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## Constraining the Southern Part of the Greenland Ice Sheet since the Last Glacial Maximum from Relative Sea-Level Changes, Cosmogenic Dates and Glacial-Isostatic Adjustment Models

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Constraining the southern part  
of the Greenland Ice Sheet  
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*Charlotte Jönsson Sparrenbom*

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LUNDQUA Thesis 56  
Quaternary Sciences  
Department of Geology  
GeoBiosphere Science Centre  
Lund University  
Lund 2006

LUNDQUA  
T H E S I S



# LUNDQUA Thesis 56

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**Constraining the southern part of the Greenland Ice Sheet since the Last Glacial Maximum from relative sea-level changes, cosmogenic dates and glacial-isostatic adjustment models**

*Charlotte Jönsson Sparrenbom*

## **Avhandling**

Att med tillstånd från Naturvetenskapliga Fakulteten vid Lunds Universitet för avläggande av filosofie doktorsexamen, offentligen försvaras i Geologiska Institutionens föreläsningssal Pangea, Sölvegatan 12, Lund, fredagen den 17 mars 2006 kl. 14.15

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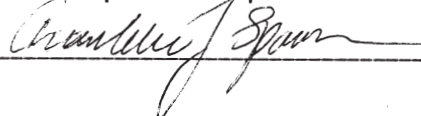
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| Title and subtitle<br>Constraining the southern part of the Greenland Ice Sheet since the Last Glacial Maximum from relative sea-level changes, cosmogenic dates and glacial-isostatic adjustment models  |                                       |                       |
| Abstract<br>New results are presented from the investigation of relative sea-level changes in the Nanortalik and Qaqortoq-Narsarsuaq areas in SW Greenland from c. 11 000 cal. years BP to the present. Isolation and transgression sequences from seven lakes and seven tidal basins are identified using some of the traditional methods such as stratigraphic description, magnetic susceptibility, saturated induced remanent magnetisation (SIRM), loss on ignition, and macrofossil analyses. Macrofossils and bulk sediments have been dated by AMS radiocarbon dating.<br>We also demonstrate that the use of the new XRF-scanning technique, combined with lithological description, pinpointed macrofossil analyses and radiocarbon dating, provide a quick and effective way of investigating isolation contacts/transgression sequences for the reconstruction of sea-level changes. In SW Greenland, the initial relative sea level fall was rapid and present-day level was reached at ~9000 cal. yr BP and continued falling until at least 8800 cal. yr BP. Between 8000 and 6000 cal. yr BP sea level reached its lowest level of around ~10 m below h.a.t. The late Holocene transgression was more gradual as it occurred over a longer time interval. Present sea-level was reached between ~2000-0 cal. yr BP. We have used glacial-isostatic adjustment models to determine the ice sheet evolution in southern Greenland from the LGM until the present. The sea-level observations from the Nanortalik and Qaqortoq areas are used to constrain the different ice-model scenarios tested. In situ produced cosmogenic <sup>10</sup> Be and <sup>26</sup> Al in bedrock and erratics give inference concerning the basal regime in the two areas. Our ice sheet history reconstruction shows an ice sheet extending to the shelf edge from 26,500 cal. yr BP until 22,000 cal. yr BP, followed by rapid retreat. By 12,000 cal. yr BP, the ice margin was inland of the present-day coast and by 10,500 it had reached the present margin. The ice sheet was smaller than at present from 10,500 cal. yr BP and reached a minimum of 30 km inland of the present-day margin at 9000 cal. yr BP. The neo-glacial re-advance started before 6500 cal. yr BP and the present-day margin was reached by 5500 cal. yr BP. The ice sheet was cold-based in the Nanortalik area, but warm-based and eroding in the Qaqortoq area during the Late-glacial. |                                       |                       |
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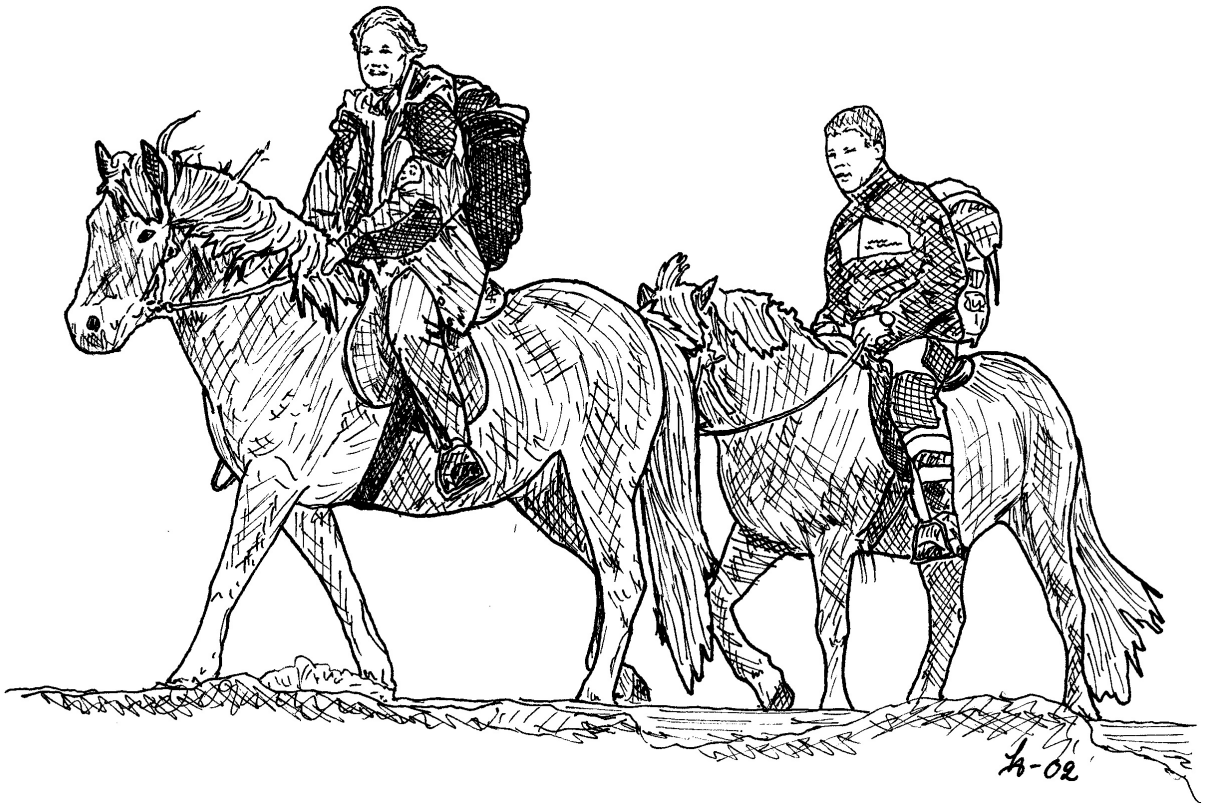


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- II: **Sparrenbom, C.J.**, Bennike, O., Björck, S. & Lambeck, K. 2006. Holocene relative sea-level changes in the Qaqortoq area, southern Greenland. *Boreas* 35(2), XX-XY.
- III: **Sparrenbom, C. J.**, Rindby, A. & Kortekaas, M. XRF-scanning, an effective method in the search for changing sea levels recorded as isolation contacts/transgression sequences. Manuscript submitted to *Journal of Paleolimnology*.
- IV: **Sparrenbom, C.J.**, Lambeck, K., Fabel, D., Fleming, K. & Purcell, A. Constraining the southern Greenland Ice Sheet since the Last Glacial Maximum from sea-level observations, cosmogenic dates and glacial-isostatic adjustment models. Manuscript to be submitted to *Earth and Planetary Science Letters*.



# Constraining the southern part of the Greenland Ice Sheet since the Last Glacial Maximum from relative sea-level changes, cosmogenic dates and glacial-isostatic adjustment models

by

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*'The great sea  
has sent me adrift;  
it moves me  
like a reed in a great river.*

*Earth and the great winds move me,  
have carried me away,  
and filled my inner parts with joy.'*

Uvavnuk, an Iglulik  
Eskimo woman, 19th c.

This thesis is based on four papers listed below as App. I-IV. The papers are reprinted with permission from Wiley (paper I) and Taylor & Francis (paper II). Paper III is submitted to *Journal of Paleolimnology* and paper IV is to be submitted to *Earth and Planetary Science Letters*.

**App. I: Sparrenbom, C. J.,** Bennike, O., Björck, S. & Lambeck, K. 2006. Relative sea-level changes since 15,000 cal. yr BP in the Nanortalik area, southern Greenland. *Journal of Quaternary Science* 21(1), 29-48.

**App. II: Sparrenbom, C.J.,** Bennike, O., Björck, S. & Lambeck, K. 2006. Holocene relative sea-level changes in the Qaqortoq area, southern Greenland. *Boreas* 35(2), in press.

**App. III: Sparrenbom, C. J.,** Rindby, A. & Kortekaas, M. XRF-scanning, an effective method in the search for changing sea levels recorded as isolation contacts/transgression sequences. Submitted to *Journal of Paleolimnology*.

**App. IV: Sparrenbom, C. J.,** Lambeck, K., Fabel, D., Fleming, K. & Purcell, A. Constraining the southern Greenland Ice Sheet since the Last Glacial Maximum from sea-level observations, cosmogenic dates and glacial-isostatic adjustment models. Manuscript to be submitted to *Earth and Planetary Science Letters*.

## Introduction

Current ideas about the ice ages and the ice sheets covering large parts of the continents was first commonly accepted by scientists a little over a century ago (Imrie & Imbrie, 1979). Religious beliefs about the great flood dominated the theories of how the landscape had become scarred and erratics moved around. In Sweden a debate about the general water decrease “vattuminskningen” in the Baltic was taking place during the mid to late 18th century and included scientists like Linné, Swedenborg and Hiärne (Frängsmyr, 1976). Reports about the land sinking in parts of southern Europe added to the debate, and a theory of land uplift was introduced as an explanation for the observations of previous high stands of sea level in Scandinavia. No generally accepted explanation or solution to these sea-level changes was given until Thomas Jamieson in 1865 presented the theory of isostasy; how the Earth’s crust is sensitive to loading and that land uplift is initiated when an ice sheet melts (Frängsmyr, 1976).

This thesis is an interdisciplinary study dealing with the sea-level changes caused by the redistribution of water-loads between continents and ocean basins as a consequence of glacial growth and decay. The deglaciation of the large continental ice sheets following the Last Glacial Maximum (LGM, *c.* 22 ka BP) caused significant vertical uplift of the formerly ice-covered areas due to glacial-isostatic adjustment. Observations of relative sea-level changes since the LGM until the present day from formerly glaciated regions help to constrain local ice-volume changes and the retreat histories.

The Greenland Ice Sheet was substantially larger during the LGM, as evident by raised shorelines, recessional moraines, perched boulders and isolation basins, e.g. Tauber (1968), Fredskild (1973), Shotton *et al.* (1974), Kelly (1975), Weidick (1975a, 1975b), Funder (1978 & 1979), Björck & Persson (1981), Björck *et al.* (1994), Rasch & Jensen (1997), Rasch *et al.* (1997), Long *et al.* (1999), Kelly *et al.* (1999), Rasch (2000), Bennike & Weidick (2001), Kaplan *et al.* (2002) and Weidick *et al.* (2004). Evidence of an ongoing late Holocene transgression has also been presented from archaeological studies showing inundation of Norse and Neo-Eskimo ruins, (e.g., Mathiassen, 1936; Bak, 1969), tidal measurements (Gabel-Jørgensen & Egedal, 1940) and from an undated drowned beach (Kuijpers *et al.*, 1999).

Until recently, only a few relative sea-level observations have been reported from southern Greenland and coherent high-quality observations were especially scarce. The glacial history and isostatic adjustment are as a consequence poorly constrained. Bennike *et al.* (2002) and Fleming & Lambeck (2004) have shown that the earlier reconstructions of the ice-volume changes in the southern part of the Greenland Ice Sheet since the LGM underestimate the changes involved.

The primary aim of the thesis has been to reconstruct relative sea-level changes and the glacial history in SW Greenland, by constraining the isostatic adjustments caused by the ice-volume changes occurring since the LGM until the present. The reconstruction of relative sea-level changes has been carried out by studies of isolation contacts and transgression sequences found in lakes and tidal estuaries in the archipelago and fjord system of SW Greenland.

The study of isolation contacts and transgression sequences is rather old considering the history of sea-level changes and the introduction of the isostasy theory. The methodology is based on sedimentation in topographic depressions (lakes/estuaries/lagoons) changing as the setting changes between marine, brackish and lacustrine environments as a consequence of the relative sea level changes caused by glacial growth and/or decay. This methodology was presumably first used by Sundelin (1917), who investigated old lake sediments in southern Sweden. Many others have throughout the 20th century followed his example and performed investigations of isolation contacts and transgression sequences to reconstruct former sea-level changes, e.g. Hyppää (1937) in Finland, Hafsten (1956) in Norway, Berglund (1964) in Sweden, Anundsen (1978) in Norway, Björck (1981) in southern Sweden and Kjemperud (1986) in Norway.

