Spatial and Temporal Evolution of a Complex Arctic Landscape

PROJECT SUMMARY

The Arctic landscape is shaped over time by a cyclic pattern of glacial advance and retreat. During glacial periods when ice sheets expand, the landscape can either be deeply eroded and sculpted by erosive glacial ice or preserved beneath non-erosive glacial ice. During interglacial periods when ice sheets shrink, subaerial weathering further modifies the landscape through movement of material by wind, water, and freeze-thaw action. Subsequent smaller ice advances may cover only part of the landscape, leading to juxtaposed surfaces with different ages and histories. Most Arctic landscapes, therefore, have complex histories and have been subjected to numerous processes that are heterogeneous over both space and time.

Here, we propose to study the spatial and temporal evolution of high-latitude landscapes in a unique natural laboratory that preserves a complex, but we think tractable, landscape history. The Thule region in Northwest Greenland contains two distinct units of glacial sediments that have been deposited in different areas; each of the sedimentary units has its own source and depositional history. We will study how each of these sedimentary units has evolved over space and time as a mechanism for understanding landscape evolution and sediment transport in glaciated regions. For each of the sedimentary units, we will ask the following questions:

1.) ***How old are the sediments?*** *Were they deposited during the most recent glacial period, or are they a product of an older glaciation?*
2.) ***What is the surface history of the sediments?*** *How long have they been exposed for? Do they record times of burial by non-erosive glacial ice?*
3.) ***How erosive was the glacial ice that covered them?*** *Was the glacial ice a highly effective agent of landscape change, or was it non-erosive and capable of preserving a relict land surface? When was the last time the sediments were deeply eroded?*
4.) ***What body of glacial ice deposited the sediments?*** *Were they deposited by the Greenland Ice Sheet, or by a smaller outlet glacier during a subsequent smaller glacial re-advance? Where were the sediments sourced?*

Intellectual Merit: Addressing these questions about Arctic landscapes will provide insight about the numerous processes that shape these surfaces over space and time. Since glaciers cover much of Earth's high-latitude land at present, and glacial cover extended into the mid-latitudes as recently as 20,000 years ago, understanding these processes is important for constraining landscape evolution over a large portion of Earth's surface. Although much work has been conducted in glaciated areas, the work we propose is unique because we are specifically targeting a landscape with a complex history in order to study the diversity of processes, spatial scales, and temporal scales that govern landscape development in glacial environments.

Broader Impacts: Broader impacts of this study include the education and career development of PhD student Corbett. Conducting this work will expose her to new analytical techniques and foster collaborations with colleagues at other institutions where portions of the laboratory work will take place. As one of only a small number of female students working independently in northern Greenland, this project represents a unique opportunity for Corbett to develop the necessary skills to continue working in the high Arctic and mentor future students.

PROJECT DESCRIPTION

1. Introduction

The surface morphology of Thule, northwest Greenland (fig. 1) is the product of numerous processes acting over different spatial and temporal scales. Due to the high latitude (76.5°N) and cold conditions in Thule, it is probable that at least some of the glacial ice is frozen to the bed and has little erosive power, implying that landscape evolution takes place over numerous glacial-interglacial cycles (Sugden, 1977, 1978; Sugden and Watts, 1977). In areas where ice is frozen to the bed, surfaces can be preserved for tens or hundreds of thousands of years beneath glacial cover (Anderson et al., 2000; Bierman et al., 1999; Blake, 1970; Briner et al., 2003; Harbor et al., 2006; Marquette et al., 2004; Stroeven et al., 2002a; Stroeven et al., 2002b; Sugden et al., 2005). Constraining the evolution of these old glacial landscapes is important for informing our understanding of high-latitude geomorphic processes, for helping to explain modern geomorphic features seen today, and for providing insight about landscape evolution in the Arctic.

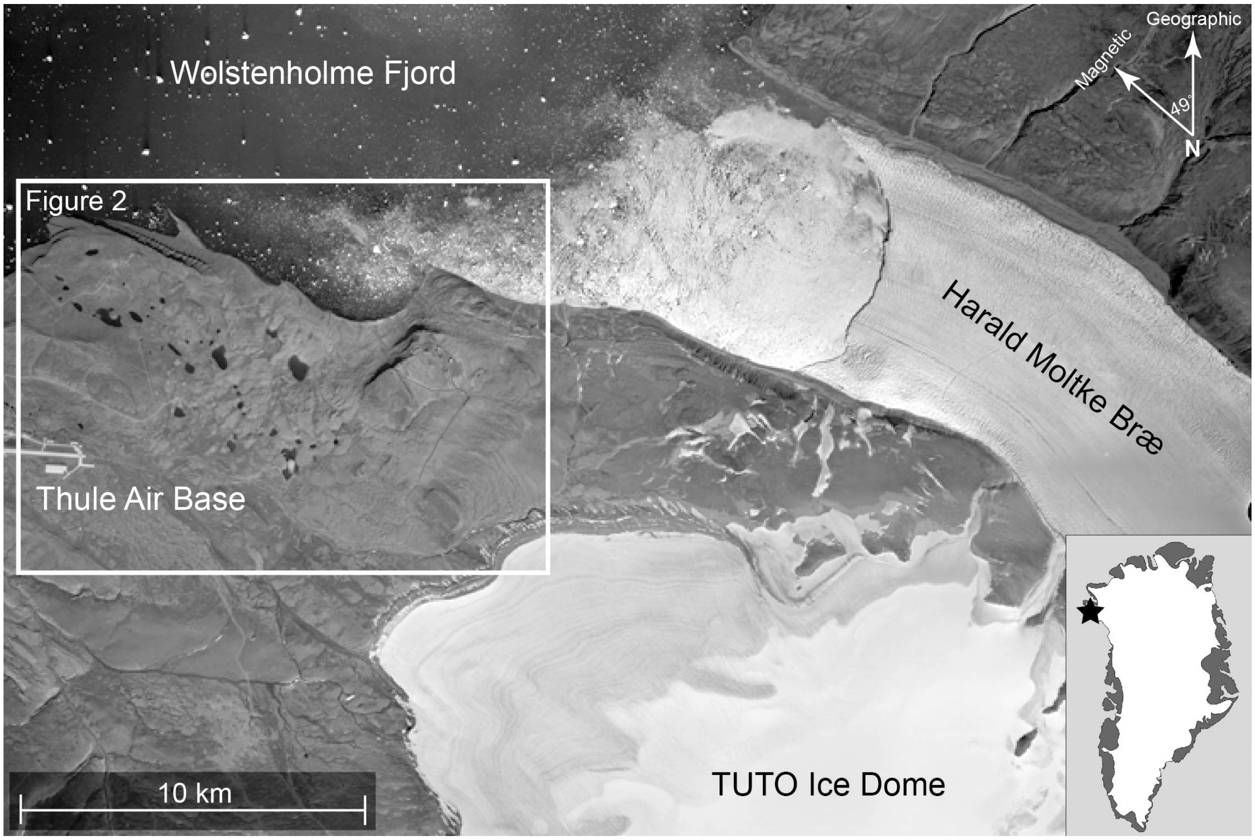


Figure 1. July 1985 air photograph of Thule showing locations discussed in the text. Inset map shows the location of Thule in northwest Greenland.

Glaciers can erode their beds in a number of different ways, including abrasion and plucking. However, most forms of subglacial erosion require basal ice to be at its melting point; this enables processes such as basal sliding, regelation, and freeze-on of rock and sediment to operate (Herman et al., 2011). Warm-based glaciers, for which the basal temperature is at the pressure melting point, can erode their beds. But under cold-based glaciers, where the basal temperature does not reach the pressure melting point, little erosion can occur (Sugden, 1978). Thus, episodes of burial caused by cold-based glacial ice are incapable of performing significant landscape reshaping.

An additional driver of landscape evolution in Greenland is the differential response of ice bodies to changes in climate. Smaller outlet glaciers are generally more sensitive to climate change than larger ice caps and ice sheets (Briner et al., 2009; Csatho et al., 2008; Hughes et al., 2012; Joughin et al., 2004; Young et al., 2011), responding to times of both warm and cold climate more rapidly than neighboring ice sheet margins. This may be the case in Thule, where the more active margin of the outlet glacier Harald Moltke Bræ is adjacent to the less responsive margin of TUTO Ice Dome (fig. 1). Therefore, periods of cool climate may affect landscapes close to Harald Moltke Bræ differently than those farther away.

The proposed work will provide insight about how these unique Arctic landscapes evolve over both space and time. We have purposefully chosen to study the Thule area because of its complexity; we plan to use our work in Thule as a way of shedding light on the diverse array of spatially and temporally heterogeneous processes that shape glacial landscapes and govern sediment transport. This work will be a key part of Corbett's PhD Dissertation research, which focuses on understanding landscape evolution and erosion in glaciated regions. Understanding this complex system requires a specialized chemical approach, in particular the use of multiple cosmogenic nuclides (^{10}Be, ^{26}Al, and ^{14}C) in tandem. Corbett aided in the development of this methodology at University of Vermont during her MS degree and continues to be one of only a small community of researchers to utilize it.

