Relative sea-level changes since 15 000 cal. yr BP in the Nanortalik area, southern Greenland

C. J. SPARRENBOM,¹* O. BENNIKE,² S. BJÖRCK¹ and K. LAMBECK³

¹ Centre for GeoBiosphere Science, Quaternary Geology, Lund University, Sweden

² Geological Survey of Denmark and Greenland, Copenhagen, Denmark

³ Research School of Earth Sciences, Australian National University, Canberra, Australia

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ABSTRACT: We present new results for relative sea-level change for southern Greenland for the interval from 9000 cal. yr BP to the present. Together with earlier work from the same region this yields a nearly complete record from the time of deglaciation to the present. Isolation and/or transgression sequences in one lake and five tidal basins have been identified using lithostratigraphic analyses, sedimentary characteristics, magnetic susceptibility, saturated induced remanent magnetisation (SIRM), organic and carbonate content, and macrofossil analyses. AMS radiocarbon dating of macrofossils and bulk sediment samples provides the timescale. Relative sea level fell rapidly and reached present-day level at ~9300 cal. yr BP and continued falling until at least 9000 cal. yr BP. Between 8000 and 6000 cal. yr BP sea level reached its lowest level of around ~10 m below highest astronomical tide. At around 5000 cal. yr BP, sea level had reached above 7.8 m below highest astronomical tide and slowly continued to rise, not reaching present-day sea level until today. The isostatic rebound caused rapid isolation of the basins that are seen as distinct isolation contacts in the sediments. In contrast, the late Holocene transgressions are less well defined and occurred over longer time intervals. The late Holocene sea-level rise may be a consequence of isostatic reloading by advancing glaciers and/or an effect of the delayed response to isostatic rebound of the Laurentide ice sheet. One consequence of this transgression is that settlements of Palaeo-Eskimo cultures may be missing in southern Greenland. Copyright © 2006 John Wiley & Sons, Ltd.

KEYWORDS: sea level; isolation basin; Lateglacial; Holocene; Greenland.

Introduction

Observations of relative sea-level changes through time provide constraints on volumes of past ice sheets as well as their retreat history, and data from different localities from around the world have been used to constrain the ice volumes of individual ice sheets as well as to establish the total change in ice volume for the Last Glacial Maximum and later times (Lambeck and Chappell, 2001). Greenland is one such ice sheet that has been investigated in this way (Fleming and Lambeck, 2004) and one that we address here. Holocene relative sea-level changes around Greenland have earlier been observed and reported in a number of investigations from different sites, for example in NE Greenland (Funder, 1978; Björck and Persson, 1981; Björck *et al.*, 1994; Bennike and Weidick, 2001), NW Greenland (Kelly *et al.*, 1999) and W Greenland (Rasch, 2000; Rasch and Jensen, 1997; Rasch *et al.*, 1997; Long

et al., 1999; Long and Roberts, 2002; Bennike, 2002; Long *et al.*, 2003). But only limited data are available from southern Greenland (Fredskild, 1973; Funder, 1979; Bennike *et al.*, 2002; Weidick *et al.*, 2004) and more data are needed to be able to understand the regional postglacial sea-level changes and associated isostatic rebound in this sector.

In this paper we present results from the first of two investigations on relative sea-level changes in the southern Greenland sector. It is an extension of the shoreline displacement curve published by Bennike *et al.* (2002) from the Nanortalik area in which they show that the local sea level fell during the Lateglacial period and reached present level at ~10 000 years ago and remained below this level until the present. In the current study we have addressed the sea-level change for the more recent period by coring five basins situated below present spring-tide sea level and one basin above this level.

Other evidence for Late Holocene relative sea-level changes in southern Greenland comes from marine geological and archaeological studies: (i) a subaerially weathered 'dry crust' found at ca. 9.3–10 m below present sea level (b.s.l.) in a core taken in Narsaq harbour dated to >2800 cal. yr BP (Bennike *et al.*, 2002; Weidick *et al.*, 2004); (ii) an undated drowned beach at 3–4 m b.s.l. situated close to the Norse

* Correspondence to: Charlotte Sparrenbom, Centre for GeoBiosphere Science, Quaternary Geology, Lund University, Sölvegatan 12, 223 62 Lund, Sweden. E-mail: charlotte.sparrenbom@geol.lu.se

settlement at Brattahlid (Kuijpers *et al.*, 1999); and (iii) Norse and Neo-Eskimo ruins situated close to the present spring-tide water level (Mathiassen, 1936; Bak, 1969). Furthermore, from tidal measurements between 1883 and 1885, and again from 1932 to 1934, Gabel-Jørgensen and Egedal (1940) reported that the land in southern Greenland was sinking at a rate of 3.9 ± 0.38 mm per year during the 48 years between the two measurements. Evidence for the presence of Palaeo-Eskimo settlements is extremely rare in southern Greenland, possibly because their areas of habitation have been inundated by the rising sea through Holocene time, and new information on regional sea-level change, especially between 4000 cal. yr BP and 250 cal. yr BP, may shed light upon where investigations need to be focused to find evidence of Inuit ancestors possibly reaching southern Greenland.

Field area

The Nanortalik area is situated in south Greenland (Fig. 1) at around 60° N. The landscape is dominated by fjords reaching depths over 600 m and alpine mountains reaching heights of 1500 m near the coast and up to 2000 m further inland, with the ice-free land area being around 100 km wide. The offshore

shelf is relatively narrow, mostly less than 100 km. Glacially abraded, rounded and flattened mountains are common in the outer archipelago, especially at the mouth of the fjords. The bedrock in the region mainly consists of granites, gneissose granites, diorites, migmatized meta-sediments and meta-volcanics (Escher and Watt, 1976).