Commonly used proxies for investigating these records of isolation and transgression include lithological descriptions, magnetic susceptibility measurements, saturation isothermal remanent magnetisation (SIRM), analyses of organic, carbonate and minerogenic contents, diatom analyses and macrofossil analyses. Some of these analyses are very time consuming and/or require large samples. During the course of this project, we therefore tried to apply X-ray fluorescence spectrometry (XRF) scanning when the opportunity arose. The XRF scanning methodology is fairly new, rapid and a non-destructive way of analysing geochemical variations in sediment sequences. Variations in

different elements are of significance as the differences reflect changes in environment and/or climate. By analysing the geochemical variability of a range of elements, it is easy to pinpoint the stratigraphic level of the isolation contact and the transgression sequence. This methodology has proven to be a useful tool for investigating isolation and transgression sequences, and can help researchers in the future to reconstruct sea-level changes in a reliable and more rapid way.

In addition to other ice-constraining data, in-situ cosmogenic nuclide analysis has been performed within this project to provide rock exposure ages and consequently, to give an inference of the basal regime of the ice sheet since the LGM. The theory of exposure dating of rock surfaces by in situ cosmogenic nuclides started in the 1950's and practical applications began in the mid-1980. In general, the concentration of cosmogenic nuclides observed in a rock sample is a function of two independent variables, exposure time and erosion rate (see Gosse & Phillips, 2001).

The reconstruction of the glacial history of SW Greenland since the LGM has been carried out by glacial-isostatic adjustment modelling, which is a combination of the mathematical formulation describing the Earth's structure and mechanical response to surface-load changes and ice models that represent the spatial and temporal changes in ice extent and thickness. Ten ice models have been developed and a range of plausible ice-retreat and ice-readvance scenarios have been tested. The sea-level reconstruction made during this project, together with those of Bennike *et al.* (2002), as well as the inference of the basal thermal regime from the in-situ cosmogenic nucleid exposure ages, have via the glacial-isostatic modelling, helped us to constrain which ice-sheet history is the most probable for SW Greenland.

## Study area

My study area is located in southwest Greenland, south of N 64° (Fig. 1).

The landscape in the study area can be divided into two different categories, with a common characteristic of numerous dissecting valleys and fjord troughs, extending from the outer coast to the inland ice margin (Sugden, 1974). The southernmost Nanortalik area, extending from around Sydprøven and eastwards, is dominated by alpine mountains reaching heights of 1500 m a. s. l. near

the coast and up to 2000 m a. s. l. further inland. West of Sydprøven, the landscape is barren, glacially abraded and dominated by rounded and flattened mountains reaching elevations of 500 m a.s.l. near the coast, but becoming more alpine in character towards the inland reaching up to 1500 m a.s.l. The glacially eroded and over-deepened fjords in the western area reach depths greater than 600 m b. s. l. while the fjords in the Nanortalik area reach depths of around 400 m b. s. l.. The ice-free land area varies in width from around 100 km in the Qaqortoq and northernmost area towards Ameralik (south of Nuuk), to just a few kilometres around Fredrikshåbs Isblink. In the Nanortalik area, the ice-free zone is around 65 km wide. The offshore shelf is relatively narrow throughout the southwest Greenland and extends *c.* 70 km from the coast.

The bedrock in the region mainly consists of gneisses in the northernmost part, granites, gneissose granites and diorites in the area around Qaqortoq-Narsarsuaq and granites, migmatized meta-sediments and meta-volcanics around Nanortalik (Escher & Watt, 1976; Escher & Pulvertaft, 1995).

The precipitation varies from around 860 mm per year at the outer coast to 600 mm per year near the inland ice margin (DMI, 2006). At the outer coast, cool, cloudy and foggy conditions with mean temperatures around 5–6°C are common during summer months, caused by the meeting of the cold East Greenland Current and the warmer Irminger Current.

Dwarf-shrub heaths with mosses and lichens dominate the vegetation. *Empetrum nigrum*, *Betula glandulosa* and *Salix glauca* constitute major elements of the heaths.

## Methods

The methodologies performed during the course of this project are described briefly in this section. More detailed descriptions are made in Appendices I-IV. Participants responsible for contributing to and/or executing the different parts of this investigation are listed in Table 1.

### Fieldwork

To collect new ground-truth data, fieldwork was carried out in two parts of the study area, one in

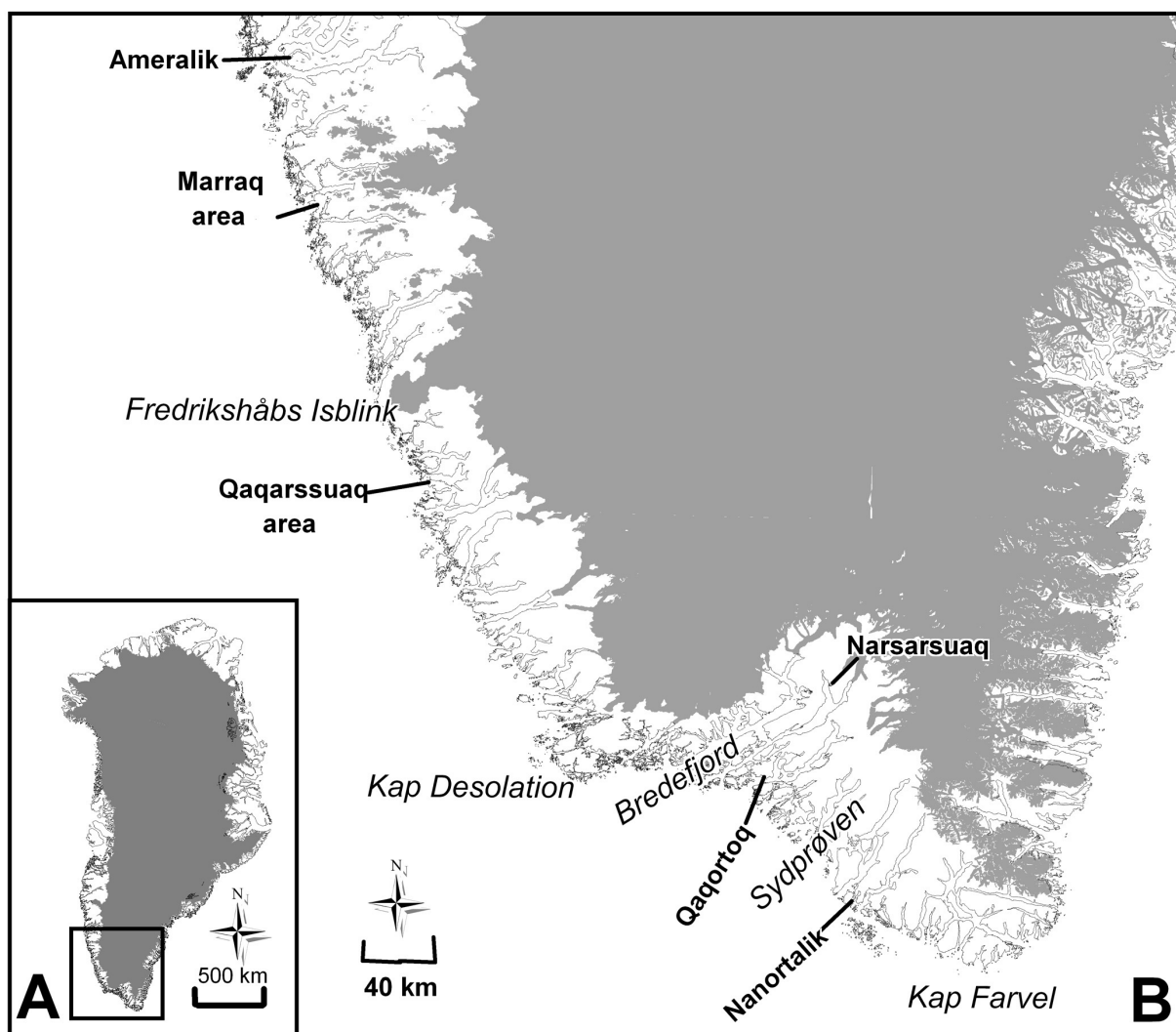


Fig. 1. (A) Map of Greenland where the rectangle defines the study area. (B) Map showing an overview of the localities within the study area, as discussed in the text.

the archipelago around Nanortalik (*c.* W 45°, N 60°, for more details see Appendix I) in the summer of 2001, and the other in the area around Qaqortoq-Narsarsuaq (*c.* W 46°, N 61°, for more details see Appendix II) in the summer of 2002.

Fieldwork included bathymetry investigations of small lake and estuarine lagoon basins with echo sounder in order to find suitable coring sites. Coring positions were determined with GPS and a Russian corer was used to collect multiple overlapping sediment sequences. The cores were described lithologically, wrapped for shipment to the laboratory where they are stored at 4°C.

The sill elevations were measured in the field using a clinometer, an echo sounder and measurement rods, but measurements were also carried out photogrammetrically in the laboratory by Hans Jepsen (GEUS).

Rock samples were collected with hammer and chisel from horizontal surfaces with no topograph-

ic shielding and, where possible, from erratics situated on top of these surfaces for further analysis of cosmogenic nucleid production. Positions of samples were determined with GPS.

### **Macrofossil analysis**

Macrofossil analysis is based on multicellular plant and animal remains (Lowe & Walker, 1997). Most macrofossil remains found in a sediment body are derived locally (autochthonous) and provide good information about the changes in the environment around the deposition site through time (Lowe & Walker, 1997; Birks & Birks, 2000). The changes in macrofossil assemblages help differentiate between freshwater and marine environments, which enabled us to establish when a basin became isolated and when the first inundation occurred. The resolution of samples from the sediment cores was 1-2 cm and each sample was wet sieved using



Table 1. *Compilation of methodology and executer.*

|  | Sea-level data collection                                 |   | Exposure data  |                                | Glacial-isostatic adjustment models            |   |
|--|---|---|--|--------------------------------|--|---|
| Site                                   | Nanortalik  |   | Qaqortoq   | Nanortalik bedrock             | Qaqortoq                                       | -   |
|  | N25, N26, N27, N28 and N29                                | N30   | Q1, Q3, Q4, Q5, Q6, Q9, K1, K3, I1 and Nu1                       | sample                         | Akia bedrock, Akia erratic & Nordfjeld bedrock |   |
| Fieldwork                              | C. J. Sparrenbom<br>O. Bennike<br>S. Björck<br>K. Lambeck | C. J. Sparrenbom<br>O. Bennike<br>S. Björck | C. J. Sparrenbom<br>H. Alexanderson<br>K. Ljung<br>N. Sparrenbom | C. J. Sparrenbom<br>O. Bennike | C. J. Sparrenbom                               | -   |
| Magnetic susceptibility                | C. J. Sparrenbom<br>V. Ersek                              | C. J. Sparrenbom<br>V. Ersek                | C. J. Sparrenbom   | -                              | -  | -   |
| SIRM                                   | C. J. Sparrenbom<br>V. Ersek                              | C. J. Sparrenbom<br>V. Ersek                | -  | -                              | -  | -   |
| XRF                                    | -   | C. J. Sparrenbom<br>A. Rindby               | C. J. Sparrenbom   | -                              | -  | -   |
| Macrofossil analyses                   | C. J. Sparrenbom  | O. Bennike                                  | C. J. Sparrenbom   | -                              | -  | -   |
| Loss on ignition                       | C. J. Sparrenbom<br>V. Ersek                              | C. J. Sparrenbom<br>V. Ersek                | -  | -                              | -  | -   |
| Cosmogenic nucleid production          | -   | -   | -  | D. Fabel<br>C. J. Sparrenbom   | D. Fabel<br>C.J. Sparrenbom                    | -   |
| Formulation, relative sea-level change | -   | -   | -  | -                              | -  | As described in Lambeck <i>et al.</i> (2003)  |
| Testing of reasonable Earth models     | -   | -   | -  | -                              | -  | Lambeck <i>et al.</i> 1998, Fleming and Lambeck 2004  |
| Developing Ice models                  | -   | -   | -  | -                              | -  | S. Greenland – C.J. Sparrenbom<br>Greenland north of N 64° - Fleming & Lambeck (2004)<br>Outside Greenland – Lambeck & Purcell (2003) |
| Testing scenarios                      | -   | -   | -  | -                              | -  | C. J. Sparrenbom<br>K. Lambeck, A. Purcell & K. Fleming   |

a 0.2 mm sieve. Identification of macrofossils remains was done under a low power stereo-microscope and also provided material for AMS radiocarbon dating.

### Radiocarbon analysis

Radiocarbon analyses provided ages for the time of isolation and transgression of each basin. AMS radiocarbon dating were carried out on selected terrestrial or freshwater macrofossils, and bulk sediment samples where suitable macrofossils were not found. The radiocarbon dating was carried out at the Radiocarbon Dating Laboratory in Lund and the Poznan Radiocarbon Laboratory. The radiocarbon dates were calibrated using the software OxCal v.3.10, based on the terrestrial INTCAL04 data set of Reimer *et al.* (2004).