2. The Thule Landscape

The landscape in Thule is an ideal place to conduct this work because it preserves evidence of numerous different processes operating over different spatial and temporal scales. Corbett has conducted fieldwork in Thule three times, twice on NSF-funded projects and once on her own independent project, and has had ample opportunity to study the landscape. Her mapping efforts, both in the field and on air photographs, indicate the existence of several distinct sedimentary units that likely have different ages, sources, and transport histories (fig. 2).

The clay-rich glacial till (fig. 2) covering most of the landscape preserves evidence of extensive surface weathering including polygon-shaped rings several meters across that are known to develop on permafrost surfaces. Many of the rocks here are heavily weathered and exhibit features such as weathering pits and exfoliation. Conversely, the sandy glacial till (fig. 2) found only close to the fjord preserves less evidence of weathering and contains boulders with fresh surfaces. This landscape is hummocky and contains large glacial moraines, which contrasts greatly with the rest of the Thule area. Finally, a narrow strip of sediments near the coast preserves wave-cut benches that likely represent a period of higher relative sea level after the last glaciation; the limit of marine evidence has previously been mapped to ~50-60 m above modern sea level in Thule (England and Bednarski, 1986; Morner and Funder, 1990; Nichols, 1953).

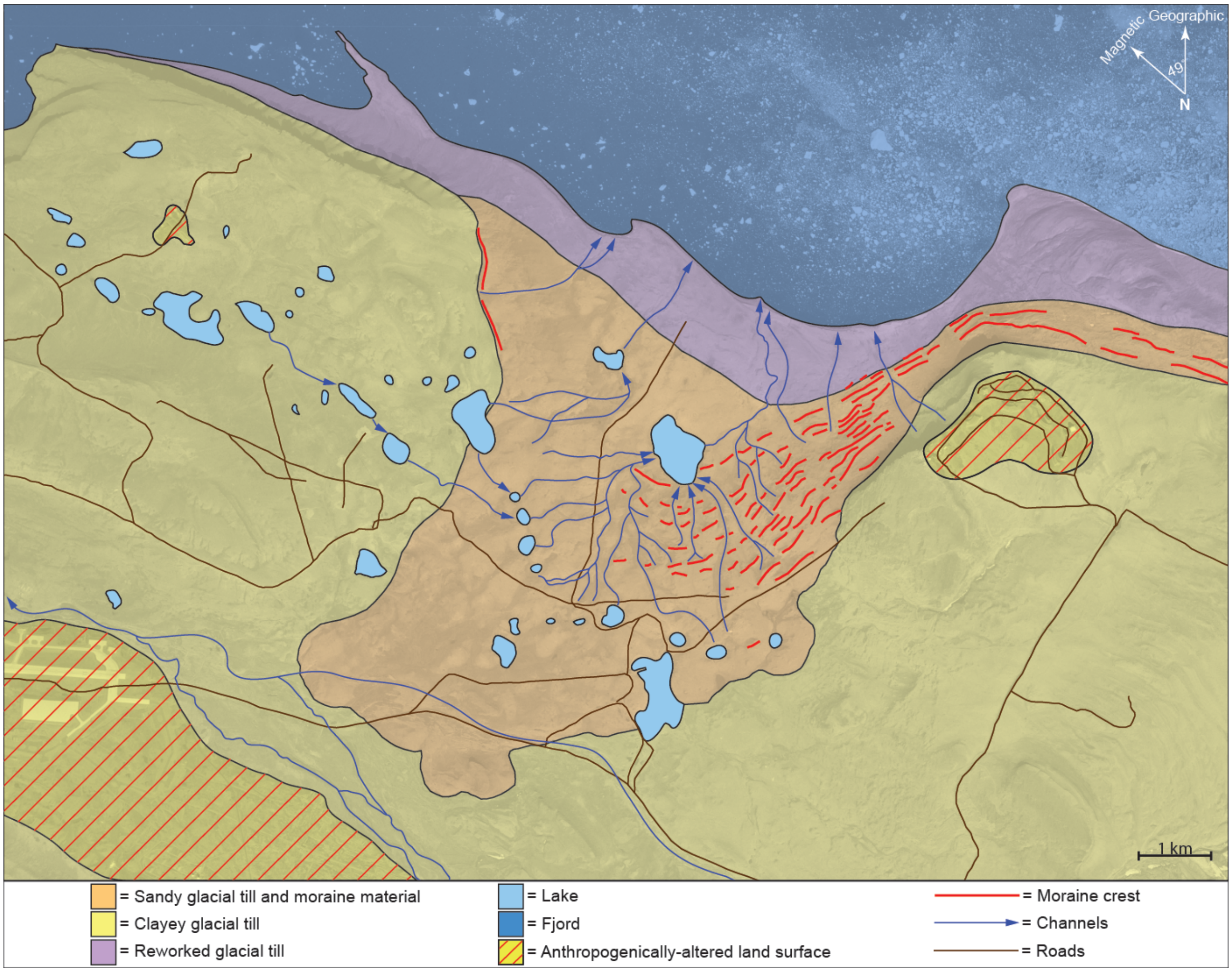


Figure 2. Surficial geomorphic map created by Corbett based on fieldwork and air photographs.

We have purposefully targeted this landscape for two key reasons. First, its complexity will allow us to learn about a diverse array of processes operating on glacial landscapes. The findings from this work, therefore, will be transferrable to other high-latitude regions that are glaciated today as well as mid-latitude regions that were glaciated during the last ice age. Second, the unique setup in Thule will allow us to approach questions of landscape evolution using a variety of complimentary techniques. The abundance of quartz in the rocks there makes analysis of cosmogenic nuclides viable, thus providing information on the age and exposure history of the glacial till. Parts of the sandy till unit overlie shell-rich marine sediments, so radiocarbon dating of these shells can provide a maximum limit for the timing of the glacial advance that deposited the till. We are confident that the landscape history is both complex and yet tractable, making it an ideal setting to study the spatially and temporally diverse set of processes that shape glacial landscapes.

3. Cosmogenic Nuclides: Background and Applicability

3.1. Analysis of Cosmogenic Nuclides

In order to constrain landscape history in Thule, we will employ analysis of cosmogenic nuclides (Balco, 2011; Fabel and Harbor, 1999). These isotopes, including ^{10}Be, ^{26}Al, and ^{14}C, build up slowly in rock surfaces over time as they are exposed to bombardment by high-energy neutrons from cosmic radiation (Lal, 1988). Since the production rates of these isotopes are well constrained, determining their inventory in a rock's surface provides information about the exposure history of that surface. Cosmogenic nuclide production in rock surfaces decreases exponentially with depth; therefore, the highest concentration of the cosmogenic nuclides are in the upper meter of rock. Significant erosion of several meters of material, such as by glacial ice, strips away these nuclides and leaves a fresh surface.

In the simplest case, a surface is rapidly exposed to cosmic radiation from beneath a geologic material sufficiently thick to block cosmic-ray penetration (e.g., glacial ice), and the concentration of cosmogenic nuclides can be used to determine when exposure occurred (Balco, 2011). This method relies on the assumption that the surface was deeply eroded by the over-riding glacial ice, and all cosmogenic nuclides from prior glacial periods are removed. This method is commonly employed to determine the age of glacial features and has been used widely in Greenland (Corbett et al., 2011; Håkansson et al., 2007; Hughes et al., 2012; Levy et al., 2012; Rinterknecht et al., 2009; Young et al., 2011). Certain areas in Greenland, however, are not amenable to this approach. In areas of cold, thin ice cover, glacial ice does not erode the underlying surfaces; instead, it remains frozen to the rocks below and is not an effective erosive agent. This violates the assumption described above, since surfaces contain nuclides from the present interglacial period as well as numerous prior interglacial periods.

In this more complex case, a two-isotope approach can be used that relies upon both ^{10}Be and ^{26}Al. Analysis of two cosmogenic isotopes with different half-lives can provide information about complex exposure and burial histories (Granger and Muzikar, 2001; Nishiizumi et al., 1991; Nishiizumi et al., 1989). In the case of the two isotopes described here, ^{26}Al is produced ~6.75 times as rapidly as ^{10}Be. Over time, because its half-life is less (0.71 Ma), a greater percentage of ^{26}Al will be lost to decay than ^{10}Be (half-life 1.36 Ma) and the ^{26}Al/^{10}Be ratio will drop from 6.75 as exposure continues and the sample ages. In the event of complete burial, production of both nuclides ceases and ^{26}Al decays more quickly than ^{10}Be. If a sample is exposed again following burial, production resumes. Isotopic data is typically plotted on a two-isotope diagram that contains different zones corresponding to different sample histories (fig. 3). Using the concentrations of these two isotopes in a given sample can allow minimum limiting exposure durations, burial durations, and total histories to be calculated. This information allows constraints to be placed on the landscape's age, how long it has spent buried and preserved beneath glacial ice, and how effectively glacial ice erodes underlying surfaces.

