LUND UNIVERSITY

Glacial history of Northeast Greenland: cosmogenic nuclide constraints on chronology and ice dynamics

Håkanson, Lena

2008

Link to publication

Citation for published version (APA):
Håkanson, L. (2008). *Glacial history of Northeast Greenland: cosmogenic nuclide constraints on chronology and ice dynamics*. [Doctoral Thesis (compilation), Quaternary Sciences]. Department of Geology, Lund University.

Total number of authors:
1

General rights
Unless other specific re-use rights are stated the following general rights apply:
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.
• Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
• You may not further distribute the material or use it for any profit-making activity or commercial gain
• You may freely distribute the URL identifying the publication in the public portal

Read more about Creative commons licenses: https://creativecommons.org/licenses/

Take down policy
If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

LUND UNIVERSITY

PO Box 117
221 00 Lund
+46 46-222 00 00

LUNDQUA Thesis 61

Glacial history of Northeast Greenland: cosmogenic nuclide constraints on chronology and ice dynamics

Lena Håkansson

Avhandling

Att med tillstånd från Naturvetenskapliga Fakulteten vid Lunds Universitet för avläggande av filosofie doktorsexamen, offentligen försvaras i Geologiska Institutionens föreläsningssal Pangea, Sölvegatan 12, fredagen den 11 april 2008 kl. 13.15.

Lund 2008
Lund University, Department of Geology, Quaternary Sciences

DOKUMENTDATABLAD enl SIS 61 41 21

Organization LUND UNIVERSITY Department of Geology, Quaternary Sciences	Document name DOCTORAL DISSERTATION Date of issue 14 March 2008 Sponsoring organization
Author(s) Lena Håkansson	

Title and subtitle

Glacial history of Northeast Greenland: cosmogenic nuclide constraints on chronology and ice dynamics

Abstract

The aim of this thesis was to use cosmogenic exposure dating to investigating whether highly weathered landscapes in the Northeast Greenland fjord zone have developed during prolonged ice free conditions or have been preserved beneath cold-based ice. Previous work along the Northeast Greenland coast has presented two conflicting hypotheses for the extent of the Greenland Ice Sheet during the last glacial maximum (LGM). Land-based investigations have suggested that low gradient outlet glaciers were restricted to fjord troughs and terminated at the inner continental shelf. In contrast, marine studies have recently indicated that the margin of the Greenland Ice Sheet reached the outer shelf during the LGM.

Results from cosmogenic 10Be and 26Al exposure dating show that during the LGM, local cold-based ice-caps covered and preserved weathered interfjord plateaus in the Northeast Greenland fjord zone, whereas fjord troughs were filled up with dynamic ice draining the Greenland Ice Sheet. The dynamic ice reached at least 250 m a.s.l. at the mouth of Scoresby Sund at the southernmost end and probably ~600 m a.s.l. at the northernmost end of the fjord zone, indicating that there was a N-S gradient in glacial style presumably reflecting regional differences in topography of the coastal areas. The results presented in this thesis reveals a dynamic picture for the northeastern sector of the Greenland Ice Sheet suggesting that LGM ice margins were substantially more advanced than indicated by earlier reconstructions from the terrestrial record.

Key words: Cosmogenic, Greenland Ice Sheet, Glacial history, Ice dynamics, Scoresby Sund, Jameson Land, Store Koldewey

Classification system and/or index termes (if any):

Supplementary bibliographical information: 250 copies		Language English
ISSN and key title: 0281-3033 LUNDQUA Thesis		ISBN 978-91-87465-37-6
Recipient's notes	Number of pages 17 + 4 app.	Price 120 SEK
	Security classification	

Distribution by (name and address)

I, the undersigned, being the copyright owner of the abstract of the above-mentioned dissertation, hereby grant to all reference sources permission to publish and disseminate the abstract of the above-mentioned dissertation.

Signature _____ Date 2 March 2008

Glacial history of Northeast Greenland: cosmogenic nuclide constraints on chronology and ice dynamics

Lena Håkansson

Quaternary Sciences, Department of Geology, GeoBiosphere Science Centre,
Lund University, Sölvegatan 12, SE-223 62 Lund, Sweden

This thesis is based on four papers listed below (Appendices I-IV). All papers are published in or submitted to peer-reviewed international journals. Papers I and IV are reproduced with permission from Elsevier Ltd. and Blackwell publishing, respectively. Papers II and III have been submitted to the journals indicated. In the following, the papers are referred to by their Roman numeral.

Appendix I
Håkansson, L., Briner, J., Alexanderson, H., Aldahan, A. & Possnert, G. 2007. ^{10}Be ages from coastal east Greenland constrain the extent of the Greenland Ice Sheet during the Last Glacial Maximum. *Quaternary Science Reviews 26*, 2316-2321.

Appendix II
Håkansson, L., Briner, J.P., Aldahan, A. & Possnert, G. ^{10}Be and ^{26}Al exposure ages of tors and meltwater channels on Jameson Land, east Greenland: implications for the Late Quaternary glaciation history. Manuscript submitted to *Quaternary Research.*

Appendix III
Håkansson, L., Alexanderson, H., Hjort, C., Möller, P., Briner, J.P., Aldahan, A. & Possnert, G. The late Pleistocene glacial history of Jameson Land, central East Greenland derived from cosmogenic ^{10}Be and ^{26}Al exposure dating. Manuscript submitted to *Boreas.*

Appendix IV
Håkansson, L., Graf, A., Strasky, S., Ivy-Ochs, S., Kubik, P.W., Hjort, C. & Schlüchter, C. 2007. Cosmogenic ^{10}Be-ages from the Store Koldewey island, NE Greenland. *Geografiska Annaler 89A (3)*, 195-202.

Contents

1. Introduction 1
1.1 Background 1
1.1.1 The Canadian Arctic 3
1.1.2 Svalbard 3
1.2 Aims of the present study 3

2. Study areas 4

3. Cosmogenic nuclides 6
3.1 History 6
3.2 Theory 6
3.3 Cosmogenic exposure dating 7

4. Results: summary of papers 8
4.1 Paper I 9
4.2 Paper II 9
4.3 Paper III 10
4.4 PaperIV 10

5. Discussion 11
5.1 Rethinking the extent and dynamics of the Greenland Ice Sheet during the LGM 11
5.2 Methodological considerations 12

6. Conclusions 12

7. Ideas for future research 13

8. Acknowledgements 13

9. Swedish summary 13

References 15

Appendices

1. Introduction

1.1 Background

During periods of the last glacial cycle, ice sheets covered vast continental areas. At present, the Greenland Ice Sheet is the only larger remain from this time in the Northern Hemisphere. Nevertheless, this ice sheet still stores enormous volumes of freshwater and changes in this ice mass might have considerable consequences for the global climate and environment. Studying the history of the Greenland Ice Sheet is thus important for understanding the climate during glacial cycles, which in turn can shed light on what might happen to the ice sheet and the global climate in the nearest future.

Within formerly glaciated regions, the occurrence of highly weathered terrain has often been used as evidence either for the existence of ice free areas during the last glaciation (Ives, 1966; Nesje & Dahl, 1990; Ballantyne et al., 1998; Rae et al., 2004) or for the former distribution of cold-based ice allowing the preservation of pre-Quaternary landscapes (Sugden, 1978; Kleman, 1994; Sollid & Sørbel, 1994; Kleman & Hättestrand, 1999; Davis et al., 2006). Because highly weathered landscapes are often found on upland plateaus, the interpretation of these landscapes can constrain ice thickness and/or the thermal regime of Pleistocene ice sheets.

In the Northeast Greenland fjord zone, which comprises the presently ice-free continental margin between Scoresby Sund in the south and Germania Land in the north (Fig. 1A), interfjord plateaus and coastal lowlands are commonly strongly weathered, whereas fjords and major valleys are characterized by glacially eroded surfaces. The Late Pleistocene glacial history of this area has been reconstructed through decades of research, and based on intense bedrock weathering and the lack of deposits from the last glaciation many interfjord areas were thought to have been ice-free throughout the last glacial cycle (e.g. Washburn, 1965; Lasca, 1969; Funder & Hjort, 1973; Hjort, 1979, 1981; Björck & Hjort, 1984; Funder & Hansen, 1996; Funder et al., 1994, 1998; Hansen et al., 1999). These studies thus described a last glacial maximum (LGM) scenario with outlet glaciers from the Greenland Ice Sheet restricted to the fjord troughs and terminating on the inner continental shelf. Similar reconstructions of limited LGM ice extent were also presented for Svalbard (Boulton 1979) and for the Canadian Arctic (Dyke & Prest, 1987), suggesting a minimalist glaciation scenario throughout the Arctic during the LGM.

