Holocene relative sea-level changes in the Tasiusaq area, southern Greenland, with focus on the Ta1 and Ta3 basins

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Abstract: Results from an investigation of relative sea-level changes from *c.* 11,000 cal. yr BP to the present in the Tasiusaq area, Inner Bredefjord, southwest Greenland, are presented in this thesis. Isolation sequences from two small lakes have been identified using stratigraphic analyses, XRF-scanning, loss on ignition and macrofossil analyses. Macrofossil and bulk samples have been dated in order to establish at what time the lake basins became isolated from the sea. These data have been combined with data from one marine embayment to establish the relative sea-level changes in the Tasiusaq area for the last 11,000 years. The data show that sea level fell rapidly in early Holocene and reached present-day level at *c.* 8050 cal. yr BP, and support earlier reconstructions of the ice sheet history showing that the ice sheet started receding at *c.* 22,000 cal. yr BP and that the ice-margin recession proceeded quickly: by *c.* 12,000 cal. yr BP the ice margin was inland of the present day coast and by *c.* 10,500 cal. yr BP it had reached the present-day margin. Sea level then continued to fall below 4.4 meters below highest astronomical tide in the area and reached its lowest levels between *c.* 7000 and *c.* 2000 cal. yr BP. The absolute lowest level of the post glacial sea level in the area can, however, not be established. As the Qaqortoq area further west and the Nanortalik area further south, the Tasiusaq area experienced a transgression in the mid- to late Holocene. In the Qaqortoq and Nanortalik areas this transgression started at *c.* 6000 cal. yr BP, while it seems to have started later (*c.* 4000 cal. yr BP) in the Tasiusaq area. This possibly reflects different forcing mechanisms working at different times between the sites; Nanortalik and Qaqortoq mainly being influenced by the collapse of the Laurentide peripheral bulge and Tasiusaq primarily being influenced by the re-advance of the Greenland ice sheet starting at the mid-Holocene climate deterioration.

This new data from the Tasiusaq area can hopefully be used to improve the earlier glacial-isostatic adjustment models and thereby enable us to achieve a better spacial resolution for the ice sheet history in the Holcene.

Keywords: isolation sequences, Holocene, southern Greenland, sea-level changes, isostasy, Greenland ice sheet

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Relativa havsnivåförändringar i Holocen tid i Tasiusaqområdet, södra Grönland, med fokus på sjöarna Ta1 och Ta3

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Sammanfattning: Jordens havsnivå förändras ständigt och dessa förändringar kan ha olika orsaker: i ett längre geologiskt tidsperspektiv är det processer i jordens inre som påverkar havsnivån, men i ett kortare perspektiv spelar till exempel tillväxten och avsmältningen av inlandsisar stor roll. Under kvartärtiden har den sistnämnda processen varit den dominerande vad gäller att påverka havsnivåerna: vid istider har havsnivån varit låg och vid mellanistider har den varit hög.

Sedan den senaste istiden har de flesta inlandisarna på norra halvklotet smält bort - den enda som finns kvar är den grönländska inlandsisen. Genom att försöka förstå hur denna is betett sig kan vi lära oss hur klimat-, havsnivå- och miljöförändringar samverkar och påverkar isen, och därigenom förhoppningsvis lära oss att förutspå hur den kommer att bete sig i framtiden, när klimatet förändras.

Under den senaste istiden låg isen tjock ända ut till shelfkanten på Grönland och tryckte ner landmassorna därunder. Efter hand som klimatet förändrades drog isen sig tillbaka och när den försvann från ett område började landet i området höja sig. Genom att undersöka sedimentlagerföljder från sjöbassänger och havsvikar belägna på olika nivåer och mäta höjden på deras trösklar kan vi erhålla de relativa havsnivåförändringarna. Dessa kan sedan användas för att analysera inlandsisens utbredning och tjocklek genom modellering.

I denna studie har jag undersökt sediment från två sjöbassänger i Tasiusaqområdet i den inre delen av Bredefjord på sydvästra Grönland. I sedimenten registreras förändringar, som visar hur miljön i bassängerna skiftat från saltvatten till färskvatten, när bassängerna blivit isolerade från havet. Miljöförändringarna leder till att sedimentens sammansättning samt deras flora-, fauna- och kemiska innehåll förändras. Genom att undersöka hur sedimenten förändras fysiskt, och genom att analysera makrofossilinnehåll, mäta mängden organiskt material genom glödförlust och använda automatiserad röntgenfluorecensspektrometri (XRF-scanning) för att mäta kemiska variationer genom lagerföljden, kan jag bestämma var i lagerföljden bassängerna blivit isolerade. Genom att sedan kol-14-datera makrofossil och bulkprover över och under isoleringen, har jag kunnat bestämma när isoleringen ägde rum: bassäng Ta1 på 26 meter över högsta astronomiska tidvattennivå (h.a.t.) isolerades för ungefär 8750 år sedan, och bassäng Ta3 på 12 meter över h.a.t. för ungefär 8500 år sedan. När dessa data kombineras med liknande data från en havsvik i samma område, som först blivit isolerad och sedan översvämmats av havet igen, kan jag fastställa hur den relativa havsnivån förändrats i Tasiusaqområdet under de senaste 11 000 åren. Detta har jag sedan kunnat jämföra med tidigare modelleringsresultat över hur isen smält av på sydvästra Grönland.

Jag har kunnat fastslå att den relativa havsnivån sjönk väldigt fort under tidig Holocen i Tasiusaqområdet. Mellan ca. 9000 och 8000 år före nutid var den relativa landhöjningen ungefär 33 mm/år. Detta betyder att isen smälte av fort från detta område: för 13 000 år sedan låg iskanten vid dagens kustlinje och för 10 500 år sedan hade den nått den nivå där iskanten ligger idag. Isen fortsatte sedan att smälta av och nådde sin miniminivå cirka 30 km inåt land från dagens iskant räknat, runt 9000 år före nutid. I Tasiusaqområdet visar sig detta genom att havsnivån fortsatte sjunka under dagens nivå och nådde sin lägsta nivå någon gång mellan 7000 och 2000 år före nutid. Exakt när den nådde sin lägsta nivå och vilken denna nivå var har dock inte kunnat fastställas. För ungefär 4000 år sedan började den relativa havsnivån kring Tasiusaq att stiga igen, och havsnivån nådde dagens strax före nutid. Denna havsnivåstigning i senare delen av Holocen beror antagligen framför allt på att inlandsisen började växa till igen på grund av att klimatet försämrades; när isen växte till tryckte den återigen ner landet framför sig vilket gav upphov till att den relativa havsnivån höjdes i området framför isen.

Förhoppningen är att dessa nya data från sydvästra Grönland ska kunna användas för att förbättra de modeller och isavsmältningsscenarion som tidigare framställts, så att kunskapen om den Grönländska inlandsisen och dess beteende ökar och att vi bättre förstår hur den har betett sig och kanske också hur den kommer att bete sig i framtiden.

Nyckelord: isoleringslagerföljder, Holocen, södra Grönland, havsnivåförändringar, isostasi, grönländska inlandsisen

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”Men, da Du spurgte, om Landet var frit for Is eller ikke, eller det var bedækket med Is ligesom Havet, da skal Du vide det for vist, at det er en ringe Del af Landet, hvor der er bart for Is, men alt det øvrige er bedækket med den, og Folk vide ikke, om Landet er stort eller lidet, fordi alle Fjeldstrækninger og ligeledes alle Dale ere skjulte af Isen, saa at man ingensteds finder Aabning derpaa. Folk have ofte forsøgt at gaa op paa Landet paa de Fjelde, som ere de højeste paa forskjellige Steder, for at se sig om og for at prøve, om de fandt nogen Del af Landet, som var fri for Is og beboelig, men man har ingensteds kunnet opdage sligt foruden de nu beboede Egne, som kun udstrække sig kort langs med selve Kysten.”

”But, when you asked whether the land was ice-free or not or whether it was covered with ice as the ocean, you should know for sure that it is but a small part of the country which is free from ice. All the rest is covered by it and people do not know whether the country is big or small, because all mountain ranges and all valleys are hidden by the ice and nowhere is there an opening to be found. People have often tried to climb the land on the highest mountains, to have a look around and to see if they could find any part of the country that was free of ice and habitable. But nothing of the sort has been found except for the currently populated areas, which only extend a short way along the coast.”

From ”Kongespejlet”, a description of Greenland from the 13th century. Here from Steenstrup, K.J.V., 1893: Bidrag til Kjendskab til Bræerne og Bræ-Isen i Nord-Grønland. *Meddelelser om Grønland*, 4th book. (Translation: author)

1 Introduction

1.1 Background

Average global sea levels have fluctuated throughout geological time and relative sea level at any particular place varies with time and space. Several different natural processes act together to cause sea-level changes: local regional uplift or subsidence of the land; changes in atmospheric pressure, winds and ocean currents; changes in the mass of ocean water caused by the accumulation or melting of ice sheets; changes in the volume of ocean water in response to temperature and salinity changes; and changes in the volume of ocean basins. These parameters are driven by internal Earth processes such as movement in the mantle and flexure or movements in the crust, as well as external processes like ice sheet growth and decay, marine sedimentation and, on a smaller scale, temperature changes of ocean water. These processes, which act on different temporal and spatial scales, create a complex pattern of local sea-level change (Geophysics Study Committee et al., 1990). Reconstructions of sea-level changes through time can thus provide information and constraints on the timing, rates and magnitudes of the changes in ice mass during glacial cycles as well as information on the distribution of ice between major ice sheets at any given time (Lambeck & Chappell, 2001).

During the Quaternary the periodic exchange of mass between ice sheets and oceans has acted as the dominant contribution to sea-level change; glacials being times of sea-level lowstand and interglacials being times of relative high-stand. Regional and local changes caused by uplift and subsidence of the coastal zone or by changes in regional and local climate are then superimposed on these global signals (Lambeck & Chappell, 2001).

Large and rapid climate changes during the transition from the last glacial maximum (LGM) to the Holocene caused most of the ice sheets in the northern Hemisphere to decay. The Greenland Ice Sheet (GIS) experienced considerable reduction but is presently the only remaining ice sheet in the northern Hemisphere. The formerly ice covered areas on Greenland experienced significant vertical uplift due to the glacio-isostatic adjustment. The Earth's response to the retreat of the expanded Greenland Ice Sheet can be seen as relative sea-level changes around Greenland since the LGM (Fleming & Lambeck, 2004).

The southern part of the GIS is a key area in understanding how the different Earth system components act together and affect climate. In this area many of these components meet and interact in a complex manner. By studying the glacial history of the area, insights into palaeoclimatic and sea-level changes and their environmental responses will be given. These insights are crucial to predictions of future climate changes (Sparrenbom et al., 2008).

Until recently there have been few relative sea-level observations in southern Greenland. The most recent observations from the Late-glacial and Holocene periods are reported from isolation- and transgression basins in the Nanortalik, Qaqortoq and Narsarsuaq areas, southwest Greenland (Sparrenbom et al., 2006 a and b; Sparrenbom, 2006; Bennike & Sparrenbom, 2007). They have investigated sea-level changes as well as performed a modelling analysis (Sparrenbom, 2006c) aiming to constrain Late-glacial and Holocene isostatic adjustment due to the ice sheet's retreat history in the region using observational data from Bennike et al. (2002) and Sparrenbom et al. (2006 a and b). Their new data and the comparison with model predictions confirm the conclusions of Bennike et al. (2002) and Fleming & Lambeck (2004), who concluded that the ice extent and ice thickness has been underestimated for the LGM (Sparrenbom, 2006c). Sparrenbom et al. (2006c) tested several ice sheet scenarios and their results suggest that the ice sheet expanded all the way out to the shelf edge during the LGM, that ice sheet recession began early (*c.* 22,000 cal. yr BP) and that the ice-margin recession proceeded quickly. 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 around 9000 cal. yr BP. This can be seen as a rapid fall in relative sea level in the area from *c.* 11,000 cal. yr BP. Sea level reached the present day level at *c.* 9000 cal. yr BP and then continued to fall rapidly until at least 8800 cal. yr BP (Sparrenbom et al., 2006b). Before 6500 cal. yr BP the neo-glacial re-advance of the ice sheet started and the present day margin was reached by 5500 cal. yr BP (Sparrenbom et al., 2006c). This is seen as a mid- to late Holocene transgression which is slow and gradual. It started some time before 6000 cal. yr BP and sea level reached present-day level in south Greenland some time between 2000 cal. yr BP and present (Sparrenbom et al., 2006b). This late relative sea-level rise is a consequence not only of the re-advancing ice sheet but also of the decay of the Laurentide peripheral bulge and/or ocean warming (water expansion) and melting of non-polar ice. Different kinds of evidence for a rapid late glacial and early Holocene regression and a late Holocene transgression has already been found at several sites from different parts of Greenland (Sparrenbom et al., 2006 a and b; Bennike et al., 2002; Long et al., 1999; Kuijpers et al., 1999).