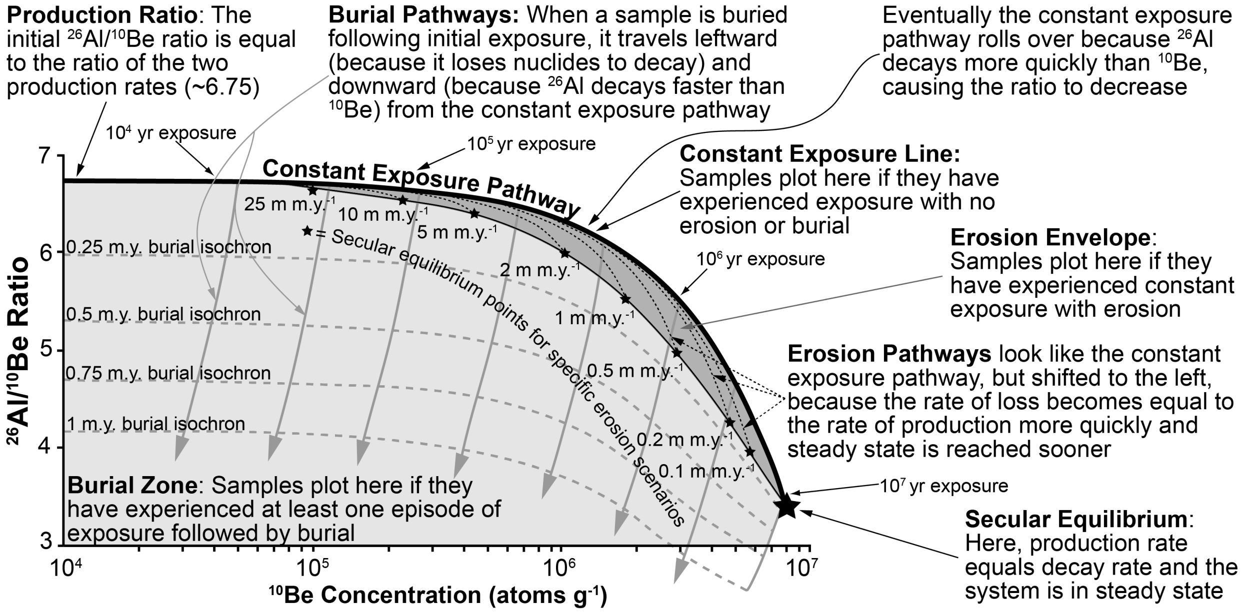


Figure 3. Schematic depiction of how two-isotope cosmogenic data are plotted, with explanations about important processes and how they are manifested in the isotope data.

3.2. Using the Cosmogenic Two-Isotope Approach to Study Non-Erosive Glacial Ice

The two-isotope approach has been utilized in high-latitude landscapes with non-erosive glacial ice to constrain landscape history and development. Isotopic evidence for non-erosive glacial ice has been found in Baffin Island, Canada (Bierman et al., 1999; Briner et al., 2003; Briner et al., 2006), Newfoundland, Canada (Gosse et al., 1993; Gosse et al., 1995), Scotland (Phillips et al., 2006), and western Greenland (Corbett et al., 2013). In all of the above cases, exposed land surfaces are hundreds of thousands of years old despite being covered by glacial ice up until ~10,000 years ago. Chemically, this is indicated by discordant ^{10}Be and ^{26}Al ages, and ^{26}Al/^{10}Be ratios that fall below the constant exposure pathway. Surfaces were likely preserved beneath non-erosive glacial ice and therefore record a history of many glacial-interglacial periods over geologic time. These findings demonstrate that ancient landscapes can still exist in glaciated regions, and that glacial ice is an ineffective agent of geomorphic change under certain conditions.

4. Hypotheses

We have two primary hypotheses regarding the history of the Thule landscape. These hypotheses are based on surficial mapping, preliminary data, and knowledge from other Arctic landscapes. These hypotheses can be supported with analysis of cosmogenic isotopes in rocks, radiocarbon dating of marine shells, and analysis of sediment sequences excavated in the field area. Together, these hypotheses form a comprehensive story about how the Thule landscape has evolved over time (fig. 4).

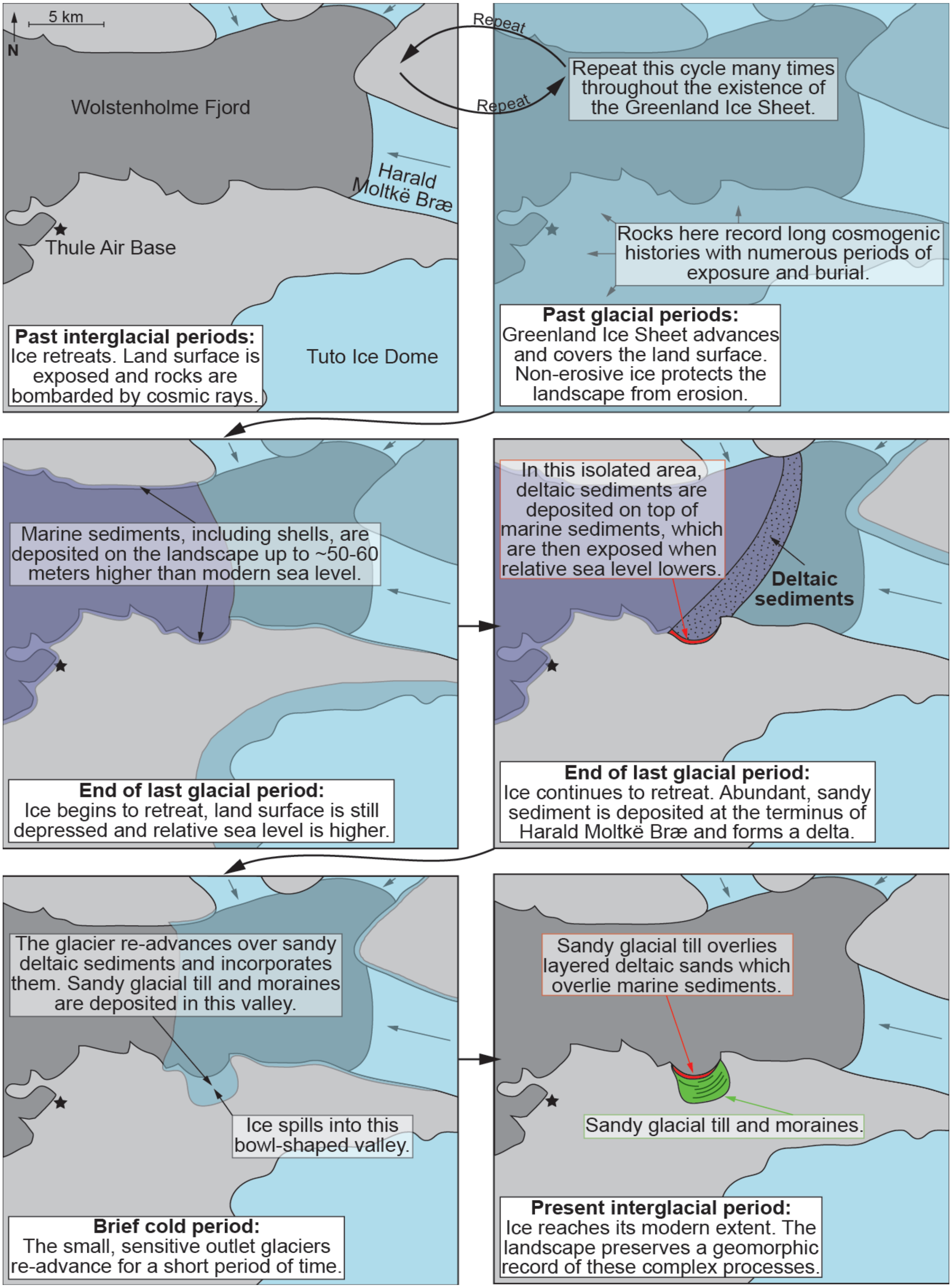


Figure 4. Illustration of the hypothesized evolution of the Thule landscape.

4.1. Hypothesis #1: The clay-rich glacial till was deposited prior to the last glacial period. It represents a relict landscape that has been preserved beneath non-erosive glacial ice.

4.1.1. Samples and Analysis

To address this hypothesis, Corbett sampled surface material from 30 large, quartz-rich, glacially-deposited boulders on the portion of the landscape covered by the clay-rich glacial till unit. She collected these samples during summer 2011, while in Thule for another project, as well as during summer 2013 while working independently. We will analyze the concentrations of three different cosmogenic nuclides in these samples as a means of discerning their age and exposure history. Using three different nuclides (^{10}Be, ^{26}Al, and ^{14}C) with three different half-lives (1.36 million years, 0.71 million years, and 5,730 years) will allow us to investigate exposure and burial over different timescales.