### Magnetic susceptibility

The magnetic susceptibility ( $\chi$ ) is expressed as  $\mu\text{m}^3/\text{kg}$  and is a measure of the extent to which a sediment can be magnetized, which depends on its mineral composition. High susceptibility values indicate a high content of magnetic particles, i.e. a sediment with a high minerogenic content, and

low values indicate the absence of magnetic particles, i.e. often a more organic sediment. However, this is a simplification as the magnetic susceptibility may also be a measure of the amount of magnetotactic bacteria. The magnetic susceptibility was mainly used to facilitate core correlations. Two types of methodologies were applied, depending upon the instrumentation. For volumetric measurements (see Appendix I), a Geofyzika Brno KLY-2 susceptibility bridge was used on naturally wet samples. The samples were cut out in steps of 1-5 cm, the length depending on lithological changes. For the cores investigated from our second field area (Qaqortoq-Narsarsuaq, see Appendix II), magnetic susceptibility scanning was carried out using a Bartington MS2E high-resolution sensor controlled by a Tamiscan automated stage measuring every 4 mm.

### Saturation isothermal remanent magnetism (SIRM)

The same samples used for the volumetric magnetic susceptibility measurements, were put in a Redcliff pulse-magnetizer (model 700 BSM) to induce a field of 1 T to achieve saturation isothermal remanent magnetisation. A Molspin Minispin spinner magnetometer was then used to measure



the remanent magnetisation. SIRM was measured on each sample, both naturally wet, and after drying at 55°C for 12–24 hours. The authigenically formed magnetic mineral greigite ( $\text{Fe}_3\text{S}_4$ ) forms in anoxic environments in fresh, marine or brackish water where sulphate supply is limited (Walden *et al.*, 1999; Sandgren & Snowball, 2001). Greigite can be expected in isolation sequences when the environment changes from marine aerobic conditions to brackish anaerobic conditions.

### **Loss on ignition (LOI)**

The loss on ignition (LOI) method is a quantitative determination based on sequential heating of sediment samples. The method is based on the weight-loss principle, where organic, carbonate and minerogenic content can be determined by weighing the samples before and after ignition at different temperature ranges (Dean, 1974). Samples are dried for 12–24 hours at 105°C and cooled to room temperature in a desiccator to reach their dry constant weight (Heiri *et al.*, 2001; Bengtsson & Enell, 1986). The method can be divided into two parts; The first constituting an oxidation of the organic matter into carbon dioxide and ash in a furnace at 550°C for four hours, secondly followed by a decay of carbonate minerals into calcium oxide and carbon dioxide at 950°C during two hours (Heiri *et al.*, 2001). The organic and carbonate content can thereafter be calculated from the equations given in Heiri *et al.* (2001) and Bengtsson & Enell (1986). The remaining part of the sample after the ignitions is the minerogenic residue.

### **XRF core scanning**

X-ray fluorescence spectrometry (XRF) scanning is a new, rapid and non-destructive method, without any need for prior sample preparation, and can be used for high-resolution analysis of sedimentary sequences. By scanning the core surface, the geochemical variations can be found throughout the sediment sequence. Variations in different elements are of significance as the differences may reflect changes in depositional environment and/or climate. By analysing the geochemical variability of a range of elements as has been done in the investigation presented in Appendix II and III, it is easy to pinpoint the stratigraphic level of the isolation contact and the transgression sequence. We have had the opportunity to use two different XRF-scanners: the Cortex-instrument (AVAATECH)

and Itrax-instrument (Cox Analytical systems) and comparisons between results from the two are presented in Appendix III as well as a comparison to a set of multi-proxy analyses presented in Appendix I. Measurements in the Itrax core scanner were made in steps of 200  $\mu\text{m}$ , every measurement step lasting 1 second. The elements measured were Al, Si, P, S, K, Ca, Ti, V, Cr, Mn, Fe, Ni, Cu, Zn, Se, Rb, Sr, Zr, Ba and Pb. The measurements on the Cortex instrument were made in steps of 1–5 cm, the step sizes being pre-programmed in varying lengths depending on lithological changes. Every measurement step lasted 30 seconds and an average was calculated to give counts per second. The elements measured were K, Ca, Fe, Mn, Cu, Ti, and Sr (for more details, see Appendix II and III).

### **In situ cosmogenic nuclide production analysis**

The concentration of cosmogenic nuclides observed in a rock sample is a function of two independent variables; exposure time and erosion rate.  $^{10}\text{Be}$  and  $^{26}\text{Al}$  extracted from quartz are the cosmogenic nuclides used in this study. The rock samples were crushed and quartz separated from the sample by magnetic and heavy liquid separation followed by selective chemical dissolution according to Talvitie (1951). Most of the laboratory work was carried out at the Australian National University and the Accelerator mass spectrometry (AMS) measurements were carried out at the ANTARES AMS facility at the Australian Nuclear Science and Technology Organisation (Fink *et al.*, 2004), following the procedures of Fink *et al.* (2000). To calculate apparent exposure ages, we employed the standard models of Lal (1991), with sea-level and high latitude ( $>60^\circ$ ) nuclide production rates of  $5.1 \pm 0.3$  atoms  $\text{g}^{-1} \text{year}^{-1}$  ( $^{10}\text{Be}$ ) and  $31.1 \pm 1.9$  atoms  $\text{g}^{-1} \text{year}^{-1}$  ( $^{26}\text{Al}$ ), scaled to altitude and latitude (Stone, 2000), with a sea-surface temperature of 5°C.

### **Glacial-isostatic adjustment modelling**

To be able to predict sea-level changes for any time or location, we require a geophysical model to provide estimates for the spatial and temporal gaps between the fragmentary pieces of evidence that exists.

As mentioned earlier, glacial-isostatic adjustment modelling involves the mathematical formulation describing the Earth's structure and mechanical response to surface-load changes as a consequence of the rearrangement of water between

the continents and the oceans, and ice models that describes the spatial and temporal changes in the extent and thicknesses of the former expanded ice sheets. Different methods for analysing and calculating former sea levels and isostatic displacement have evolved during the history of sea-level reconstruction, all with different assumptions and simplifications regarding to the parameters involved. During glacial cycles, the redistribution of water and ice masses on the Earth's surface causes a relative sea-level change  $\Delta\zeta_{\text{rsl}}$  at a position  $\varphi$  on the Earth's surface for a time that can be schematically expressed as (Lambeck, 1993):

$$\Delta\zeta_{\text{rsl}}(t, \varphi) = \Delta\zeta_{\text{esl}}(t) + \Delta\zeta_{\text{i}}(t, \varphi) + \Delta\zeta_{\text{w}}(t, \varphi),$$
 where  $\Delta\zeta_{\text{esl}}$  represents the ice-volume equivalent sea level,  $\Delta\zeta_{\text{i}}$  is the ice-load (glacial-isostatic) component that includes the gravitational effects associated with changes in ice mass and the redistribution of mantle material due to the surface-load changes,  $\Delta\zeta_{\text{w}}$  is the water-load (hydro-isostatic) component, again including the gravitational effects, with respect to changes in the oceans' mass and the redistribution of mantle material.

The formulation used takes into account grounded ice, the oceans' changing surface area, the shape of the ocean basin, as well as changes in the Earth's rotation produced by the redistribution of mass in the earth-ice-ocean system. The equation above is a simplification and the complete formulation used is described in Lambeck *et al.* (2003). The computer programs used are the latest versions developed by ANU and have evolved over a 20 year period (e.g. Nakada & Lambeck, 1987; Johnston, 1993; Lambeck & Johnston, 1998; Lambeck *et al.*, 2003). A more detailed description on the glacial-isostatic modelling methodology is presented in Appendix IV.

#### Earth models

The Earth is described by models consisting of three layers; an elastic lithosphere of thickness  $H_l$ , an upper mantle extending down to the seismic discontinuity at 670 km depth with a viscosity  $\eta_u$ , and a lower mantle extending down to the mantle-core boundary at a depth of 2891 km with a viscosity  $\eta_l$ . While this is a simplification, a greater degree of layering is not justified in the current study as there is a larger uncertainty associated with the ice load history. The Earth is assumed to behave as a fully compressible, viscoelastic Maxwell body, meaning that it instantaneously deforms elastically when a load is applied, followed by a slower,

time-dependent viscous response. The relaxation constant is dependent upon the ratio of the viscosity/rigidity of the material i.e. the contents of the Maxwell body.

The bulk- and shear elastic moduli and density are described by the seismic model PREM (Preliminary Reference Earth Model, Dziewonski & Anderson, 1981). Because of lateral inhomogeneities in lithosphere thickness and mantle viscosity, as well as our imperfect knowledge of the Earth's radial structure, versions of the three-layer rheology model with differing values of lithosphere thickness and mantle viscosity were used to derive some measure of the uncertainty arising from the simplifying assumptions. Several combinations of earth rheology have been tested with lithosphere thicknesses varying from 50 km up to 100 km, upper mantle viscosity varying between  $10^{20}$  PaS and  $10^{21}$  PaS and the lower mantle viscosity varying between  $5 \times 10^{21}$  PaS and  $10^{23}$  PaS. These parameter values are within the range of previously performed glacial-isostatic adjustment modelling (i.e. Lambeck *et al.*, 1998; Fleming & Lambeck, 2004).

#### Ice models

The spatial and temporal changes in the global ice-mass regime are described by recent ice models developed by ANU (Lambeck & Johnston, 1998; Lambeck *et al.*, 2003, Fleming & Lambeck, 2004). The ice sheets considered are: North America (Laurentide, Cordilleran and Innuitian), Europe (Fennoscandia, British Isles, Kara-Barents Seas), Antarctica, Greenland and other areas of less extensive glaciation (Alaska, Tibet, Taymyr, Putorana Plateau, Siberia, Swiss Alps, Patagonia, South Atlantic). The development of these ice models is an ongoing process, with the model's characteristics constrained by geomorphological and sea-level change evidence as it becomes available. The models used in this study are those of Lambeck & Purcell (2003) for the far-field ice. We have divided the Greenland Ice Sheet into two parts, the first and the topic of this work is the ice sheet over southern Greenland (south of N 64°), while the second part is the rest of the ice sheet, as described by Fleming & Lambeck (2004).

To construct southern Greenland's glacial history, ten ice models were developed using the quasi-parabolic functions of Paterson (1994). The procedure used is described in more detail in Appendix IV. The ice models range from a maximum model extending to the shelf edge (-400 m contour

of present-day) to a minimum model extending to *c.* 40 km inland from today's ice margin. Because of the low resolution of the terrain model for this region, these ice sheet models include the mainland without a detailed consideration of the dissecting fjords. The other models are intermediate steps in between the above limiting margins and represent a range of plausible ice-margin scenarios. These ice models are used in various combinations to create several different melting scenarios. Each scenario is tested and the results analysed and compared with the observations. As the ice heights are effectively unknown, we have used a scaling parameter ( $\beta$ ) for the ice sheet, to test each scenario with different ice thicknesses and achieve the best fit possible between the predictions and the observations.

## Results - summary of papers

### Authorship contributions

This thesis includes four co-authored papers (Appendices I-IV). I am responsible for writing the four manuscripts, with input received from Ole Bennike, Svante Björck and Kurt Lambeck in paper I and II, from Anders Rindby and Marloes Kortekaas in paper III and from Kurt Lambeck, Derek Fabel and Kevin Fleming in paper IV. The manuscripts have also benefited from comments made by Morten Rasch (paper I and II), Michael Kelly (paper II), Siv Olsson (paper III), Ole Bennike (Paper IV) and Svante Björck (Paper III). Kevin Fleming has provided language corrections in paper III, IV and the thesis manuscript. The map figures are based on digital vector files provided by GEUS (printed with permission), but the design, layout and added details are my own. All other figures are my own creation, except the artwork on the back of the contentspage and on the front page of each appendix, which were created by Helena Alexanderson (printed with her permission).

### Paper I

**Sparrenbom, C.J.,** Bennike, O., Björck, S. & Kurt Lambeck. 2006. Relative sea-level changes since 15 000 cal. yr BP in the Nanortalik area, southern Greenland. *Journal of Quaternary Science* 21, 29-48.

This paper presents the results from the first of two field investigations included in this project on relative sea-level changes in southern Greenland. The investigation is an extension of the Late-glacial shoreline displacement curve from the Nanortalik area published by Bennike *et al.* (2002). This work overlaps their record and extends it all through the Holocene until the present. Bennike *et al.* (2002) showed that the local sea level reached at least 33 m above mean sea level (m a. m. s. l.) at *c.* 14,000 cal yr BP and fell rapidly from around 12,000 cal. yr BP to reach just above present day sea level at *c.* 10,000 years ago.

Our study includes one isolation basin situated above present spring tide sea level at *c.* 3.2 m above highest astronomical tide (m a. h. a. t.) and five below, with the lowest situated at -7.8 m a. h. a. t. The isolation sequences in the six basins show abrupt lithological changes with a general succession of coarse minerogenic sediments deposited in a (glacio) marine environment followed by laminated sediments, often with black iron sulphide-rich lamina deposited in a brackish environment, and then shifting abruptly into a freshwater deposited brownish algae gyttja. The pre-isolation sediments are dominated by marine brown algae such as *Sphacelaria* sp., *Rhizoclonium* sp. and *Desmarestia* sp., Foraminifera, the blue mussel *Mytilus edulis*, hydrozoans of the order Hydroidea and flatworms of the order Tricladida.