The concept of restricted LGM glaciation in the Northeast Greenland fjord zone has, however, recently been challenged by marine data. Seismic profiling indicates the presence of a prominent moraine c. 50 km from the shelf break off the Kejsar Franz Joseph Fjord (Fig. 1A), interpreted to be a LGM terminal or recessional moraine (Evans et al., 2002). Furthermore, submarine channels, emanating from the lip of shelf troughs down the continental slope, have been interpreted as generated by a grounded ice sheet margin on the outer shelf or at the shelf break (Ó Cofaigh et al., 2004). Both these studies thus suggest grounded ice on the Northeast Greenland shelf during the LGM, but are not giving any further evidence of ice cover on land. However, Wilken & Minert (2006) suggested that channels on the shelf slope could rather have formed by outlet glaciers restricted to cross-shelf troughs and terminating some distance out on the shelf.

In recent years, cosmogenic exposure dating methods have provided new techniques to interpret differentially weathered landscapes (Stroeven et al., 2002; Fabel et al., 2002; Briner et al., 2003, 2005, 2006; Landvik et al., 2003; Marquette et al., 2004; Davis et al., 2006; Harbour et al., 2006) and in combination with new marine coring and imaging techniques this has led to a new understanding of the extent and dynamics of Late

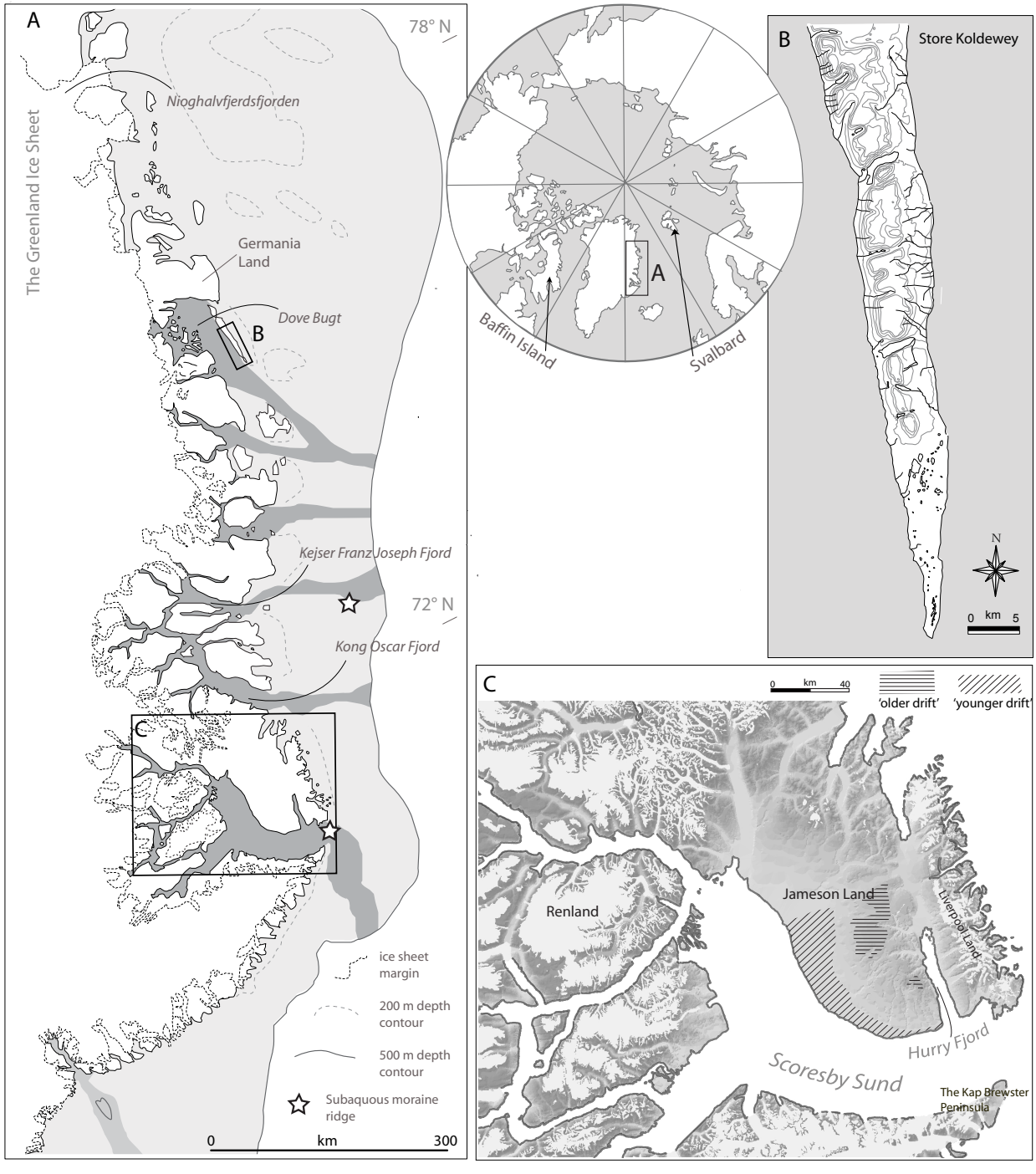

Figure 1. A. Map of Northeast Greenland. Study areas are marked with framed boxes and subaquous moraine ridges are marked with stars at the mouth of Scoresby Sund (Dowdeswell et al., 1994) and on the shelf off the Kejsar Franz Joseph Fjord (Evans et al., 2002). B. Map of the Store Koldewey island with 100 m contour lines. C. The Scoresby Sund area with distribution of 'older' and 'younger drift' after Ronnert & Nyborg (1994) and Möller et al. (1994)

Pleistocene ice sheets in differentially weathered fjord zones elsewhere in the Arctic.

1.1.1 The Canadian Arctic

Field investigations on eastern Baffin Island (Fig. 1A) identified areas with differences in the degree of weathering, so called weathering zones, which were used to suggest restricted glaciation in the eastern Canadian Arctic during the LGM (Pheasant & Andrews, 1973; Boyer & Pheasant, 1974). In the 1980s seismic stratigraphy (MacLean et al., 1986) and marine cores from the continental shelf off Baffin Island (Jennings et al., 1996) revealed evidence for grounded ice in these areas, challenging the minimalist concept presented by earlier studies. Recently, Baffin Island has been the focus of several studies applying cosmogenic exposure dating to weathering zone research. Bierman et al. (1999) obtained cosmogenic ^{26}Al and ^{10}Be data from tors in the southern part of the island, indicating that sampled surfaces had experienced multiple periods of exposure interrupted by shielding by non-erosive cold-based ice. Based on cosmogenic exposure dating and lake cores Miller et al. (2001) suggested that the southernmost part of Baffin Island was inundated by the LGM Laurentide Ice Sheet but that coastal interfjord uplands remained ice free. However, more recent work indicates that the LGM ice was even more extensive further to the north on Baffin Island. There, analyses of cosmogenic exposure dating suggests LGM ages for erratics perched on highly weathered inter-fjord plateaus and coastal lowlands, implying that cold-based ice dynamically connected to the Laurentide Ice Sheet covered these areas while ice streams filled the fjords (Briner et al., 2003, 2006).

1.1.2 Svalbard

During several decades it has been debated weather ice-free areas existed on Svalbard (Fig. 1A) during the LGM (e.g. Salvigsen, 1977; Forman, 1989; Mangerud et al., 1998). Based on cosmogenic ^{10}Be exposure dating of erratics and bedrock, Landvik et al (2003) presented evidence for the existence of nunataks on northwest Svalbard. Their results indicated that the last ice sheet that covered islands in the northwest retreated more than 80 ka ago and OSL dates of raised marine sediments close to the present-day sea level constrain the deglaciation after the last ice sheet advance to ~50 ka (Landvik et al., 2003). However, seismic stratigraphy and marine cores from further to the south on the continental shelf off western Svalbard have shown evidence for grounded LGM ice at the shelf-break (Landvik et al., 2005). Based on this they now suggest a topographically controlled LGM ice sheet configuration with ice streams filling the fjords and shelf troughs, with less dynamic ice over interfjord areas preserving delicate pre-LGM deposits. High resolution sea floor mapping on the shelf off northern and western Svalbard has revealed mega-scale lineations in cross shelf troughs suggesting that a topographically controled ice sheet reached the shelf break around almost all of western and northern Svalbard (Ottensen et al., 2007).

1.2 Aims of the present study

In Northeast Greenland two conflicting have been presented, from terrestrial and marine records, respectively: (i) extensive coastal areas were ice free whereas glacial ice filled the fjords as low gradient outlet glaciers terminating at the inner continental shelf or, (ii) the margin of the Greenland Ice Sheet reached all the way to the outer shelf or even to the shelf-break.

The aim of this thesis is to evaluate these two hypotheses, by applying cosmogenic exposure dating to erratics and bedrock in weathered interfjord areas in Northeast Greenland. A key objective is also to constrain the thermal regimes of the Late Pleistocene ice sheet advances, by investigating whether highly weathered landscapes along the Northeast Greenland coast have developed during prolonged

Figure 2. A. The summit plateau of the Store Koldewey island, looking north. B. Boulder on the summit plateau of Store Koldewey. C. Unconsolidated landforms of the 'older drift' on interior Jameson Land. D. Weathered sandstone bedrock. E. Tors on interior Jameson Land. F. Sampling of erratic boulder resting on regolith adjacent to tor-rich areas.

ice free conditions or have been preserved beneath cold-based ice.