4.1.2. Supporting Results

The following results would lead us to accept hypothesis #1:

- Single-isotope exposure ages calculated from ^{10}Be, ^{26}Al, and ^{14}C will not be in agreement because the samples contain inherited nuclides from prior periods of exposure, violating the assumption of simple exposure history.
- When plotted on the two-isotope diagram (fig. 3), samples will fall below the constant exposure line and will plot in the burial zone, indicating at least one period of exposure followed by burial with limited erosion.
- Calculated minimum limiting exposure duration, burial duration, and total sample history will be considerably older than the onset of the present interglacial period.
- The above suggest that the landscape has been buried beneath non-erosive, cold-based ice. It is a preserved relict feature that contains a record of many glacial advances and retreats over geologic time.

4.2. Hypothesis #2: The sandy glacial till was deposited during a re-advance of outlet glaciers in Thule. This re-advance occurred during a cold period post-dating the last ice age.

4.2.1. Samples and Analysis

To address this hypothesis, Corbett sampled surface material from an additional 30 large, quartz-rich, glacially-deposited boulders from the crests of moraines within the sandy glacial till. She collected these samples during her independently-run 2013 field season. We will analyze these samples for cosmogenic nuclide concentrations as described above. Corbett also conducted detailed sedimentological analysis in the field by digging numerous pits to examine the sequences of different sedimentary units. We will use this data to recreate the sequence of events preserved in the Thule area, and will use radiocarbon dating to determine the age of shells collected from marine sediments.

4.2.2. Supporting Results

The following results would lead us to accept hypothesis #2:

- Single-isotope exposure ages calculated from ^{10}Be, ^{26}Al, and ^{14}C will be concordant since the till was deposited by a warm-based, erosive outlet glacier.

- When plotted on the two-isotope diagram (fig. 3), samples will plot along the constant exposure line indicating that they were deeply eroded before deposition.
- Sedimentological analysis will demonstrate that glacial till overlies layered sediments deposited during a time when the area was ice-free. This sedimentary sequence can be used to infer that outlet glaciers re-advanced after regional deglaciation was complete.
- Radiocarbon dates from shells embedded in the marine sediments will date to the end of the last glacial period or the beginning of the present interglacial period, providing a maximum limit for the timing of the ice re-advance that deposited the sandy till.
- The above suggest that the sandy till was deposited by a re-advance of outlet glaciers that post-dated the last glacial period. This re-advance may date to the Younger Dryas ~11,500 years ago (Alley, 2000) or the 8200 Event ~8,00 years ago (Alley and Ágústsdóttir, 2005), which are both brief cold periods registered in the Greenland Ice Sheet ice cores.

5. Proposed Study

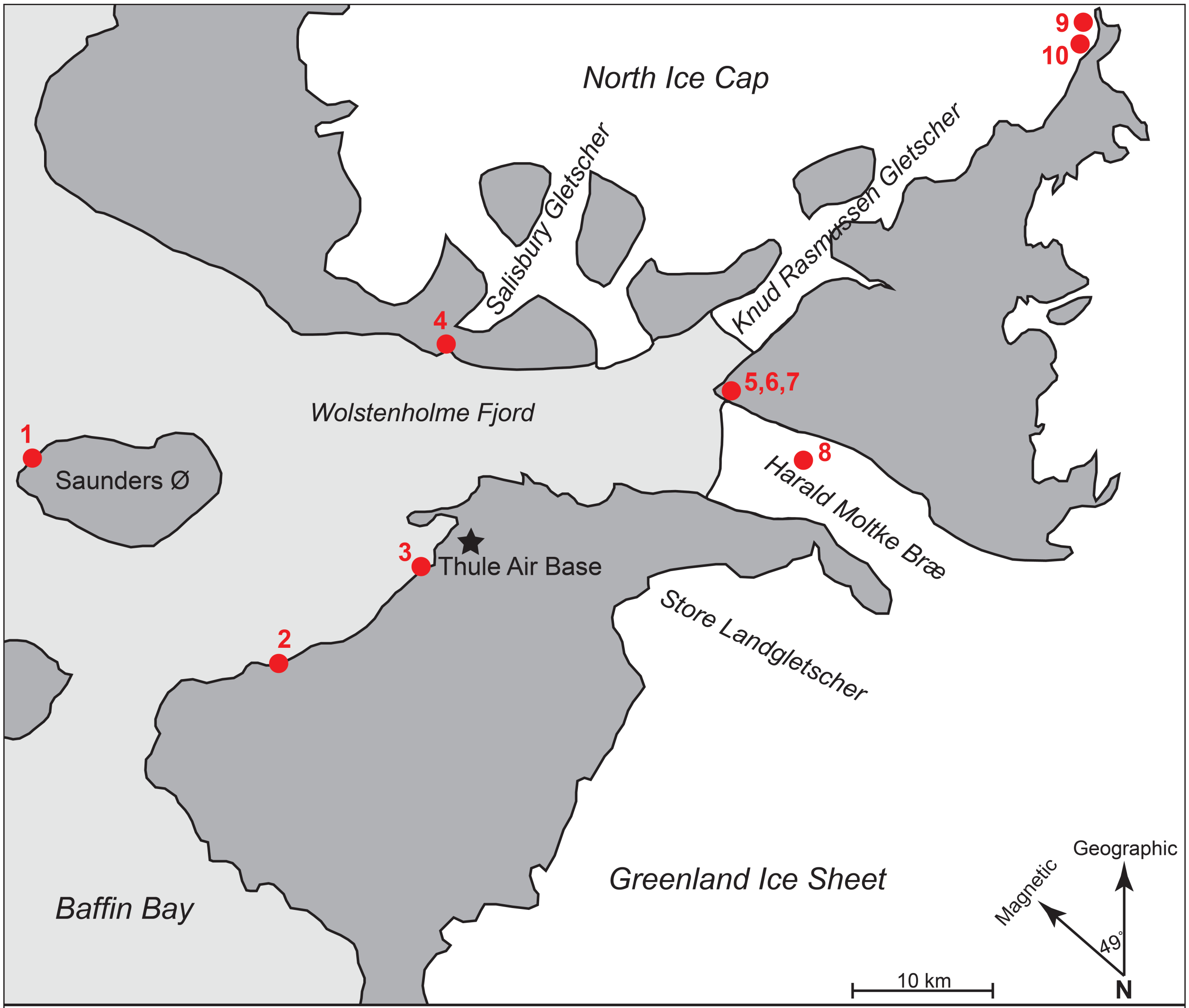
5*.1. Study Area and Previous Work*

Thule (fig. 1), a United States Air Base, is located at ~68.6°W, 76.5°N on the coast of northwestern Greenland. It is bordered on the east by the Tuto Ice Dome on the north by the Harald Moltke Bræ. Much of the original work conducted in Thule was targeted at understanding local glaciological conditions so that the nuclear power plant at Camp Century, as well as the ice ramps and ice road leading to it, could be constructed and maintained (Bishop, 1957; Davis, 1967; Goldthwait, 1960, 1971; Griffiths, 1960; Nobles, 1960; Waterhouse et al., 1963).

Existing chronology in Thule has dominantly focused on constraining the timing of early Holocene ice retreat (fig. 5). Reservoir-corrected radiocarbon ages on shells in raised marine material range from ~8200-9200 ^{14}C yr BP, or ~9,000-10,500 calibrated yr BP, providing a minimum limit for the timing of ice retreat from the fjord (Crane and Griffin, 1959; Morner and Funder, 1990). Additional chronology has attempted to constrain mid-Holocene ice retreat (fig. 5); shell fragments in the Harald Moltke Bræ outlet glacier date to 7000 ^{14}C yr BP (Morner and Funder, 1990) and fossilized plants embedded in the North Ice Cap margin date to 4800 ^{14}C yr BP (Goldthwait, 1960), suggesting mid-Holocene retreat of the northwest Greenland cryosphere.

5*.2. Proposed Research and Preliminary Results*

In order to investigate the age and history of the clay-rich glacial till that covers much of the Thule landscape, Corbett has already sampled surface material from 22 large glacially-deposited boulders (fig. 6a). These boulders span over 20 km in both the north-south and east-west directions and provide a representative sampling of the Thule land surface. We will analyze a subset of the boulders, ~15 in total, for cosmogenic isotopes. Three preliminary minimum limiting ^{10}Be ages from these boulders are 28,320 ± 1,470 yr, 21,710 ± 1,210 yr, and 26,380 ± 1,440 yr.