During winter, the snow cover in the Nanortalik area is deep and constant apart from windswept ridges. 'Storisen', a wide zone of drift ice following the East Greenland Current, reaches the area in late winter (ca. March) and melts off during the summer, normally disappearing from the area around late June. When the cold East Greenland Current meets the warmer Irminger Current it causes cool, cloudy and foggy conditions during the summer months with mean temperatures around 5–6 °C at the outer coast.

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

Methods

Fieldwork was carried out during three weeks in August 2001. A large Zodiac inflatable boat was used to transport coring

Figure 1 (A) Map of Greenland where the rectangle marks the sector where the investigated sites are located. (B) Map of the southern Greenland sector with the rectangle defines the field area. (C) Map showing the location of investigated sites (N14–N24 investigated in 1999 (Bennike *et al.*, 2002) and N25–N30 investigated in 2001)

equipment and people from a base in Nanortalik to the different coring sites. Coring positions were determined with GPS or, in the case of sites N29 and N30, taken from the sea chart. The bathymetry of the submarine basins was investigated with an echo sounder to find suitable coring sites. A small specially designed Zodiac, with a funnel hole in the centre, was used as a coring platform. During coring, the small Zodiac was usually roped tightly to three points on the shore. Using a Russian corer, multiple overlapping core sediment sequences were collected from the different basins. The cores were described and then wrapped for shipment back to the laboratory in Lund, where the cores are stored at 4 °C.

As the aim of the investigation is to establish when sea level was situated at a certain level, it is important to take tides into consideration. The marine influence in a basin will start and stop when the saline oceanic water ceases to cross the sill of the basin. The highest astronomical tide is therefore of importance, as that controls when marine waters can enter the basin. Storm events may also be of importance but harder to establish in detail, and will not affect the different sites evenly because of differences in location and exposure. The highest astronomical tide has been calculated by O. Andersen (KMS) using the global tidal model AG (Andersen Grenoble, 1995.1) for each site and it varies between sites from 184 cm to 188 cm above mean sea level. The mean tidal amplitude for the area is ca. 0.75 m and 1.5 m at neap and spring tides, respectively (Farvandsvæsenet, 2000, 2001).

The altitude of the sill of the lake was measured with a digital altimeter and a clinometer, while the threshold levels of the tidewater basins were measured using an echo sounder and coring rods. The accuracy of the sill measurements depends on the method used (Table 1). By noting the time for every measurement, tidal corrections were possible. The total uncertainty at each site depends on: the accuracy of the measurement; the interpreted threshold development; and the uncertainty in the tidal correction. The total uncertainty is then the square root of the sum of the variances of the three contributing factors, i.e.

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

where σ_1^2 is the measurement variance, σ_2^2 is the variance of the threshold development and σ_3^2 is the variance of the tidal correction. The total uncertainty of the relative sea-level determination for each site is given in Table 1.

Detailed lithological descriptions were carried out in the laboratory before subsampling. Measurements of magnetic susceptibility and saturation isothermal remanent magnetisation (SIRM), organic and carbonate contents were carried out on closely spaced samples from all cores. The magnetic susceptibility (χ) is a measure of the extent to which a sediment can be magnetised and is expressed as ($\mu\text{m}^3 \text{kg}^{-1}$), and depends on the mineral composition of the sediment. High susceptibility values may indicate a higher content of magnetic particles, i.e. a sediment containing more minerogenic particles, and low values may indicate the absence of magnetic particles, i.e.

often a more organic sediment. However, this is a simplification since the magnetic susceptibility may also be a measure of the amount of magnetotactic bacteria. The measurement on naturally wet samples is particularly useful to facilitate core correlations, but in combination with SIRM it is also a supplementary method to recognise isolation events, i.e. changes in depositional environment (Björck, 1979). The susceptibility measurements were made with a Geofyzika Brno KLY-2 susceptibility bridge on naturally wet samples.

A Redcliff pulse-magnetiser (model 700 BSM) has been used to induce a field of 1 T to achieve saturation isothermal remanent magnetisation, and a Molspin Minispin spinner magnetometer was used to measure the remanent magnetisation. SIRM was measured on naturally wet sediment as well as on sediments that were dried at 55 °C for 12–24 hr. The authigenically formed magnetic mineral gregite (Fe_3S_4) forms in anoxic environments in fresh, marine or brackish water where sulphate supply is limited (Walden *et al.*, 1999; Sandgren and Snowball, 2001). It can be expected in isolation sequences when the environment changes from marine aerobic conditions to brackish anaerobic conditions.

Analyses of plant and animal macrofossils were used to check the interpretations of environmental changes, particularly isolations/transgressions, implied by the other analyses. Samples for macrofossil analyses were wet-sieved using a 0.2-mm sieve.

AMS radiocarbon dating was 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. 3.5 (Bronk Ramsey, 2001) and v. 3.9 (minor changes in 2003), based on the INTCAL98 dataset of Stuiver *et al.* (1998), and using the terrestrial calibration curve. The radiocarbon analyses provide ages for the time of isolation and transgression of each basin.

Results

The six investigated sites are described below. We continue to use site name codes from Bennike *et al.* (2002), where N stands for Nanortalik. Sediment depths in the descriptions refer to depth below water surface. Altitude of the thresholds are related to metres above (+) or below (–) the highest astronomical tide (m a.h.a.t. and m b.h.a.t., respectively).