The presence of marine organisms often ends abruptly at the isolation contact, where they are replaced by freshwater taxa. These freshwater taxa probably migrate into the isolated lake by surface run-off from small rivers, draining lakes further inland, but some species may be transported by birds. The most commonly found freshwater organisms are the cladocerans *Daphnia* sp. and *Alona* sp., Chironomids, *Isoëtes lacustris*, *Nitella* sp., *Plumatella repens*, Rhabdocoela flatworms, the water-crowfoot *Batrachium confervoides*, larval cases from Trichoptera, *Hippurid vulgaris* and *Lepidurus arcticus*.

That a transgression has occurred is usually obvious in the sediments, but it is not often as clearly visible as the isolation contact. The changes in the sediments seem more gradual than at the isolation and it is difficult to define a "transgression contact". This is a consequence of the rate of sea level change being high during the isolation and lower during the transgression. In some cases, as in sites N28 and N29, the in- and out-flowing tidal currents have eroded parts of the sedimentary column during the slower marine ingression. Physi-

cally, the ingression is shown by higher amounts of mineral particles in the prevailing gyttja sediments. This change is often, but not always, seen as higher magnetic susceptibility and higher SIRM values. In most of the investigated sequences, macrofossil analyses were necessary to establish exactly where to place the first marine ingression and these analyses confirm a gradual environmental change process, with several marine species appearing in small numbers at the same time as freshwater species gradually decline in number of individuals. It is common to find both marine and freshwater species in fairly large numbers in the sediment column *c.* 10–15 cm above the first marine ingression. The first marine taxa to immigrate into the basins are often Foraminifera, the brown algae *Sphacelaria* sp., *Rhizoclonium* sp. and *Desmarestia* sp., bivalves like *Mytilus edulis* and *Macoma balthica*, hydrozoans of the order Hydrozoa, the ice-cream-cone worm *Pectinaria* and flatworms of the order Tricladida.

In connection with both isolations and transgressions, the oribatid mite *Ameronothrus lineatus* appears in the transitional sediments, possibly favoured by the brackish tidal conditions. *Ameronothrus lineatus* habitat is at or near the sea shore (Hammer, 1944) and it has previously been reported from isolation sequences by Bennike (1992, 1995) and Bennike *et al.* (2002).

From the investigations of these six basins, we can conclude that the relative sea level reached the present-day level at *c.* 9300 cal. yr BP and continued to fall rapidly until at least 9000 cal. yr BP. The isostatic rebound associated with the ice recession in the area caused rapid isolations of the basins that are seen as distinct isolation contacts in the sediments. In combination with the results of Bennike *et al.* (2002), we can conclude that this accelerated regression between 12,000 and 9000 cal. yr BP implies a fast ice sheet recession during at least parts of the Late-glacial and the early Holocene.

Between 8000 and 6000 cal. yr BP sea level reached its lowest level of around -10 m a. h. a. t. At around 5000 cal. yr BP, sea level had reached above -7.8 m a. h. a. t. and slowly continued to rise, not reaching present day sea level until today. So, in contrast to the rapid sea-level fall, the late Holocene transgression is less well defined in the sequences and the process must have occurred over a longer time interval.

The slow sea-level rise during the mid to late Holocene, starting sometime before 5000 cal. yr BP, may have been a consequence of isostatic re-

loading by neo-glacial growth of the Greenland Ice Sheet and/or an effect of the collapse of the Laurentide peripheral bulge.

Evidences for the presence of Palaeo-Eskimo settlements are rare in southern Greenland, possibly because their areas of habitation have been inundated by the rising sea throughout the late Holocene, and new information about regional sea-level change, especially between 4000 yr BP and 250 yr BP, may shed light upon where investigations need to be focussed to find more evidence of Inuit ancestors reaching southern Greenland.

## Paper II

Sparrenbom, C.J., Bennike, O., Björck, S. & Kurt Lambeck. 2006. Holocene relative sea-level changes in the Qaqortoq area, southern Greenland. *Boreas* 35, in press.

In this paper, we present a shoreline displacement study from the Qaqortoq-Narsarsuaq area, from *c.* 11 000 cal. yr BP until the present, based on three sites situated below present highest astronomical tide and seven sites situated above highest astronomical tide (m a.h.a.t.). Eight of the sites contained isolation contacts and two also provided evidence of a late Holocene transgression. Maximum and minimum altitudes for relative sea level are provided from one deglaciation sequence at *c.* 40 m a.h.a.t. and one marine lagoon sequence at -8.7 m a.h.a.t.

The sites containing isolation contacts and transgression sequences provide shoreline displacement observations extending from 31 m a.h.a.t. at *c.* 11 000 cal. yr BP down to below *c.* -2.7 m a.h.a.t. at *c.* 8800. At around 3750 cal. yr BP, sea level had reached above -2.7 m a.h.a.t. and continued to rise slowly, reaching the present-day level between *c.* 2000 cal. yr BP and the present. A minimum must have occurred between 8000 and 6000 cal. yr BP, when sea level reached its lowest level of around -6 to -8 m a.h.a.t.

As in the previously investigated Nanortalik area (Appendix I) the early Holocene isolation sequences from the Qaqortoq area show abrupt lithological changes. The general sedimentary succession consist of coarse minerogenic sediments deposited in a (glacio) marine environment, changed into dark iron sulphide-rich laminated sediment deposited in a brackish environment, and abruptly shifted into a freshwater deposited brownish algae gyttja. Pre-isolation sediments are dominated by macrofossils of the marine brown al-



gae *Rhizoclonium* sp. and *Sphacelaria* sp. Also common in the marine sediments are the blue mussel *Mytilus edulis*, hydrozoans of the order Hydroidea, flatworms of the order Tricladida and Foraminifera. The presence of marine organisms often ends abruptly at the isolation contact, and is succeeded directly by freshwater taxa. The most commonly found remains of freshwater organisms are ephippia of cladocerans, larval head capsules of chironomids, oospores of the green-algae *Nitella* sp. and *Chara* sp., megaspores of *Isoëtes* sp., statoblasts of *Plumatella repens*, achenes of the water-crowfoot *Batrachium confervoides*, *Lepidurus arcticus* eggs and *Hippuris vulgaris* fruits.

The first marine ingression is not as clearly visible as the isolation contacts. As discussed in Appendix I, it is a consequence of the rate of sea-level change being high during the time of isolation and low during the transgression. The changes in the sediments are gradual and it is therefore difficult to define a "transgression contact". Physically, the change is often seen as an increase in magnetic susceptibility values as a consequence of the increased amount of mineral particles. The XRF-scanning results from the transgression sequence of site Q3 show a reverse trend to the isolation contacts scanned, i.e. an increase in all elements measured, except copper, which decreases. The macrofossil analyses show a gradual environmental change with several marine species appearing in small numbers concurrently with a gradual decline of freshwater species and numbers of individuals. Both marine and freshwater species are commonly found in large numbers in the first centimetres of the sediment column above the first marine ingression. Freshwater species tolerating slightly brackish conditions increase in numbers just after the marine ingression, probably as a result of less competition as freshwater taxa intolerant of brackish conditions disappear. The first immigrating marine taxa are often the brown algae *Sphacelaria* sp. and *Rhizoclonium* sp., the bivalve *Mytilus edulis*, hydrozoans of the order Hydroidea and flatworms of the order Tricladida.

Like in the Nanortalik area, the oribatid mite *Ameronothrus lineatus* appears in the sediments in connection with isolations and transgressions (Bennike *et al.*, 2002).

From our Qaqortoq investigations, we can conclude that, like in the Nanortalik area, the relative sea level fell rapidly in the Late-glacial and early Holocene from *c.* 11,000 cal. yr BP and reached the present-day level at *c.* 9000 cal. yr BP. The sea level continued to fall rapidly until at least 8800

cal. yr BP, shown by the distinct isolation contacts in the low elevation basins. This implies a fast recession of the ice sheet during parts of the Late-glacial and the early Holocene. The mid to late Holocene transgression was on the contrary slow and gradual, as it started sometime before 6000 cal. yr BP and reached the present-day level between 2000 cal. yr BP and the present.

The shorelines from around 11 000 cal. yr BP tilt almost 5 m/10 km towards the Greenland Ice Sheet in the northeast, while younger shorelines, at *c.* 9000 cal. yr BP, slope *c.* 4 m/10 km. The northeasterly sloping shorelines show that the uplift rate was smaller in the inland than at the outer coast, indicating that the rebound is responding primarily to a removal of ice from the coastal and shelf zone.

Compared with the results from the Nanortalik area (Appendix I), most of the ice retreat, i.e. the isostatic rebound, occurred later in the Qaqortoq area as a consequence of the sites being situated further inland. The data also suggest that relative sea level reached slightly lower altitudes in the Nanortalik area than in the Qaqortoq area, consistent with the more inland position of the Qaqortoq area and possibly reflecting differences in ice thickness, i.e. differences in ice load changes, between the two areas. The mid-Holocene transgression seems to have reached present-day sea levels earlier in the Qaqortoq area than in the Nanortalik area, which as a consequence of the closer proximity to the ice mass centre in the Qaqortoq area may imply that the transgression was caused by a Holocene thickening of the Greenland Ice Sheet. This late Holocene sea-level rise implies reloading by advancing glaciers superimposed on the isostatic signal from the North American ice sheet. One consequence of this transgression is that evidence of Palaeo-Eskimo settlements from *c.* 4000 cal. yr BP and onwards also in this area, may have been inundated by the sea.

### **Paper III**

**Sparrenbom, C.J., Rindby, A. & Kortekaas, M.** XRF-scanning, an effective method in the search for changing sea levels recorded as isolation contacts/transgression sequences. *Manuscript submitted to Journal of Paleolimnology.*

The study of isolation contacts and transgression sequences has provided a useful tool when reconstructing relative sea levels in near-coastal environments (e.g., Sundelin, 1917; Hyppää, 1937; Hafsten, 1956; Berglund, 1964; Anundsen, 1978;

Björck, 1981; Kjemperud, 1986). Proxies used to investigate these records have varied and included lithological descriptions, magnetic measurements, loss on ignition, diatom and microfossil analyses. Some of these analyses are very time consuming and/or require large samples.

In this paper, we therefore present a test of the use of X-ray fluorescence spectrometry (XRF) scanning, a new, useful, rapid and non-destructive method, that requires no prior sample preparation, for the high-resolution geochemical analysis of sedimentary sequences. By scanning the core surface, the geochemical variations can be found throughout the sediment sequence. Variations in different elements are of significance as the differences indirectly can be interpreted in terms of changes in the depositional environment and/or climate. Previously, XRF scanning has mainly been applied to marine core investigations e.g. Röhl & Abrams (2000) and Lamy *et al.* (2001). Recently, XRF-scanning data has also been used as a proxy for identifying climatic changes in lacustrine sediments (Daryin *et al.*, 2005).

We have investigated sedimentary sequences from two different sites in southern Greenland, both with an isolation contact and a transgression sequence. One of the investigated sequences is taken from site Q3 (Appendix II) where the previously performed XRF-scanning executed in the Cortex-instrument (AVAATECH) is complemented with new XRF measurements on the Itrax-instrument (Cox Analytical systems). We compare the results from seven different elements (K, Ca, Ti, Mn, Fe, Cu and Sr).

We demonstrate from the comparison of the results from the two different instruments that the XRF-scanning results are reliable and reproducible, with minor discrepancies occurring as a consequence of the sediments heterogeneous nature, small differences in sensor and/or scanner design and measurement resolution.

The other investigated sequence is from site N30, on which a set of multi-proxy analyses were performed to determine when the isolation and transgression occur (Appendix I). Newly performed XRF-scanning on the Itrax-instrument has made a comparison possible between XRF-scanning and the traditional methods used to identify the changes. Measured elements are Al, Si, P, S, K, Ca, Ti, V, Cr, Mn, Fe, Ni, Cu, Zn, Se, Rb, Sr, Zr, Ba and Pb. Some general trends have been identified; for example the relatively higher content of organic matter deposited in freshwater environments, leads to higher values of selenium,

copper, nickel and lead (Lemly, 1999; e.g., Nussey *et al.*, 2000; e.g., Matagi *et al.*, 1998). These four elements have an affinity to bind to organic matter and/or to bioaccumulate. Generally, in the near-coastal marine and estuarine environments, oxic conditions prevail and minerogenic matter, precipitated oxides and heavier biological particles like shell fragments dominate the sediments. As a consequence, Fe, Ti, K, Rb, Zr, Ca and Sr can be expected to show higher values. By analysing the variability of a range of elements, as has been done in this investigation, it is possible to pinpoint the stratigraphic level of the isolation contact and the transgression sequence. A few microfossil samples can verify the XRF-interpretations and at the same time provide organic material for radiocarbon analyses.

Our results show that XRF-scanning, together with lithological description and pinpointed microfossil analysis combined with radiocarbon analyses, is a quick and effective way of investigating isolation contacts/transgression sequences for the reconstruction of sea-level changes. We suggest the use of the following elements for an easy identification of the transitions between marine, lacustrine and brackish environments; Fe, Mn, Al, Si, K, Ca, Sr, Ti, Se, Cu and Zr.

