-Nuclide Apparent Exposure Ages[c]		Paired-Nuclide Minimum Limiting Durations and Uncertainties[d]						
Sample Name[a]	Sed. Unit[b]	^{10}Be Age (ka)	^{26}Al Age (ka)	Exposure Duration	1σ Exposure Unc. (ky)	1σ Exposure Unc. (%)	Burial Duration	1σ Burial Unc. (ky)	1σ Burial Unc. (%)	Total History
GT014	C	22.3	21.7	13	1	7	88	92	105	111
GT015	C	29.4	26.9	22	2	7	267	112	42	300
GT016	C	27.3	24.3	21	1	6	378	80	21	410
GT018	C	28.7	28.2	---	---	---	---	---	---	---
GT019	C	22.7	20.1	16	1	5	458	75	16	484
GT021	C	77.5	59.0	96	4	4	627	55	9	734
GT022[(R)]	C	10.7	10.7	---	---	---	---	---	---	---
GT023[(R)]	C	10.6	11.6	---	---	---	---	---	---	---
GT027	S	28.0	29.7	---	---	---	---	---	---	---
GT030	S	22.9	23.3	---	---	---	---	---	---	---
GT035	S	23.2	24.2	---	---	---	---	---	---	---
GT036	S	23.7	20.7	18	1	7	491	88	18	520
GT038	S	12.0	12.3	---	---	---	---	---	---	---
GT039	S	11.8	14.8	---	---	---	---	---	---	---
GT040	S	20.4	23.1	---	---	---	---	---	---	---
GT042	S	25.8	26.8	---	---	---	---	---	---	---
GT043	S	26.9	27.7	---	---	---	---	---	---	---
GT044	S	16.5	17.3	---	---	---	---	---	---	---
GT049	S	25.2	26.6	---	---	---	---	---	---	---
GT050	S	18.1	18.4	---	---	---	---	---	---	---
GT051	S	21.3	23.5	---	---	---	---	---	---	---
GT052	S	23.1	24.3	---	---	---	---	---	---	---
GT053	S	19.0	18.8	---	---	---	---	---	---	---
GT054	C	18.5	16.6	11	1	8	493	105	21	515
GT055[(R)]	C	10.7	11.8	---	---	---	---	---	---	---
GT056	C	22.2	23.1	---	---	---	---	---	---	---
GT057	C	27.2	28.7	---	---	---	---	---	---	---
GT058	C	23.8	22.7	15	1	7	142	91	64	168

[a]Sample names followed by (R) are those interpreted to have only experienced the most recent period of exposure; these ages were used to correct the remaining samples.

[b]Describes the sedimentary unit from which the boulder was collected (C = clay-rich diamict, S = sandy diamict, see Fig. 1)

[c]Ages were calculated using the northeastern North American production rates of 3.93 ± 0.19 atoms g^{-1} yr^{-1} for ^{10}Be and 26.5 ± 1.3 atoms g^{-1} yr^{-1} for ^{26}Al (Balco et al., 2009) and the Lal (1991)/Stone (2001) scaling scheme in CRONUS. Ages have been scaled for elevation, sample density, sample thickness, latitude, and longitude.