Tidal basin N25 (N 60.1896°, W 45.0760°)

The site is a marine tidal basin with a threshold consisting of a coarse sediment lag (pebbles and rocks) at 6.3 m b.h.a.t. The

Table 1 Assessment of total uncertainty for each site investigated in 2001

Site	Measured elevation (m a.m.s.l.)	Measurement method	Measurement uncertainty (m)	Assessment of threshold uncertainty (m)	Tidal uncertainty (m)	Total uncertainty (m)
N25	–4.5	Rods	0.1	±0.3	0.5	±0.6
N26	5	Clinometer	0.2	±0.1	0.5	±0.5
N27	–0.45	Rods	0.1	±0.0	0.5	±0.5
N28	–5.95	Rods	0.1	+1/–2	0.5	+1.1/–2.1
N29	–1.45	Rods	0.1	+1/–2	0.5	+1.1/–2.1
N30	1.25	Rods	0.1	±0.3	0.5	±0.6

basin is located 10 km northeast of Nanortalik in the Tasermiut fjord and is the most inland site investigated to yield isolation or transgression results. It is oval in shape, ca. 1500 m long and 400 m wide, and a series of lakes drain into it via a waterfall. The water depth at the coring site varies with the tides, between 9.5 m and 11 m, but in some parts of the basin, depths of up to 22 m were recorded. At the isolation contact at 1200 cm, the sediments change from greenish grey sandy clayey gyttja silt, into laminated greyish brown sandy clayey algal-rich silt gyttja (Fig. 2). Marine algae, foraminifera and *Mytilus edulis* also disappear above this level and a freshwater fauna with Cladocera and Chironomidae start to dominate (Fig. 3). The organic car-

bon and carbonate content increase at around 1200 cm and a small peak is visible in all the magnetic parameters (Fig. 2). The transgression event is harder to establish from the lithological analyses alone as there are several possibilities indicated by the sedimentary changes and changes in the magnetic parameters, as well as by the organic carbon and carbonate content at 1181 cm, 1163.5 cm, 1078 cm, 1061 cm, 1044.5 cm and 1027 cm. But from the macrofossil analyses the transgression can be established at 1061 cm (Fig. 3). The transgression is a more gradual transition than the isolation event, with freshwater taxa such as *Isoetes lacustris*, *Rhabdocoela* and Cladocera slowly decreasing in numbers while marine algae,

Figure 2 Core log for site N25, the magnetic susceptibility, $SIRM/\chi$ (scale bar on top), $SIRM$ wet and dry, carbon content (mass% of dry weight), carbonate contents (mass% of dry weight, scale bar on top) and minerogenic residue (mass% of dry weight). Ages given are calibrated years BP (cal. yr BP) or interpreted interpolated ages between several dates, all in cal. yr BP

Figure 3 Simplified macrofossil diagram showing the result from the macrofossil analyses of site N25. Ages given are cal. yr BP or interpreted interpolated ages between several dates, all in cal. yr BP. Note the different scales for the different taxa

Foraminifera and *Mytilus edulis* increase in numbers at the same time. The small number of poorly preserved marine macrofossils appearing in the interval between 1200 cm and 1063 cm can possibly be explained by wave-induced erosion and re-sedimentation of older sediments. The presence of reworked material is supported by the old radiocarbon age of $15\,690 \pm 90$ ^{14}C yr BP for a bulk sediment sample from 11.635 cm (Poz-7175, Table 2). Alternatively, the occurrence of marine macrofossils in small numbers during periods clearly dominated by freshwater species may be a result of storm events that transported marine waters and organisms over the relatively narrow and low threshold which is located towards the south-southwest and is exposed to southwesterly storms. The age of the isolation of the basin is determined to around 9500 cal. yr BP based on a bulk sediment sample (9470–9630 cal. yr BP) just above the isolation contact, a macrofossil sample of *Nitella* sp. (9020–9490 cal. yr BP) at and above the isolation contact and a sample of the moss *Drepanocladus* cf. *badius* (9750–10 490 cal. yr BP) just below the contact (Table 2). The time of the transgression is dated to around 2500 cal. yr BP based on a sample of the following taxa; Bryopsida indet., *Nitella* sp., *Empetrum* sp., *Isoetes lacustris*, *Daphnia pulex*, *Batrachium confervoides* and chironomids (2340–2740 and 2150–2250 cal. yr BP) at 1057–1061 cm (Table 2).

Lake N26 (N 60.1278 °, W 45.0621 °)

The lake is located ca. 9 km east of Nanortalik close to the mountain Jakobinerhøjen at the mouth of Tasermiut fjord. The threshold consists of rock at an altitude of ca. 3.2 m a.h.a.t. With an irregular shape, the basin measures ca. 150 × 500 m. There is no obvious inlet to the lake, so inflow of material is limited to that brought by surface runoff. The water depth at the coring site is 5.5 m, but depths of up to 10 m were recorded in the basin. Sedimentary changes from brownish grey silty sand to dark brown and black FeS-laminated sandy clayey algal-rich silt gyttja overlain by clayey silt gyttja can be observed around the isolation (Fig. 4). Marine algae, Hydroidea indet. and *Mytilus edulis* disappear at the isolation and a freshwater fauna with the cladocerans *Daphnia* sp. and *Ceriodaphnia* sp. and chironomids appear and increase in abundance (Fig. 5). Organic carbon and carbonate content increase at the same level (Fig. 4). SIRM and susceptibility also increase during the transition from the marine to the freshwater environment at 920 to 915 cm. The age of the isolation is established to ca. 10 300 cal. yr BP on the basis of three bulk sediment samples (one at 916–918 cm with the age of 9900–10 650 cal. yr BP, one at 914–916 cm dated to 9900–10 600 cal. yr BP and one at 910–914 cm with an age of