1. 8200 & 8750 ^{14}C yr BP (reservoir-corr. radiocarbon)
Shells in raised marine material (40 m a.s.l.)
Age of early Holocene marine limit
Morner and Funder (1990)

2. 8895 ^{14}C yr BP (reservoir-corr. radiocarbon)
Shells in raised marine material
Age of early Holocene marine limit
Morner and Funder (1990)

3. 9005, 8965, 8360, & 8170 ^{14}C yr BP (reservoir-corr. radiocarbon)
Shells in raised marine material
Age of early Holocene marine limit
Morner and Funder (1990)

4. 9150 ^{14}C yr BP (reservoir-corr. radiocarbon)
Shells in raised marine material (35 m a.s.l.)
Age of early Holocene marine limit
Morner and Funder (1990)

5. 9000 +/- 350 ^{14}C yr BP (reservoir-corr. radiocarbon)
Shells in raised beach (10 m a.s.l.)
Constraint for LGM Harald Moltke Bræ retreat
Goldthwait (1960)

6. 9040 ^{14}C yr BP (reservoir-corr. radiocarbon)
Shells in raised marine material
Constraint for LGM Harald Moltke Bræ retreat
Morner and Funder (1990)

7. 9880 +/- 500 ^{14}C yr BP (reservoir-corr. radiocarbon)
Shells in raised marine material
Constraint for LGM Harald Moltke Bræ retreat
Crane and Griffin (1959)

8. 6980 ^{14}C yr BP (reservoir-corr. radiocarbon)
Shell fragments in Harald Moltke Bræ shear plane
Indicator of Mid-Holocene Harald Moltke Bræ retreat
Morner and Funder (1990)

9. < 200 ^{14}C yr (radiocarbon)
Lichens on rock at bottom of ice tunnel
Age of North Ice Cap re-advance over patterned ground
Goldthwait et. al (1960)

10. 4760 +/- 220 & 520 +/- 200 ^{14}C yr (radiocarbon)
Material from North Ice Cap shear plane
Timing of North Ice Cap development/expansion
Goldthwait et. al (1960)

Figure 5. Summary of existing chronology in the Thule area.

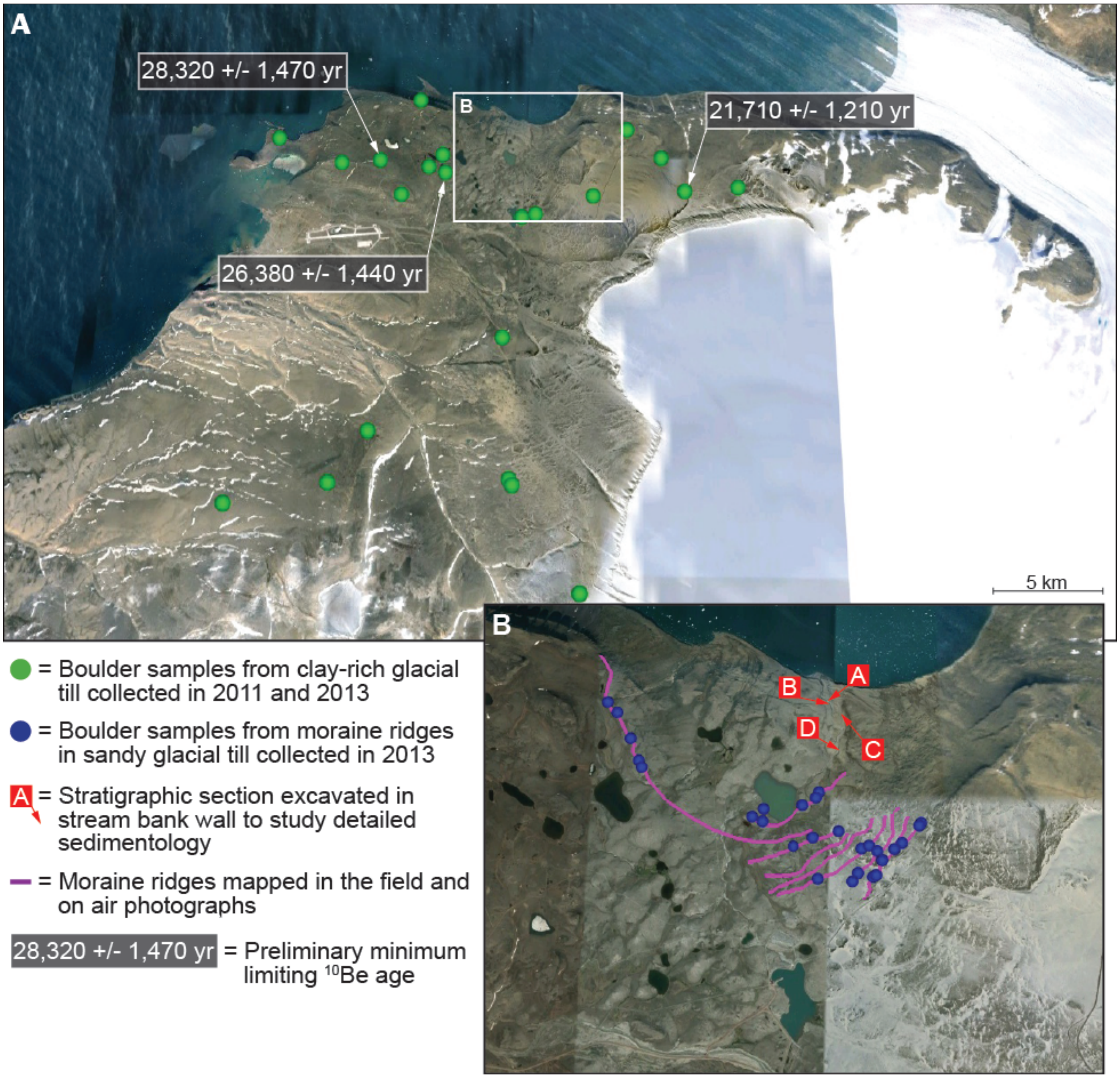


Figure 6. Landsat satellite imagery (2013) from the Thule area showing sample sites and preliminary data.

In order to investigate the age and history of the sandy glacial till deposited near the fjord, Corbett has already sampled surface material from 28 additional boulders along the crests of glacial moraines (fig. 6b). These moraines were mapped in detail both in the field and on air photographs. Corbett also excavated stratigraphic sections from the banks of a stream that has down-cut through the sandy till and into the sediments below. She collected six samples of shells that were found embedded in the marine sediments the excavations exposed. Preliminary observational data show a sequence of sediments that has marine material at the bottom (i.e. oldest), followed by layered deltaic sands, followed by sandy glacial till at the top (i.e. youngest; fig. 7).

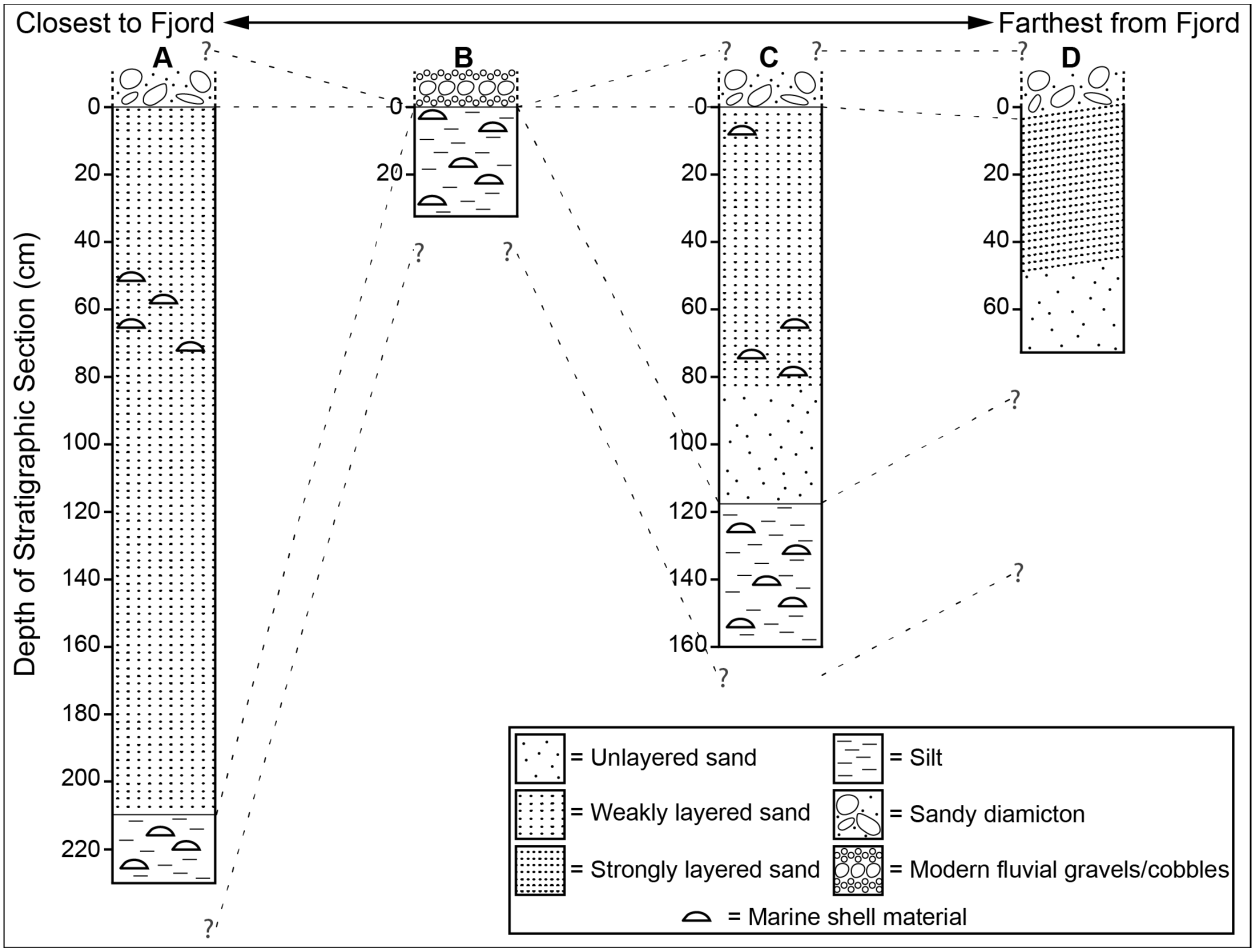


Figure 7. Field observations from stratigraphic sections excavated in the sandy glacial till.