Weidick (1988) writes that the deep and straight Bredefjord in southwest Greenland must have acted as a major drainage path for the southern part of the Greenland Ice Sheet, and recent data collected from the inner Bredefjord area (Sparrenbom et al., 2006c) seem to support this and suggest that the ice was thinner in this specific area. The Bredefjord area thus seems to be the key region for ice sheet drainage in the south, but very few data have been available from the area so far.

1.2 Aims

This thesis aims to present reconstructions of earlier sea levels from two different lake basins (Ta 1 and Ta 3, where Ta is short for Tasiusaq with a site number) in the inner Bredefjord area in order to date the deglaciation of the region but above all to establish the late glacial and Holocene isostatic adjustment in the area. A shoreline displacement study from the Tasiusaq area based on these two lakes and data from one marine embayment (Fredh, 2008) is presented, the shoreline displacement observations extending from 25.8 meters above highest astronomical tide (m a.h.a.t.) to -3.5 m a.h.a.t.

The investigated basins are all situated below the marine limit and have thus been isolated as a consequence of the Earth's uplift following deglaciation after the LGM. The lowest basin (Fredh, 2008) has also been submerged fairly recently due to the late Holocene relative sea-level rise.

Isolation contacts in Greenland are found in near-coastal environments where the relative sea level has fallen and the sediments have changed from marine to freshwater deposition, and are recorded in the sediments as lithological, chemical and physical changes as well as a change in flora and fauna (e.g. Bennike et al., 2002; Sparrenbom et al., 2006d). Sparrenbom et al. (2006d) show that X-ray fluorescence spectrometry (XRF) scanning together with lithological description and pinpointed macrofossil analysis, combined with radiocarbon dating, is a quick and effective way of investigating isolation contacts and transgression sequences for the reconstruction of relative sea-level changes. These methods, as well as Loss On Ignition (LOI), will be used in this investigation to reconstruct the relative sea-level changes and the isostatic adjustment of the Tasiusaq area.

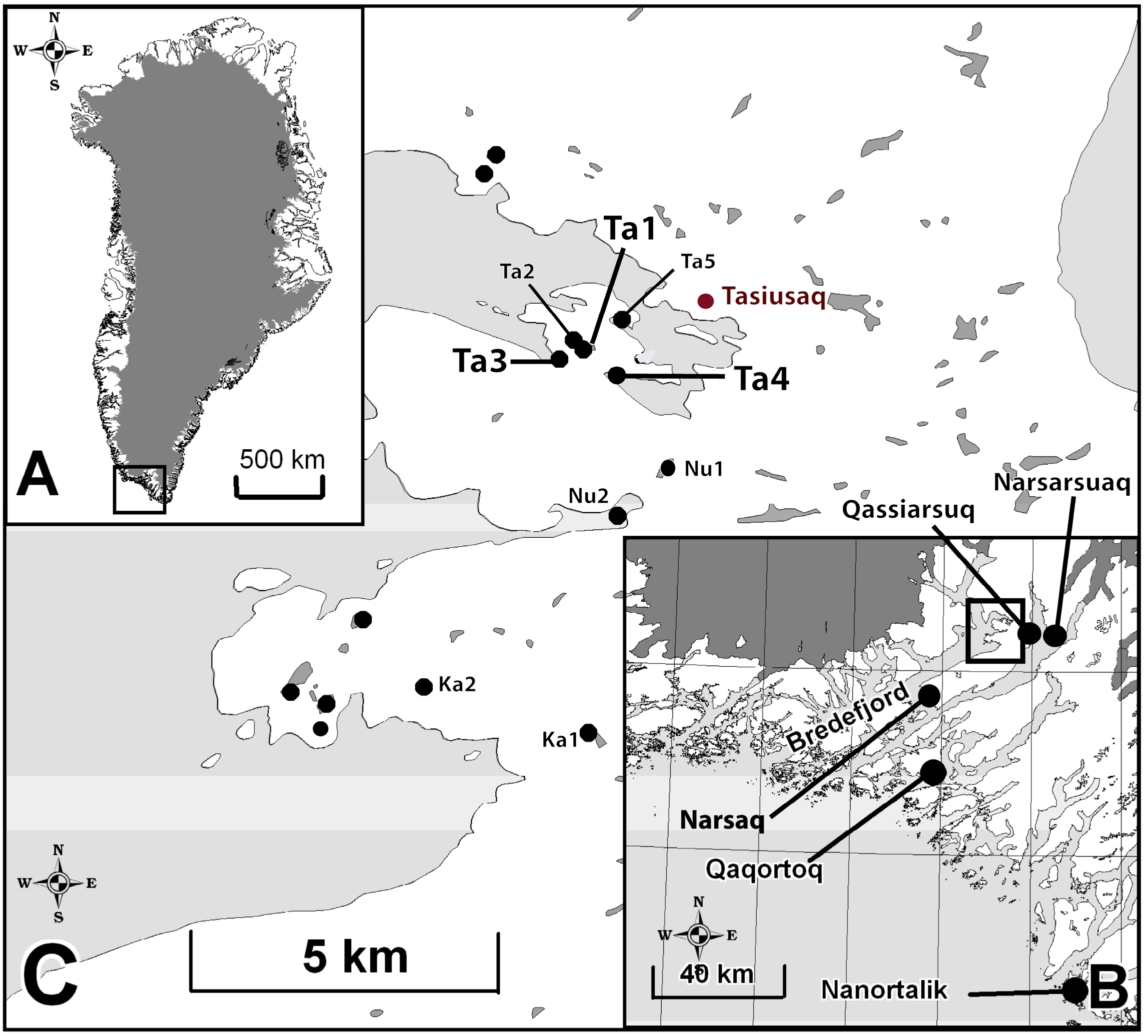

Figure 1. (A) Map of Greenland where the rectangle defines the Julianehåb district. **(B)** Map of south-western Greenland where the rectangle defines the field area and the Nanortalik and Qaqortoq areas are marked. **(C)** Map showing the location of the two sites described in this thesis as well as other sites mentioned in the thesis.

2 Field area

The study area is situated in southwest Greenland, north of N 61°, in the inner Bredefjord region around the small hamlet of Tasiusaq, approximately 7 km west of Qassiarsuq (Fig. 1). Bredefjord is part of the Julianehåb district (N 60-61.5°, W 45-47°) which also comprises the Nanortalik and Qaqortoq areas (Fig. 1).

The landscape is dominated by rounded and flattened mountains and plateaus reaching elevations of 400 m a.s.l. in the immediate territory and over 1000 m a.s.l. further north. Bredefjord, to the west, is a glacially eroded, over-deepened, broad and straight fjord reaching depths greater than 600 meters (Weidick, 1988). At present the ice front is *c.* 20 km away and the coast *c.* 50 km to the southwest. The offshore shelf is relatively narrow throughout southwest Greenland and extends *c.* 70 km from the coast (Bennike et al., 2002).

The bedrock in southern Greenland can be broadly divided into two groups: the Ketilidian rocks that are dominated by granitic and granodioritic rocks and formed in connection with mountain-building processes 2000-1800 million years ago, and the Gardar rocks formed several hundred million years later, *c.* 1300 million years ago, by volcanic processes (Sørensen, 2006). The immediate study area around Tasiusaq is located in the Qassiarsuq complex – a roughly east-west trending graben structure between Qassiarsuq and Tasiusaq. It is part of the Gardar rift and comprises a sequence of alkaline silicate tuffs and extrusive carbonates inter-layered with sandstones and their subvolcanic equivalents (Andersen, 1997).

The present day mean annual temperature for Narsarsuaq, across the fjord from Qassiarsuq, is 4.8°C. Mean monthly temperatures range from 10.3°C in July to -6.8°C in January with a mean annual precipitation of *c.* 600 mm per year (DMI, 2007). A characteristic of the region is the katabatic winds emanating from the ice cap. These drying winds can reach gale force and may persist for many days (Cappelen et al., 2001).

Dwarf shrub heaths with mosses and lichens dominate the vegetation in the area. Major elements of the heaths are *Empetrum nigrum*, *Betula glandulosa* and *Salix glacula*. In sheltered areas occasional patches of *Betula pubescens* may be found.

3 Methods

3.1 Fieldwork

Fieldwork was carried out during three weeks in August 2007. Two large Zodiac dinghies were used to carry out reconnaissance in the area and to transport equipment and people to the different coring sites. The bathymetry of the basins was investigated with an echo sounder to find suitable coring sites, and the exact coring positions were then determined with GPS. A small Zodiac, with a funnel hole in the centre, was used as a coring platform and during coring the boat was roped tightly to three points on shore. Multiple core sediment sequences were collected from the different basins using a Russian corer. In total, fourteen basins at altitudes between -4.4 m a.h.a.t. to 54 m a.h.a.t. were cored, two of which are described in this thesis. The cores were described in the field and then wrapped for shipment back to the laboratory in Lund, where they are stored at 4°C.

Since the aim of the investigation is to establish when sea level was situated at a certain altitude, the changing tide levels need to be taken into consideration. The highest astronomical tide controls when marine waters can enter a basin. This will determine when the marine influence into a basin starts and stops, and the highest astronomical tide is therefore of great importance. The tidal variation was measured in the field using a tide gauge during a period of five days (Fig. 2). The tidal range and highest astronomical tide for the area have been calculated using these

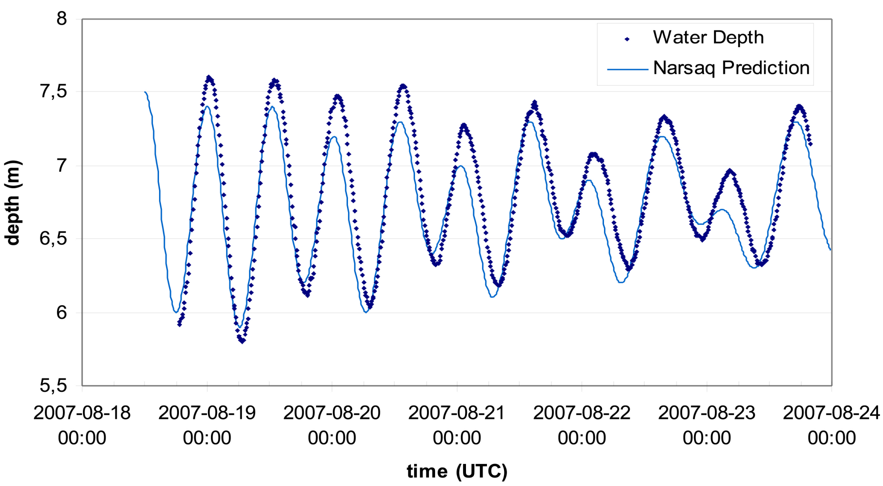

Figure 2. Tidal observations from the Tasiusaq area from the 18-24 of august 2007 compared to the predicted tidal levels from Narsaq (Farvandsvæsenet, 2007).

measurements by Dan Zwartz at the Research School of Earth Sciences at the Australian National University in Canberra. The tidal range for the Tasiusaq area is *c.* 3.3 m at spring tide, and the highest astronomical tide is *c.* 1.6 m above mean sea level.

An echo sounder and coring rods were used to determine the threshold altitudes for submarine basins, and heights above sea level were measured with a DGPS with a base station installed in the settlement of Tasiusaq. The DGPS data was processed and altitudes calculated by Dan Zwartz (ANU). Estimates of the accuracy of the height measurements are presented in Table 1. The total uncertainty at each site depends on the accuracy of the DGPS measurements, the interpreted development of the threshold and the uncertainty in tidal correction. The total uncertainty is:

$$\sigma_{total} = (\sigma_1^2 + \sigma_2^2 + \sigma_3^2)^{1/2}$$

where σ_1 is the uncertainty of the DGPS measurement, σ_2 is the uncertainty of the development of the threshold and σ_3 is the uncertainty of tidal span and time.

3.2 Core descriptions

The cores were described in detail in the laboratory in Lund with respect to minerogenic and organic content, sediment structures and colours, occurrence of macrofossils and the characteristics of boundaries. All unit boundaries were measured and the cores were photographed as presented in Appendix A.

3.3 Macrofossil analysis

Macrofossil analysis is based on the occurrence of multicellular plant and animal remains and can be used to reconstruct paleoclimatic conditions as well as changes in the environmental conditions (Lowe & Walker, 1997; Birks & Birks, 2000). Since the majority of plant macrofossils found in a sediment core are of local origin (autochthonous) they provide information on the depositional environment of the site through time as well as the trophic status and salinity of the lake/marine basin itself (Lowe & Walker, 1997). The changes in macrofossil assemblages throughout the sediments thus help to differentiate between lacustrine and marine environments and can therefore provide information on when a basin became isolated from the sea.

Samples for macrofossil analysis were taken every 5 cm along the cores with tighter sampling around lithological boundaries, especially around the isolation levels. Samples from Ta1 were taken according to the tilt of the sediments (Appendix A). The samples were then wet sieved using a 0.2 mm sieve. Identification of macrofossils was done using a low power stereomicroscope and also provided material for AMS radiocarbon dating.