2. Study areas

Fieldwork was conducted during four summer expeditions in 2003-2006 and samples for cosmogenic exposure dating presented in this thesis were collected from two areas in Northeast Greenland: the Store Koldewey island (76 °N) in the northernmost part and the Scoresby Sund area (70 -71 °N) in the southernmost part of the fjord zone (Fig. 1A).

The possibility arose to work on the Store Koldewey island in connection with the Greenland Sea cruise of the German research vessel "Polarstern" in the summer of 2003. This island is ~100 km long and situated at the outlet of the Dove Bugt Embayment blocks the outlet for major glacial advances from the Dove Bugt embayment (Fig. 1A). The landscape is dominated by mountain plateaus (~600-900 m a.s.l.) commonly cut by U-shaped

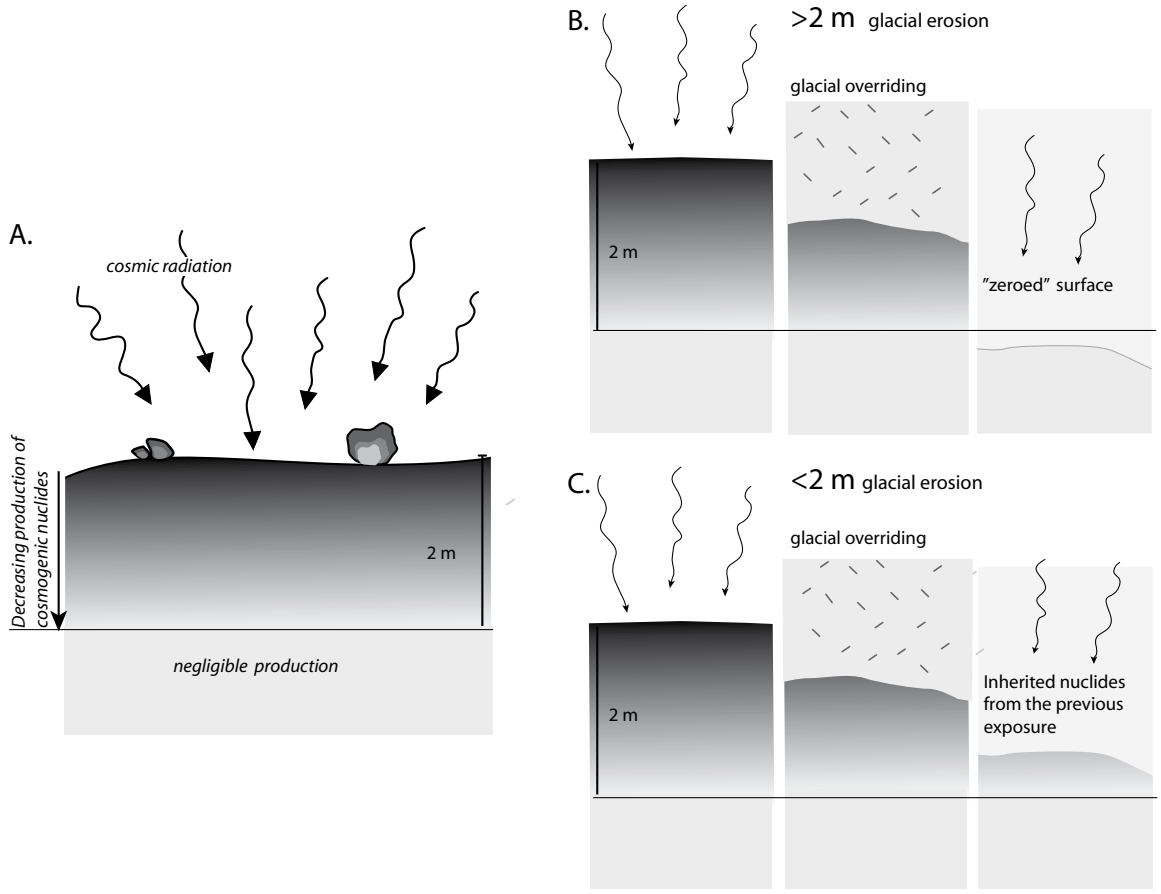

Figure 3. A. Cosmic radiation can produce cosmogenic nuclides in bedrock and boulders. The production takes place in the uppermost ~2 m of rock and decreases exponentially with depth. B. An example where a bedrock surface is overridden by glacial ice which erodes away >2 m of rock and thus all cosmogenic nuclides produced during the previous exposure are eroded away. When the bedrock surface again gets exposed following ice retreat, it is "zeroed" from old nuclides. C. In this example overriding ice erodes <2 m of rock reulting in that following deglaciation the exposed bedrock surface will still contain nuclides from the previous exposure

valleys trending from west to east (Figs 1B, 2A). Cosmogenic exposure dating results from boulders sampled on these plateaus (Fig. 2B) are presented in Paper IV.

The main fieldwork area during this project was the Jameson Land peninsula north of Scoresby Sund (Fig. 1C). Here three summer field seasons were spent in 2004-2006. In addition, a one-day helicopter trip took us to the Kap Brewster peninsula, on the southern side and at the very mouth of the fjord. Erratic boulders were sampled on the Kap Brewster Peninsula (Paper I) and samples from both erratics and bedrock were collected from interior Jameson Land (Fig. 2F; Papers II, III).

The Jameson Land Peninsula is composed of Mesozoic sedimentary rocks, mostly sandstone, and has an asymmetric topographic profile. From the interior plateau areas the terrain gently slopes towards Scoresby Sund in the west and south whereas the eastern margin, facing Hurry Fjord, has a steeper gradient (Fig. 1C). On Jameson Land two areas covered with Late Pleistocene sediments have been identified: the 'older-drift' on the central plateaus (Fig. 2C) and the 'younger drift' on the lowlands along the Scoresby Sund coast (Fig. 1C; Möller et al., 1994; Ronnert & Nyborg, 1994). Between these two sediment covered regions the sandstone landscape is highly weathered, exhibiting blockfields and well-developed tors (Figs 2D, E).

3. Cosmogenic nuclides

3.1 History

Already in the 1950´s it was proposed by Davies & Schaffer (1955) that cosmogenic isotopes produced within minerals could be applied to geological problems. At that time all studies of the interactions between cosmic rays and minerals were restricted to meteorites because production rates in terrestrial rocks were much too low for the analytical instrumentation available. Until the early 1980´s and the development of accelerator mass spectrometry (AMS) the studies of cosmogenic isotopes produced in terrestrial rocks stayed on a theoretical level (Lal & Peters, 1967). With AMS it finally became possible to measure even the extremely low concentrations of cosmic ray-derived isotopes within rocks from the surface of the Earth. Since the first studies demonstrating the usefulness of AMS for routine measurements of cosmogenic nuclides (Nishiizumi et al., 1986; Phillips et al., 1986), the use of cosmogenic nuclides to earth science related problems has increased significantly and this method is still continuously developing. One of the more common general applications to this technique has been to use the cosmogenic nuclide concentrations in a particular rock surface to estimate the time it has been exposed to cosmic radiation, so called cosmogenic exposure dating. If we can assume that a surface is related to a specific geologic event (e.g. a glaciation), then cosmogenic exposure dating provides means of directly dating this event.

3.2 Theory

Cosmic ray particles entering the Earth's atmosphere produce a cascade of secondary radiation, which in turn can produce cosmogenic nuclides (e.g. ^{10}Be, ^{14}C, ^{21}Ne, ^{26}Al, ^{36}Cl) in the atmosphere but also within minerals in the uppermost ~2 m of the lithosphere, so called terrestrial cosmogenic nuclides (Fig. 3A; Gosse & Phillips, 2001). The cosmic ray intensity is significantly reduced closer to the surface of the Earth which causes nuclide production rates to be much lower in rocks compared to the production rates in the atmosphere. Neutrons are those secondary cosmic ray particles responsible for the larger part of the production of terrestrial cosmogenic nuclides. A small fraction of the production is, however, caused by protons and muons.

For cosmogenic exposure dating purposes the most commonly used terrestrial cosmogenic nuclides are ^{10}Be and ^{26}Al, which are often measured in quartz separates. There are several reasons for choosing quartz; it has a simple structure, is widely distributed in rocks at the surface of the Earth and ^{10}Be and ^{26}Al production rates are high within quartz. It is also a relatively resistant mineral and thus easy to separate from other minerals using selective mineral dissolution with dilute acids (Kohl & Nishiizumi, 1992).

The rate at which cosmogenic isotopes are produced in the lithosphere is a function of altitude, latitude and time. The cosmic ray flux increases with higher altitude as air pressure and the shielding effect of the atmosphere decrease. At low latitudes the geomagnetic field will repel more incoming cosmic radiation, resulting in lower production rates compared to areas closer to the poles. In addition, changes in the geomagnetic field intensity will influence cosmic ray flux at low latitudes through time, but can be ignored for high latitudes. However, changes in air pressure over longer time periods might influence production rates on all latitudes. Such changes might be caused by the redistribution of high and low pressure systems due to climatic changes.