Table 2 AMS radiocarbon and calibrated dates for sites N25–N30

Site	Laboratory no.	Depth (cm)	Age (^{14}C yr BP)	Calibrated age 2σ (95.4%)	Material	Comments
N25	Poz-7174	10.235	1280 ± 30	1140–1290	Gyttja	
N25	LuA-5846	10.57–10.61	2450 ± 85	2340–2740 (92.8%)	Bryopsida indet., <i>Nitella</i> , <i>Empetrum</i> , <i>Isoetes</i> , <i>Daphnia</i> , <i>Batrachium</i> and Chironomidae	Transgression
N25	Poz-7321	10.765	5580 ± 40	6290–6450	Gyttja	N25
N25	Poz-7175	11.635	15690 ± 90	18150–19450	Gyttja	N25
N25	Poz-7320	11.95	8560 ± 50	9680–9640 (2.6%) 9630–9470 (92.8%)	Gyttja	Isolation
N25	LuA-5848	11.98–12.00	8270 ± 100	9020–9480	<i>Nitella</i>	Isolation
N25	Poz-7415	12.02	8720 ± 50	9550–9910	Gyttja silt	Isolation
N25	LuA-5847	12.01–12.03	8990 ± 90	9750–10400	<i>Drepanocladus</i> cf. <i>badius</i>	Isolation
N26	LuA-5225	9.10–9.14	8845 ± 115	9550–10250	Gyttja	Isolation
N26	LuA-5226	9.14–9.16	9110 ± 110	9900–10600	Gyttja	Isolation
N26	LuA-5227	9.16–9.18	9130 ± 105	9900–10650	Gyttja	Isolation
N27	Poz-7172	6.445–6.455	1550 ± 30	1350–1530	Gyttja	Above transgression
N27	LuA-5349	6.68–6.685	705 ± 85	520–790	Gyttja	Transgression
N27	Poz-7173	6.945–6.95	2810 ± 30	2840–3000 (92.0%) 2790–2830 (3.4%)	Gyttja	Below transgression
N27	LuA-5348	7.58–7.59	8410 ± 115	9000–9600	Gyttja	Isolation
N28	LuA-5351	13.275–13.285	4375 ± 95	4650–5350	Gyttja	Transgression
N28	Poz-7178	13.39–13.40	8250 ± 50	9030–9430	Gyttja	Isolation
N28	LuA-5350	13.419–13.427	8310 ± 95	9030–9500	Gyttja	Isolation
N29	LuA-5849	11.77–11.855	2395 ± 85	2300–2750 (93.1%) 2150–2250 (2.3%)	Bryopsida indet., <i>Nitella</i> , <i>Empetrum</i> , <i>Isoetes</i> , <i>Daphnia</i> , <i>Juniperus</i> , Chironomidae adult	Transgression
N29	Poz-7176	11.79–11.80	2290 ± 30	2300–2360 (59.8%) 2180–2250 (33.6%) 2150–2170 (2.1%)	Gyttja	Transgression
N29	LuA-5316	11.86	7300 ± 95	7940–8340	Silty gyttja	Transgression (below hiatus)
N29	LuA-5315	11.97	8085 ± 95	8600–9300	Silty gyttja	Isolation
N30	LuA-5313	1.09	945 ± 90	1030–1060 (1.9%) 670–1000 (93.5%)	<i>Juniperus communis</i> , <i>Empetrum</i>	Transgression
N30	LuA-5352	1.09–1.095	1725 ± 90	1410–1830	Gyttja	Transgression
N30	LuA-5312	1.13	1020 ± 80	730–1090	<i>Juniperus communis</i> , <i>Empetrum</i>	Transgression
N30	LuA-5311	1.39	8350 ± 80	9130–9530	<i>Empetrum</i> and <i>Hippuris vulgaris</i>	Isolation
N30	LuA-5314	1.9	9325 ± 130	10 200–11 100	Gyttjasilt

Figure 4 Core log for site N26, the magnetic susceptibility, SIRM/ χ (scale bar on top), SIRM wet and dry, carbon contents (mass% of dry weight), carbonate contents (mass% of dry weight, scale bar on top) and minerogenic residue (mass% of dry weight). Ages given are cal. yr BP or interpreted interpolated ages between several dates

9550–10 250 cal. yr BP, Table 2) at the transition between the two sedimentation environments.

Tidal basin N27 (N 60.1321°, W 45.0513°)

The site is a tidal basin located ca. 9 km east of Nanortalik close to site N26 and the mountain Jakobinerhuen at the mouth of the Tasermiut fjord. Bare bedrock constitutes the threshold at an altitude of 2.3 m b.h.a.t. A series of lakes drain into this oval-shaped basin. The basin measures ca. 1250 × 160 m. The water depth at the coring site is ca. 6 m, but in some parts of the basin,

depths of up to 15 m were recorded. Today the environment in the basin changes twice a day because of the tides, from being part of the sea to becoming an isolated water body.

Below the isolation found at ca. 757–759 cm, the sediments consist of greyish gyttja with gravel and sand, changing into laminated brown gyttja containing black iron sulphide-rich laminae (Fig. 6). Above the isolation contact, laminated gyttja continues another ca. 5 cm, with colours that vary from reddish to more greyish brown. Marine brown algae, *Mytilus edulis* and *Tricladida* indet. disappear above the isolation and a freshwater fauna with Cladocera especially *Daphnia* sp., Chironomidae and *Plumatella* sp. starts to dominate (Fig. 7). The organic carbon and carbonate content increase below

Figure 5 Simplified macrofossil diagram showing the results from the macrofossil analyses of site N26. Ages given are cal. yr BP or interpreted interpolated ages between several dates, all in cal. yr BP. Note the different scales for the different taxa

the isolation contact, probably as a consequence of the threshold reaching above the low tide level and the basin becoming 'semi-isolated', i.e. isolated during low tides twice a day resulting in brackish water conditions. Both the organic and the carbonate content are rather high during the isolation phase compared to the marine environment before the isolation. The magnetic susceptibility curve shows a small rise at the isolation and decreases above the contact at ca. 750 cm (Fig. 6). The magnetic susceptibility varies as a consequence of the concentration of magnetic particles, which is mostly controlled by the variation of the minerogenic content. Figure 6 shows that susceptibility values increase and decrease when the minerogenic residue increases and decreases, respectively.