3.4 Radiocarbon analysis

Radiocarbon analysis was used to provide ages for the isolation in both basins. Three samples of selected macrofossils and one bulk sample, where not enough macrofossils could be found, were picked out for AMS radiocarbon dating: one above the isolation level and one below from each core. The radiocarbon dating was carried out at the Radiocarbon Dating Laboratory in Lund. The dates were calibrated using the computer program OxCal v3.10 (Bronk Ramsey 2005), based on the terrestrial IntCal04 data set of Reimer et al. (2004). In one sample bones from the stickleback *Gasterosteus aculeatus* were used for dating. As the fish lived in a brackish environment the pure terrestrial calibration data set could not be used. The marine reservoir effect had to be taken into consideration and the terrestrial set was therefore combined with the marine Marine04 data set of Hughen et al. (2004). The data sets were mixed 50±10% so as to represent brackish conditions.

3.5 Loss On Ignition (LOI)

With the loss on ignition method the content of organic and carbonate matter in a sample is indicated by the weight loss following combustion in a furnace (Bengtsson & Enell, 1986; Heiri et al., 2001). The organic content is related to the productivity in the basin and the influx of organic matter from the surroundings. Therefore it can be used to establish the transition from a marine to a lacustrine environment, the main assumption being that more organic matter is buried in the sediments in a lake than in the sea.

Samples of 1-3 mg wet sediment were taken every 5 cm along the cores, with tighter sampling around lithological boundaries (one sample taken just above the boundary and one below). During sampling of the tilted sediments of Ta1 (Appendix A), the samples were taken according to the tilt. At the suspected isolation levels – from 1207.5 to 1209.5 cm in Ta1 and from 912 to 914 cm in Ta3 – samples were taken every 5 mm. The wet samples were dried over night at 105°C, weighed and then burned in a furnace at 550°C for 4 hours (Heiri et al., 2001). The burned samples were left to cool in a desiccator and weighed. In order

Table 1. Assessment of total uncertainty for the investigated sites.

Site	Measured elevation (m a.m.s.l.)	Measurement uncertainty (m)	Assessment of threshold uncertainty (m)	Tidal uncertainty (m)	Total uncertainty (m)
Ta1	25.8	0.1	0.1	0.5	0.5
Ta3	12.2	0.1	0.3	0.5	0.6

to establish the carbonate content the samples were then burned at 950°C for two hours, left to cool in a dessicator and weighed yet again (Heiri et al., 2001). During ignition at 550°C organic matter oxidates into carbon dioxide and ash, leaving a residue of minerogenic and carbonate matter. During the second ignition the carbonate minerals decay into calcium oxide and carbon dioxide and only minerogenic matter is left. The organic and carbonate content can be calculated using the equations given in Heiri et al. (2001) and Bengtsson & Enell (1986).

3.6 XRF core scanning

X-ray fluorescence spectrometry (XRF) scanning was carried out at the Core Processing Lab at the Department of Geology and Geochemistry at Stockholm University using an Itrax XRF Core Scanner. The scanner is a late development in non-destructive analytical instrumentation and is aimed at palaeoclimate research (Department of Geology and Geochemistry, SU, 2007). There is no need for prior sample preparation and by scanning the flat core surfaces the geochemical variations of heavy elements throughout the sediment sequences can be found.

The chemistry of the sediments depends on the nature of the material available, the depositional environment, and the changes the sediments undergo through time. Variations in different elements are therefore important, since the differences may reflect changes in depositional environment and/or climate. Generally, in near-coastal and estuarine environments oxic conditions prevail and minerogenic matter, oxide precipitation and heavier biological particles like shell fragments dominate the sediments. As a consequence Fe, Ti, K, Ca and most of the other measured elements exist in higher concentrations in marine environments than in freshwater environments. Copper, however, tends to bind with organic matter, and as the amount of organic matter deposited in freshwater environments is, in general, higher than in marine environments, there will generally be higher values of copper in the freshwater deposited sediments. Analysing the geochemical variability of a range of elements thus makes it easy to pinpoint the stratigraphic level of the isolation contact. (Sparrenbom et al., 2006d).

The data output is an "intensity value" (counts sec^{-1}) rather than a concentration and it is therefore important not to compare count rates, but to analyse the variability pattern (Department of Geology and Geochemistry, SU, 2007; Sparrenbom et al., 2006d).

The core from Ta3 was measured from 890 to 930 cm, positioning the expected isolation approximately in the middle, at scanning steps of 2 mm, every measurement step lasting 20 seconds. The entire core from Ta1 was measured at scanning steps of 2 mm and with every measurement step lasting 90 seconds.

The 26 elements measured were calcium (Ca), potassium (K), iron (Fe), manganese (Mn), silicon (Si), titanium (Ti), zinc (Zn), strontium (Sr), copper (Cu), aluminium (Al), rubidium (Rb), vanadium (V), chromium (Cr), zirconium (Zr), bromine (Br), sulphur (S), phosphorous (P), argon (Ar), nickel (Ni), tantalum (Ta), tungsten (W), lead (Pb), yttrium (Y), selenium (Se), arsenic (As) and chlorine (Cl) (although not all elements were present in both cores). Sparrenbom et al. (2006d) suggest the use of Se, Fe, Mn, Al, Si, K, Ca, Sr, Ti, Cu and Zr for an easy identification of the transitions between marine, lacustrine and brackish depositional environments. These elements, with the exception of Se and Al that are present in too low quantities, are the ones considered further in this investigation, with the addition of the Si/Ti ratio since it may be a proxy for biogenic silica (e.g. Moreno et al., 2007), i.e. amount of diatoms, in the sediment and thus also a proxy for aquatic productivity. All elements measured are, however, presented in Appendix B and C. Cu in Ta1 and Cu and Si in Ta3 display counts that are close to the detection limit, but the elements are still included in the analysis. Although the counts are too low for the small fluctuations in the plotted curves to be considered, the general trends (Cu increasing at the isolation and Si decreasing) are so obvious that they cannot be ignored.

Figure 3. Lake Ta1 seen from the west (Photo: Daniel Fredh)

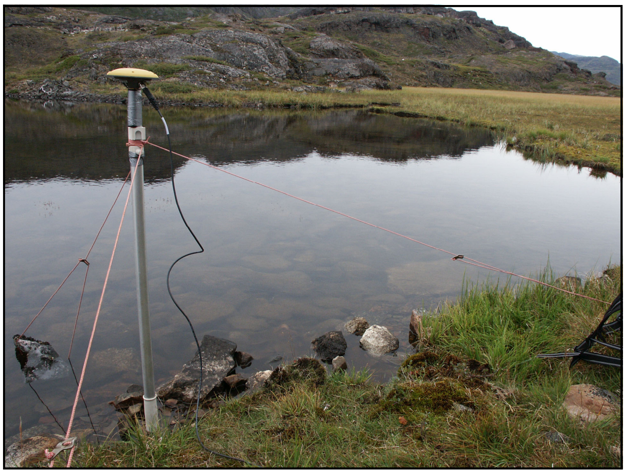

Figure 4. Threshold of lake Ta1 (photo: Charlotte J. Sparrenbom)

Table 2. Description of the lithology of the investigated sediments.

Lake	Ta1	
Unit	**Depth (cm)**	**Description**
5	1170-1207.5	Brown clayey algae gyttja.
4	1207.5-1209.5	Laminated light brown clayey algae gyttja/light grey silty clay. UB: S
3	1209.5-1256	Grayish green sandy silty clay with gravel. UB:VS
2	1256-1261	Pinkish gray silty clayey diamict with sand and gravel mixed with grayish green sandy silty clay with some gravel. UB:VG
1	1261-1270	Pinkish gray silty clayey diamict with sand and gravel. UB:VG
Lake	**Ta3**	
Unit	**Depth (cm)**	**Description**
7	870-880	Brown algae-rich gyttja
6	880-897	Dark brown algae-rich gyttja. UB:S
5	897-905	Light brown algae-rich clay gyttja. Faint lamination of dark brown gyttja. UB:G
4	905-912	Dark brown algae-rich clay gyttja. UB:G
3	912-914	Laminated brown clay gyttja/gray silty gyttja clay. Very dark brown clay gyttja at 912-912.5. UB:VS
2	914-931	Grayish green silty gyttja clay with some shell fragments. UB:S
1	931-970	Grayish green silty gyttja clay with some gravel. Faint lamination of darker gyttja clay. Shell fragments at 935 cm. UB:VG

UB – upper boundary, VS – very sharp, S – sharp, G – gradual, VG – very gradual.

4 Results

The two sites investigated are described below. Sediment depths in the descriptions refer to depth below water surface and the altitude of the thresholds is related to meters above highest astronomical tide (m a.h.a.t.). Coring positions and threshold altitudes are indicated in the heading of each site.

The lithology of the sediments is presented in Table 2, Fig. 6 and Fig. 11. The results from the XRF-scanning are presented in Fig. 6 and Fig. 11, and the results from the macrofossil analysis as well as the LOI in Fig. 5 and Fig. 10. The radiocarbon dates are presented in Table 3. All XRF-measured elements are presented in Appendix B and C, and larger macrofossil diagrams are presented in Appendix D.

4.1 Lake Ta1 (N 61°08.267', W 45°39.367'), +25.8 m

The lake is irregular in shape and measures *c.* 450 x 200m (Fig. 3). There is no obvious inlet to the lake, so inflow of material is mainly limited to surface run-off. Maximum water depth is 15.9 m and the depth at the coring site is 9.2 m. The threshold constitutes the outlet of the lake towards Bredefjord, situated 450 m to the west. It consists of boulders and pebbels at an altitude of 25.8±0.5 m a.h.a.t. (Fig. 4, Table 1)

The isolation contact at 1207.5 cm can be seen as a sharp transition from greyish green silty clay to brown clayey algae gyttja (Table 2). The transition zone is 2 cm wide and consists of laminations of silty clay and clayey algae gyttja.

Below the isolation marine organisms such as the blue mussel *Mytilus edulis*, marine flatworms of the order Tricladida, remains of the fan worm *Pectinaria* and marine brown algae dominate the macrofossil community (Fig. 5). These species disappear totally above the isolation and are replaced by freshwater taxa that probably migrated into the isolated lake by surface runoff or by transport of birds. The freshwater community consists of midge larvae (Chironomidae), different types of cladocerans, oospores of charophyte algae such as *Chara* sp., statoblasts of the freshwater bryozoan *Plumatella repens,* and other freshwater taxa. In the transition zone the ostracode *Sarcypridopsis aculeata* appears. According to Mezquita et al. (1999) this species is usually found in brackish waters. It has a wide salinity range and is a freshwater species that usually tolerates high mineral content and occasionally

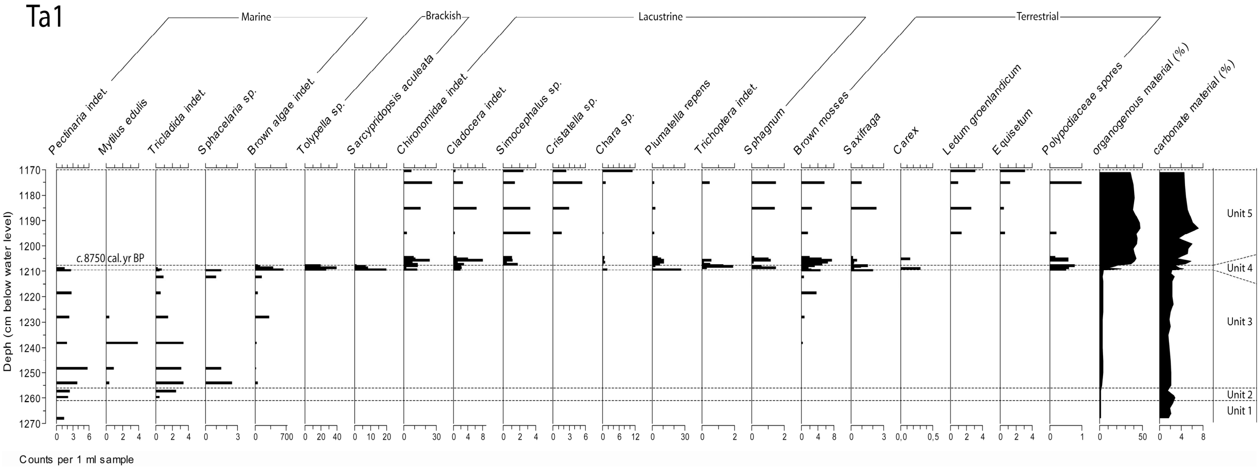

Figure 5. Macrofossil diagram showing the results from the macrofossil analyses as well as the LOI-results from site Ta1. Note the different scales for the different taxa (larger version presented in Appendix D).

appears in coastal lagoons (Mischke et al., 2006; Mezquita et al., 1999). Spores of the green algae *Tolypella* sp., or Stonewort, are also abundant in the transition zone. Stoneworts live in fresh or brackish water, which is low in nutrients (ARKive, 2007). The appearance of these taxa suggests that the basin first became semi-isolated, i.e. isolated during low tide resulting in a brackish environment favouring these species, before an entirely lacustrine environment was established. In Figure 5 it is also clear that the amount of organic carbon increases significantly above the isolation as a freshwater environment was established, and that the carbonate content is higher in the lacustrine than the marine environment.