Cosmogenic exposure dating depends on correct determination of production rates. At any particular sampling site, two parameters are required to calculate the site specific production rate: (i) a scaling scheme describing the variation in production rates with time, elevation and latitude and, (ii) a reference production rate that is usually taken at present time,

sea level and high geomagnetic latitude. Several different scaling schemes have been suggested for the normalization of data to sea level exposure at high latitudes (Lal, 1991; Stone, 2000; Dunai, 2001; Lifton et al., 2005; Desilets et al., 2006). The most commonly used scaling scheme is the one first developed by Lal (1991) and later modified by Stone (2000), which is also used in this study.

3.3 Cosmogenic exposure dating

The calculation of nuclide exposure ages based on a singe nuclide, e.g. ^{10}Be, relies on the assumptions that the sampled surface has, (i) been constantly exposed and lacks inherited isotopes from previous exposures (requiring at least ~2 m of glacial erosion, Davis et al., 1999; Briner et al., 2006) and, (ii) experienced only minimal postdepositional erosion. These requirements will be fulfilled for most scoured bedrock surfaces and erratics in settings where substantial glacial erosion (>2 m) have taken place (Fig. 3B). Also, the texture of a surface (e.g. glacial striae) can provide strong evidence for negligible postdepositional erosion. Under these ideal circumstances a single nuclide may define the actual exposure age of a surface. However, in many cases the nuclide concentrations will reflect at least two variables; exposure and erosion. In terrain that has been covered by cold-based ice, or ice eroding <2m (Fig. 3C) nuclide concentrations might, in addition, reflect a third variable and that is shielding from cosmic radiation for substantial periods of time.

By measuring two radionuclides with different half-lives in the same sample, e.g. ^{10}Be and ^{26}Al, complex exposure/erosion/shielding histories can be constrained. Normally, the ^{26}Al/^{10}Be ratio is plotted against the logarithm of measured ^{10}Be concentration (Fig. 4; Lal, 1991; Bierman et al., 1999; Gosse & Phillips, 2001). The ^{26}Al/^{10}Be ratio of a particular sample can plot in four areas in this diagram, all describing different sample histories which is shown graphically in Figure 4 and explained below.

I. Samples which have experienced constant exposure with no erosion will plot on the "constant exposure curve". In a continuously exposed surface ^{10}Be and ^{26}Al will be produced at a constant ratio (^{26}Al/^{10}Be=6.1). If a surface is exposed for long enough (>100 ka), then the faster decay of ^{26}Al (half-life of 700 ka) relative to ^{10}Be (half-life of 1.3 Ma; Fink & Smith, 2007) will lead to a gradual decrease in the ^{26}Al/^{10}Be ratio which is reflected in the 'banana-shape' of the constant exposure curve in Figure 4A. Examples are shown for where on the constant exposure curve a sample would plot if it has been exposed for 100, 400 or 800 ka, respectively (Fig. 4A). Saturation is reached at the endpoint of this curve, which means that the production of ^{10}Be and ^{26}Al equals the loss of radionuclides through decay.

II. Any constantly exposed eroding surface will plot within the so called "steady state erosion island" (Lal, 1991). If a sample has experienced constant, gradual and continuous erosion, then it would plot on the curve for the specific erosion rate. Figure 4A shows examples of erosion curves for three different erosion rates (e=1, 3 and 10 mm ka^{-1}). In an eroding surface, saturation will be reached at lower nuclide concentrations as shown by the end-points of erosion curves. The lower boundary of the erosion island, shown with a dashed line, represents the continuum of erosion end points resulting from a range of possible erosion rates.

III. Samples plotting below the "steady-state erosion island" indicate that exposure has been interrupted by one or several shielding events. If the surface gets partly or entirely shielded from cosmic radiation, e.g. by non-erosive ice, then this will lead to a decrease in the ^{26}Al/^{10}Be ratio due to the faster decay of ^{26}Al relative to ^{10}Be. When a surface gets exposed again the ^{26}Al/^{10}Be ratio will increase. The distance below the "steady-state erosion island" is proportional to the duration of shielding. Bierman et al. (1999) described three classes of complex exposure

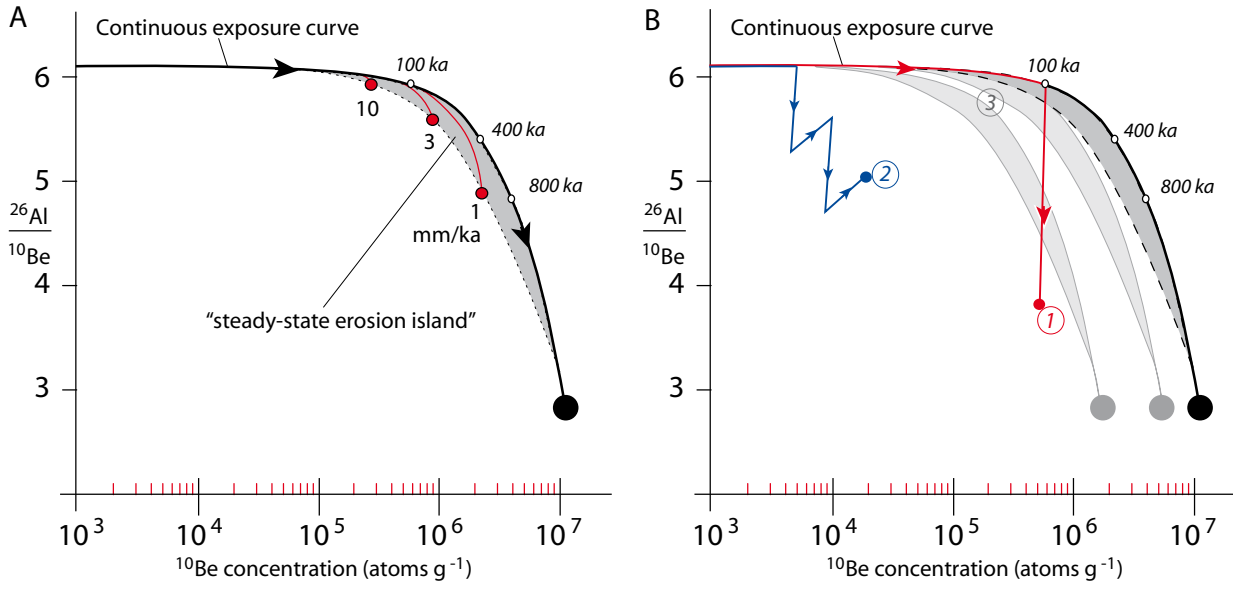

Figure 4. Two-isotope diagrams for interpreting ^{10}Be and ^{26}Al measurements.

histories and examples of these are shown in Figure 4B: The red line (1) shows continuous surface exposure without erosion for ~100 ka, followed by ~400 ka of burial by sufficiently thick ice or sediment. The blue zigzagged curve (2) shows how nuclide concentrations can evolve in a sample which had repeated periods of burial and exposure. The amplitude of this curve will be controlled by the duration of each exposure and burial period. The shaded area (3) shows exposure under cover, implying that a surface was only partly shielded from cosmic radiation by, e.g., sediment, snow or thin ice. The "steady-state erosion island" will be displaced to the left in the diagram as the shielding increases.

IV. Samples with ^{26}Al/^{10}Be ratios higher than the production ratio of 6.1 will plot above the "constant exposure curve" and can not be explained by any combination of exposure, erosion and shielding. Such high ratios might be due to problems during preparation or AMS measurement. It seems to be more common for samples with young exposure ages to plot above the constant erosion curve. This might be because low nuclide concentrations will be more sensitive to process blank correction. As an example, if the Be-blank was too high or the Al-blank too low, then this might have a disproportionate effect on the ^{26}Al/^{10}Be ratios, driving them upward on the plot.

Where a rock or boulder surface has been shielded from cosmic radiation for long periods (a total of ~200 ka or longer), the ^{10}Be and ^{26}Al concentrations can be used to calculate a minimum total exposure and total burial duration in accordance to the red line in Figure 4B. An important limitation with this approach is that the ^{26}Al/^{10}Be ratios do not evolve significantly during shorter periods (tens of thousands of years) and thus shorter periods of cold-based ice cover can not be resolved by this approach.

4. Results: summary of papers

Several researchers have contributed to this project. Those who have been involved in data contributon and preparation of the manuscripts appear as authors on Paper I-IV. Contributions are summarized in Table 1.