#### Paper IV

**Sparrenbom, C.J., Lambeck, K., Fabel, D., Fleming, K. & Purcell, A.** Constraining the southern Greenland Ice Sheet since the Last Glacial Maximum from sea-level observations, cosmogenic dates and glacial-isostatic adjustment models. *Manuscript to be submitted to Earth and Planetary Science Letters.*

The deglaciation of the large continental ice sheets following the Last Glacial Maximum (LGM, *c.* 22 ka BP) caused significant vertical uplift of the formerly ice-covered areas due to glacial-isostatic adjustment. Observations of relative sea-level changes since the LGM until the present day from formerly glaciated regions help to constrain local volume changes and retreat history.

The Greenland Ice Sheet was substantially larger during the LGM, as evident by raised shorelines, recessional moraines, perched boulders and isolation basins reported by a number of authors (e.g. Funder (1978) and Björck *et al.* (1994) from the Scoresby Sund area, Björck & Persson (1981) from the Hochstetter Forland in the NE, Kelly *et al.* (1999) from the Thule region, Rasch (2000), Rasch & Jensen (1997), Rasch *et al.* (1997) and

Long *et al.* (1999) from Disko Bugt, and Bennike & Weidick (2001) from Nioghalvfjerdingsfjorden).

Until recently, only a few relative sea-level observations have been presented from southern Greenland and the glacial history and isostatic adjustment are, as a consequence, poorly constrained. Bennike *et al.* (2002) and Fleming & Lambeck (2004) have shown that the earlier reconstructions of the ice-volume changes in southern Greenland since the LGM, underestimate the changes involved.

In this study, we therefore present a modelling analysis that aims to constrain the Late-glacial and Holocene isostatic adjustment and concurrently determine the ice sheet evolution in southern Greenland during this time. Isolation and transgression sequences from 0-14,000 cal. yr BP from the Nanortalik (Bennike *et al.*, 2002; Appendix I) and the Qaqortoq-Narsarsuaq area (Appendix II) and new data, in the form of in situ produced cosmogenic  $^{10}\text{Be}$  and  $^{26}\text{Al}$  in bedrock and erratics from the Nanortalik and Qaqortoq areas, are used to constrain the different ice-model scenarios tested. The cosmogenic data supplements the sea-level observations by providing information about the exposure time, and consequently provide an inference of the basal regime.

The best fitted scenario in our study shows an ice sheet extending to the shelf edge from c. 26,500 cal. yr BP until around 22,000 cal. yr BP. The ice thickness in central southern Greenland during the LGM must have been of the order of 4000-4500 m, and the ice sheet was rather thick on the shelf as well (c. 1000-1500 m). From c. 22,000 cal. yr BP, the ice retreat proceeded quickly and by c. 12,000 cal. yr BP, the ice margin was located inland of the present-day coast. By c. 10,500 the ice margin had reached its present-day position and became smaller than at present from about this time, reaching a minimum of c. 30 km behind the present-day margin at c. 9000 cal. yr BP. A neoglacial re-advance started before 6500 cal. yr BP and the present-day margin was again reached by c. 5500 cal. yr BP. The ice sheet was thick, cold-based and non-eroding in the Nanortalik area, but thinner, warm-based and eroding in the Qaqortoq area during the Late-glacial. The in situ cosmogenic production indicate that the ice sheet has been basally frozen in the Nanortalik area for at least the last glaciation occurring after c. 66 ka BP and probably in the whole area east of Sydprøven. By contrast, the ice sheet must have been rather thin in the Bredefjord area, probably functioning as a major drainage pathway and a quick ice retreat

corridor. As indicated by the Quaternary map of south-west Greenland by Weidick (1987), the ice sheet was probably warm based, causing extensive erosion in the Sydprøven to the Kap Desolation region, from the coast towards Narsarsuaq c. 70 km into the fjord area.

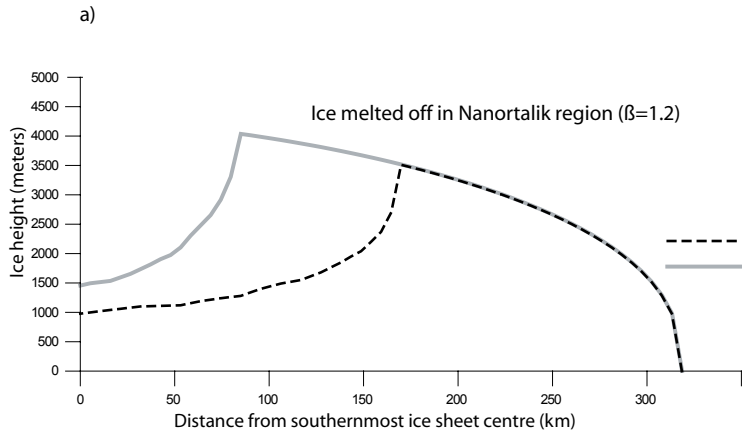
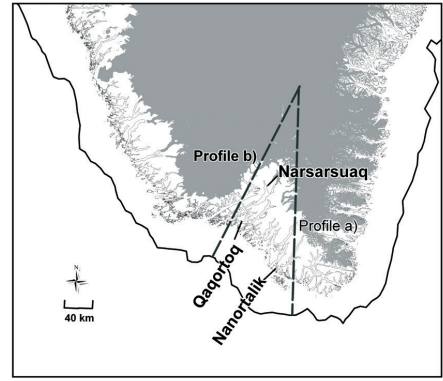
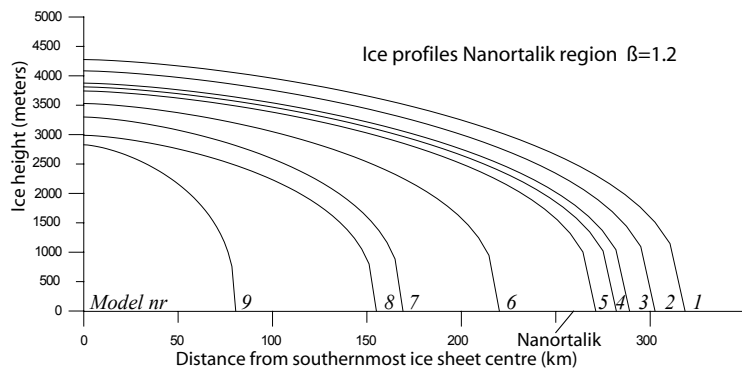
A comparison between the predictions from our best fitted scenario and older observations was performed and the results show an acceptable correspondence in the Bredefjord and Kap Farvel areas. In the area around Marraq, the predictions underestimate the relative sea level and the discrepancies between predictions and observations are larger. To solve the miss-fit in the Marraq area, a thicker ice retreating faster than in our scenario is required for the Late-glacial times. However, the data quality is poor, and new more reliable data is necessary before altering the ice models and retreat scenario. All but one prediction underestimate relative sea levels in the Qaqarssuaq area compared to the observations and this miss-fit in the Late-glacial and early Holocene can be solved by an increase in ice thickness in the ice models during the Late-glacial. Changing the ice retreat in the early to mid Holocene to a scenario with less ice recession (i.e. a minimum ice margin closer to the coast), would give higher sea-level predictions in the mid to late Holocene and solve the current miss-match. The sea-level observation data from this area is, however, uncertain because different altitudes have been published for the same observation and new data would be preferred. The two areas with the least correspondence between observations and predictions are also those farthest away from our sea-level observation sites in the Nanortalik and Qaqortoq areas. Hence, the Marraq and the Qaqarssuaq miss-fits, indicate that the results from our best-fitted model should not be extrapolated too far. To continue the modelling exercise further, more precise observations from the northern areas (N°63-N°64) are therefore needed.

## **Additional results**

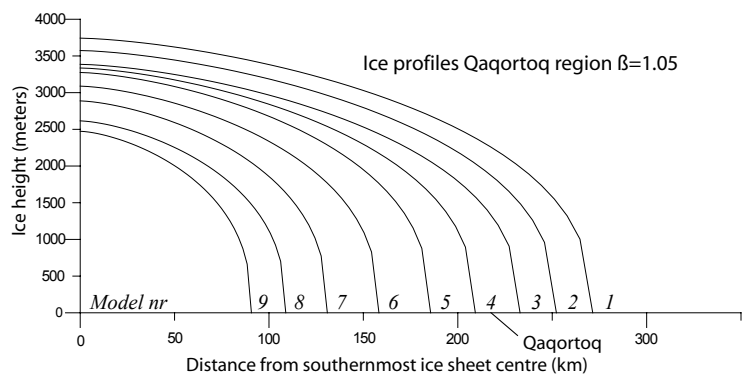
### **Glacial-adjustment modelling**

The results from the modelling analyses presented in Appendix IV demonstrated that out of the tested ice-retreat scenarios, the “Lu scenario” outcome provided the best fit to the observed relative sea levels presented in Appendices I and II. The Lu scenario is illustrated in Fig. 2 by two ice profiles,



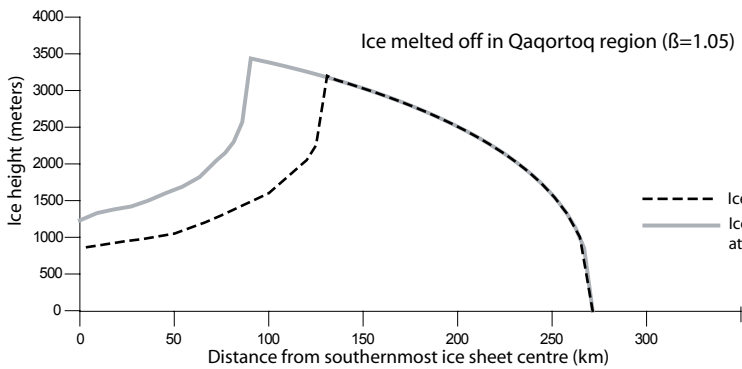


b)



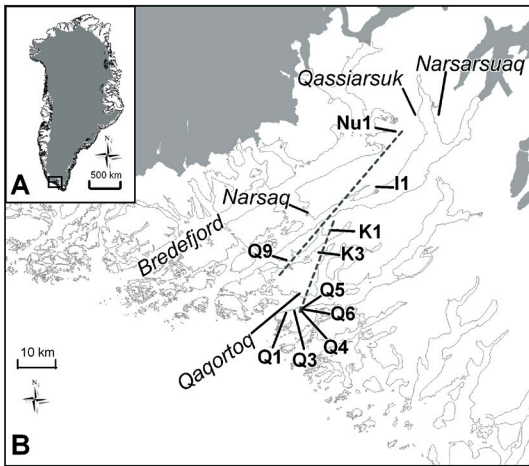
| Ice model                                       | Ice scenario Lu      |
|---|----------------------|
| 1. Shelf edge (-400 m)                          | 26,500-22,000        |
| 2. Between shelf edge and outer islands         | 19,000               |
| 3. Outer islands                                | 17,000               |
| 4. Between outer islands and present coast      | 15,000               |
| 5. Present coast                                | 13,000               |
| 6. Between present coast and present ice margin | 12,000               |
| 7. At present ice margin                        | 10,500 and back 5500 |
| 8. Minimum 1                                    | 9500 and back 6500   |
| 9. Minimum 2                                    | 9000                 |

d)



f)

Fig. 2. a) Ice profiles for the nine models included in ice scenario Lu, Nanortalik area. b) Location of the two ice profiles shown in a), c), e) and f). c) Ice height change as taken from scenario Lu between the LGM and the present, and between LGM and the minimum ice at 9000 cal. yr BP, Nanortalik area. d) Ice scenario Lu e) Ice profiles for the nine models included in ice scenario Lu, Qaqortoq area. f) Ice height change as taken from scenario Lu between the LGM and the present and between LGM and the minimum ice at 9000 cal. yr BP, Qaqortoq area.



a) Map of Qaqortoq area showing the gradient profiles from b) and c).