Most XRF-scanned elements show a decrease at and after the isolation at 1207.5 cm (Fig. 6), except Cu which increases. However, Zr shows no distinct pattern. The Si/Ti ratio increases at the isolation suggesting an increase in biogenic silica above the isolation.

The age of the isolation is determined to *c.* 8750 cal. yr BP. This is based on the interpolation (Fig. 7) between one bulk sample taken immediately above the isolation (8300-8550 cal. yr BP; Table 3) and one macrofossil sample of *Gasterosteus aculeatus*, fish bones from the stickleback, taken in the transition zone below the isolation contact (8845-9290 cal yr. BP; Table 3). This lowermost sample was calibrated for marine reservoir effect using a mix of the terrestrial IntCal04 data set (Reimer et al., 2004) and the marine Marine04 data set (Hughen et al., 2004). The 2σ error bars have been conservately set to ±200 cal. yr BP.

4.2 Lake Ta3 (N 61°08,133', W 45°39,800'), +12.2 m

This elongated lake measures *c.* 200 x 50m and has no inlets (Fig. 8). The threshold is situated at an altitude of 12.2±0.6 m a.h.a.t. (Table 1), consists of boulders and pebbles and constitutes the outlet of the lake towards Bredefjord, located *c.* 100 m to the west (Fig. 9). The lake is shallow with a maximum depth equal to the coring depth of 1.2 m.

The sediments around the isolation level consist of dark brown algae-rich clay gyttja and greyish green silty gyttja clay. The isolation level is placed at the onset of the algae-rich gyttja at 912 cm, just above a transition zone with laminated clay gyttja/gyttja clay which ends with a layer of very dark clay gyttja (Table 2). At this level marine species of brown algae, *Mytilus edulis*, Foraminifera, and Pectinaria disappear, while lacustrine fossils such as Chironomidae, cladocerans like *Daphnia* sp. and *Simocephalus* sp., *Plumatella repens*, the charophyte algae *Chara* sp. and *Nitella* sp., and statoblasts of

Table 3. AMS radiocarbon and calibrated dates.

Site	Lab. no.	Depth (cm)	Age, ^{14}C yr BP	Calibrated age yr BP 2σ (95,4%)	Comments	Material
Ta1	LuS7498	1206-1206.5	7590±60	8300-8550 (93.6%) 8210-8240 (1.8%)	Above isolation	Clayey algae gyttja
Ta1	LuS7499	1208-1209.5	8355±65	8845-9290 (91.6%) 8780-8835 (3.4%)	Below isolation	*Gasterosteus aculeatus*
Ta3	LuS7500	910-912	8105±60	8860-9270 (89.8%) 8770-8840 (5.6%)	Above isolation	Brown mosses, *Saxifraga, Draba, Polypodiaceae*, bark
Ta3	LuS7501	912-914	7860±60	8540-8980 (95.4%)	Below isolation	Brown mosses, *Saxifraga, Draba, Menyanthes, Empetrum, Polypodiaceae*

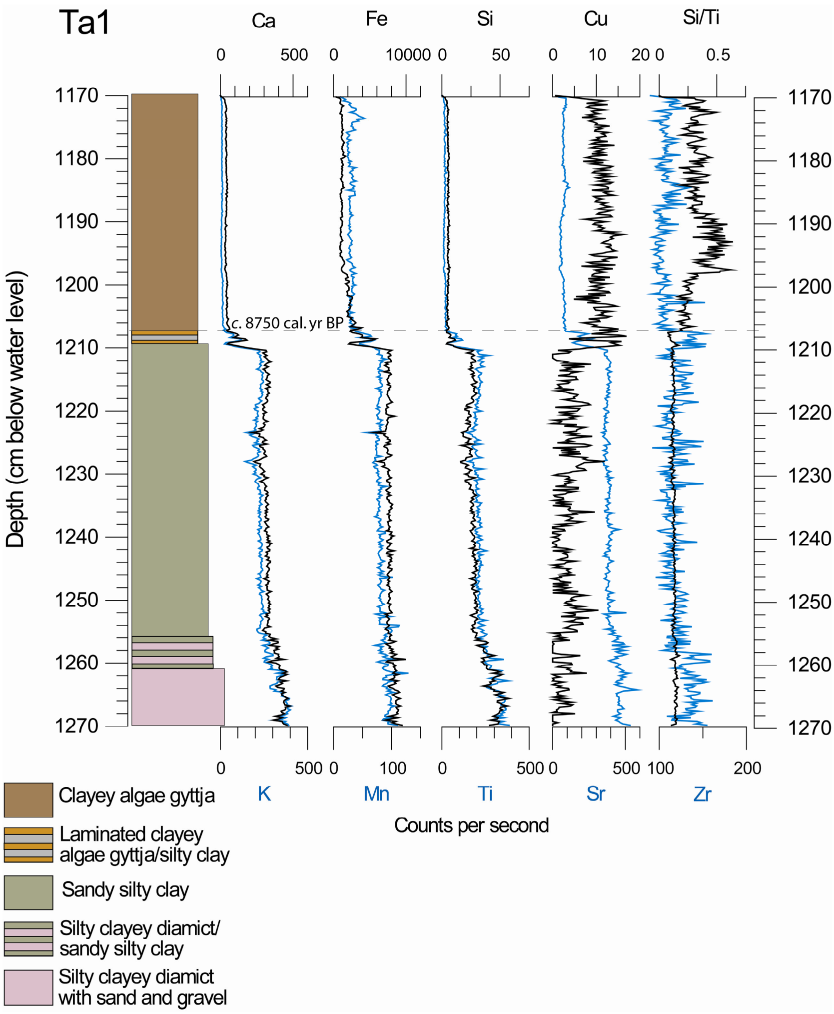

Figure 6. Simplified core log and XRF-scanned elements for site Ta1. Note the different scales for the different elements.

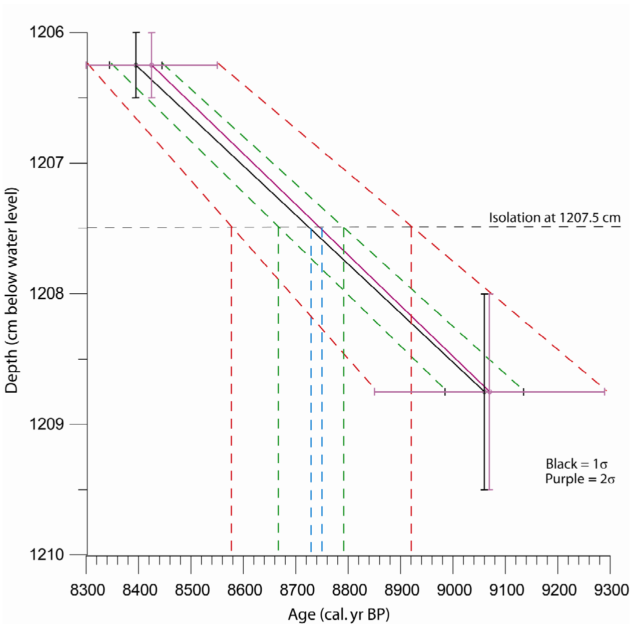

Figure 7. Interpolation between radiocarbon samples LuS7498 and LuS7499 (Table 3). Blue lines represent the centre of the dates, green lines the extremes for 1σ and red lines the extremes for 2σ. If a stable sedimentation rate is assumed this gives the age span of *c.* 8750±200 for the isolation level.

Figure 8. Lake Ta3 seen from the west towards Bredefjord in the distance (Photo: author).

Figure 9. Threshold of Lake Ta3 (Photo: Charlotte J. Sparrenbom).

the freshwater bryozoan *Christatella* sp. become abundant (Fig. 10). The brackish species *Sarcypridopsis aculeata* and *Tolypella* sp. are found above the isolation contact, in the algae-rich clay gyttja, and not only in the transition zone as in Ta1. As in Ta1 the presence of these species suggests that the basin experienced a brackish phase before limnic conditions completely took over. *Sarcypridopsis aculeata* and *Tolypella* sp. would have established themselves in the basin during the brackish phase due to their ability to survive during such conditions, but as freshwater species became more abundant they gradually disappeared. *Tolypella* in particular is a pronounced pinoeer species and does not compete well with other plants (Blindow, 1998).

The amount of organic carbon starts to increase just before 912 cm and continues to build up through the sediment column (Fig. 10); no great changes can however be detected in the carbonate content of the sediments.

Most of the elements investigated by XRF-scanning show marked changes at the isolation level (Fig. 11). Ca, K, Fe, Mn, Si, Ti and Sr all show a decrease, while Cu increases. As in Ta1 Zr shows no distinct pattern. The Si/Ti ratio increases at the isolation.

The age of the isolation is determined to *c.* 8500 cal. yr BP based on a macrofossil sample of brown mosses, pieces of Saxifraga leaves, seeds from *Draba* sp., *Menyanthes* sp. and *Empetrum* sp. and some spores from *Polypodiaceae* taken in the transition zone immediately below the isolation contact (8540-8980 cal. yr BP; Table 3). One sample (LuS7500) of mosses, Saxifraga leaves, spores, bark and *Draba* seeds was also dated immediately above the isolation. This, however, gave an age older than the sample below, probably due to reworking of the sediments in the lake, and is not considered further (Table 3). The 2σ error bars have been set to ±200 cal. yr BP.

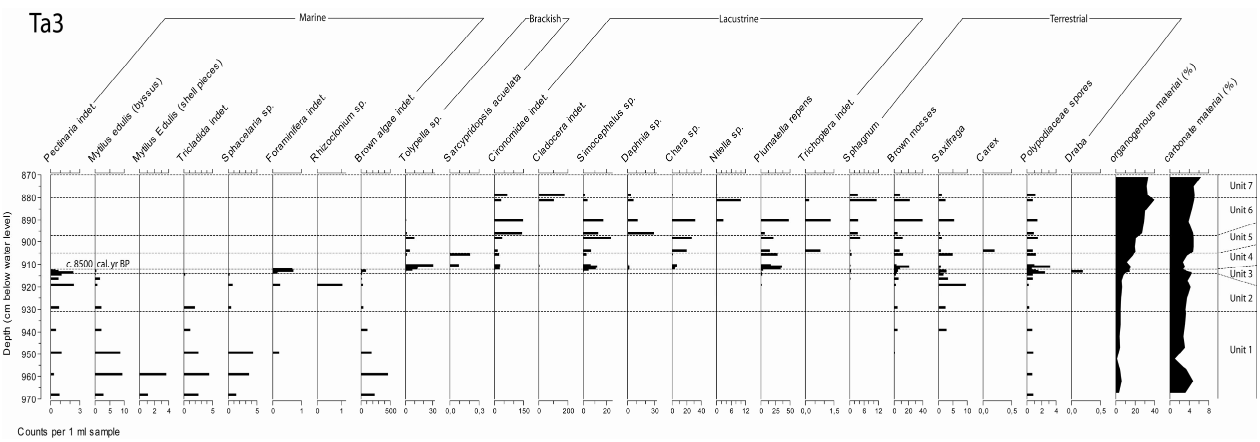

Figure 10. Macrofossil diagram showing the results from the macrofossil analyses as well as the LOI-results from site Ta3. Note the different scales for the different taxa (lager version presented in Appendix D).