Task	Paper I	Paper II	Paper III	Paper IV
Fieldwork	Håkansson, L. Alexanderson, H.	Håkansson, L.	Håkansson, L. Alexanderson, H. Hjort, C.	Håkansson, L.
Participating in fieldwork		Elizabeth Thomas	Elizabeth Thomas	Ole Bennike, Holger Cremer Nadja Hultzsch Martin Klug Svenja Kobabe Berndt Wagner
Sample preparation for cosmogenic exposure dating	Håkansson, L.	Håkansson, L.	Håkansson, L.	Graf, A. Strasky, S.
Providing cosmo lab facilities	Briner, J.P. Dept. Geol., Buffalo, NY	Briner, J.P. Dept. Geol., Buffalo, NY	Briner, J.P. Dept. Geol., Buffalo, NY	Schlüchter, C. Inst. Geo. Sci., Bern
AMS and target packing	Possnert, G. Aldahan, A. Uppsala	Possnert, G. Aldahan, A. Uppsala	Possnert, G. Aldahan, A. Uppsala	Kubik, P. Ivy-Ochs, S. ETH Zürich
Data interpretation	Håkansson, L. Briner, J.P.	Håkansson, L Briner, J.P.	Håkansson, L. Alexanderson, H. Hjort, C. Möller. P.	Håkansson, L.

Table 1. Contributors to the research results presented in Papers I-IV.

4.1 Paper I

Håkansson, L., Briner, J., Alexanderson, H., Aldahan, A., Possnert, G. 2007. ^{10}Be ages from coastal east Greenland constrain the extent of the Greenland Ice Sheet during the Last Glacial Maximum. Quaternary Science Reviews 26, 2316-2321.

Paper I reports on ^{10}Be-ages from four erratic boulders perched at c. 250 m a.s.l. on the Kap Brewster peninsula at the mouth of Scoresby Sund. The average ^{10}Be-ages, calculated with an assumed maximum erosion rate of 1 cm ka^{-1} and no erosion (respectively, 17.3 ± 2.3 ka and 15.1 ± 1.7 ka) overlap with a period of increased sediment input to the Scoresby Sund fan (19-15 ka). These results suggest that active ice channeled in the Scoresby Sund trough reached at least 250 m above the present sea level at the mouth of the fjord during the LGM. This implies that the LGM ice margin reached further out on the continental shelf than has hitherto been assumed. It is also suggested that active ice in the fjord during may have been buttressed to the north by cold-based ice, thus giving indirect evidence for the presence of ice on the Jameson Land peninsula during the LGM.

4.2 Paper II

Håkansson, L., Briner, J.P., Aldahan, A., Possnert, G. ^{10}Be and ^{26}Al exposure ages of tors and meltwater channels on Jameson Land, east Greenland: implications for the Late Quaternary glaciation history. Submitted to Quaternary Research.

Paper II presents ^{10}Be and ^{26}Al results from the weathered sandstone landscapes of interior Jameson Land and aims at testing for the preservation of tors and to investigate if the area was indeed covered by ice during the LGM as indirectly indicated in Paper I. Samples were collected from three different surface types; (i) the top surfaces of tors, (ii) the bottoms of meltwater channels and, (iii) fluvially eroded outcrops adjacent to channels. Isotope concentrations indicate that tors have been preserved through multiple glacial cycles beneath cold-based ice, whereas the average ^{10}Be exposure age of 16.9 ± 2.4 ka on meltwater channels suggests that these

were eroded after the LGM.

It is proposed that the sandstone landscapes on interior Jameson Land evolved by three main processes during at least the last two glacial cycles: (i) during interglacial and interstadial periods of exposure, sandstone surfaces weathered at a rate of ~10 mm ka^{-1}, (ii) during periods of burial by cold-based ice, weathered rock slabs might have been decoupled from tors by entrainment of cold-based ice and, (iii) during deglaciations, meltwater followed existing fracture systems in the sandstone and eroded areas between tors by >2 m. Paper II presents evidence for that Jameson Land was at least partly covered by cold-based ice during the LGM, but it does not conclude whether this ice was local or dynamically connected to the Greenland Ice Sheet.

4.3 Paper III

Håkansson, L., Alexanderson, H., Hjort, C., Möller, P., Briner, J., Aldahan, A., Possnert, G. The late Pleistocene glacial history of Jameson Land, central East Greenland, derived from cosmogenic ^{10}Be and ^{26}Al exposure dating Submitted to Boreas.

The main objective of Paper III is to test whether or not the Greenland Ice Sheet covered Jameson land during the LGM, by using cosmogenic ^{10}Be and ^{26}Al exposure dating on erratics sampled from the central parts of the peninsula. ^{10}Be-ages from a total of 44 erratics, resting both on weathered sandstone and sediment-covered surfaces, range between 10.7 and 262.1 ka. Eight erratics from weathered sandstone and till surfaces cluster around ~70 ka whereas ^{10}Be-ages from glaciofluvial landforms are substantially younger and range between 10.7 and 46.6 ka. Deflation is thought to be an important process on the sediment covered surfaces and the youngest exposure ages from such settings are suggested to result from exhumation. The older (>70 ka) samples have discordant ^{26}Al and ^{10}Be data and are interpreted to have been deposited by the Greenland Ice Sheet several glacial cycles ago. The younger exposure ages (≤70 ka) are interpreted to represent deposition by a Late Saalian Greenland Ice Sheet advance but also by an early Weichselian advance from a local Liverpool Land-based ice-cap. The exposure ages younger than Saalian are explained by periods of shielding by cold-based ice during the Weichselian.

Paper III supports previous studies in that the Saalian ice sheet advance was the last to deposit thick sediment sequences and western erratics on interior Jameson Land. However, instead of Jameson Land being ice-free throughout the Weichselian it is documented that local cold-based ice covered and shielded large areas for substantial periods during the last glacial cycle.

4.4 Paper IV

Håkansson, L., Graf, A., Strasky, S., Ivy-Ochs, S., Kubik, P., Hjort, C., Schlüchter, C. 2007. Cosmogenic ^{10}Be-ages from the Store Koldewey island, NE Greenland. Geografiska Annaler 89A (3), 195-202.

The aim of Paper IV is to test whether or not the Store Koldewey island on the outer coast of Northeast Greenland was overridden by the Greenland Ice Sheet during the LGM. A total of seven samples for cosmogenic exposure dating were collected from weathered bedrock and boulders on the summit plateau of the island and from a moraine ridge on the glacially scoured lowland adjacent to the fjord. Among the samples from the summit plateaus, the two southernmost boulders give young exposure ages (11.5 ± 0.7 and 14.6 ± 0.8 ka), in contrast to the rest of the boulders (27.6 ± 1.6 and 79.1 ± 3.1 ka). Samples from weathered bedrock also give older ages (42.2 ± 2.2 ka and 147.1 ± 5.0 ka). A sampled boulder from the moraine ridge yieldes a ^{10}Be exposure age of 13.1 ± 0.9 ka.

Based on these exposure ages, Paper IV suggests that unscoured mountain plateaus at the outer coast in Northeast Greenland were covered, at least partly, by cold-based ice during the LGM. Because the dataset is small and all sampled boulders consist

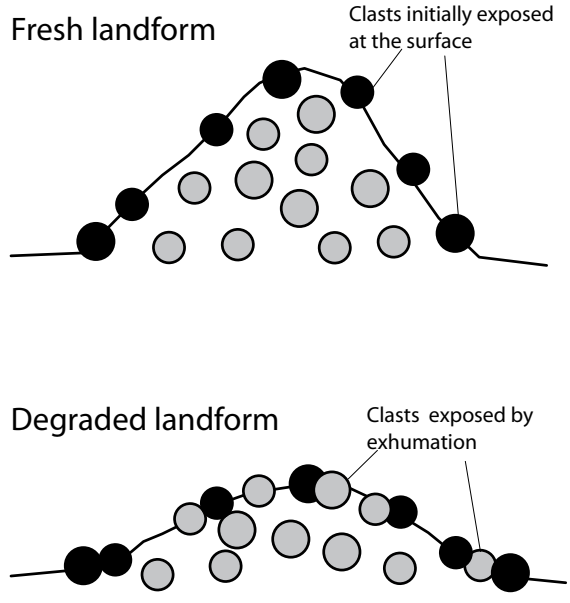

Figure 5. Degradation of unconsolidated landforms occurs as fine grained matrix is transported down slope by the action of wind, water and creep. Clasts initially exposed at the surface of the fresh landform are illustraded by black circles whereas clasts deposited whithin the landform are grey. As the landform degrades clasts are exhumed at the surface. Exhumed clasts will give anomalously young exposure ages.

of local bedrock, it is, however, left open whether the ice here was dynamically connected to the Greenland Ice Sheet or not. Regardless of the LGM ice sheet extent, this paper adds to a growing body of evidence suggesting considerable antiquity of crystalline unscoured terrain proximal to great ice sheets.