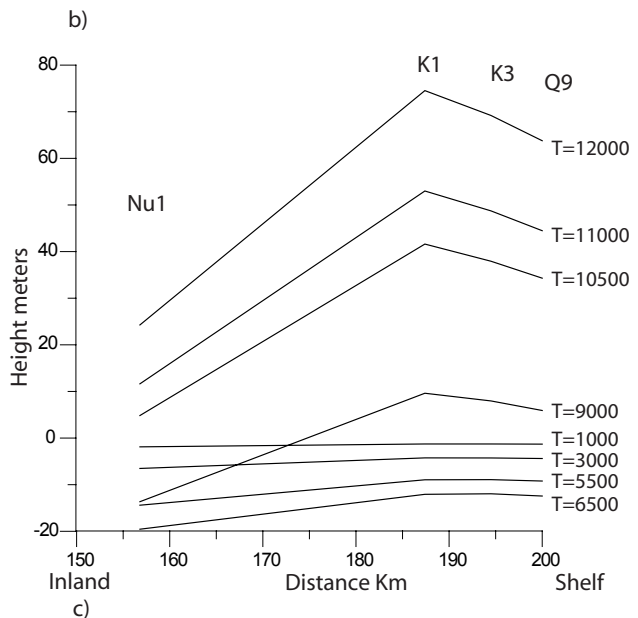
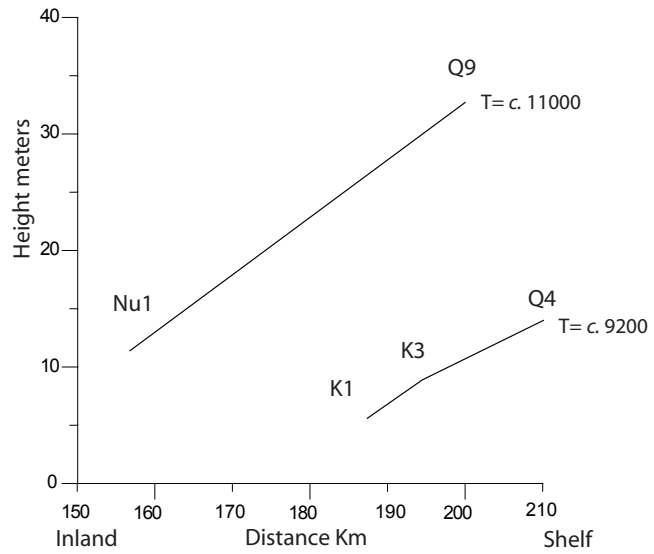


Fig. 3. a) Map showing the isobase gradient profiles from the Qaqortoq-Narsarsuaq area. b) Observed gradients at 11,000 cal. yr BP between sites Nu1 and Q9, and at 9000 cal. yr BP between sites K1, K3 and Q4. c) Predicted gradients between Nu1, K1, K3 and Q9 at different times.

one through the Nanortalik (Fig. 2a) area and the other through the Qaqortoq area (Fig. 2e) (see Fig. 2b for the location of the ice profiles), showing the ice elevation profiles for the nine ice models included in the retreat scenario. Fig. 2d presents the retreat and advance history of scenario Lu (for more details, see Appendix IV). Included in Fig. 2 is also an illustration of the change in ice thickness for the two profiles (Fig. 2c for the Nanortalik profile and Fig. 2f for the Qaqortoq profile). This is to demonstrate that the change in ice thickness (i.e. ice volume loss) from the LGM until the present is greatest in the area outside the present ice margin represented by ice model 7. This in contrast to the formerly glaciated regions in the northern hemisphere where the greatest ice-mass changes, and therefore the greatest land uplift, occurred in

the area of the former ice sheets centre, shown as outwards tilting shorelines e.g. Scandinavia (SW Sweden by Björck & Digerfeldt (1991); western-central Norway by Kjemperud (1986); eastern Sweden by Berglund (2004)). The reason for this difference is, of course, that there is still an ice sheet in Greenland loading the Earth. The greatest land uplift is therefore expected to be found some distance from the present ice margin and the shorelines are expected to either tilt inland towards the ice sheet, or show the greatest uplift some distance between the present coast and the inland, resulting in a “bent” shoreline tilt with an outer part tilting outwards and an inner part tilting towards the inland (see for example Funder & Hansen, 1996). I have therefore extended the modelling exercise presented in Appendix IV to investigate

and compare the predicted shoreline gradients to the observed.

The gradient profiles or synchronous shorelines, situated perpendicular to the isobases, are constructed for the Qaqortoq-Narssarsuaq area (Fig. 3a). In Fig. 3b the observed shoreline gradients are presented, one extending *c.* 44 km between site Nu1 and Q9, isolated around 11,000 cal. yr BP and the second extending *c.* 23 km between sites K1, K3 and Q4, all isolated around 9000 cal. yr BP. The observations indicate a tilt of about 5.5 m/10 km at *c.* 11,000 cal. yr BP and *c.* 4 m/10 km at 9000 cal. yr BP, in both cases in a north-easterly direction towards the present ice sheet. The predicted shoreline gradients presented in Fig. 3c are constructed between site Q9, K1, K3 and Nu1 for different times, ranging from 12,000 cal. yr BP to 1000 cal. yr BP. The predictions differ somewhat to the observations, with a south-westerly tilting gradient from around 187 km (distance from the southern ice centre) towards the shelf area at both 11,000 cal. yr BP (5.3 m/10km) and 9000 cal. yr BP (3 m/10 km). From around 187 km and inwards, the predicted gradients tilt in a north-easterly direction towards the present ice with gradients of almost 14 m/10km at 11,000 cal. yr BP and 8.5 m/10 km at 9000 cal. yr BP. As there are no sites available between site Nu1 and Q9 that were isolated at around 11,000 cal yr BP, we do not know if this miss-fit is, in fact, real. If gradients are constructed between the Nu1 and Q9 predictions without inserting the K1 and K3 predictions, the results are north-easterly tilting shorelines of 8.5 m/10 km at 11,000 cal. yr BP and 5.5 m/10 km

at 9000 cal. yr BP. This result still points towards a discrepancy between the observations and the predictions. So, concern must be shown to the different directions in the shoreline gradient for the more coastal area as the predictions point towards a south-westerly tilting gradient and the observations show a north-easterly tilt towards the inland. Obviously, there is still a discrepancy between the observations and the Lu-scenario predictions. This discrepancy shows that the model can be improved further, for which there are three possibilities;

- An increased neo-glacial that would cause a greater downward displacement (download) for the inland sites than for those located further out on the coast. This would change the gradient in favour of a north-easterly downwards tilt.

- A larger ice load located on the coast and/or shelf area during LGM would cause the more shelf-near sites to rebound more than the inland sites, hence, again changing the gradient in favour of a north-easterly downwards tilt.
- An earlier ice retreat in the shelf-coastal area would cause the outer near-shelf sites to rebound to higher elevations more rapidly, and is also a possible scenario for changing the tilt of the gradients to a north-easterly downwards direction.

Between these three options, the larger ice load on the shelf and/or coastal area appears to be the most likely option, as an earlier ice retreat is contradicted by deglaciation dates reported from the area i.e. Fredskild (1973), Bennike *et al.* (2002), Kaplan *et al.* (2002), Ljung & Björck (2004) and Weidick *et al.* (2004). The oldest post-glacial organic sediment found in southernmost Greenland is reported from a lake at Angissoq Island, located in the outer archipelago and has an apparent age of  $\geq 14,000$  cal yr BP (Björck *et al.*, 2002). As the ice retreat in scenario Lu is already very early, with the ice margin reaching the outer island at 15,000 cal. yr BP and the present coast at 13,000 cal. yr BP, an even earlier scenario is the least probable option. Likewise, there is, to the author's present knowledge, no evidence suggesting a significantly increased neo-glacial. A more significant neo-glacial load would also change the relative height of site Nu1 the most, while the outer near-coastal sites K1, K3 and Q9, would be less affected. To correct for the miss-fit between the observed and predicted gradients, it is a relative height change of site K1, K3 and Q9 with respect to each other that is required. Therefore, the increased ice load in the near-coast and/or shelf area is the more likely option.

To illustrate our results geographically, maps of the ice sheet extent and coastline have been produced for different epochs between 12,000 cal. yr BP until the present (Fig. 4 a-h). The maps shown in Fig. 4 are produced from our computation of relative sea-level changes and the Global DTM 5 (GE Tech, University of Leeds) terrain model, having a 5'x5' resolution. This terrain model's resolution is too poor to show much detail, and as the archipelago area investigated has a very varied topography, the resulting maps only show the coastline at a coarse scale. Therefore, these maps should not be used for more detailed investigations. A high-resolution digital terrain model is thus needed to produce more detailed maps, and this would be

*Constraining the southern part of the Greenland Ice Sheet since the Last Glacial Maximum from relative sea-level changes, cosmogenic dates and glacial-isostatic adjustment models*

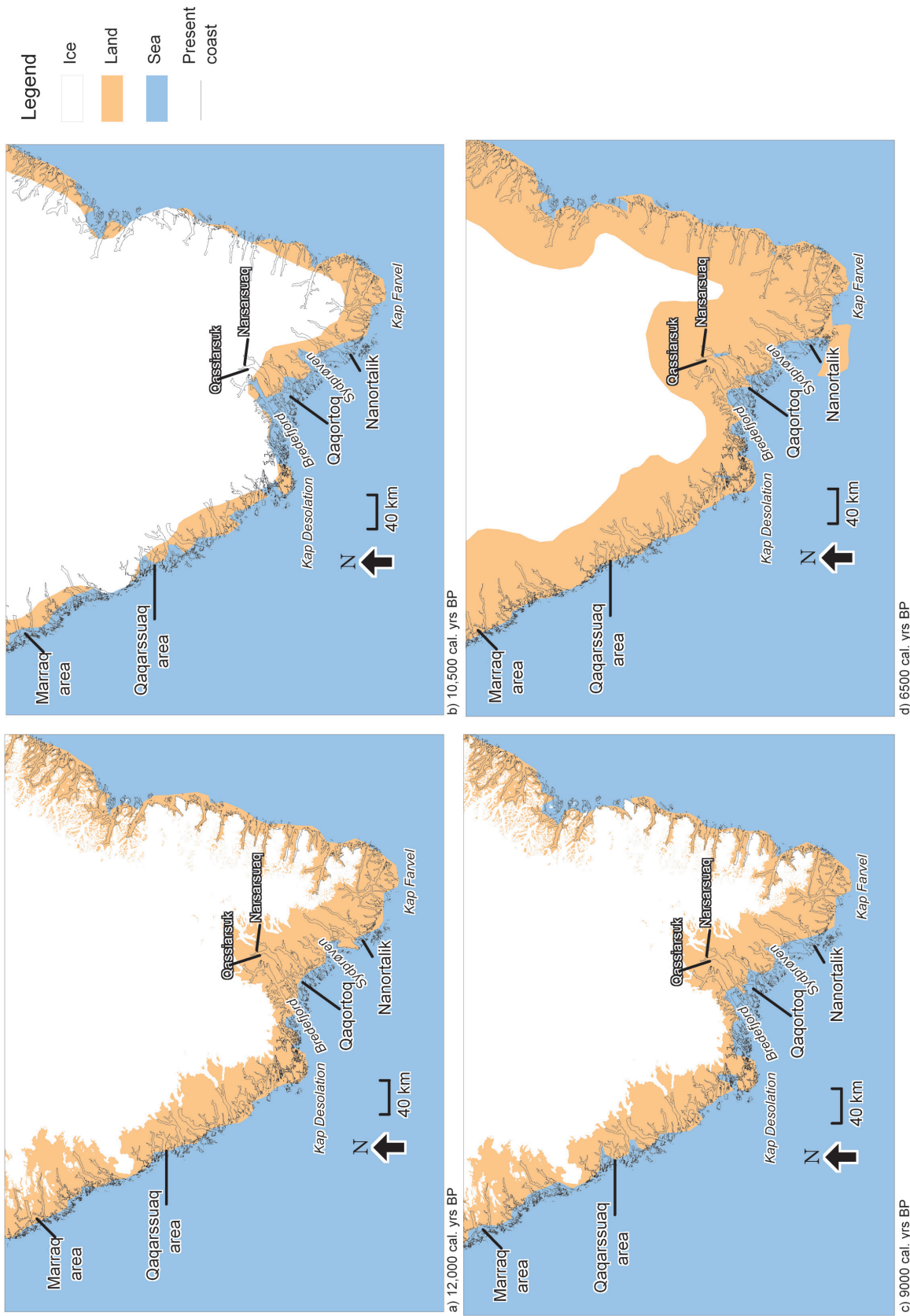


Fig. 4. Maps showing the southern part of the Greenland Ice Sheet extent and the large-scale coastline resulting from the Lu scenario prediction at times; a) 12,000 cal. yr BP, b) 10,500 cal. yr BP, c) 9,000 cal. yr BP, d) 6,500 cal. yr BP.