Analysis of cosmogenic isotopes in boulder samples will follow a specific sequence designed to maximize knowledge we can gain from each sample while still making efficient use of funds (fig. 8). First, we will analyze each sample for ^{10}Be concentration and calculate ages. Boulders that have minimum limiting ^{10}Be ages greater than ~20,000 years will also be analyzed for ^{26}Al. We only perform two-isotope analysis on the older samples because, when uncertainties are taken into account, the ^{26}Al/^{10}Be ratios indicative of various sample scenarios cannot be resolved for young samples with low isotope concentrations. With these data, we will be able to distinguish whether the samples have been continuously exposed or whether they have been alternately exposed and buried (fig. 3); we will also be able to numerically model minimum limiting exposure durations, burial durations, and total histories. For samples that indicate complex exposure histories with periods of burial, we will perform analysis of a third cosmogenic isotope, ^{14}C. Since the half-life of ^{14}C is so short (5,730 years), any isotopes produced in rocks during the previous interglacial period will have decayed away. Therefore, ^{14}C can be used to determine the timing of retreat following the last glacial period even in samples that have complex histories and contain inherited ^{10}Be and ^{26}Al. For samples with minimum limiting ^{10}Be ages of less than ~20,000 years, ^{14}C can also be used in order to detect small amounts of inherited nuclides because of its short half-life.

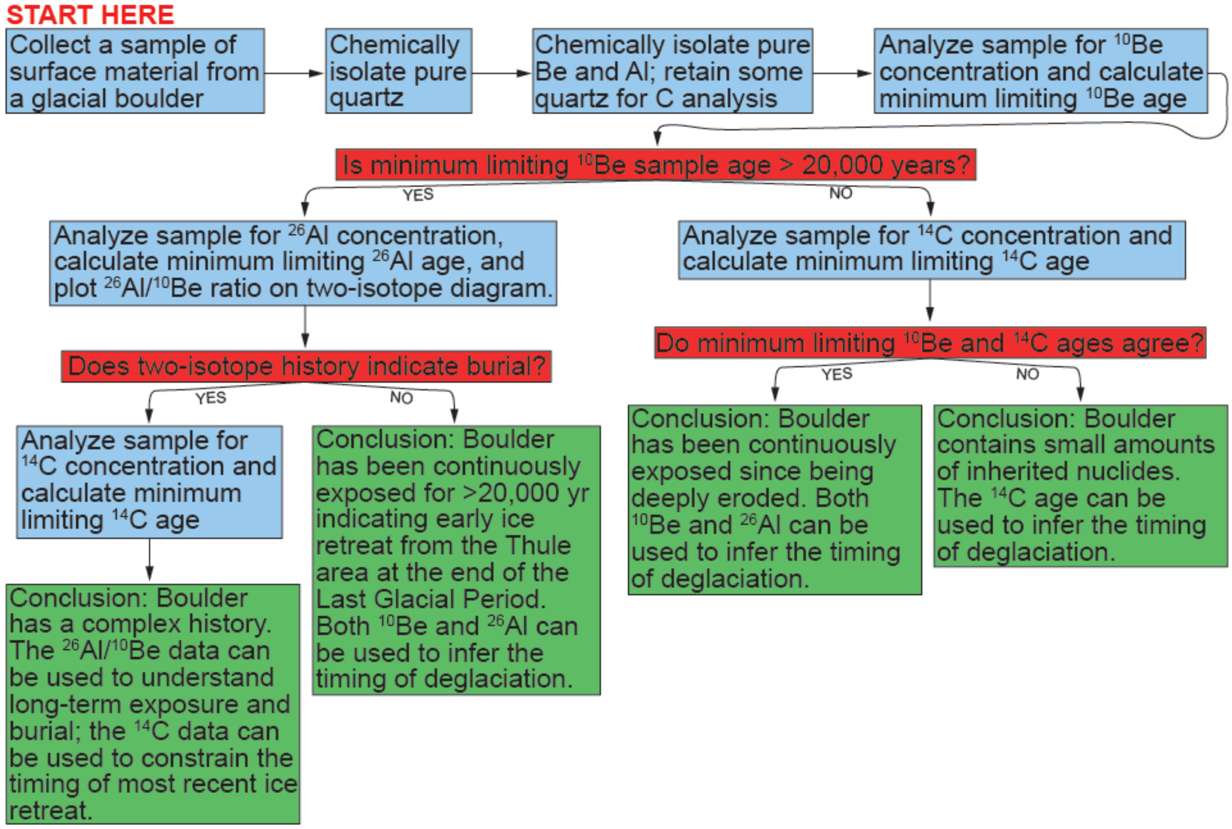


Figure 8. Flow chart describing cosmogenic isotope analysis strategy.

Analysis of sedimentological data and radiocarbon ages of marine shells will be used to complement the cosmogenic data set. We will use the sequence of overlaid sediments exposed near the fjord to discern a history for the area; this will provide insight about the source and depositional history of the sandy glacial till. Radiocarbon ages from shells in the marine sediments found below the sandy glacial till will provide a maximum limiting age for the till and can be used to validate cosmogenic ages.

Preliminary data suggests that the Thule landscape has a complex history in both space and time. Mapping in the field and on air photographs shows the existence of two very different glacial till units with different histories. Observation of weathering features in the clay-rich glacial till, as well as old (~20,000-30,000 yr) minimum limiting ^{10}Be ages, demonstrate that landscape has experienced long durations of surface exposure, possibly indicative of preservation throughout multiple glacial-interglacial cycles. Detailed sedimentological observations reveal that the sandy glacial till overlies marine sediments, suggesting that outlet glaciers readvanced after regional deglaciation had already occurred. Additional chronological information is needed to continue exploring this complex history.

5.3. Field and Laboratory Methods

In the field, Corbett sampled the upper-most several centimeters of material from the top of large glacially-deposited boulders using a hammer and chisel. She recorded latitude/longitude and elevation data with a handheld Garmin GPS that has a positional uncertainty of <10 m and an elevation uncertainty of <25 m. She also took measurements of the slope of the boulder's surface, the thickness of the sample collected, and the level to which the boulder is shielded from cosmic ray bombardment by topographic features; these data will all be used to scale or correct the cosmogenic data. To study the sediments in detail, she excavated six soil pits and ten stratigraphic sections and made observations about sediment size, layering, sorting, and other notable characteristics such as marine shells or glacially-striated rocks.

Cosmogenic samples will be prepared as outlined in Corbett et al. (2011). We will isolate quartz from the rock using a series of both physical and chemical processes, and Be and Al from the quartz through a series of chemical processes. In order to ensure that samples are corrected for the amount of native (i.e. not cosmogenic) Al in the quartz, we will use detailed inductively coupled plasma optical emission spectrometry methods developed at University of Vermont (Corbett et al., 2013).

Isotopic measurements for ^{10}Be and ^{26}Al will be conducted by accelerator mass spectrometry at the Scottish Universities Environmental Research Center with collaborator Dr. Dylan Rood. Ratios for ^{10}Be/^{9}Be and ^{26}Al/^{27}Al will be measured against known standards so that the concentration of the cosmogenic isotopes in quartz can be calculated (Nishiizumi et al., 2007). Measurement precisions will likely be ~1-3% for ^{10}Be and ~5% for ^{26}Al. Isotopic measurements for ^{14}C will be conducted by accelerator mass spectrometry at Purdue University with collaborator Dr. Nathaniel Lifton. Cosmogenic data will be modeled using the online CRONUS Earth calculator in order to determine minimum limiting exposure ages (Balco et al., 2008).

6. Corbett's Ongoing Dissertation Research

Corbett's PhD dissertation focuses on understanding landscape development and sediment transport in glacial environments. As part of her MS research, she studied an ancient landscape in Upernavik, Greenland that has been preserved beneath non-erosive ice cover for as long as a million years (Corbett et al., 2013). The proposed work in Thule will complement the work in Upernavik by broadening our spatial understanding of subglacial erosion efficiency.