The sedimentary transition from a freshwater environment into a marine environment at the transgression (level 669 cm) is reflected by a change from dark brown algae gyttja into a brown, green, and grey laminated algae gyttja with marked black iron sulphide lamination (Fig. 6). All the magnetic parameters measured show a marked decrease at this level. Carbon and carbonate content show large fluctuations, probably as a result of the constantly changing environment due to saltwater inflow twice a day. Foraminifera, Hydroidea and some brown algae enter the basin while the freshwater taxa Cladocera, Chironomidae and *Isoetes lacustris* slowly decrease in numbers (Fig. 7). The age of the isolation of the basin is established to around ca. 9300 cal. yr BP (Table 2) based on a bulk sediment sample at the isolation contact at 758–759 cm (9000–9600 cal. yr BP). The time of the transgression is determined to around 2100 cal. yr BP (at level 668 cm) on the basis of an interpolation between two bulk sediment samples, one from above the transgression at 645 cm (1350–1530 cal. yr BP) and the other taken below the transgression at 694.5–695 cm (2840–3000 and 2790–2830 cal. yr BP) (Table 2). The uncertainty of this transgression date is hard to estimate, especially considering any marine reservoir effect, but it certainly

amounts to at least a few hundred years. The error bars for this interpolated age have been set to –750 and +900, which are the minimum and maximum departures of the measured ages of the bulk samples from the interpolated mean. A third bulk sediment sample from level 668–668.5 cm gave an age of 520–790 cal. yr BP. This date is likely to be too young, as the sample above this level is older and the sample below was dated to ca. 2900 cal. yr BP.

Marine embayment N28 (N 63.0316°, W 44.9083°)

This marine embayment is located ca. 23 km southeast of Nanortalik at Narlusoq island and measures ca. 250 × 125 m. Bedrock or boulders form the threshold at 7.8 m b.h.a.t. and the maximum depth measured in the basin is 20 m. The water depth at the coring sites varied between ca. 8.3 m and 12 m as a consequence of tidal changes during the day and shifting positions of the coring platform but the overlapping cores could be successfully correlated visually as well as with the magnetic scans. The isolation contact is placed at 1340.5–1341.5 cm at the transition from dark brown to black FeS-laminated silt gyttja with a high content of minerogenic material to lighter brown sandy clay algal rich silt gyttja (Fig. 8). Marine brown algae, Foraminifera, Tricladida and Hydroidea disappear above this level and a freshwater fauna with Cladocera, Chironomidae and *Plumatella* sp. starts to dominate (Fig. 9).

The organic carbon and carbonate contents first increase just above 1345 cm and continue to increase until level 1332 cm where they both suddenly decrease. The magnetic parameters (Fig. 8) show high peaks at the isolation contact at 1341 cm and then fluctuate highly until 1326 cm where they reach the same high values as before the isolation. The mid- to late Holocene

Figure 6 Core log for site N27, the magnetic susceptibility, SIRM/ χ (scale bar on top), SIRM wet and dry, carbon contents (mass% of dry weight), carbonate contents (mass% of dry weight, scale bar on top) and minerogenic residue (mass% of dry weight). Ages given are cal. yr BP or interpolated ages between several dates, all in cal. yr BP

transgression in south Greenland, from a freshwater environment into full marine conditions, has usually been found to be a gradual process, but in the cores from this site the lithologic change is very sharp. The freshwater sequence is only

ca. 6 cm thick, and from the radiocarbon analyses we conclude that the sequence is incomplete and that erosion has removed significant parts of it. The first incursion of marine water into the basin is seen at 1334 cm on the basis of macrofossil analyses

Figure 7 Simplified macrofossil diagram showing the result from the macrofossil analyses of site N27. Ages given are cal. yr BP or interpolated ages between several dates, all in cal. yr BP. Note the different scales for the different taxa

(Fig. 9). Foraminifera, *Pectinaria* sp. and some marine brown algae enter the basin and freshwater species such as Cladocera, Chironomidae and *Plumatella* sp. start a slow decline.

The isolation of the basin is dated to ca. 9250 cal. yr BP (Table 2) based on two bulk sediment samples (one above the isolation at 1339–1340 cm dated to 9030–9430 cal. yr BP and one below the isolation at 1341.9–1342.7 cm dated to 9030–9500 cal. yr BP). The time of the transgression is determined to have occurred before 5000 cal. yr BP based on a marine bulk sediment sample taken at 1327.5–1328.5 cm (Table 2). This date presents a minimum age of the transgression event as it is taken above the hiatus in marine sediments. The transgression must therefore have started at this time or earlier.