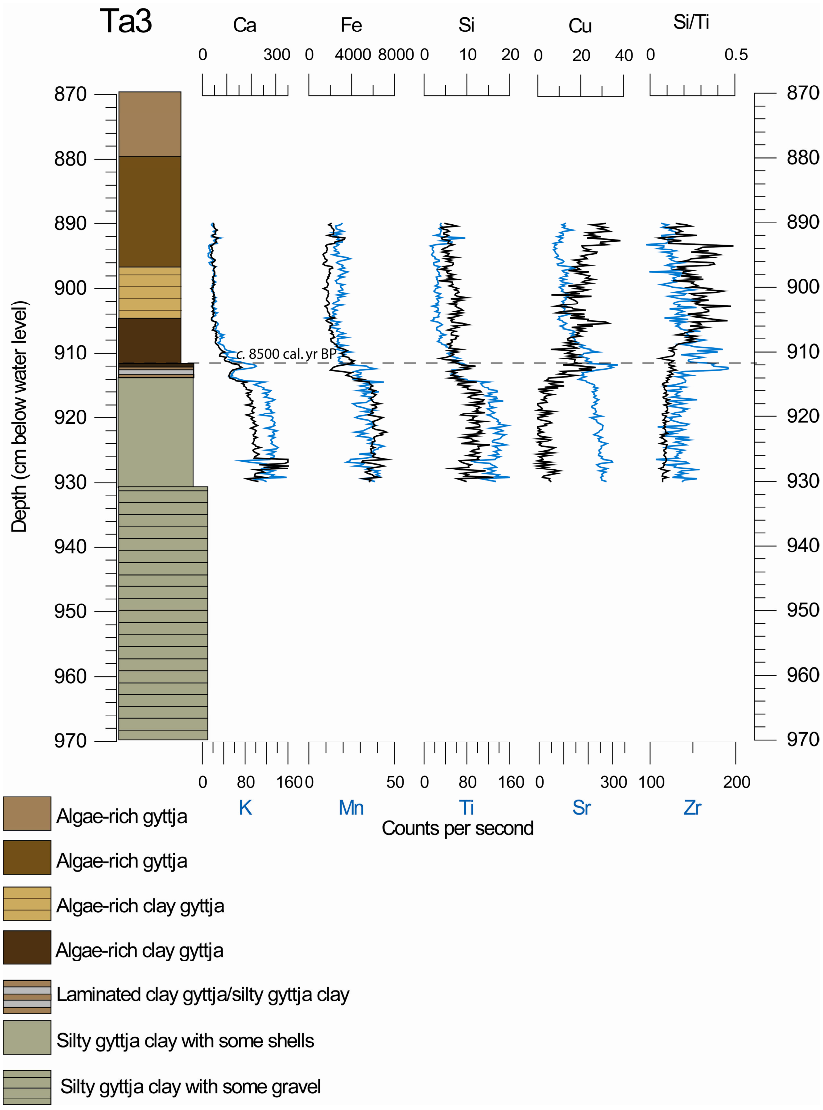

Figure 11. Simplified core log and XRF-scanned elements for site Ta3. Note the different scales for the different elements. Note also that the Ca-value at 926 cm has been cut of at 350 counts (true count is 1972) to allow the variability to be seen throughout the sequence. The high Ca-value can probably be explained by the scanner running across a shell piece at the surface of the core.

5 Discussion

5.1 Basin isolation – from a marine to a lacustrine environment

The two isolation sequences analysed in this investigation both show abrupt lithological changes at the isolation levels, just as the previously investigated basins in the Nanortalik and Qaqortoq areas (Sparrenbom et al., 2006 a and b). The sediments change from minerogenic sediments deposited in a marine environment, to laminated minerogenic/gyttja sediments representing a brackish phase, to freshwater deposited brown (clayey) algae gyttjas. The macrofossil analyses of the cores show that the minerogenic sediments are dominated by marine brown algae. The blue mussel *Mytilus edulis*, flatworms of the order Tricladida and remains of the fanworm *Pectinaria* are also common in these marine sediments. In the transition zone the ostracode *Sarcypridopsis aculeata* and spores from the green algae *Tolypella* sp. appear. These species are probably favoured by the brackish conditions prevailing in the basin as the marine influence diminishes and it slowly changes into a freshwater environment. At the isolation level the presence of marine organisms ends abruptly and they are replaced by freshwater taxa that probably migrate into the isolated lakes by surface runoff or by bird transport. The most common lacustrine organisms are midge larvae (Chironomidae), cladocerans, statoblasts of *Plumatella repens* and oospores of the green algae *Chara* sp. and *Nitella* sp.

The amount of organic carbon increases as a freshwater environment is established and XRF-scanning shows that the chemistry of most of the investigated elements undergoes distinct changes at the isolation: Fe, Mn, K, Ca and most of the other measured elements exist in higher concentrations in the marine

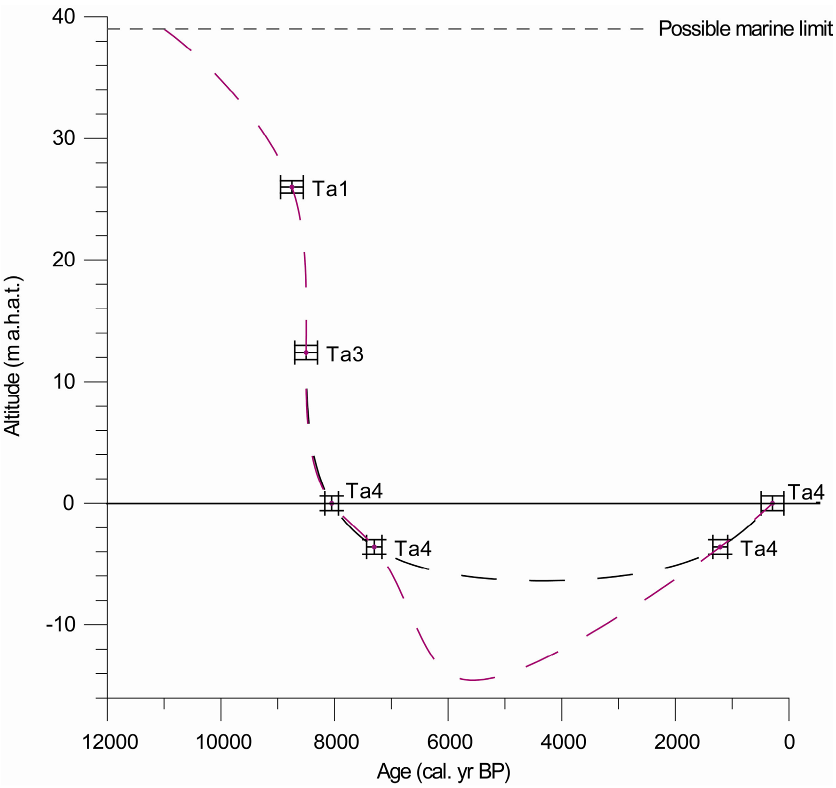

Figure 12. Relative sea-level change in the Tasiusaq area during the Late glacial and Holocene as indicated by the isolation ages of the two sites described in this thesis as well the isolation and transgression ages of the marine embayment described by Fredh (2008). Altitude errors are listed in Table 1 and age error bars of 2σ are shown. The black dashed line represents a smoothed curve fit supposing the transgression started at *c.* 4000 cal. yr BP, and the red dashed line represents a curve fit supposing the transgression started at *c.* 6000 cal. yr BP.

sediments than above the isolation level due to minerogenic matter, oxide precipitation and heavier biological particles like shell fragments dominating marine sediments. Copper, on the other hand, tends to bind with organic matter and its levels increase above the isolation level (Sparrenbom et al., 2006d).

5.2 Relative sea level changes in the Tasiusaq area

The isolation and transgression ages shown in Fig. 12 summarize the sea-level change at the two sites described in this thesis as well as the one described by Fredh (2008). Since these three study sites are situated close to each other (Fig. 1) they will have experienced little differential isostatic rebound, and can be used for a common shore displacement curve. Eleven other basins were also cored during the fieldwork and they are currently being examined. Preliminary results from these basins show that the lowermost basin cored, Nu2 at -4.4 m a.h.a.t. (Fig.1; Nu being short for Nunataq), was isolated. This shows that local sea level must have been lower than -4.4 m a.h.a.t. at some point in time, but an absolute lower limit of the post-glacial sea level in the area cannot be established. The highest lake cored with an isolation is lake Ta2 at a level of *c.* 32 m a.h.a.t. (Fig. 1). Two lakes at *c.* 42 m a.h.a.t. (Ka1; Fig.1) and *c.* 54 m a.h.a.t. (Ka2; Fig.1) do not appear to have been isolated and we can conclude that the marine limit in the area is somewhere between *c.* 32 and 42 m a.h.a.t. A possible marine limit observed on a terrace east of lake Ta3 as well as the top of a series of beach ridges close to lake Ta1 were measured to *c.* 41 m a.h.a.t. However, the terrace and beach ridges probably represent storm events and in order to be able to compare the actual marine limit to the isolation levels, the altitude measured needs to be lowered a couple of meters. The marine limit of the area is thus set to *c.* 39 m a.h.a.t. and is presented in Fig. 12 as the maximum sea level altitude.

In order to plot and make predictions about the uppermost part of the shore displacement curve from the Tasiusaq area, the timing of the deglaciation has to be established. According to the data in the best-fitted model analysis of Sparrenbom et al. (2006c) the ice was situated at the present coast at *c.* 13,000 cal. yr BP and reached the present ice margin at *c.* 10,500 cal. yr BP (Table 4). The distance from Tasiusaq to the present ice margin is *c.* 20 km and the distance from the coast to the ice margin is approximately 70 km. This suggests that the ice retreated at a speed of 30 m/yr. It would thus take the ice *c.* 650 years to retreat from Tasiusaq to the present ice margin, which sets the deglaciation age of the Tasiusaq area to *c.* 11,100 cal. yr BP. A marine limit at 39 m a.h.a.t at 11,000 cal. yr BP is thus used in the shore displacement diagram (Fig. 12) in order to make an estimated plot of the shore displacement before 8750 cal. yr BP. This seems to fit well with the rest of the data if compared to the shore displacement data from the Nanortalik and Qaqortoq areas (Fig. 13).

The shore displacement data presented in Fig. 12 show a rapid regression between *c.* 9000 and 8000 cal. yr BP. This implies a quick deglaciation in the early

Table 4. Data for ice retreat scenario Lu (Sparrenbom et al., 2006c) showing when the ice margin reached different positions.

Shelfedge (-400 m)	Between shelf edge and outer islands	Outer islands	Between outer islands and present coast	Present coast
26,500-22,000	19,000	17,000	15,000	13,000
Between present coast and present ice margin	**At present ice margin**	**Minimum 1**	**Minimum 2**	
12,000	10,500 and back 5500	9500 and back 6500	9000	

Holocene. At *c.* 8100 cal. yr BP sea level reached present day level and continued to fall below -4.4 m a.h.a.t. The regression minimum was reached between 7000 and 2000 cal. yr BP with the most likely age at around 6000 to 4000 cal. yr BP. The transgression started some time before 1200 cal. yr BP and sea level reached present day level in the area some time after 1000 cal. yr BP.

5.2.1 Regression

The rapid regression in the Tasiusaq area is consistent with the data from the Nanortalik and Qaqortoq areas that also experienced rapid sea-level fall in the Late glacial and early Holocene (Sparrenbom et al., 2006 a and b), implying a rapid recession of the ice sheet. The regression rate between *c.* 9000 cal. yr BP and *c.* 8000 cal. yr BP is approximately 2.5 m/100 years which gives an absolute value of land uplift of *c.* 3.3 m/100 years if sea level rise is taken into account (Lambeck & Chappell, 2001). This is approximately the same uplift rate as experienced in the Qaqortoq area (Sparrenbom et al., 2006b) suggesting that the ice receded at roughly the same speed in both areas. Compared with the results from Nanortalik and Qaqortoq (Sparrenbom et al., 2006 a and b) the ice retreat occurred later in the Tasiusaq area (Fig. 13) due to its more inland position. The best fitted ice retreat scenario of Sparrenbom et al. (2006c) suggests that the ice sheet started receding at *c.* 22,000 cal. yr BP and that the ice-margin recession proceeded quickly: by *c.* 12,000 cal. yr BP the ice margin was inland of the present day coast and by *c.* 10,500 cal. yr BP it had reached the area of the present ice margin (Table 4). In Fig. 14 the predicted sea level change from the best-fitted ice model scenario of Sparrenbom et al. (2006c)

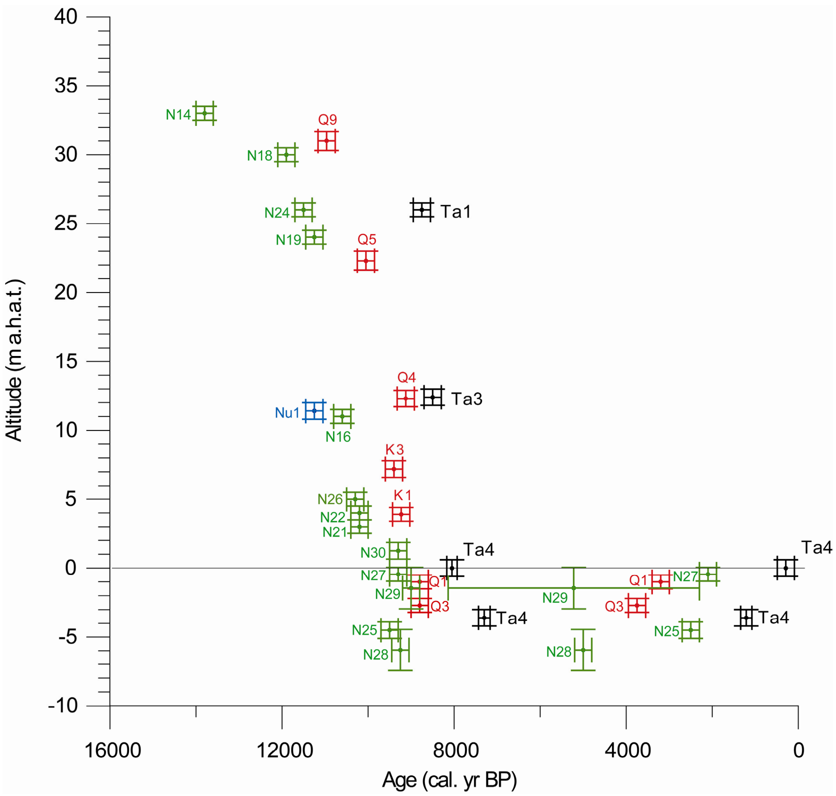

Figure 13. Relative sea-level change in the Tasiusaq (black), Qaqortoq (red), Nanortalik (green) and Nunataq (blue) areas during the Late glacial and Holocene as indicated by the isolation and transgression ages of the sites described in this thesis and by Fredh (2008), Sparrenbom et al. (2006 a and b) and Bennike et al. (2002).

is plotted together with our reconstructions of relative sea level from the Tasiusaq area. The observed sea level data fit rather well with the predictions and our data do not oppose the theory presented by Sparrenbom et al. (2006c). The regression seems to have occurred slightly later in the Tasiusaq area and proceeded slightly faster than the model would suggest. It is possible that a scenario with a slightly later regression, setting the deglaciation of the Tasiusaq area to 11,000 cal. yr BP, might produce a better fitting model. By up- or downscaling the ice thickness of the starting model (by changing the so called β-factor) a better fit might also be achieved. A β-factor of 1.05 (increasing the ice thickness by 5%) gives the best fit for the Qaqortoq area and a factor of 1.1 for the Nanortalik area (Sparrenbom et al., 2006c). This might also be true for Tasiusaq and is something that should be modelled.