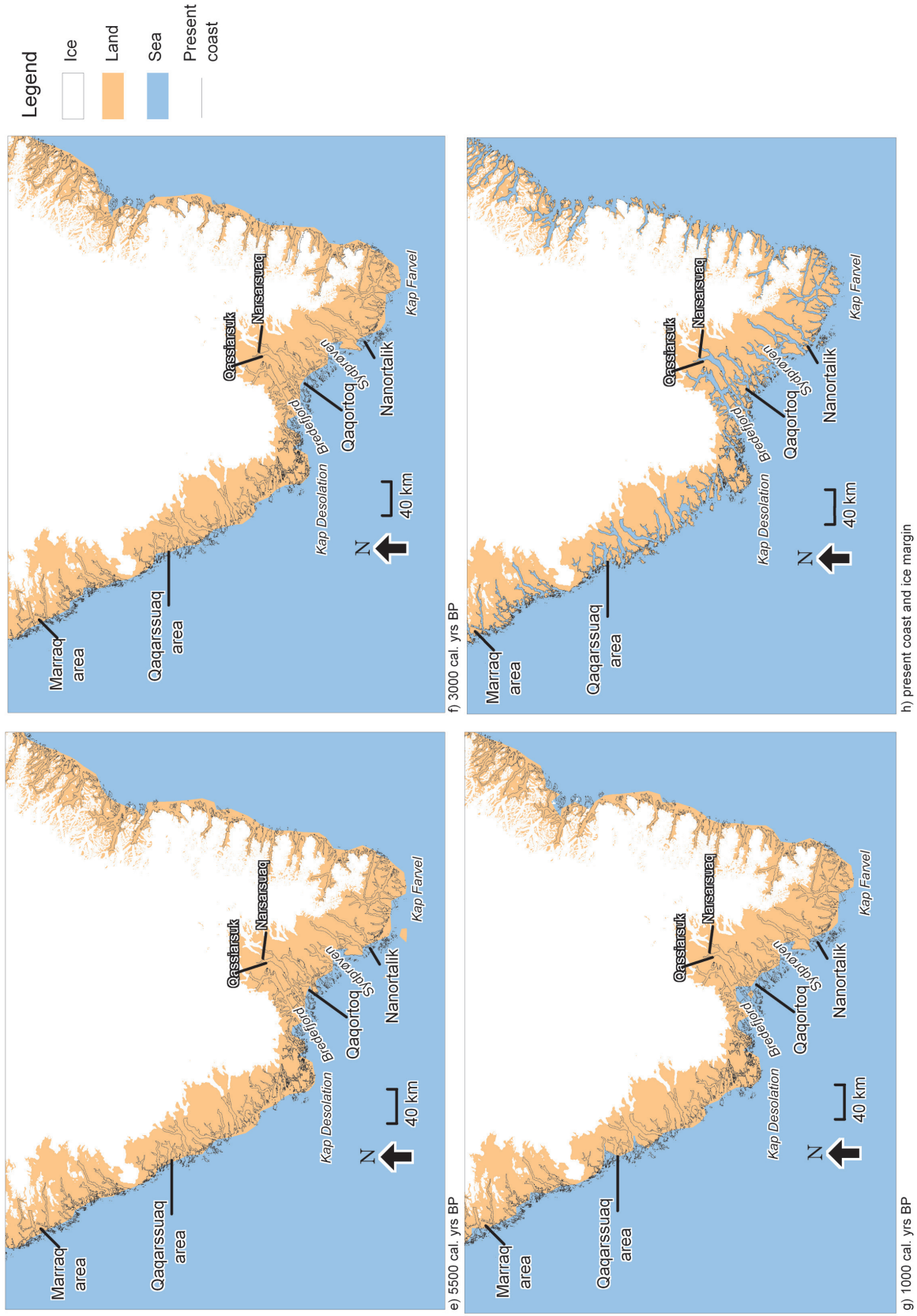


Fig. 4 e) 5500 cal. yr BP f) 3000 cal. yr BP g) 1000 cal. yr BP and h) the present. Note that the maps have been produced with a digital terrain model with 5'x5' resolution and only show the coastline at a coarse scale. These maps should not be used for more detailed

useful information for archaeologists searching for evidence of Palaeo-Eskimo settlements/activities.

## Discussion

The use of near-coastal basins for reconstructing sea-level changes was used for the first time almost a century ago (Sundelin, 1917), but the methodology is still successfully used today and can become even more effective when newer core scanning methods are applied. The new XRF-scanning methodology has demonstrated that in the future, we can extract reliable sea-level data much quicker from isolation basins, but with the same or even better precision than has been possible before. XRF-scanning can contribute to more relative sea-level observations becoming available faster, which will help to constrain ice-sheet histories and in understanding past climate.

A debate has proceeded for some time about the extent of the SW Greenland ice margin during the LGM and about its maximum thickness. Several different LGM ice margin extents have been presented for southern Greenland (Weidick, 1976; Andersen, 1981; Funder, 1989; Kelly, 1985; Funder & Hansen, 1996; Bennike & Björck, 2002) but recent results from glacial-isostatic adjustment modelling by Bennike *et al.* (2002) and Fleming & Lambeck (2004) suggest that the maximum ice models presented (i.e. Andersen, 1981) underestimate the ice thickness and/or the extent in southern Greenland. Our sea-level observations and the resulting best-fitted ice model scenario presented in Appendix IV, agree well with their conclusion about a larger and/or thicker ice sheet, as the amount of uplift is extensive considering the ice sheet now present. The amount of land uplift in southern Greenland is in fact comparable with that of near-ice-margin localities in Svalbard and Norway (Bennike *et al.*, 2002), although the relative sea-level curves from southern Greenland are below the present-day level during most of the Holocene (Appendix I & II). However, there are marked differences between Greenland and the areas in Svalbard and Norway, as there is still an ice sheet occupying a large portion of Greenland. The change in ice thickness (i.e. ice volume loss) from the LGM until the present is for the case of Greenland greatest in the area outside of the present ice margin. The greatest land uplift is therefore expected to be found some distance from the present margin towards the near-coast/shelf

area. The shoreline gradients are expected to either tilt inland towards the ice sheet, as reported, for example, by Zwartz *et al.* (1999) in Antarctica, or show the greatest uplift some distance between the present coast and the inland, resulting in a “bent” gradient, with an outer part tilting downwards towards the shelf and an inner part tilting downwards towards the inland, as shown by the map of Funder & Hansen (1996). This phenomenon reflects the incomplete deglaciation of a region. Our best-fitted ice model scenario (Appendix IV) presents a much larger ice sheet for SW Greenland than anyone has presented before, and in our latest results there are indications that our ice model scenario still underestimates the changes in ice mass in the coastal and/or shelf area. This suggestion arose from the obvious discrepancies between the observed and predicted gradients in the coastal area.

Another differing factor between Greenland and the case of Scandinavia, is its position on the peripheral bulge zone surrounding the area of the former North American ice sheets, which significantly complicate sea-level analyses.

The third significant difference between Greenland and the other formerly glaciated regions in the Northern Hemisphere is the inferences of a neo-glacial re-advance during the mid to late Holocene. The results presented here also show that the crustal subsidence taking place from the mid Holocene until the present-day cannot be explained by the collapse of the Laurentide peripheral bulge alone, but a significant neo-glacial re-advance is needed. Wahr *et al.* (2001) have earlier shown that a neo-glacial re-advance is needed for the area around Kellyville to account for the recent crustal subsidence and suggested that the mode of the West Greenland ice sheet in that area has changed from one of retreat to one of expansion between 4000 and 3000 years ago. The neo-glacial re-advance in SW Greenland may have started already before 6500 cal. yr BP, as suggested by the results from the Qaqortoq area. These results correspond well with those of van Tatenhove *et al.* (1996), who suggested that the Greenland Ice Sheet was smaller than at present along the entire west coast between *c.* 10,000 and 5700 cal. yr BP. According to the investigations of the N14-lake at Angissoq Island by Andresen *et al.* (2004), climatic conditions were at their Holocene optimum between 8000-6500 cal. yr BP with warm and humid conditions. The increased humidity may explain the start of the ice sheet re-advance as indicated by the sea-level observations. Dahl-Jensen *et al.* (1998) also suggest

that the maximum Holocene warmth occurred between *c.* 8000 and 5000 years ago, as suggested from their models based on present day bore-hole temperatures in the central parts of the Greenland Ice Sheet. Andresen *et al.* (2004) have found indications of dryer and colder climatic conditions from about 3700 cal. yr BP. At this time, our best-fitted ice-sheet model has already reached the size of the present-day, and the colder conditions could have lead to stable ice conditions without much net ablation. As the neo-glacial re-advance must have been gradual as suggested by the slow sea-level rise, we can expect small changes in climate leading to a net accumulation caused by greater humidity, and then a stabilisation when the climate again turned colder and drier. The reason we cannot find other verification other than relative sea-level observations of an earlier glacial re-advance, is most probably that the ice sheet covers it. The ice-free areas of today were further from the ice margin then, and the influence might not have been great enough to be registered until the ice margin had already been in an advancing mode for some time.

The differences in landscape characteristics between the Nanortalik and the Qaqortoq area were pointed out by Sugden (1974), who classified the landscape types based on intensity and type of glacial erosion. He conclude that linear ice sheet erosion is dominant in the Qaqortoq-Narsarsuaq area, while a mountain valley glacier landscape dominates in the more southerly Nanortalik area. Our results and Sugden's classification are well illustrated in the Quaternary map of southwest Greenland by Weidick (1987), showing low, bare and eroded bedrock in the coastal area from Sydprøven to Kap Desolation and *c.* 70 km inland from there towards Narsarsuaq. The three cosmogenic nucleid measurements from bedrock and erratics in the Qaqortoq area show that erosion has taken place in Late-glacial times, which corresponds well with the low and bare landscape and the broad and deep fjords dissecting it. In contrast, the area east of Sydprøven is characterised by widespread glacio-fluvial sediments in the valleys and alpine mountains (Weidick, 1987). The single cosmogenic nuclide measurement from Nanortalik Island indicates that the alpine landscape east of Sydprøven comprises older preserved rock surfaces, indicating cold-based ice condition during at least the last glaciation.

On the west coast of Greenland south of N°65, the land is dissected by numerous fjord troughs reaching depths down to 600 m and some even deeper, while the land area north of N°68 comprise

fewer fjords. The difference in landscape characteristics between the northern and southern west coast contributed to faster ice recession by several millennia in the fjords in the south, coherent with our best-fitted model scenario, suggesting an early and quick retreat. The retreat mechanism dominating was the calving of icebergs into the many fjords as opposed to the inland, where melting was the dominant retreat mechanism (Weidick, 1984; Funder, 1989). This is also supported by the observation and glacial-isostatic adjustment modelling for site Nu1 in the inner Bredefjord area. The early isolation age and the low altitude of the basin threshold suggest that the ice sheet in the Bredefjord area was thin. The fact that Bredefjord is over 600 m deep, broad, straight and the bedrock barren and eroded, indicates that it has been one of the main drainage paths for the Greenland Ice Sheet and also a possible way for a quick ice retreat by calving. Late Weichselian moraines or ice marginal deposits on the Nanortalik Banke are located *c.* 70 km southwest of Qaqortoq (Weidick, 1987; Funder, 1989) and bordering an over-deepened area (deeper than 1400 m) in Julianehåb Bugt. These bathymetric features and the existence of the deep Bredefjord, the Tunulliarfik fjord and the Igaliko fjord agree with the interpretation of a warm based ice sheet extending out to the shelf edge during the LGM in the Qaqortoq area. The fjords worked as effective ice drainage paths, probably creating an ice stream resulting in a thinner ice sheet, i.e. a smaller load. This is also supported by the modelling results showing a smaller ice load in the Qaqortoq-Narsarsuaq area, whereas the Nanortalik area with a cold-based non-eroding ice sheet in the alpine landscape supports the likelihood of a more prominent ice load.

## Conclusions

Coherent high quality observations of Holocene relative sea-level change in southern Greenland are scarce and have mostly been restricted to observations from the Nanortalik area (Bennike *et al.*, 2002) with only few scattered observations from other localities (Fredskild, 1973; Funder, 1979; Weidick *et al.*, 2004). Based on our studies from the Qaqortoq and Nanortalik areas, we can draw the following conclusions about sea-level changes in southern Greenland:



- The relative sea-level fall in SW Greenland in the Lateglacial and earliest Holocene was rapid, with a relative uplift of the Nanortalik area of about 12 mm/yr and of about 15 mm/yr in the Qaqortoq area. The fall in sea level continued until some time after 9000 cal. yr BP around the Nanortalik area and until at least 8800 cal. yr BP in the Qaqortoq area. This implies a fast recession of the ice sheet during parts of the Lateglacial and the early Holocene. A comparison between the results from the Nanortalik and Qaqortoq areas demonstrate that the ice retreat occurred later in the Qaqortoq area as a consequence of the sites' more inland position.
- The new Holocene relative sea-level observations in southern Greenland demonstrate what previously only been suggested; that sea levels were below the present-day level for almost the complete past 10,000 years. Our investigation of near-coastal lakes and marine tidal estuarine basins provide evidence that the local sea-level reached almost 10 m below the highest astronomical tide in the interval from 8000–6000 cal. years BP. The data also suggest that relative sea level reached slightly lower elevations in the Nanortalik area than in the Qaqortoq area, consistent with the more inland position of the Qaqortoq area and possibly reflecting differences in ice thickness, i.e. differences in ice load changes, between the two areas. During the mid-Holocene, at or before *c.* 5000 cal. yr BP, sea level was rising again as evident from the Nanortalik area, with a mean submergence during this time of 1.5–2 mm/yr. Evidence from the Qaqortoq area shows a mean submergence of the area of *c.* 3 mm/yr at around 3750 cal. yr BP. The relative sea-level rise in the mid- to late-Holocene was slow and more gradual than the sea level fall shown during the Late-glacial and early Holocene. The mid-Holocene transgression seems to have reached present-day sea levels earlier in the Qaqortoq area than in the Nanortalik area, which as a consequence of the closer proximity to the ice mass centre in the Qaqortoq area may imply that the transgression was caused by a Holocene thickening of the Greenland Ice Sheet.
- Our glacial-isostatic adjustment modelling analyses shows that the best-fitted ice-change scenario is as follows: The ice sheet extended all the way out to the shelf edge during the LGM from at least 26,500 cal. yr BP until *c.* 22,000 cal. yr BP. The LGM ice sheet melting began early (*c.* 22,000 cal. yr BP) and the retreat of the ice-margin proceeded quickly. The ice thickness in central southern Greenland during the LGM must have been of the order of 4000–4500 m. By 12,000 cal. yr BP, the ice margin was located behind the present-day coast and by 10,500 cal. yr BP it had reached its present-day position. The ice sheet was smaller than the present-day ice sheet after 10,500 cal. yr BP and reached a minimum at *c.* 30 km behind the present-day margin by *c.* 9000 cal. yr BP. A neo-glacial re-advance started some time before 6500 cal. yr BP and the present-day margin was reached again by *c.* 5500 cal. yr BP. From our glacial-isostatic modelling, we can also conclude that the ice sheet was thicker in the Nanortalik area than in the Narsarsuaq-Qaqortoq area.
- The previous conclusion about ice thickness is also supported by our new cosmogenic nuclide apparent exposure ages, indicating a thicker basally frozen ice sheet in the Nanortalik area, and a thinner warm based eroding ice in the Qaqortoq-Narsarsuaq area. The ice sheet must have been rather thin in the Bredefjord area, which probably functioned as a major drainage pathway and a quick ice retreat corridor.
- In the Qaqortoq area, the shorelines from *c.* 11 000 cal. yr BP tilt almost 5 m/10 km towards the Greenland Ice Sheet in the northeast, while younger shorelines, at *c.* 9000 cal. yr BP, tilt *c.* 4 m/10 km. The north-easterly tilting shorelines show that the uplift rate has been smaller inland than at the outer coast, indicating that the rebound is responding to the larger amount of ice removed from the coastal and shelf zones. The discrepancy between the observed and the predicted shoreline gradients indicates that the Lu ice model scenario can still be improved upon, and the most likely option is an increased ice load in the near-coast and/or shelf area.
- In our study of isolation contacts and transgression sequences in near-coastal environments, we have found a quick, reliable and non-destructive method for the identification of the transitions by sediment sequences analysis using XRF-scanning. By analysing the variability of a range of elements, it is quite easy to identify the location of the isolation contact and the transgression sequence. The use of the following elements are suggested for an easy identification of transitions; Se, Fe, Mn, Al, Si, K, Ca, Sr, Ti, Cu and Zr. XRF-results are reproducible but minor discrepancies might occur as a consequence of the heterogeneous nature of the sediments and the small differences in sen-

son and/or scanner design and measurement resolution. The XRF-scanning analyses, together with a few pinpointed macrofossil analyses and radiocarbon dating of the macrofossils identified, provide a reliable and quick way for the reconstruction of relative sea-level changes.