Tidal basin N29 (N 60.0300°, W 44.9303°)

The threshold of this ca. 300 × 250 m marine embayment is made up of boulders located 3.3 m b.h.a.t. It is located ca. 23 km southeast of Nanortalik by Narlusoq island and the maximum depth measured in the basin is 22 m. As a consequence of tidal changes during the day and horizontal movements of the coring platform between each coring, water depth varied between ca. 11.6 and 12.8 m. The isolation contact is placed at 1197.5 cm, at the transition from light greyish brown sandy clayey silty gyttja to brown, black and grey laminated sandy clayey silty gyttja with FeS laminae (Fig. 10). At this level, marine algae, foraminifera, Tricladida and Hydroidea disappear and freshwater organisms with Cladocera, Chironomidae and *Nitella* sp. start to dominate (Fig. 11). The organic carbon content first increases just below the isolation contact at ca. 1203 cm and continues a general increase until ca. 1194 cm where it suddenly decreases. The carbonate curve has roughly the same shape as the carbon curve, except between 1200–1207 cm where there is a high peak in the carbonate curve corresponding to a high concentration of shell fragments (Fig. 10). The magnetic parameters (Fig. 10) decrease from around the isolation with a high peak just above the onset of marine conditions at 1185.5 cm. The lithology at the assumed lacustrine–marine transition shows a sharp erosive contact and the brown, black and grey laminated sandy clayey silty gyttja containing FeS (bands) laminations changes abruptly into a brownish grey sandy silt gyttja. Two ¹⁴C-dated bulk samples confirm the erosive contact; the sample below the contact at 1186 cm has an age of ca. 8140 cal. yr BP and the sample above was dated to ca. 2300 cal. yr BP (Table 2). The macrofossil analyses show a fairly abrupt change from freshwater taxa to marine taxa, compared to most of the other sites; from an environment dominated by Cladocera, Chironomidae and *Nitella* sp. to an environment dominated by marine algae, foraminifera and *Pectinaria* sp. (Fig. 11).

The age of the isolation of the basin is established as ca. 9000 cal. yr BP (Table 2) on the basis of a bulk sediment sample at the isolation contact at 1197 cm (8600–9300 cal. yr BP). The transgression is determined to have occurred sometime between 8140 cal. yr BP and 2300 cal. yr BP on the basis of the bulk sediment sample taken from both above the hiatus at 1179–1180 cm and below the hiatus at 1186 cm (Table 2).

Tidal basin N30 (N 60.0408°, W 44.9033°)

This tidal basin is also located ca. 23 km southeast of Nanortalik north east of the island of Narlusoq and measures ca. 500 × 200 m. The threshold, situated at an altitude of ca.

Figure 8 Core log for site N28, the magnetic susceptibility, dry SIRM/ χ (scale bar on top), dry SIRM, carbon contents (mass% of dry weight), carbonate contents (mass% of dry weight, scale bar on top) and minerogenic residue (mass% of dry weight). Ages given are cal. yr BP or interpreted interpolated ages between several dates

0.6 m b.h.a.t., is made up of boulders and the maximum depth in the rather shallow basin was measured to around 2.6 m. The water depth at the coring site was measured to ca. 0.8 m and as the coring was done during low tide, no variations in depth at the coring site were registered. The isolation contact is placed at 139.5 cm at the transition from greenish brown sandy clayey silty gyttja to brown sandy silty algal rich gyttja (Fig. 12). Below the isolation contact *Tricladida* indet. dominates the environment, but disappear above this level and a freshwater flora

and fauna with Cladocera, Chironomidae and *Isoëtes lacustris* takes over (Fig. 13).

Both the organic carbon and carbonate content increase at the isolation contact level. The magnetic susceptibility (Fig. 12) decreases at the isolation contact while the SIRM measurements show little change. The transgression, with a first marine incursion seen from macrofossil analyses at 112 cm, was gradual and the sediments change from dark brown clayey silty sandy gyttja into grey clayey silty sandy

Figure 9 Simplified macrofossil diagram showing the results from the macrofossil analyses of site N28. Ages given are cal. yr BP or interpreted interpolated ages between several dates. Note the different scales for the different taxa

gyttja with visible shell fragments. The macrofossil analyses show that *Pectinaria* sp. and *Macoma balthica* enter the basin at 112 cm while at the same time Cladocera, Chironomidea and *Isoëtes lacustris* decrease in numbers (Fig. 13). The freshwater flora and fauna almost totally disappear at ca. 102–104 cm.

The age of the isolation of the basin is established to ca. 9300 cal. yr BP (9130–9530 cal. yr BP) (Table 2) based on a macrofossil sample containing *Empetrum nigrum* and *Hippuris vulgaris* from 139 cm depth. The time of transgression is determined to ca. 900 cal. yr BP from a macrofossil sample, contain-

ing *Juniperus communis* and *Empetrum nigrum*, taken at 113 cm, just below the first marine incursion (Table 2).

Discussion

Basin isolation

In the Nanortalik area, early Holocene isolation sequences show abrupt lithological changes from coarser minerogenic sediments deposited in a (glacio-) marine environment forming

Figure 11 Simplified macrofossil diagram showing the results from the macrofossil analyses of site N29. Ages given are cal. yr BP or interpolated ages between several dates. Note the different scales for the different taxa

Figure 12 Core log for site N30, the magnetic susceptibility, SIRM/ χ (scale bar on top), SIRM wet and dry, carbon contents (mass% of dry weight), carbonate contents (mass% of dry weight, scale bar on top) and minerogenic residue (mass% of dry weight). Ages given are cal. yr BP or interpreted interpolated ages between several dates

laminated sediment, often with black iron sulphide-rich laminations deposited in a brackish water environment, and often shifting abruptly into a freshwater deposited brownish algae gyttja. The macrofossil analyses show that 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 Hydro-

idea and flatworms of the order Tricladida. Even tiny bones of the small fish *Gasterosteus aculeatus* have been found in one of the basins below the isolation contact. In connection with isolation and transgression sequences, the oribatid mite *Ameronothrus lineatus* appears in the transitional sediments, possibly favoured by the changes between marine and lacustrine conditions. This oribatid lives at or near the sea shore (Hammer,