Synchronous shorelines, situated perpendicular to the isobases, have been constructed for the Nanortalik-Qaqortoq-Tasiusaq area (Fig. 15). They are based on the shore displacement diagram of Fig. 12 and the data from Fig. 13 and drawn for every 1000 years from 11,000 cal. yr BP to 1000 cal. yr BP. The shoreline for 11,000 cal. yr BP also includes data from lake Nu1 as a comparison. In order to include data from the Nanortalik area, which is situated further south than the Qaqortoq and Tasiusaq areas (Fig. 1) it has been projected along the isobases according to Fig. 15a. This projection assumes isobases that are parallel to each other and to the coast. This is however not necessarily true since the isobases are dependent on the shape of the ice, and this is one of the things being modelled by e.g. Sparrenbom et al. (2006c). The shoreline diagrams are however included in the thesis for the sake of argument, but should be regarded with some caution, at least between Nanortalik and Qaqortoq.

Fig. 15b shows that the rate of uplift was greatest at the beginning of the deglaciation and slowed down as the ice retreated further from the area. After *c.* 8000 cal. yr BP, when the ice had reached its minimum position *c.* 30 km inland of the present ice margin (Sparrenbom et al., 2006c), the uplift slowed down significantly, and between *c.* 9000 and *c.* 7000 cal. yr BP the shorelines remained rather stable.

The shorelines tilt in a south-westerly direction towards the shelf edge in the early- to mid-Holocene indicating greater uplift towards the ice. This is what would be expected from a completely deglaciated area (e.g. Björck & Digerfeldt, 1991). Sparrenbom (2006) argues that since there is still an ice present in Greenland loading the Earth, the greatest land uplift would be expected to be found some distance from the present ice margin and the shorelines would be 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 with an outer part tilting outwards and an inner part tilting towards the inland. The data of Sparrenbom (2006) indicate this, showing shorelines tilting in a north-easterly direction as opposed to our shorelines tilting to the southwest. Sparrenbom (2006) however used the data from lake Nu1 (Fig.1; Fig. 13; Sparrenbom et al., 2006b) in order to create the shoreline

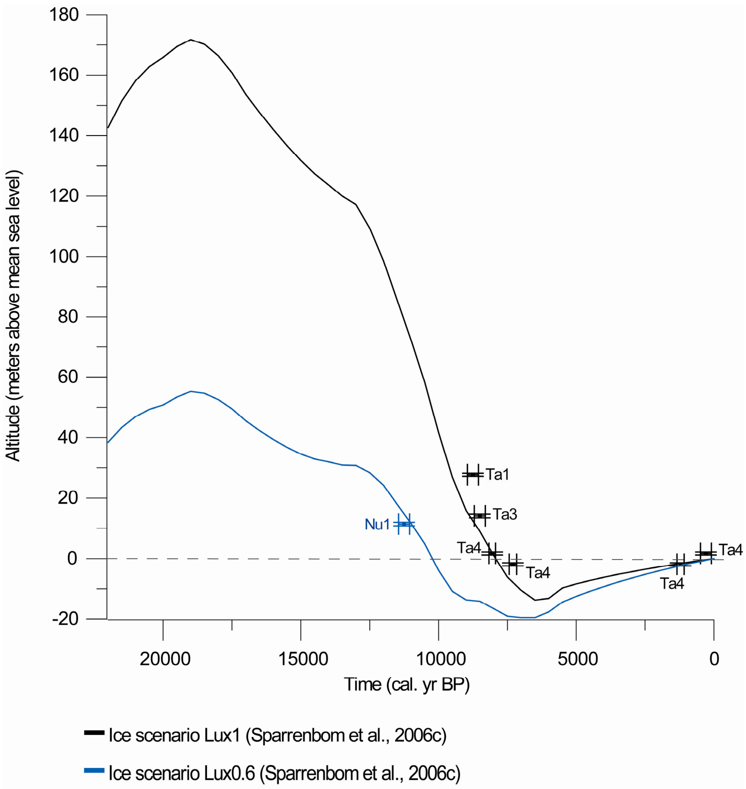

Figure 14. Reconstructions of relative sea-level changes from sites Ta1, Ta3 and Ta4 together with predicted sea-level changes from ice melting scenario Lu (Sparrenbom et al., 2006c), and observations from site Nu1 (Sparrenbom et al., 2006b) with ice melting scenario Lux0.6 (Sparrenbom et al., 2006c).

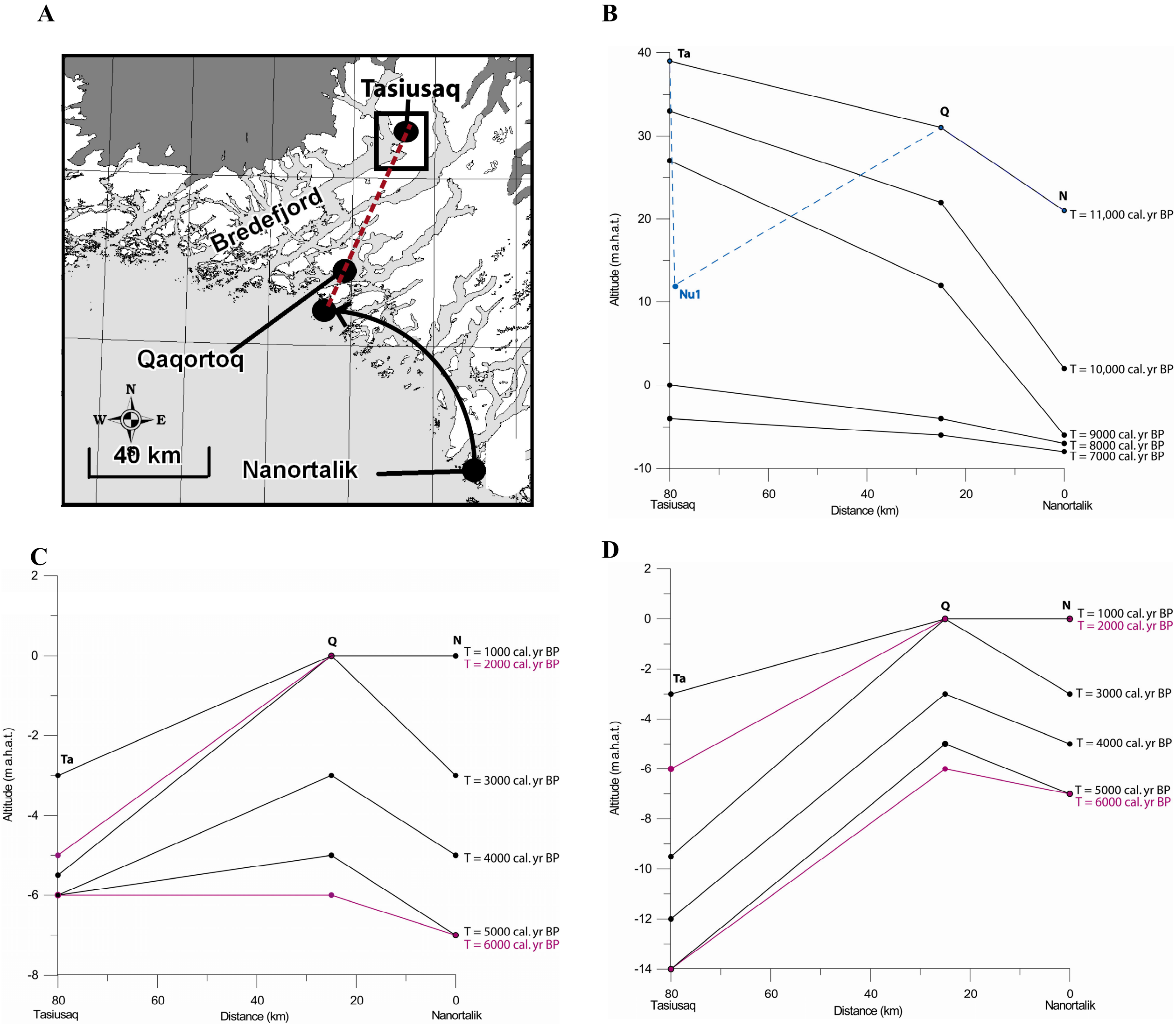

Figure 15. (A) Map of Nanortalik-Qaqortoq-Tasiusaq area showing the gradient profile from (B), (C) and (D). The Nanortalik area has been projected along the isobases according to the map in order to be able to use the data from the area. **(B)** Shoreline gradients between the Nanortalik and Tasiusaq area from 11,000 to 7000 cal. yr BP based on the data from Fig. 12 and Fig. 13. **(C)** Shoreline gradients between the Nanortalik and Tasiusaq area from 6000 to 1000 cal. yr BP based on the data from Fig. 12 and Fig. 13 supposing a transgression in the Tasiusaq area starting at *c.* 4000 cal. yr BP. **(D)** Shoreline gradients between the Nanortalik and Tasiusaq area from 6000 to 1000 cal. yr BP based on the data from Fig. 12 and Fig. 13 supposing a transgression in the Tasiusaq area starting at *c.* 6000 cal. yr BP. Note the different altitudes for the different diagrams.

diagrams and our Fig. 15b shows that if this data is included in the shoreline diagram for 11,000 cal. yr BP the tilt becomes very odd indeed; it suggests that the Nunataq area somehow experienced much less uplift than the areas further towards the coast as well as the Tasiusaq area one kilometre to the northwest. This seems highly unlikely and suggests that the isolation data from lake Nu1 must have some other explanation than the one presented in Sparrenbom (2006). This can also be seen in Fig. 13 where the data from Nu1 suggest that the area experienced an earlier isolation than all the other three areas. Either the dates are too old, explained by for example recycling of organic material, or uptake of old carbon in the dated macrofossils; or it is possible that the threshold estimate is incorrect. It is for example possible that the small fjord that the lake is draining into today (Fig. 1) was blocked and dammed by ice during early Holocene. This would lead to Nu1 draining into the fjord towards Tasiusaq instead and the threshold in that direction is situated at an elevation of 30-40 m a.h.a.t. More detailed investigations would, however, be needed in order to know this for sure. Our south-westerly tilting shorelines based on the more reliable Tasiusaq data seem more probable. The effect of the remaining ice sheet is seen in our diagrams as a smaller shoreline tilt between Qaqortoq and Tasiusaq than between Nanortalik and Qaqortoq (Fig. 15b). The shorelines between Nanortalik and Qaqortoq tilt 0.5 m/km at 11,000 cal. yr BP, 0.8 m/km at 10,000 cal. yr BP and 0.7 m/km at 9000 cal. yr BP. These gradients are comparable in magnitude to those found in completely deglaciated areas (e.g. Björck & Digerfeldt, 1991). If the area had been completely deglaciated the Tasiusaq area would probably have kept experiencing an uplift and the shorelines would have shown a greater tilt from Tasiusaq than they do now when the present ice sheet loading the Earth halts the uplift of the area.

5.2.2 Sea level below the present-day level

In the Tasiusaq area sea level reached the present day elevation at *c.* 8050 cal. yr BP and stayed below more or less until the present day. This can be explained by the fact that the ice continued to retreat behind the present day margin; according to Sparrenbom et al. (2006c) it reached a minimum of 30 km inland of the present-day margin from around 9000 cal. yr BP and then stayed behind until it reached the present-day margin again around 5500 cal. yr BP (Table 4). According to Andresen & Björck (2005) Holocene climatic optimum conditions peaked between 8000 and 6500 cal. yr BP with warm and humid conditions and this would explain the behaviour of the ice sheet. Sea level in the Tasiusaq area reached below -4.4 m a.h.a.t. some time after *c.* 8000 cal. yr BP, but an absolute lower limit of the post-glacial sea level is impossible to establish without more data from the region.