5. Discussion

5.1 Rethinking the extent and dynamics of the Greenland Ice Sheet during the LGM

In the Scoresby Sund area cosmogenic exposure dating results have contributed with three lines of evidence for testing the two contrasting hypotheses presented for the LGM extent of the ice sheet in the Northeast Greenland fjord zone (Papers I-III). The first piece in this jig-saw puzzle was presented in Paper I, which shows evidence for active ice at the mouth of the Scoresby Sund trough reaching at least 250 m a.s.l., thus implying that the LGM ice margin reached further out on the continental shelf than has hitherto been assumed. It is also suggested that active ice in the fjord during the LGM may have been buttressed to the north by cold-based ice, thus giving indirect evidence for the presence of ice on the Jameson Land peninsula. Presented in Paper II, LGM exposure ages of meltwater channels on interior Jameson Land indeed show the presence of cold-based ice. In addition, Paper III presents exposure ages of erratics showing no indications of material transport by the Greenland Ice Sheet onto interior Jameson Land during the LGM. From these three lines of evidence a LGM scenario evolves for the Scoresby Sund area where local, mostly cold-based, ice-caps covered Jameson Land and coalesced with active ice in Scoresby Sund.

Paper IV presents exposure ages from the Store Koldewey island ~650 km further to the north, at the northernmost end of the fjord zone and tests for the regionality of the scenario presented for the Scoresby Sund area (Papers I-III). The exposure age results from Store Koldewey do indeed suggest that also interfjord plateaus in the northernmost part of the fjord zone were covered by cold-based ice. It is however, not concluded in Paper IV whether or not ice was dynamically connected to the Greenland Ice Sheet.

At Store Koldewey and further to the north the shelf is unusually broad and shallow and the modern ice sheet margin is commonly situated at sea level, whereas further to the south in the fjord zone the present ice sheet margin is fringed by high mountains (Fig. 1A). Based on a regional synthesis of the Greenland margin, Bennike & Björck (2002) suggested that these differences in the landscape might have allowed the LGM ice sheet to expand much further out on the shelf north of the fjord zone compared to in the fjord zone. This N-S gradient in glacial style would imply that ice at the outer coast was thicker around Store Koldewey and north thereof compared to Scoresby Sund, which opens up for the possibility that the Greenland Ice Sheet indeed expanded beyond Store Koldewey during

the LGM. On the southernmost summit plateau of Store Koldewey, closest to the outlet of the Dove Bugt embayment (Fig. 1A), two boulders show apparent exposure ages compatible with the LGM deglaciation, whereas boulders with older exposure ages are situated further to the north (Paper IV). If interpreting the southernmost boulders as deposited by the ice sheet, then a scenario could be suggested where active ice from the Greenland Ice Sheet filled up the Dove Bugt embayment and was buttressed by local cold-based ice on the Store Koldewey plateaus. However, at the outlet of the embayment where active ice was no longer channelized between high mountains, the ice flow would diverge and this could result in glacial transport of erratics onto the very southernmost part of the island. In line with this reasoning the position of boulders with apparent exposure ages compatible with the LGM deglaciation at ~600 m would indicate the thickness of active ice at the outlet of the Dove Bugt embayment.

The work presented in this thesis suggests a topographically controlled configuration of the northeastern sector of the Greenland Ice Sheet. Based on the cosmogenic exposure dating efforts alone, the exact ice marginal position on the continental shelf can not be constrained. However, I hypothesize that relatively fast-flowing ice draining the ice sheet was channelized in cross-shelf troughs and was thus capable of reaching further out on the shelf compared to the local cold-based ice-caps on interfjord areas which would have had steeper surface gradients.

5.2 Methodological considerations

Recently, many studies have shown the importance of considering surface lowering of landforms for interpreting cosmogenic exposure age on drift, especially on old (pre-LGM) features. Putkonen & O'Neil (2006) proposed that degradation universally affects all sloping unconsolidated landforms and in a case study from southernmost South America, Kaplan et al. (2007) show that apparent exposure ages from erratics are much younger than the landforms that they rest upon. Cobbles and boulders can be exhumed from the surface of unconsolidated landforms as fine grained matrix is transported down slope by the action of wind, water and creep (Putkonen & Swanson, 2003). These processes might lead to that cobbles and boulders will not get exposed at the sediment surface until long after their deposition, which in turn will lead to anomalously young exposure ages (Fig. 5; Putkonen & Swanson, 2003).

The above mentioned studies have major implications for the application of cosmogenic exposure dating to an area like interior Jameson Land, which is to a large extent covered by pre-Weichselian sediments. Paper III suggests that wind erosion is one of the most important surface lowering processes acting on unconsolidated landforms on Jameson Land. This is based on the existence of extensive deflation surfaces on sediment covered plateaus and the accumulation of sand dunes in sheltered positions (Adrielsson & Alexanderson, 2005). Stormy conditions during periods of the last glacial cycle are further indicated by dust in the Renland ice core (Fig. 1; Johnsen et al., 1992). Based on the cosmogenic exposure dating results from the 'older drift'-covered areas on interior Jameson Land (Paper III) it is stressed that deflation is an important process to consider when applying exposure dating to clasts on sandy unconsolidated landforms elsewhere in the Arctic.

6. Conclusions

In this thesis I suggest that during the LGM, local cold-based ice-caps covered and preserved weathered interfjord plateaus in the Northeast Greenland fjord zone whereas fjord troughs were filled up with dynamic ice draining the Greenland Ice Sheet. In Scoresby Sund and probably also in the Dove Bugt embayment, the active ice was so thick

that it must have been buttressed by cold-based ice on interfjord plateaus. This scenario further implies ice streams thick enough to reach at least 250 m a.s.l. at the mouth of Scoresby Sund and ~600 m a.s.l. at the outlet of the Dove Bugt embayment.

The work presented here demonstrates that throughout the Northeast Greenland fjord zone the LGM ice limits were substantially more extensive than defined by earlier land-based work but that there was a N-S gradient in glacial style presumably reflecting regional differences in the topography of the coastal areas.

7. Ideas for future research

Taken together, my work applying cosmogenic exposure dating to differentially weathered landscapes in the Northeast Greenland fjord zone has provided insights into the dynamic behavior of the northeastern sector of the Greenland Ice Sheet during the LGM. The regionality of these results could be further investigated by applying this approach to other weathered interfjord plateaus in Northeast Greenland. This would be of particular importance for further constraining whether the Greenland Ice Sheet indeed overrode some coastal plateaus in the northernmost part of the fjord zone. Furthermore, an important focus would be to further investigate the LGM ice marginal position on the continental shelf.

8. Acknowledgements

First of all, I would like to thank my main PhD-advisor Christian Hjort for introducing me to the exiting field of polar research and for supporting me and sharing his extensive knowledge and experience from East Greenland. I also want to thank my co-advisors Per Möller, Svante Björck, Raimund Muscheler and Johan Kleman for their assistance and support.

I am deeply grateful for all the help and support that I have got from Jason Briner at the Geology Department in Buffalo, NY. Thank you for your never-ending enthusiasm and interest in my work and for introducing me to your amazing lab! I also want to acknowledge all the people in the Paleoclimate Lab in Buffalo and especially Elizabeth, Dale, Nic and Yarrow for being such a great team.

I want to thank everybody at the Quaternary Department in Lund and especially Lena Adrielsson and Nicolaj Krog Larsen for many constructive and inspiring discussions.

I also want to thank Anders Schomacker, Helena Alexanderson, Maria Jensen, and Lena Adrielsson (again), not only for being such great colleagues but also for making my life during the last four years so much easier.

I had the pleasure of spending a great field season on Store Koldewey in 2003 with Ole Bennike, Holger Cremer, Nadja Hultzsch, Martin Klug, Svenja Kobabe and Berndt Wagner. Thank you!

The research presented here was generously funded by the following grants: Helge Ax:son Johnsons Foundation, Swedish Society of Anthropology and Geography, Kungliga Fysiografiska Sällskapet, Kungliga Vetenskapsakademien, Kurt and Alice Wallenbergs Foundation, NorFa and the Japetus Steenstrup Foundation.

Special thanks go to my family and friends for their support, especially to Sanna and Anja for always being there for me and to Staffan for being so patient and for believing in me.

9. Swedish summary

Senpleistocen nedisningshistoria på Nordöstgrönland: kosmogen exponeringsdatering, isutbredning och isdynamik

Under den senaste istiden var periodvis stora delar av landmassorna på norra halvklotet istäckta. Idag är den Grönländska inlandsisen den enda

större återstoden av detta, men likväl binder den tillsammans med isen i Antarktis och jordens mindre glaciärer väldigt stora mängder vatten. Förändringar i dessa isars utbredning och volym kan få mycket stora konsekvenser för den globala miljön och för balansen i klimatet. Att undersöka spåren från den Grönländska Inlandsisens forntid är därför en viktig del i att skapa en ökad kunskap om istidscyklernas klimatförhållanden som i sin tur kan bidra till en bättre förståelse för vad som är på väg att hända med våra polarisar idag.