Figure 13 Simplified macrofossil diagram showing the results from the macrofossil analyses of site N30. Ages given are cal. yr BP or interpolated ages between several dates. Note the different scales for the different taxa

1944) and has been reported from isolation sequences before by, for example, Bennike (1992, 1995) and Bennike *et al.* (2002). The presence of marine organisms often ends abruptly at the isolation contact, to be replaced quickly by freshwater taxa. Most of the freshwater taxa probably arrive at the isolated lake by surface runoff from small rivers, draining lakes further inland, but some species may also be transported by birds. The most commonly found freshwater organisms are cladocerans like *Daphnia* sp. and *Alona* sp., Chironomids, *Isoëtes lacustris*, *Nitella* sp., *Plumatella repens*, Rhabdocoela flatworms, the water-crowfoot *Batrachium confervoides*, larval cases from Trichoptera, some *Hippuris vulgaris* and *Lepidurus arcticus*. Occasional bones from the fish *Gasterosteus aculeatus* have also been found above the isolation contact from site N26.

Basin ingression

The transition from freshwater sediments into marine sediments is often not as clearly visible as the isolation contacts. This is a consequence of the gradient of the sea-level change being high during the isolation and lower during the transgression. It is usually obvious in the sediments that a marine ingression occurs, but in most cases macrofossil analyses were necessary to establish exactly where to place it. The changes in the sediments are more gradual than during the isolation and it is therefore difficult to define a 'transgression contact'. Physically, the change is often seen as a higher amount of mineral particles, which often but not always shows up as higher magnetic susceptibility and higher SIRM values; in fact, biogenic magnetite can give higher signals than minerogenic sediments. 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 marine ingression. The macrofossil analyses have shown that the environmental change is gradual with several marine species showing up in small numbers at the same time as freshwater species gradually decline in numbers of individuals. It is not unusual to find both marine and freshwater species in fairly large numbers in the first 10–15 cm of the sediment column above the registration of the first marine ingression. The marine taxa that first migrate into the basins are often Foraminifera, brown algae such as *Sphacelaria* sp., *Rhizoclonium* sp. and *Desmarestia* sp., bivalves such as *Mytilus edulis* or *Macoma balthica*, hydrozoans of the order Hydroidea, the ice-cream-cone worm *Pectinaria* and flatworms of the order Tricladida. Remains of the marine fish *Mallotus villosus* have been found in the transgression sequence of N25 and in fully marine sediments in N28.

A Lateglacial and Holocene sea-level curve from the Nanortalik area

The isolation and transgression ages shown in Fig. 14 are a summary of the seven sites from Bennike *et al.* (2002) (Table 3) and the six sites described in this paper. The sea levels shown are the inferred values for the individual sites and no adjustment has been made for possible differential isostatic signals between sites that do not lie on the same isobase for the reason that the orientation and gradient of the isobases cannot be determined with accuracy from the available data. The sites N16, N18, N19, N21, N22, N24, N28, N29 and N30 are at very comparable distances from the present ice margin and from the shelf edge and differential isostatic signals for these sites are likely to be small. The oldest isolation basin

(site N14) also lies further offshore and its elevation would be increased if projected onto a sea-level curve for the main cluster of sites. Therefore Fig. 14 should not be interpreted as a sea-level curve for any specific location but as a general representation of change over the area spanned by the data points.

All ages are calibrated to yr BP using OxCal (v. 3.9) with 2σ error bars, with the exception of the transgression age of basin N27 for which the age is the result of an interpolation between dates above and below the transgression as discussed above. The altitude error bars are based on the total uncertainty presented in Table 1. No basins suitable for coring with thresholds below -7.8 m b.h.a.t. have been found in the area and we cannot establish firmly the maximum lowest Holocene sea level attained in the area. The sediments from sites N28 and N29 show erosive contacts (i.e. hiatuses) and this implies a dynamic environment with strong bottom currents eroding the soft gyttja sediments and could indicate, especially for site N28 where the threshold is wide, that the lowest sea level in the area was close to this threshold altitude. The fact that marine macrofossils are found in the sediment column from N25 during a freshwater-dominated period, could also imply that sea level was close to the threshold and that marine sediments were washed in during storm events. Thus the lowest sea level in the Nanortalik region could not have been much lower than ca. 10 m below highest astronomical tide and occurred between 8000 and 6000 cal. yr BP (Fig. 14). The observations presented in Fig. 14 show a slow regression between 14 000 and 12 000 cal. yr BP and an accelerated regression between 12 000 and 9000 cal. yr BP. This implies a fast recession of the ice sheet during at least parts of the Lateglacial and the early Holocene. The slower transgression starting at sometime before 5000 cal. yr BP could reflect either a readvance of the Greenland ice sheet and/or a delayed collapse of the Laurentide peripheral bulge. It has been suggested that the ice sheet margin reached its present position at around 9500 BP, and from 9000 BP to 3000 BP the ice margin was behind this position (Weidick *et al.*, 2004). This suggestion correlates very well with the sea-level observations presented here, as sea level fell below the present at around 9300 cal. yr BP and then rose from around the mid-Holocene to reach the present level fairly recently. Neoglacial growth and/or a delayed isostatic response to the changes in the Laurentide and/or the Greenland ice sheets can explain such behaviour in relative sea level. It could also be a combination of both processes.