Two different shore displacement curves have been created for the Tasiusaq area (Fig. 12): one for a transgression starting at *c.* 4000 cal. yr BP which suggests a lowermost sea level of *c.* -6 m a.h.a.t, and one for a transgression onset at *c.* 6000 cal. yr BP as suggested by Sparrenbom et al. (2006c). This second curve is based on the best fitted model scenario of Sparrenbom et al. (2006c) and suggests that relative sea level reached *c.* -14 m a.h.a.t. at its lowest. If compared to the data from Nanortalik and Qaqortoq (Fig. 13) this seems to be a very low altitude and if the suggestion of Sparrenbom et al. (2006b) that the differences in relative sea level altitude could reflect differences in ice thickness, i.e. differences in ice load changes, is correct this would suggest a rather massive ice load in the Tasiusaq area compared to the Nanortalik and Qaqortoq areas. The low altitude of the lowermost sea level in the Tasiusaq area could, however, be explained by the fact that Tasiusaq, being situated further inland than Qaqortoq and Nanortalik, was affected by the remaining ice sheet that pressed down the Earth. Exactly how much this could influence the lowermost sea level in the Tasiusaq area is difficult to say, but creating new models with different β-factors (modelling a different ice cover) and comparing them to the data from Tasiusaq could shed some light on this.

5.2.3 Transgression

The transgression in the Tasiusaq area starts some time before 1200 cal. yr BP (Fredh, 2008). Sparrenbom et al. (2006c) suggest that the neo-glacial re-advance of the ice sheet started some time before 6500 cal. yr BP and their best fitted model sets the onset of the transgression to *c.* 6000 cal. yr BP (Fig. 14). The transgression, however, seems to have taken place later in the Tasiusaq area than in the Nanortalik and Qaqortoq areas (Fig. 13). Sparrenbom et al. (2006b) argue that the transgression seems to have reached present-day sea levels earlier in the Qaqortoq than the Nanortalik area and, since the Qaqortoq area is situated closer to the ice mass centre, that this may imply that the transgression was caused by a Holocene thickening of the Greenland Ice Sheet. This should, however, result in an even earlier transgression in the Tasiusaq area, due to its position closest to the expanding ice sheet. According to our data this is, however, not the case (Fig. 13). As stated earlier, two possible shoreline scenarios have been created: one with the transgression starting at *c.* 4000 cal. yr BP and one with it starting at *c.* 6000 cal. yr BP (Fig. 12). The shoreline diagrams based on the two shore displacement scenarios from the Tasiusaq area (Fig. 12) and the data from the Nanortalik and Qaqortoq areas show the same thing (Fig. 15 c and d); they both show the same pattern but with a much greater uplift in the Tasiusaq area in the event of a transgression starting at *c.* 6000 cal. yr BP. The 4000 cal. yr BP-shoreline diagram (Fig. 15c) shows, as does the shore displacement data (Fig. 13), that the Nanortalik and Qaqortoq areas experienced a transgression starting around 6000 cal. yr BP while the relative sea level in the Tasiusaq area remained at *c.* -6 m a.h.a.t. The transgression started earlier in the Qaqortoq than the Nanortalik area and between *c.* 4000 and *c.* 3000 cal. yr BP the Tasiusaq area started to experience a transgression of its own. Present day sea levels were reached later in this area than in Nanortalik and Qaqortoq. The 6000 cal. yr BP-shoreline diagram (Fig. 15d) shows a transgression starting in all three areas at around 6000 cal. yr BP. The transgression still started earlier in the Qaqortoq area and Nanortalik and Qaqortoq both reached present day sea levels earlier than Tasiusaq. If the transgression took place solely due to the GIS expanding it would be expected to start first in the area closest to the ice, i.e. Tasiusaq, and also to reach present day sea levels first in this area.

The late Tasiusaq transgression, or maybe rather the early Nanortalik and Qaqortoq transgressions, might instead reflect the influence of the Laurentide peripheral bulge; Nanortalik and Qaqortoq experiencing a transgression around 6000 cal. yr BP due to the collapsing peripheral bulge. According to e.g. Andresen & Björck (2005), Weidick et al. (2004) and Kaplan et al. (2002) the mid-Holocene climate deterioration with dryer and cooler conditions set in around 5000 cal. yr BP, followed by a further marked setback around 3500 cal. yr BP. It is possible that this was the time when the ice sheet started advancing rather than around 6500 cal. yr BP as suggested by Sparrenbom et al. (2006c), and that this process is the one primarily causing the transgression recorded in our basins from the Tasiusaq area; a transgression starting around 4000 cal. yr BP in the area (Fig. 12) and reaching present day sea level sometime after 1000 cal. yr BP matches these climate data very well. It also concurs with data from Weidick et al. (2004) who present the relative sea-level history of the Narsaq area: our data from Tasiusaq fit well on their curve with a transgression starting at *c.* 4500 cal. yr BP. The recession seems to be faster and start later according to our data, but this can be explained by Tasiusaq's more inland position (i.e. a more near-ice position) relative to Narsaq (Fig. 1). A model scenario where the neo-glacial re-advance was set to *c.* 5000 cal. yr BP instead of 6500 cal. yr BP (Table 4) could shed new light on this.

Another theory that might possibly explain the late transgression in the Tasiusaq area, keeping to the assumption that the ice started re-advancing around 6500 cal. yr BP, is that the ice advance took place further south. The end of the warm and humid Holocene climate optimum (e.g. Andresen & Björck, 2005) might have led the East Greenland Current and the Irminger Current to bring precipitation to the southern part making the ice sheet grow more here than further north around Tasiusaq. This would have led Nanortalik and Qaqortoq to experience an earlier transgression. However, it would also imply that Nanortalik was pressed down first due to its position closest to the ice and this does not seem to be the case (Fig. 13, Fig. 15d).

There are, as we can see, many factors in play and the advance of the GIS as well as the collapse of the Laurentide peripheral bulge are only two among many factors controlling the relative sea level changes in the Julianehåb district. In order to sort out how the transgression in the Tasiusaq area actually developed and better pinpoint a starting time, more data is needed from the area. Hopefully the two remaining marine basins (Ta5 and Nu2; Fig. 1) can provide us with that in a near future. It is very difficult to make any predictions as to exactly what factors are the driving ones and a new round of modelling analyses should be performed to account for these new findings. With our new sea-level data, the models and ice history scenarios of Sparrenbom et al. (2006c) can be refined in both space and time.

5.2.4 Bredefjord

Based on a very early isolation (*c.* 11,250 cal. yr BP) from lake Nu1 (Fig. 1), Sparrenbom et al. (2006b and c) suggest that the Late-glacial ice sheet in the Bredefjord area was thin and that Bredefjord acted as a calving bay/fjord with a floating glacier disintegrating rapidly during the Late-glacial and earliest Holocene. This theory is partly based on the modelling results of Sparrenbom et al. (2006c): in order to get a more reasonable match between the data from Nu1 and the model, a β-factor of 0.6 (indicating an ice sheet of 60% of the original value) was used for the area (Fig. 14). The theory of an early ice-retreat in the inner Bredefjord area is, however, not supported by our new data from Tasiusaq. On the contrary, our data imply that Bredefjord did not have any special role in the deglaciation of the area and fits the data from Nanortalik and Qaqortoq suggesting that the ice retreated quickly, starting at the shelf edge around 22,000 cal. yr BP, proceeding eastwards and reaching the present day margin around 10,500 cal. yr BP (Sparrenbom et al., 2006b). Our data may imply a slightly faster regression in the Tasiusaq/inner Bredefjord area than further out at the coast, but no other great differences can be found. However, this does not contradict the idea of e.g. Weidick (1988) and Sparrenbom (2006) that Bredefjord has acted as a major drainage path for the southern part of the GIS earlier during the glaciation, but there are no signs supporting an extraordinary ice retreat in our area during the Late-glacial or early Holocene and as previously stated there must be some other explanation for the data from lake Nu1 than the one presented by Sparrenbom (2006).

6 Conclusions

- The relative sea-level fall in the early Holocene was rapid at the time when the Tasiusaq area became ice-free and the regression lasted from *c.* 9000 to *c.* 8000 cal. yr BP.
- The fast regression confirms the best reconstruction of ice sheet history by Sparrenbom et al. (2006c) that shows that the ice sheet started receding at *c.* 22,000 cal. yr BP and that the ice-margin recession proceeded quickly: by *c.* 12,000 cal. yr BP the ice margin was inland of the present day coast and by *c.* 10,500 cal. yr BP it had reached the present margin.
- The shorelines from 11,000 cal. yr BP until *c.* 8000 cal. yr BP slope towards the coast in the southwest showing that the uplift was greater in the inland than at the coast. The smaller shoreline tilt between Tasiusaq and Qaqortoq than Qaqortoq and Nanortalik suggests that the present ice sheet loading the Earth halted the uplift of the Tasiusaq area.
- Between *c.* 8000 cal. yr BP and the present day the sea level has been lower than at present in the Tasiusaq area.
- Sea level in the area reached its lowest level some time between 7000 and 2000 cal. yr BP.
- The transgression in the Tasiusaq area probably started around 4000 cal. yr BP when the mid-Holocene climate deterioration had set in and the GIS started its re-advance. The sea-level reached present-day levels some time after 1000 cal. yr BP.
- It is possible that the early transgressions in the Nanortalik and Qaqortoq areas reflect the collapse of the Laurentide peripheral bulge more than the re-advance of the GIS. More modelling is, however, needed to be able to know this for sure.

7 Further research

In order to improve the ice model of Sparrenbom et al. (2006c) more data is needed from the area. Hopefully the remaining 11 basins will be able to provide this, but in order to, for example, establish the absolute lower limit of the post-glacial sea level in the area, isolation basins with thresholds lower than the ones obtained would need to be found. Trying to better establish the marine limit of the Tasiusaq area as well as adjacent regions could also provide useful material. It would also be interesting to try to establish what caused the erroneous data from lake Nu1. New samples for radiocarbon dating could be taken and the threshold situated towards Tasiusaq could be measured.

In a wider picture more data from the northern areas of southern Greenland as well as data from SE Greenland is required in order to improve our understanding of the evolution of the ice sheet in southern Greenland. The new data could be used for new modelling analyses further constraining the evolution of the ice sheet. Sparrenbom (2006) also suggests that the ice-sheet models used for the southern Greenland ice sheet could be improved by coupling the existing results to more detailed glaciological models that consider ice streams and climate forcing. To my current knowledge this has not been done and is also an interesting idea for future research.

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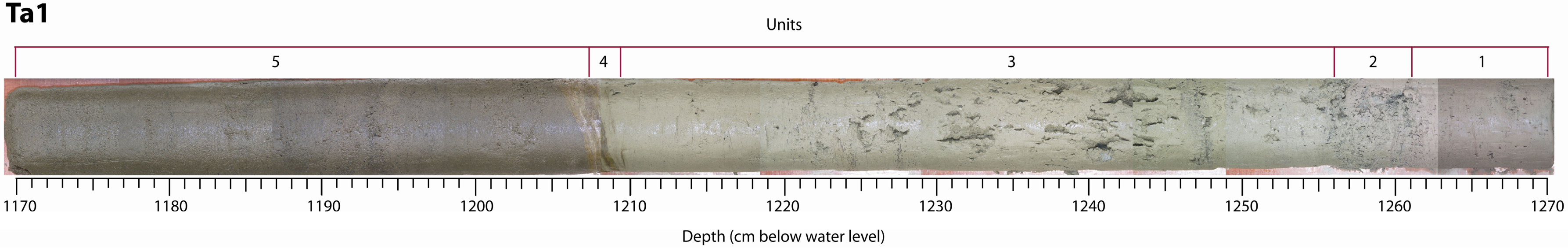
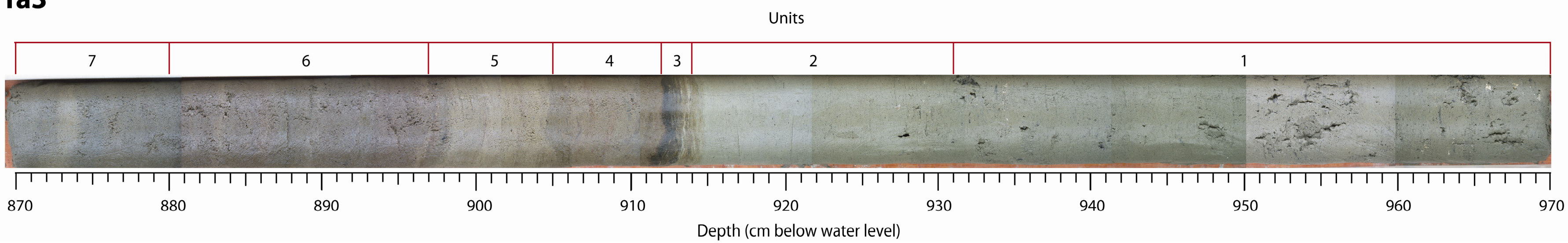
Appendix A

Pictures of the cores from sites Ta1 and Ta3 with lithological units marked.
Note that the pictures are montages of several pictures and that the colour shifts not necessarily reflect the actual appearance of the cores.