Corbett is also currently using numerous novel techniques to understand subglacial erosion under broader regions of the Greenland Ice Sheet. She has measured cosmogenic ^{10}Be concentrations in 100 cobble-sized rocks embedded in the ice margin from three locations in western Greenland in order to study the source and transportation history of these materials. She has participated in work targeted at measuring ^{10}Be in silt-sized material both embedded in the ice margin and in the bottom of the GISP2 ice core. Her work on subglacial erosion suggests that inner regions of the Greenland Ice Sheet are non-erosive, and landscapes as old as several million years may be preserved subglacially in the center of Greenland. A review manuscript about this work, as well as a book chapter, are currently in preparation.

In order to conduct these analyses, Corbett participated in significant methodological development in the University of Vermont cosmogenic laboratory. These methodological optimizations allowed her to conduct the high-precision two-isotope measurements necessary for the study in Upernavik, and these new methods will be utilized for the study in Thule. Corbett has also measured some of the youngest ^{10}Be samples (the cobbles, described above) analyzed at Lawrence Livermore National Laboratory. She is currently preparing a manuscript reviewing these methodological developments.

7. Intellectual Merit

This work will make meaningful contributions to the understanding of how the geomorphology of glacial landscapes evolves over space and time. The processes operating on these landscapes are inherently complex and difficult to understand; our work in Thule will provide knowledge about these processes that can be transferred to other landscapes that are currently glaciated or have been glaciated in the past.

Studying the erosivity of glacial ice in Thule will provide an important constraint on the spatial distribution of erosion rates around Greenland. Prior work has found highly-erosive ice in central western Greenland (Corbett et al., 2011; Levy et al., 2012; Rinterknecht et al., 2009; Young et al., 2011) and southeastern Greenland (Hughes et al., 2012), but weakly-erosive ice in northwestern Greenland (Corbett et al., 2013) and central eastern Greenland (Goehring et al., 2010; Håkansson et al., 2008; Kelly et al., 2008). This pattern suggests a complex spatial heterogeneity that can be addressed with additional data from understudied areas. Since non-erosive glacial ice has been documented in the Canadian Arctic (Bierman et al., 1999; Briner et al., 2003; Marquette et al., 2004), Scandinavia (Harbor et al., 2006; Stroeven et al., 2002b), and Antarctica (Lilly et al., 2010; Sugden et al., 2005), and likely exists in Thule as well, our proposed work will shed light on processes that operate on many high-latitude landscapes. These areas, which preserve relict surfaces that have been preserved for hundreds of thousands of years beneath non-erosive ice, record long-term information about landscape development and warrant further study. Since a considerable portion of Earth's land surface is ice-covered, understanding subglacial erosion is important for constraining landscape development, movement of material, and transport of sediments and nutrients to the oceans.

Studying the juxtaposition of the two different glacial sedimentary units will provide further insight about how these glacial landscapes are shaped over time. Many glaciated regions contain large ice sheets in close proximity with smaller, more responsive ice caps and outlet glaciers. When these different bodies of ice respond differently to climatic charge, they create a landscape that is spatially complex and heterogeneous in terms of age, sediment source, and transport history.

8. Broader Impacts

8.1. Education of PhD Student Corbett

This project provides the opportunity for Corbett to learn two new analytical techniques: analysis of the cosmogenic isotope ^{14}C and dating of organic material with organic ^{14}C (although these are the same isotope, they are formed and analyzed by very different mechanisms). Corbett will travel to Purdue University to conduct cosmogenic ^{14}C analysis with Dr. Nathaniel Lifton and will learn about sample preparation, sample analysis, and data reduction. She will also travel to the University of California Irvine to conduct radiocarbon dating with Dr. John Southon. Although radiocarbon is a widely-used chronological technique, the analytical work is usually outsourced to commercial labs and few scientists have the opportunity to gain hands-on experience. Corbett will study sample preparation, analysis, and data interpretation for this technique as well. These new analytical techniques and collaborations will be useful to Corbett throughout her graduate career and beyond.

Corbett will also travel to the Scottish Universities Environmental Research Center to conduct analysis of cosmogenic ^{10}Be and ^{26}Al. Although she has already conducted similar work at Lawrence Livermore National Laboratory several times, she will build new collaborations by making these measurements in a new laboratory with more advanced techniques. Since Corbett plans to continue working with cosmogenic isotopes later in her career, fostering this collaboration will be important to planning future projects and conducting future analysis.

This project represents an opportunity to support the education of a minority student. Corbett is one of only a handful of female graduate students working in northern Greenland. Further, she has conducted almost all of her education within the state of Vermont. This project also represents Corbett's first independent polar research project. Although she visited Thule two times (2011 and 2012) with other groups, her 2013 field season was independently funded, planned, and executed. She developed the ideas, hypotheses, and approach described here. Obtaining National Science Foundation support for the analytical work will allow her to learn to manage grant funds, thereby facilitating grant management later in her career.

8.2. Dissemination of Scientific Results Through Public Media

Corbett has received specific training in strategies for disseminating scientific research to the public through newspaper, television, and online media. She consciously seeks out opportunities to share her work with a larger audience by working with University and journal press staff. Her most recent publication, also focused on non-erosive glaciers in Greenland, was covered by LiveScience, NBC, and The History Channel (Appendix A). She plans to continue working with University, local, and national media to ensure that her work is publically-accessible and communicated in a way that is easy for non-scientists to understand.

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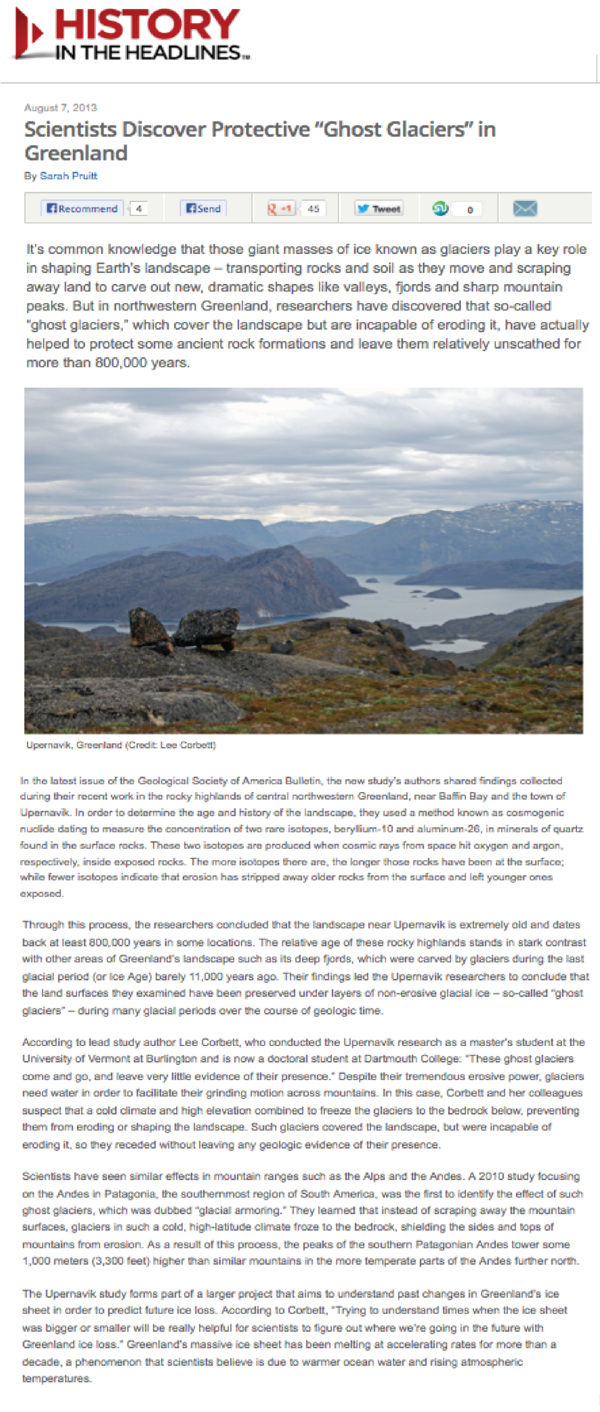
Appendix A. Examples of Corbett's Science in the Public Media



August 7, 2013

Scientists Discover Protective "Ghost Glaciers" in Greenland

By Sarah Pruitt

It's common knowledge that those giant masses of ice known as glaciers play a key role in shaping Earth's landscape – transporting rocks and soil as they move and scraping away land to carve out new, dramatic shapes like valleys, fjords and sharp mountain peaks. But in northwestern Greenland, researchers have discovered that so-called "ghost glaciers," which cover the landscape but are incapable of eroding it, have actually helped to protect some ancient rock formations and leave them relatively unscathed for more than 800,000 years.