The data in the diagram in Fig. 14 are uncorrected for differential isostatic rebound and should be seen as raw data and not as a relative sea-level curve for any specific locality. We are currently working on relative sea-level changes in a second area of southern Greenland (Qaqortoq-Narsarsuaq). When this analysis is completed we will be in a better position to establish the gradients and rates of crustal rebound and to draw conclusions about ice thickness and ice margin locations for the Lateglacial period. This work is important as observations of relative sea-level changes in southern Greenland are few and provide few constraints for glacial-isostatic adjustment models. Poor agreement is seen between results from glacial-isostatic adjustment models reconstructing sea-level and glacial history with those few observations available at present (Bennike *et al.*, 2002; Tarasov and Peltier, 2002; Fleming and Lambeck, 2004). Fleming and Lambeck (2004) present a curve for the Kap Farvel area that shows a predicted relative sea-level rise for the entire Lateglacial and Holocene, and conclude that their model underestimates the amounts of ice melted from the region. This conclusion agrees well with our observations. Tarasov and Peltier (2002) produce a curve for the Julianehåb area showing a transgression from the LGM until around 10 000 BP, when the presented relative sea-level curve reaches almost 60 m a.s.l.

Figure 14 Relative sea-level changes in the Nanortalik area during the Lateglacial and Holocene as indicated by isolation and transgression ages of 13 different basins. Altitude errors are listed in Table 1 and age error bars of 2σ are shown as given in Table 2. Note that some age spans are divided into two or three periods. Note also that the transgression for site N29 is dated by two samples on each side of a hiatus and shows a large span for this reason. The transgression age for site N28 is a minimum date, taken from a sample above a hiatus in marine sediments

Table 3 Selected AMS radiocarbon ages from the basins studied by Bennike *et al.* (2002)

Site	Laboratory no.	Depth (cm)	Age ^{14}C yr BP	Calibrated age 2σ (95.4%) OxCal v. 3.9	Material	Comments
N14	Ua-14844	765–771	$11\,665 \pm 125$	14 850–15 050 (2.3 %) 13 150–14 150 (93.1%)	<i>Bryum</i> sp.	Isolation
N18	Ua-15414	367.5–370	$10\,200 \pm 110$	11 250–12 650	<i>Daphnia pulex</i>	Isolation
N24	Ua-15902	262	$10\,015 \pm 120$	11 150–12 150	Bulk	Above isolation
N19	Ua-15417	793–796	9810 ± 175	10 550–12 050	<i>Warnstorfia exannulata</i>	Above isolation
N16	Ua-15412	589–591.5	9240 ± 95	10 610–10 680 10 210–10 600	<i>Batrachium confervoides</i> , <i>Empetrum nigrum</i>	Isolation
N22	Ua-15419	1125–1128	8905 ± 90	9700–10 250	<i>B. confervoides</i> , <i>Hippuris vulgaris</i> , <i>E. nigrum</i> , <i>Bryum</i> sp., <i>W. exannulata</i>	Above isolation
N21	Ua-15418	700–704.5	8930 ± 80	9750–10 240	<i>B. confervoides</i> , <i>E. nigrum</i>	Isolation

From 10 000 years BP and onwards the curve shows a regression that continues until the present. Tarasov and Peltier (2002) compare their modelled relative sea-level curve for south Greenland to a single observation and because this one point does not match their model prediction, they suspect the observation to be erroneous. Their model prediction does not show much resemblance to the observations presented in this

work either, implying that their model needs to be modified. In Bennike *et al.* (2002) the analysis is more extensive for the area because it deals only with southern Greenland. Even though the comparison between the observations and the predictions are unsatisfactory, they conclude that the model underestimates the reduction in ice thickness and that the timing of the recession needs to be considered in more detail. The

analyses imply rapid melting before the earliest isolations and this conclusion agrees well with our observations. Observational data from only one area will not give a unique solution and it is therefore important that more data are collected before new extensive modelling analyses can be made.

Conclusions

Holocene relative sea-level changes in southern Greenland have previously been observed mostly on land and in lakes and they indicate that levels were below present sea-level for the past 10 000 yr. In this paper we present evidence that the local sea-level reached ~ 10 m below highest astronomical tide (slightly lower than 7.8 m b.h.a.t.) in the interval from 8000 to 6000 cal. yr BP. Combined with earlier results we can draw the following conclusions about sea-level changes in the Nanortalik area of southern Greenland:

1. The relative sea-level fall in the early Holocene was rapid from the time the area became ice-free, whereas the relative sea-level rise in the mid- to late Holocene was slower and more gradual.
2. The fall in sea level between 12 000 and 10 200 cal. yr BP shown by Bennike *et al.* (2002) continued until at least 9000 cal. yr BP, by which time sea level reached below -7.8 m b.h.a.t. and continued to fall some time after that. The relative uplift of the area during that time was ca. 12 mm yr^{-1} .
3. Between 8000 and 6000 cal. yr BP, sea level in the Nanortalik area reached its lowest level at around 10 m b.h.a.t.
4. During the mid-Holocene, at or before ca. 5000 cal. yr BP, sea level again reached above -7.8 m b.h.a.t. and continued to slowly rise until the present day. The mean submergence of the area during this time was $1.5\text{--}2 \text{ mm yr}^{-1}$.

Our results explain why Norse ruins are found so close to the present shore (Bak, 1969); because since the Norse people built their houses around 1000 years ago, relative sea level has risen ca. 0.5–1 m. Also, evidence for the presence of Palaeo-Eskimo cultures is extremely rare in southern Greenland. The lack of Palaeo-Eskimo ruin sites is not necessarily evidence of their absence. If these early Palaeo-Eskimos reached Greenland, settlements are likely to be found below present sea level because local sea level has risen 5–6 m since 4000 cal. yr BP. The question remains Did Palaeo-Eskimo cultures reach this part of Greenland? If so, has the evidence been preserved, or have tidal currents and wave action destroyed them?

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