Dagens kunskap om Östgrönlands nedisningshistoria bygger på de omfattande studier som utförts framför allt under de senaste decennierna. Det råder dock fortfarande delade meningar om Inlandsisens utbredning och om förekomsten av isfria områden under det senaste globala nedisningsmaximat för ca 20 000 år sedan. Resultat från undersökningar på land tyder på att stora delar av de idag isfria landområdena också varit fria från is under hela den senaste istiden. Uppfattningen om en begränsad glaciation under denna tidsperiod står dock i kontrast till resultat från maringeologiska undersökningar vilka tolkats som att is nått hela vägen ut till kontinentalsockeln under det senaste nedisningsmaximat.

Inom mitt avhandlingsarbete har jag velat testa hypoteserna om den Grönländska inlandsisens utbredning genom en omfattande dateringssatsning baserad på analys av kosmogena isotoper (^{10}Be och ^{26}Al) i berggrund och flyttblock, s.k. kosmogen exponeringsdatering. Nedan följer en beskrivning av denna metodik.

Vår jord utsätts för en ständig dusch av kosmisk strålning, till största delen neutroner och protoner med tillräckligt stor energi för att orsaka kärnreaktioner då de kolliderar med andra partiklar. Vid dessa kärnreaktioner kan kosmogena isotoper bildas. Produktionen sker i huvudsak uppe i atmosfären men förekommer även i berggrundens översta två meter, orsakad av den kosmiska strålning som når jordens yta. Då en bergyta täcks av ett tillräckligt tjockt lager is, snö, sediment eller vatten upphör denna produktion. Dessutom medför sönderfall av de radioaktiva isotoperna, samt erosion av berget, att koncentrationen av redan ackumulerade isotoper minskar. Om erosionen från en täckande is varit tillräcklig (mer än 2 meter) så kommer isens underlag att bli ”nollställd” från gamla isotoper. Om isen däremot inte har eroderat fullt så mycket, eller kanske inte alls, så kommer den bergyta som exponeras efter isens tillbakadragande att innehålla ”ärvda” isotoper från tidigare exponeringsperioder. När isen drar sig tillbaka och bergytor exponeras igen, fortsätter produktionen av kosmogena isotoper. Om man analyserar innehållet av kosmogena isotoper i en yta som isen ”nollställt” får man en uppskattning av hur lång tid som gått sedan området blev isfritt och metoden fungerar som en absolut dateringsteknik. För en yta som inte blivit ”nollställd” ger analysen av två olika radioaktiva isotoper med olika sönderfallshastigheter (oftast ^{10}Be och ^{26}Al) inte någon absolut ålder, men kan däremot påvisa huruvida en bergyta under upprepade perioder har varit omväxlande exponerad och övertäckt av icke-eroderande glaciär-is.

Senare års utveckling av tekniken att analysera kosmogena isotoper som ackumulerats i litosfären har öppnat nya möjligheter för att testa de motsägelsefulla hypoteserna om den Grönländska inlandsisens utbredning i tid och rum samt förekomsten av isfria områden under den senaste nedisningen. Genom att provta och analysera både berggrund och flyttblock på de starkt förvittrade högplatåerna och de kustnära lågländerna i den Nordöstgrönländska fjordzonen är det alltså nu möjligt att utforska både Inlandsisens utbredning, och dess eroderande, alternativt landskapsbevarande karaktär. Analys av flyttblocken gör det möjligt att avgöra när en dynamisk och materialtransporterande is sist var så stor att den täckte dessa områden. Berggrundsproverna kan visa om de starkt förvittrade ytorna bevarats under upprepade perioder av övertäckning av kallbaserad, mer passiv is eller om vittringen är ett resultat av att dessa områden var isfria under senaste nedisningen.

Detta tillvägagångssätt har lett till en ny och mer dynamisk bild av den Grönländska inlandsisen

under det senaste nedisningsmaximat. I mitt avhandlingsarbete föreslår jag att lokala kallbaserade iskappor började tillväxa på de idag isfria kustnära platåerna längs den nordöstgrönländska kusten. Under nedisningsmaximat växte dessa samman med inlandsisens utlöparglaciärer som var kanaliserade i de många fjordarna. De kallbaserade iskapporna förblev förmodligen lokala, utan dynamisk koppling till inlandsisen. Det är dock möjligt att inlandsisen expanderade över även de högre kustområdena i den nordligaste delen av fjordzonen.

References

Adrielsson, L. & Alexanderson, H. 2005: Interactions between the Greenland Ice Sheet and the Liverpool Land coastal ice cap during the last two glacial cycles. Journal of Quaternary Science 20 (3), 269-283.

Ballantyne, C. K., McCarroll, D., Nesje, A., Dahl, S. O. 1998: The last ice sheet in North-West Scotland: Reconstruction and implications. Quaternary Science Reviews 17, 1149-1184

Bennike, O. & Björck, S. 2002: Chronology of the last recession of the Greenland Ice Sheet. Journal of Quaternary Science 17, 211-219.

Bierman, P. R., Marsella, K. A., Patterson, C., Davis, P. T. & Caffee, M. 1999: Mid-Pleistocene cosmogenic minimum-age limits for pre-Wisconsin glacial surfaces in southwestern Minnesota and southern Baffin Island: a multiple nuclide approach. Geomorphology 27, 25-39.

Björck, S. & Hjort, C. 1984: A re-evaluated glacial chronology for northern East Greenland. Geologiska Föreningens i Stockholms Förhandlingar 105, 235-243.

Boulton, G.S. 1979: Glacial history of the Spitsbergen archipelago and the problem of a Barents Shelf ice sheet. Boreas 8, 31-57.

Boyer, S.J. & Pheasant, D.R. 1974: Delimitation of weathering zones in the fiord area of Eastern Baffin Island, Canada. Geological Society of America Bulletin 85, 805-810.

Briner, J. P., Miller, G., Davies, P. T., Bierman, P. R. & Caffee, M. 2003: Last Glacial Maximum ice sheet dynamics in the Canadian Arctic inferred from young erratics perched on ancient tors. Quaternary Science Reviews 22, 437-444.

Briner, J. P., Miller, G. H., Davis, T. R. & Finkel, R. 2005: Cosmogenic exposure dating in arctic glacial landscapes: implications for the glacial history of northeastern Baffin Island, Arctic Canada. Canadian Journal of Earth Sciences 42, 67-84.

Briner, J. P., Miller, G., Davies, P. T. & Finkel, R. 2006: Cosmogenic radionuclides from fiord landscapes support differential erosion by overriding ice sheets. GSA Bulletin 118, 406-430.

Davies, R.T. & Schaffer, O. A. 1955: Chlorine-36 in nature. Annals New York Academy of Science 62, 105-122.

Davis, P. T., Bierman, P. R., Marsella, K. A., Caffee, M. W. & Southon, J.R. 1999: Cosmogenic analysis of glacial terrains in the eastern Canadian Arctic: a test for inherited nuclides and the effectiveness of glacial erosion. Annals of Glaciology 28, 181-188.

Davis, P. T., Briner, J. P., Coulthard, R. P., Finkel, R. W. & Miller, G. H. 2006: Preservation of Arctic landscapes overridden by cold-based ice sheets. Quaternary Research 65, 156-163.

Desilets, D., Zreda, M. & Prabu, T. 2006: Extended scaling factors for in situ cosmogenic nuclides: new measurments at low latitude. Earth and Planetary Science Letters 246, 265-276.

Dunai, T. 2001: Influence of secular variation of the magnetic field on production rates of in situ produced cosmogenic nuclides. Earth and Planetary Science Letters, 193, 197-212.

Dyke, A.S. & Prest, V.K. 1987: Late Wisconsin andHolocene history of the Laurentide Ice Sheet. Géographie physique et Quaternaire 41, 237-263.

Evans, J., Dowdeswell, J. A., Grobe, H., Niessen, F., Stein, R., Hubberten, H. W. & Whittington, R. J. 2002: Late Quaternary sedimentation in Kejsar Franz Joseph Fjord and the continental margin of East Greenland. In Dowdeswell, J. A., Ó Cofaigh, C. (eds.): Glacier influenced sedimentation on high latitude continental margins, 149-179. Geological Society of London: Special Publications 203, London, United Kingdom.

Fink, D. & Smith, A. 2007: An inter-comparison of ^{10}Be and ^{26}Al AMS reference standards and the

^{10}Be half-life. Nuclear Instruments and Methods in Physics Research B 259, 600-609.

Forman, S.L. 1989: Late Weichselian glaciation and deglaciaiton of the Forlandssundet area, western Spitzbegen, Svalbard. Boreas 18, 51-60.

Funder, S. & Hansen, L. 1996: The Greenland Ice Sheet – a model for its culmination and decay during and after the last glacial maximum. Bulletin of the Geological Society of Denmark 42, 137-152.

Funder, S. & Hjort C. 1973: Aspects of the Weichselian chronology in central East Greenland. Boreas 2, 69-84.

Funder, S., Hjort, C. & Landvik, J. Y.1994: The last glacial cycle in East Greenland, an overview. Boreas 23, 283-293.

Funder, S., Hjort, C., Landvik, J. Y., Nam, S.-I., Reeh, N. & Stein, R. 1998: History of a stable ice margin – East Greenland during the middle and upper Pleistocene. Quaternary Science Reviews 17, 77-123.