Upernavik, Greenland (Credit: Lee Corbett)

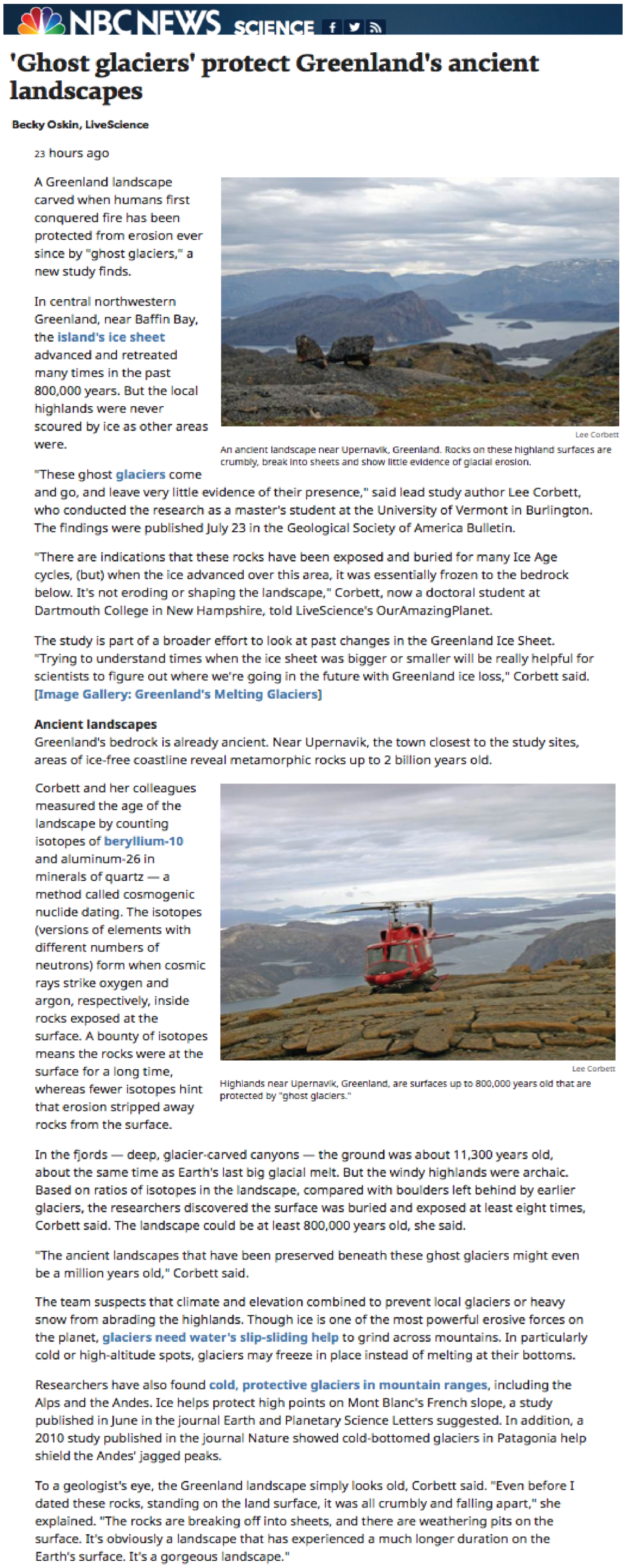
In the latest issue of the Geological Society of America Bulletin, the new study's authors shared findings collected during their recent work in the rocky highlands of central northwestern Greenland, near Baffin Bay and the town of Upernavik. In order to determine the age and history of the landscape, they used a method known as cosmogenic nuclide dating to measure the concentration of two rare isotopes, beryllium-10 and aluminum-26, in minerals of quartz found in the surface rocks. These two isotopes are produced when cosmic rays from space hit oxygen and argon, respectively, inside exposed rocks. The more isotopes there are, the longer those rocks have been at the surface; while fewer isotopes indicate that erosion has stripped away older rocks from the surface and left younger ones exposed.

Through this process, the researchers concluded that the landscape near Upernavik is extremely old and dates back at least 800,000 years in some locations. The relative age of these rocky highlands stands in stark contrast with other areas of Greenland's landscape such as its deep fjords, which were carved by glaciers during the last glacial period (or Ice Age) barely 11,000 years ago. Their findings led the Upernavik researchers to conclude that the land surfaces they examined have been preserved under layers of non-erosive glacial ice – so-called "ghost glaciers" – during many glacial periods over the course of geologic time.

According to lead study author Lee Corbett, who conducted the Upernavik research as a master's student at the University of Vermont at Burlington and is now a doctoral student at Dartmouth College: "These ghost glaciers come and go, and leave very little evidence of their presence." Despite their tremendous erosive power, glaciers need water in order to facilitate their grinding motion across mountains. In this case, Corbett and her colleagues suspect that a cold climate and high elevation combined to freeze the glaciers to the bedrock below, preventing them from eroding or shaping the landscape. Such glaciers covered the landscape, but were incapable of eroding it, so they receded without leaving any geologic evidence of their presence.

Scientists have seen similar effects in mountain ranges such as the Alps and the Andes. A 2010 study focusing on the Andes in Patagonia, the southernmost region of South America, was the first to identify the effect of such ghost glaciers, which was dubbed "glacial armoring." They learned that instead of scraping away the mountain surfaces, glaciers in such a cold, high-latitude climate froze to the bedrock, shielding the sides and tops of mountains from erosion. As a result of this process, the peaks of the southern Patagonian Andes tower some 1,000 meters (3,300 feet) higher than similar mountains in the more temperate parts of the Andes further north.

The Upernavik study forms part of a larger project that aims to understand past changes in Greenland's ice sheet in order to predict future ice loss. According to Corbett, "Trying to understand times when the ice sheet was bigger or smaller will be really helpful for scientists to figure out where we're going in the future with Greenland ice loss." Greenland's massive ice sheet has been melting at accelerating rates for more than a decade, a phenomenon that scientists believe is due to warmer ocean water and rising atmospheric temperatures.



'Ghost glaciers' protect Greenland's ancient landscapes

Becky Oskin, LiveScience

23 hours ago

A Greenland landscape carved when humans first conquered fire has been protected from erosion ever since by "ghost glaciers," a new study finds.

In central northwestern Greenland, near Baffin Bay, the island's ice sheet advanced and retreated many times in the past 800,000 years. But the local highlands were never scoured by ice as other areas were.

Lee Corbett

An ancient landscape near Upernavik, Greenland. Rocks on these highland surfaces are crumbly, break into sheets and show little evidence of glacial erosion.

"These ghost glaciers come and go, and leave very little evidence of their presence," said lead study author Lee Corbett, who conducted the research as a master's student at the University of Vermont in Burlington. The findings were published July 23 in the Geological Society of America Bulletin.

"There are indications that these rocks have been exposed and buried for many Ice Age cycles, (but) when the ice advanced over this area, it was essentially frozen to the bedrock below. It's not eroding or shaping the landscape," Corbett, now a doctoral student at Dartmouth College in New Hampshire, told LiveScience's OurAmazingPlanet.

The study is part of a broader effort to look at past changes in the Greenland Ice Sheet. "Trying to understand times when the ice sheet was bigger or smaller will be really helpful for scientists to figure out where we're going in the future with Greenland ice loss," Corbett said. **[Image Gallery: Greenland's Melting Glaciers]**

Ancient landscapes

Greenland's bedrock is already ancient. Near Upernavik, the town closest to the study sites, areas of ice-free coastline reveal metamorphic rocks up to 2 billion years old.

Corbett and her colleagues measured the age of the landscape by counting isotopes of beryllium-10 and aluminum-26 in minerals of quartz — a method called cosmogenic nuclide dating. The isotopes (versions of elements with different numbers of neutrons) form when cosmic rays strike oxygen and argon, respectively, inside rocks exposed at the surface. A bounty of isotopes means the rocks were at the surface for a long time, whereas fewer isotopes hint that erosion stripped away rocks from the surface.

Lee Corbett

Highlands near Upernavik, Greenland, are surfaces up to 800,000 years old that are protected by "ghost glaciers."

In the fjords — deep, glacier-carved canyons — the ground was about 11,300 years old, about the same time as Earth's last big glacial melt. But the windy highlands were archaic. Based on ratios of isotopes in the landscape, compared with boulders left behind by earlier glaciers, the researchers discovered the surface was buried and exposed at least eight times, Corbett said. The landscape could be at least 800,000 years old, she said.

"The ancient landscapes that have been preserved beneath these ghost glaciers might even be a million years old," Corbett said.

The team suspects that climate and elevation combined to prevent local glaciers or heavy snow from abrading the highlands. Though ice is one of the most powerful erosive forces on the planet, glaciers need water's slip-sliding help to grind across mountains. In particularly cold or high-altitude spots, glaciers may freeze in place instead of melting at their bottoms.

Researchers have also found cold, protective glaciers in mountain ranges, including the Alps and the Andes. Ice helps protect high points on Mont Blanc's French slope, a study published in June in the journal Earth and Planetary Science Letters suggested. In addition, a 2010 study published in the journal Nature showed cold-bottomed glaciers in Patagonia help shield the Andes' jagged peaks.

To a geologist's eye, the Greenland landscape simply looks old, Corbett said. "Even before I dated these rocks, standing on the land surface, it was all crumbly and falling apart," she explained. "The rocks are breaking off into sheets, and there are weathering pits on the surface. It's obviously a landscape that has experienced a much longer duration on the Earth's surface. It's a gorgeous landscape."

Articles from August 2013 on The History Channel (left) and NBC (right) websites.