## Implications and ideas for the future

The results presented in this thesis have provided new coherent high-quality sea-level observations (Appendix I and II) and in-situ cosmogenic exposure ages that constrain the glacial-isostatic adjustment of SW Greenland, and consequently narrowing the range of possible ice-sheet evolution scenarios since the LGM until the present (Appendix IV). To further improve our understanding of ice-sheet evolution in southern Greenland, new and more precise sea-level observations from the northern areas (N°63-N°64) are required.

Another inspiring possibility would be an expedition aiming to execute a SE Greenland coring campaign for isolation/transgression basins, as sea-level observations in the area between Kap Farvel and Scoresby Sund to my current knowledge, are non-existent. With the new and more precise data, a new modelling analysis would be valuable to constrain the ice-sheet's evolution in this area better. The collection of rock samples from bedrock and erratics would be combined with a coring campaign, and analyses of in-situ cosmogenic nuclide apparent exposure ages from both the Nanortalik area and further northwards in both east and west of south Greenland could provide a more extensive interpretation about the differences in ice thicknesses and ice regimes. As suggested in Appendix III, analyses of the cores collected during a new coring campaign could be restricted to lithological description, XFR-scanning and some pinpointed macrofossil analyses combined with the collection of macrofossils for radiocarbon dating, to provide rapid results for further modelling analyses.

It could be fruitful to investigate the Bredefjord area in greater detail and search for additional evidence such as Late-glacial lake sediments, indicating that the fjord was deglaciated early and has functioned as a drainage path for the ice sheet. Both the site Nu1 (Appendix II) and the modelling suggests an early and quick ice retreat here,

as well as the local bathymetry and geography, and the barren and eroded bedrock. The ice-sheet models used for the Greenland ice sheet could be improved by coupling our results to more detailed glaciological models that consider ice streams and climate forcing, as has been done by Forsström *et al.* (2003) for the Fennoscandian Ice Sheet and by Zweck & Huybrechts (2005) for all of the northern hemisphere ice sheets.

Marine investigations of the ice marginal deposits on the Nanortalik Banke, as well as the marginal deposits further north (Narssalik, Fredrikshåb, Danas, Fiskenaes and Fyllas Banke) could provide useful information to when and how these features were formed and help constrain the ice sheet extent even more. From a cost-efficient point of view, the drilling of marine cores on the Nanortalik Banke ice marginal deposit could be combined with a seismic and/or side-scan sonar survey, which to the author's present knowledge has not been done in the Julianehåb Bugt, to obtain a picture of the surface form and internal structure of the supposed marginal moraines. Apart from these rather evident suggestions to future actions to the improvement of the sea-level and glacial history reconstructions, a more detailed comparison between the glacial-isostatic ice models and the climate changes registered in the ice cores and the North Atlantic would be exciting.

## Acknowledgements

Through tears and pain, sorrow and joy, I've worked my way to complete the task of writing this thesis. Thank you my dear Niklas for always supporting me, believing in me at all times and loving me when I least deserve it. Without the help and care of many others, the task would seem endless and lonely. Therefore in particular, I would like to draw the attention towards my supervising team, Prof. Svante Björk, Dr. Ole Bennike and Prof. Kurt Lambeck, and thank them for all the discussions, disagreements, introducing me to Greenland, to the world of geophysical modelling and macrofossil analysis, but most of all for disagreeing with each other. Without so many different views, I wouldn't have learnt as much! Thank you Svante, for always being there to give me quick feedback and for all the endless certificates you've had to write. Thank you Ole, for quickly responding to my never-ending stream of questions about Greenlandic animals, plants and literature. Thank

you Kurt for keeping my brain fit, always questioning everything and for leading me back to the true path when I've drifted off. I would of course like to thank my dear mentor, Dr. Kevin Fleming for always being there to provide answers on my ponderings, for teaching me some of the mysteries of the engineering aspects of modelling and being the brother I never had. There is a long line of people who has contributed to the success of this study and to whom I especially direct a great, THANK YOU; Dr. Derek Fabel (UG), Dr. Helena Alexanderson (SU), Karl Ljung (LU), Dr. Georg Nyegaard at the Qaqortoq museum, Dr. Herb McQueen (ANU), Ass. Prof. Christian Hjort, Dr. Tony Purcell (ANU), Dr. Poul Møller Pedersen (KU), Palle Bo Nielsen (Farvandsvæsenet), Ole Andersen (KMS), Hans Jepsen (GEUS), Dr. Lena Barnekow (LU), Prof. Gunnar Digerfeldt (LU), Vasile Ersek (Oregon State), Dr. Göran Skog (LU), Dr. hab. Tomasz Goslar (Poznan), Prof. Mats Sonesson, Hans F. Jepsen (GEUS), Marloes Kortekaas (LU), Prof. Anders Rindby (Chalmers/Cox Analytical systems), Mattis Johansson (SWECO VIAK), Ass. Prof. Mats Rundgren, Prof. Per Sandgren and Ass. Prof. Ian Snowball.

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## Svensk sammanfattning

Jordens havsnivå förändras kontinuerligt. I ett längre geologiskt tidsperspektiv styrs förändringarna av processer i jordens inre, men i ett kortare tidsperspektiv spelar yttre processer, såsom tillväxt och avsmältning av inlandsisar, stor roll för havets nivåförändringar. Det grönländska istäcket är idag norra halvklotets enda inlandsis och dess tillväxt och avsmältningshistoria är relativt okänd. Genom rekonstruktion av relativa havsnivåförändringar kan vi analysera hur inlandsisens utbredning och tjocklek har varierat. För att analysera inlandsisens utbredning och tjocklek använder vi oss av numeriska glacial-isostatiska modeller och för rekonstruktion av relativa havsnivåförändringar använder vi oss av sedimentkärnor från kustnära sjöbassänger och havsvikar.

Genom att undersöka sedimentlagerföljder från bassänger belägna på olika nivåer och mäta tröskelhöjd för varje bassäng erhålls de relativa havsnivåförändringarna. I sedimenten finns förändringar registrerade som visar hur miljön i dessa bassänger har skiftat från saltvatten till färskvatten och i vissa fall från färskvatten till brackvattensmiljöer för att sedan helt övergå till saltvattensmiljö igen. Dessa miljöförändringar kan ses som förändringar i sedimentsammansättning, i sammansättningen av den fossila florin och faunan, i sedimentens magnetiska egenskaper och dess kemiska sammansättning. Genom att undersöka fysiska sedimentförändringar i lagerföljden och analysera makrofossilinnehåll, mäta magnetisk susceptibilitet, remanent magnetism efter magneisk mättnad (saturation isothermal remanent magnetism) och glödförlust, kombinerat med kol-14-analys av fossil och bulkprover, har vi kunnat bestämma när en bassäng isolerats från eller översvämmats av havet. Vi har även provat att använda en relativt ny teknik i form av automatiserad röntgenfluorescensspektrometri (X-ray fluorescence spectrometry scanning) för att mäta kemiska variationer igenom sedimentlagerföljden. Denna analysmetod har visat sig vara snabb och effektiv för identifiering av isoleringskontakter och transgressionssekvenser. Tillsammans med ett några få makrofossilanalyser kombinerat med kol-14-analys av dessa, kan framtida rekonstruktioner av relativa havsnivåförändringar med hjälp av isoleringsbassänger/transgressionssekvenser utföras snabbt och säkert.

Mitt avhandlingsarbete är koncentrerat till skärgårds- och fjordlandskapet på sydvästra Grönland. Två fältsäsonger har utgjort en del av mitt

avhandlingsarbete, en i Nanortalik-området (2001) och en i Qaqortoq-Narsarsuaq-området (2002), och har resulterat i datasamling från 18 bassänger. I fältarbetet, som mestadels har bedrivits från båt, har undersökningar av undervattenstopografi med ekolod ingått för lokalisering av lämpliga borrhplater. En Rysseborr har använts för att ta upp överlappande borrhkärnor och borrhplatsens position har bestämts med hjälp av GPS. Bassängtrösklarna har mätts i fält med clinometer, ekolod och borrhstänger samt även kontrollerats med hjälp av fotogrammetriska mätningar i laboratoriet på GEUS.

Från de undersökta bassängerna och dess sedimentlagerföljder har vi kunnat fastslå att den relativa havsnivån under senglacial och tidig-Holocen sjönk snabbt i sydvästra Grönland till för ungefär 9000 år sedan. Den relativa landhöjningen var under denna tid ungefär 12 mm/år i Nanortalik-området och ca 15 mm/år i Qaqortoq-området. Havsnivån låg under dagens från ungefär 10000 år före nutid fram till idag och nådde som lägst cirka 10 meter under dagens nivå under perioden 8000-6000 år före nutid. I Nanortalik-området var den relativa havsnivån något lägre än i Qaqortoq-området, vilket troligen reflekterar olika istjocklek i områdena och olika närhet till inlandsisen. Runt 5000 före nutid, i mitt-Holocen, började den relativa havsnivån långsamt att stiga med cirka 1,5-2 mm/år. Observationer från Qaqortoq-området tyder på en något snabbare havsnivåstigning runt 3750 år före nutid med ungefär 3 mm/år.

Även stenprover har samlats in från både berggrund och flyttblock för att kunna bestämma deras respektive exponeringsåldrar genom undersökning av halten kosmogena isotoper, såsom  $^{10}\text{Be}$  och  $^{26}\text{Al}$ . Generellt sett är koncentrationen av kosmogena isotoper beroende av exponeringstid och erosionshastighet. Inom detta projekt har vi använt analyser av kosmogena isotoper för att få en indikation på om inlandsisen varit bottensmältande eller bottenfrusen. Isens bottenförhållanden påverkar istjockleken och denna information hjälper oss att tolka och begränsa ismodellerna i den glacial-isostatiska modelleringsprocessen.

En glacial-isostatisk numerisk modell innefattar en matematisk beskrivning av jordens uppbyggnad och dess mekaniska respons på ytliga belastningsförändringar orsakade av t.ex. förändringar i inlandsisar och havsbassänger. Modellerna innefattar även en beskrivning av inlandsisar och glaciärer och deras förändringar i rum och tid. Genom att beräkna havsnivåerna för en känd tid och plats kan vi "kalibrera" våra modeller och på så sätt testa hur realistiska olika isavsmältningsscenarier är.

Vid en jämförelse med de relativa havsnivå-observationerna, har vi genom våra modelleringsexperiment kunnat dra slutsatsen att den sydvästra delen av den grönländska inlandsisen nådde ända ut till kanten av kontinentalsockeln från cirka 26500 år sedan till för 22000 år sedan. Under denna tid var inlandsisen på sydvästra Grönland i storleksordningen ca 4000-4500 m tjock. Efter 22000 år för nutid började inlandsisen smälta av och iskanten retirerade snabbt och vid 12000 år för nutid stod iskanten precis innanför dagens kustlinje. För 10500 år sedan var inlandsisen ungefär lika stor som idag men smälte av ytterligare för att vid 9000 år före nutid nå en minimal utbredning, cirka 30 km innanför dagens iskant. Redan innan 6500 år före nutid började inlandsisen åter växa och vid ungefär 5500 år före nutid nådde den dagens utbredning igen. Både från modelleringsresultaten och från erhållna exponeringsåldrarna kan vi dra slutsatsen att inlandsisen var tjockare och troligen bottenfrusen i Nanortalikområdet, medan istäcket i Qaqortoqområdet var tunnare och bottensmältande.



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