Gosse, J. C. & Phillips, F. M. 2001: Terrestrial in-situ cosmogenic nuclides; theory and application. Quaternary Science Reviews 20, 1275-1560.

Hansen, L., Funder, S., Murray, A. S. & Mejdal, S. 1999: Luminiscence dating of the last Weichselian Glacier advance in East Greenland. Quaternary Geochronology 18, 179-190.

Harbour, J., Stroeven, A. P., Fabel, D., Clarhäll, A., Kleman, J., Li, Y., Elmore, D. & Fink, D. 2006: Cosmogenic nuclide evidence for minimal erosion across two subglacial sliding boundaries of the late glacial Fennoscandian ice sheet. Geomorphology 75, 90-99.

Hjort, C. 1979: Glaciation in northern East Greenland during the Late Weichselian and Early Flandrian. Boreas 8, 281-296.

Hjort, C. 1981: A glacial chronology for northern East Greenland. Boreas 10, 259-274.

Ives, J. D. 1966: Blockfields, associated weathering forms on mountain tops and the nunatak hypothesis. Geografiska Annaler 48A, 220-223

Jennings, A.E., Tedesco, K.A., Andrews, J.T. & Kirby, M.E. 1996: Shelf erosion and glacial ice proximity in the Labrador Sea during and after Heinrich events (H-3 or 4 to H-0) as shown by foraminifera. In Andrews, J.T., Austin, W.E.N., Bergsten, H & Jennings, A.E. (eds.): Late Quaternary Paleoceanography of the North Atlantic Margins, 29-49. Geological Society Special Publications, London.

Johnsen, S. J., Clausen, H. B., Dansgaard, W., Gundestrup, N. S., Hansson, M., Jonsson, P., Steffensen, J. P. & Sveinbjørnsdottir, A. E. 1992: A "deep" ice core from East Greenland. Meddelelser om Grønland, Geoscience 29, 22 pp.

Kaplan, M. R. Coranto, A., Hulton, N. R. J., Rabassa, J.O., Kubik, P. W. & Freeman, S. P. H. T. 2007: Cosmogenic nuclide measurements in southernmost South America and implications for landscape change. Geomorphology 87, 284-301.

Kleman, J. 1994: Preservation of landforms under ice sheets and ice caps. Geomorphology 9, 19-32.

Kleman, J.& Hätterstrand, C. 1999: Frozen-bed Fennoscandian and Laurentide ice sheets during the Late Glacial Maximum. Nature 402, 63-66.

Kohl, C.P. & Nishiizumi, K. 1992: Chemical isolation of quartz for measurement of in-situ produced cosmogenic nuclides. Geochimica et Cosmochimica Acta 56, 3583-3587.

Lal, D. 1991: Cosmic ray labeling of erosion surfaces: In-situ nuclide production rates and erosion models. Earth and Planetary Science Letters 104, 424-439.

Lal, D. & Peters, B. 1967: Cosmic ray produced radioactivity on the earth. In Sitte. K. (ed): Handbuch der Physik. Springer, Berlin, pp. 551-612

Landvik, J. Y. Brook, E. J., Gualtieri, L., Raisbeck, G., Salvigsen, O. & Yiou, F. 2003: Nortwest Svalbard during the last glaciation: Ice-free areas existed. Geology 31, 905-908.

Landvik, J.Y., Ingolfsson, Ó., Mienert, J., Lehman, S.J., Solheim, A. Elverhoi, A & Ottesen, D. 2005: Rethinking Late Weichselian ice dynamics in coastal NW Svalbard. Boreas 34, 7-24.

Lasca, N. P 1969. The Surficial Geology of Skeldal, Mesters Vig, North East Greenland. Meddelelser om Grønland 176:3, 56 pp

Lifton, N, Bieber, J., Clem, J., Dulding, M., Evenson, P., Humble, J. & Pyle, R. 2005: Adressing solar modulation and long-term uncertainties in scaling secondary secondary cosmic rays for in situ cosmogenic nuclide applications. Earth and Planetary Science Letters 239, 140-161.

MacLean, B., Williams, G.L., Jennings, A.E. &

Blakeny, C. 1986: Bedrock and surficial geology of Cumberland Sound, N.W.T. Geological Survey of Canada, Ottawa.

Mangerud, J., Dokken, T.M., Hebbeln, D., Heggen, B., Ingolfsson, O., Landvik, J.Y., Mejdahl, V., Svendsen, J.I. & Vorren, T.O. 1998: Fluctuations of the Svalbard-Barents Sea Ice Sheet during the last 150,000 years. Quaternary Science Reviews 17, 11-42.

Marquette, G. C, Gray, J. T., Gosse, J. C., Courchesne, F., Stockli, L., Macpherson, G. & Finkel, R. 2004: Felsenmeer persistence under non-erosive ice in the Torngat Mountains and Kaumajet Mountains, Quebec and Labrador, as determined by soil weathering and cosmogenic nuclide exposure dating. Canadian Journal of Earth Sciences 41, 19-38.

Miller, G.H., Wolfe, A.P., Steig, E.J., Sauer, P.E., Kaplan, M.R. & Briner, J.P. 2001: The Goldilocks dilema: big ice, little ice, or "just-right" ice in the Eastern Canadian Arctic. Quaternary Science Reviews 21, 33-48.

Möller, P., Hjort, C., Adrielsson, L. & Salvigsen, O. 1994: Glacial history of interior Jameson Land, East Greenland. Boreas 23, 320-348.

Nesje, A. & Dahl, S. O. 1990: Autochtonous block fields in southern Norway – implications for the geometry, thickness an isostatic loading of the Late Weichselian Scandinavian ice sheet. Journal of Quaternary Science 5, 225-234.

Nishiizumi, K., Lal, D., Klein, J., Middleton, R. & Arnold, J. R. 1986: Production of ^{10}Be and ^{26}Al by cosmic rays in terrestrial quartz in situ and implications for erosion rates. Nature 319, 134-135.

Ó Cofaigh, C., Dowdeswell, J. A., Evans, J., Kenyon, N. H., Taylor, J., Mienert, J., & Wilken, M. 2004: Timing and significance of glacially influenced mass-wasting in the submarine channels of the Greenland Basin. Marine Geology 207, 39-54.

Ottesen, D., Dowdeswell, J.A., Landvik, J.Y. & Mienert, J. 2007: Dynamics of the Late Weichselian ice sheet on Svalbard inferred from high-resolution sea-floor mapping morphology. Boreas 36, 286-306.

Pheasant, D.R. & Andrews, J.T. 1973: Wisconsin glacial chronology and relative sea level movements, Narpaing Fiord Broughton Island, eastern Baffin Island, N.W.T. Canadian Journal of Earth Sciences 10, 1621-1642.

Phillips, F. M., Leavy, B. D., Jannick, N. O., Elmore, D. & Kubik, P. W. 1986: The accumulation of cosmogenic chlorine-36 in rocks: a method for surface exposure dating. Science 231, 41-43.

Putkonen, J. & O'Neil, M. A. 2006: Quaternary degradation of unconsolidated landforms in the wesatern North America. Geomorphology 75, 408-419.

Putkonen, J. & Swanson, T. 2003: Accuracy of cosmogenic ages for moraines. Quaternary Research 59, 255-261.

Rae, A. C., Harrison, S., Mighall, T. & Dawson, A.G. 2004: Periglacial trimlines and nunataks of the last glacial maximum: the Gap of Dunloe, southwest Ireland. Journal of Quaternary Science 19, 87-97.

Ronnert, L. & Nyborg, M. R. 1994: The distribution of different glacial landscapeson southern Jameson Land, East Greenland according to Landsat Thematic Mapper data. Boreas 23, 294-311.

Salvigsen, O. 1977: Radiocarbon datings and teh extention of the Weichselian ice sheet ic Svalbard. Norsk Polarinstitutt Årbok 1976, 209-224.

Stone, J. O. 2000: Air pressure and cosmogenic isotope production. Journal of geophysical research 105, 23753-23759.

Stroeven, A. P., Fabel, D., Hättestrand, C. & Harbour, J. 2002: A relict landscape in the centre of the Fennoscandian glaciation: cosmogenic radionuclide evidence of tors preserved through multiple glacial cycles. Geomorphology 44, 145-154.

Sollid, J. L. & Sørbel, L. 1994: Distribution of glacial landforms I Southern Norway in relation to the thermal regime of the last continental ice sheet. Geografiska Annaler 76, 25-36.

Sugden, D. E. 1978: Glacial erosion by the Laurentide ice sheet. Journal of Glaciology 83, 367-391.

Washburn, A. L. 1965: Geomorphic and vegetational studies in the Mesters Vig district. Meddelelser om Grønland 166, 60 pp.

Wilken, M. & Mienert, W. 2006: Submarine glacigenic debris-flows, deep-sea channel and past ice stream behaviour of the east Greenland continental margin. Quaternary Science Reviews 25, 784-810.

Appendix I