Ta1

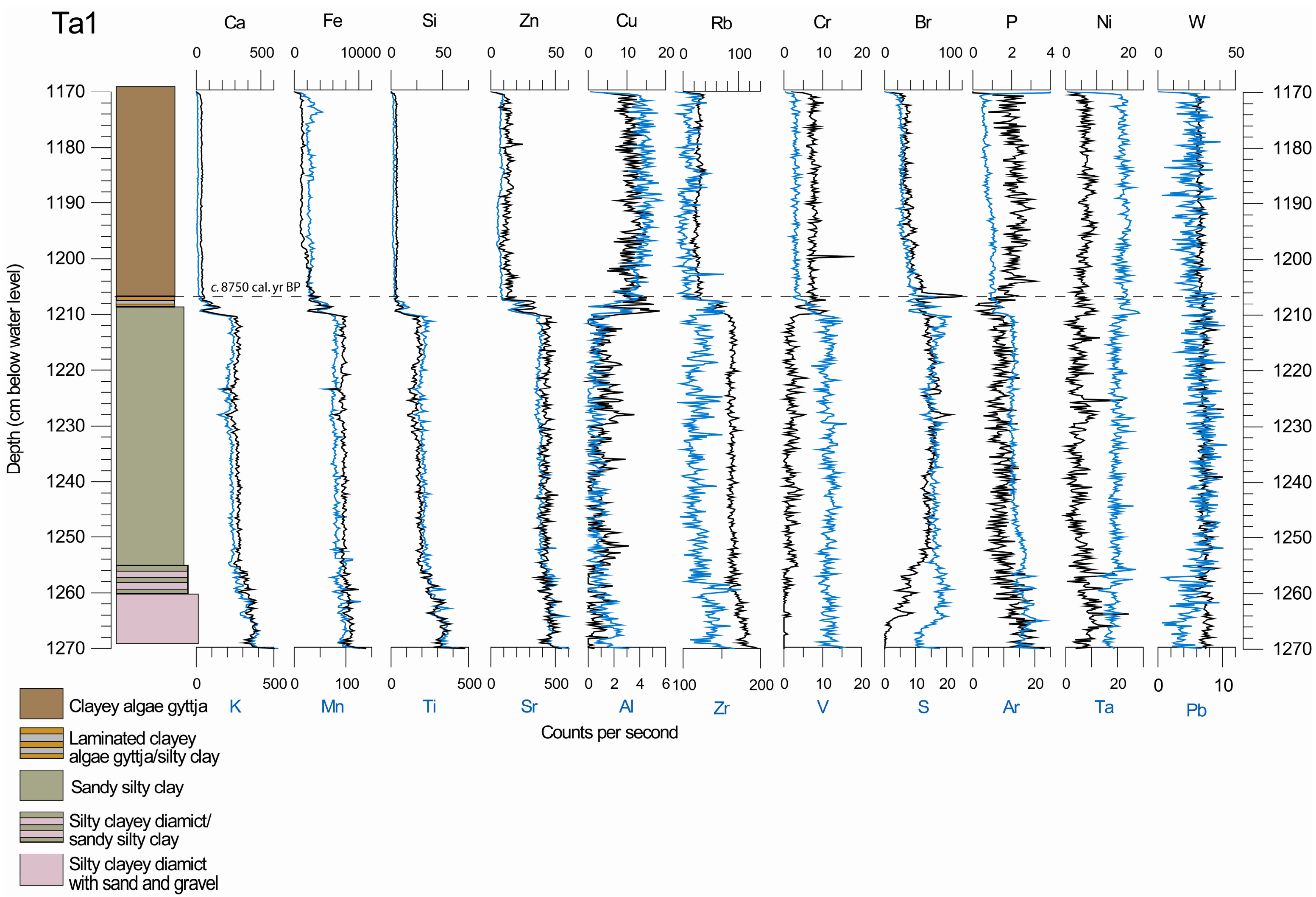


Ta3



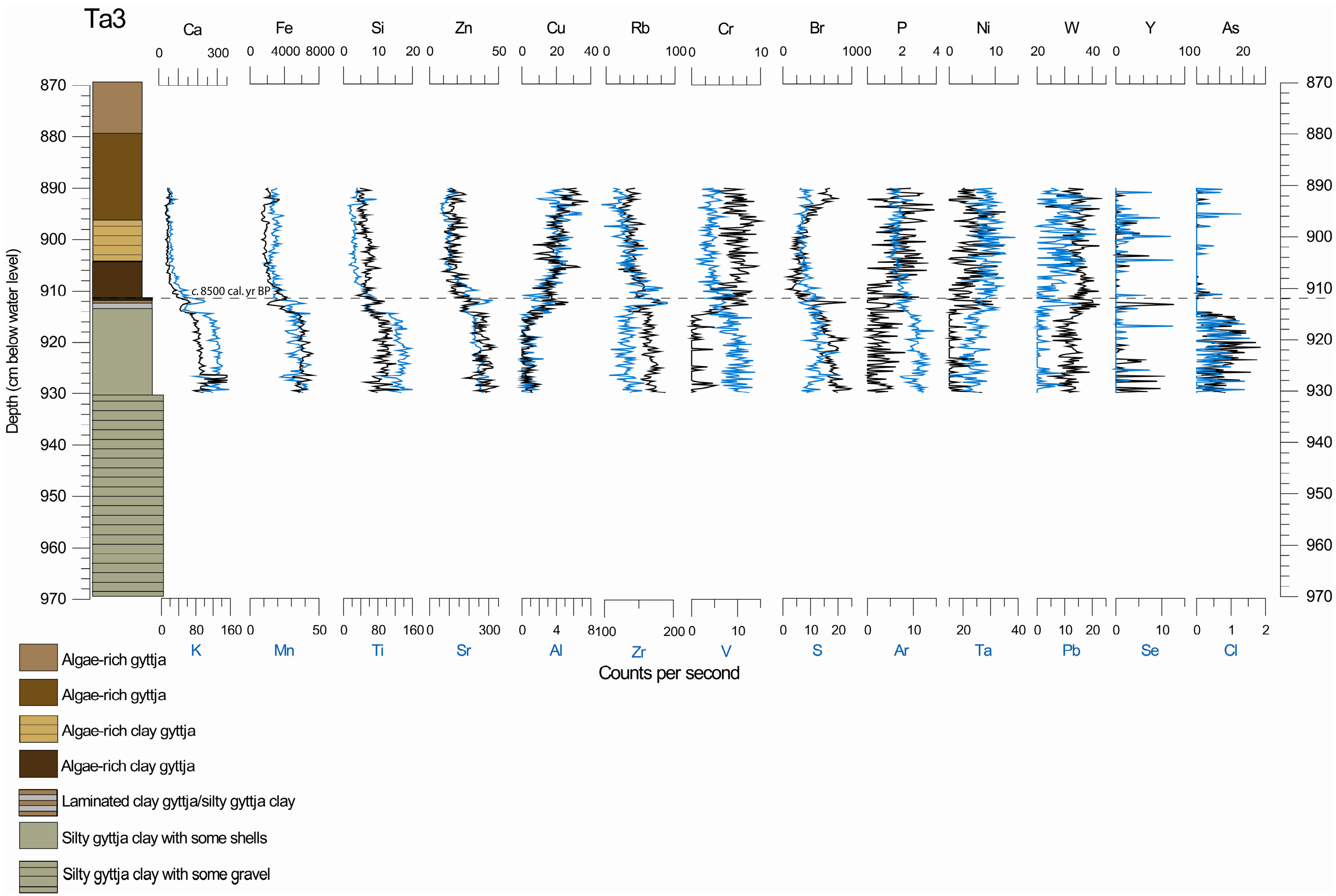
Appendix B

All XRF-scanned elements for site Ta1. Note the different scales for the different elements. Note also that the Ar value at 1170 cm has been cut of at 25 counts (true count is 57) to allow the variability to be seen throughout the sequence.



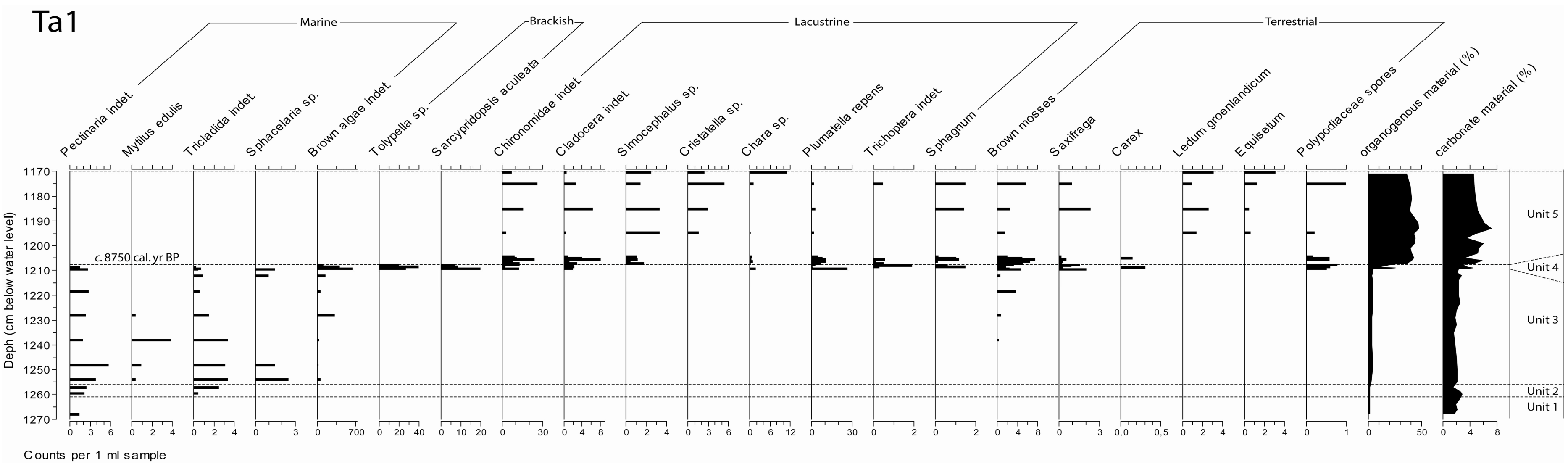
Appendix C

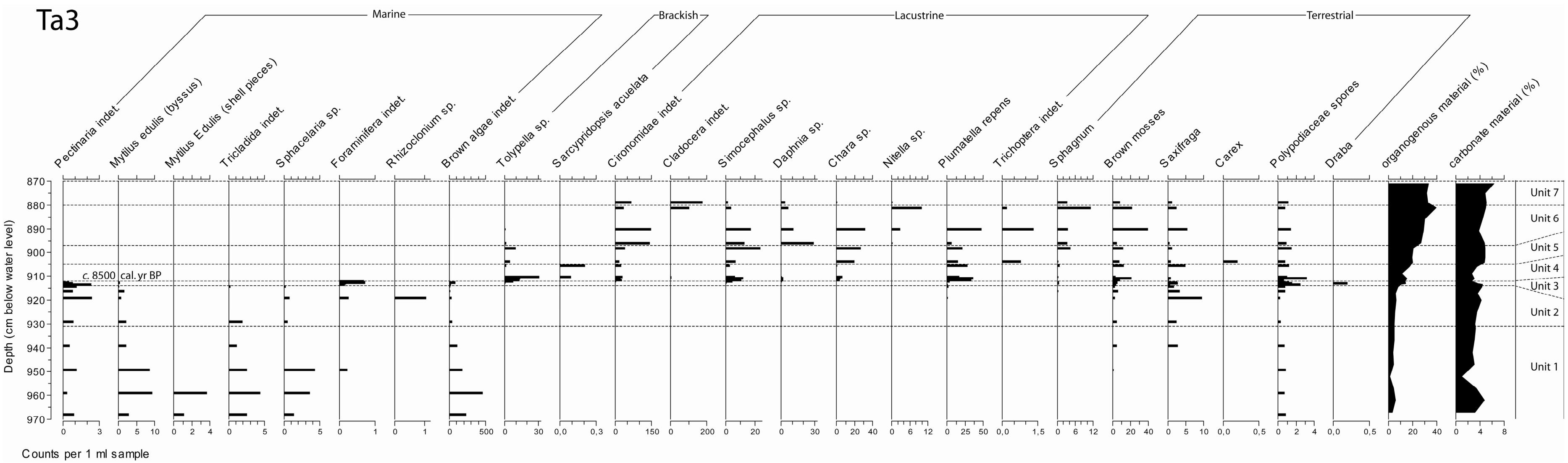
All XRF-scanned elements for site Ta3. Note the different scales for the different elements. Note also that the Ca value at 926 cm has been cut of at 350 counts (true count is 1972) to allow the variability to be seen throughout the sequence. The high Ca-value can probably be explained by the scanner running across a shell piece at the surface of the core.



Appendix D

Macrofossil- and LOI-diagrams for site Ta1 and site Ta3.





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