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Chronology of the last recession of the Greenland Ice Sheet

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ABSTRACT: A new deglaciation chronology for the ice-free parts of Greenland, the continental shelf and eastern Ellesmere Island (Canada) is proposed. The chronology is based on a new compilation of all published radiocarbon dates from Greenland, and includes crucial new material from southern, northeastern and northwestern Greenland. Although each date provides only a minimum age for the local deglaciation, some of the dates come from species that indicate ice-proximal glaciomarine conditions, and thus may be connected with the actual ice recession. In addition to shell dates, dates from marine algae, lake sediments, peat, terrestrial plants and driftwood also are included. Only offshore and in the far south have secure late-glacial sediments been found. Other previous reports of late-glacial sediments (older than 11.5 cal. kyr BP) from onshore parts of Greenland need to be confirmed. Most of the present ice-free parts of Greenland and Nares Strait between Greenland and Ellesmere Island were not deglaciated until the early Holocene. Copyright © 2002 John Wiley & Sons, Ltd.

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KEYWORDS: deglaciation; Greenland; ^{14}C dating; Quaternary; Holocene; Last Glacial Maximum.

Introduction

The Greenland Ice Sheet is the only surviving ice sheet in the Northern Hemisphere. However, investigations of landforms and Quaternary deposits show the ice sheet was much more extensive during the last glacial stage, and large parts of the Greenland subcontinent and the adjacent continental shelves around Greenland were glaciated (Funder and Hansen, 1996). During the past decades an increasing amount of data has been collected concerning the chronology of the deglaciation of the ice-free onshore parts of Greenland, and some information from the shelf also is emerging. Therefore, it is appropriate to evaluate these data on a regional scale in order to investigate the marginal changes of the ice sheet during the last termination and the early part of the Holocene. The ice cores from the Greenland Ice Sheet have produced a wealth of information about late Quaternary climatic and environmental changes, but these investigations do not throw much light on the marginal changes of the ice sheet.

Most onshore evidence comes from dated shells collected from raised marine, littoral and deltaic deposits, but additional evidence is provided by lake sediment cores and organic detritus from raised deltas. The meagre offshore evidence comes primarily from basal dates of marine sediment cores. The number of radiocarbon dates from Greenland has steadily been increasing over the past years, and more than 2000 samples have now been dated. However, only a fraction of these pertain to the chronology of the last deglaciation.

Some of the results of the ^{14}C data compilation appear in Figure 1; this shows a selection of some of the most important dates. The ice-free onshore part of Greenland is relatively well covered, although only few dates are available from southeast Greenland and Melville Bugt (Fig. 2). The dates presented are the oldest ones available from each area, and they provide a minimum age for local deglaciation. Some shell faunas are dominated by the small bivalve *Portlandia arctica* and can be characterised as ice-proximal glaciomarine, but most of the dated faunas are dominated by the bivalves *Hiatella arctica* and/or *Mya truncata*, which are widespread in the arctic (Dyke *et al.*, 1996). There are only few data points from the Greenland shelf, which partly reflects the lack of investigation, and partly the lack of Late Quaternary sediments containing datable material.

The term 'late-glacial' is used for the later part of the last glacial stage, corresponding to Greenland Interstadial 1 and Greenland Stadial 1 (Björck *et al.*, 1998b). This interval is dated by Björck *et al.* to 11 500–14 700 GRIP ice-core yr BP. The term the 'last glacial stage' corresponds to marine oxygen isotope stages 2–5d, the Weichselian of northwest Europe and the Wisconsinan of North America.

Methods

The radiocarbon dates have been normalised for isotopic fractionation and corrected for the marine reservoir effect.

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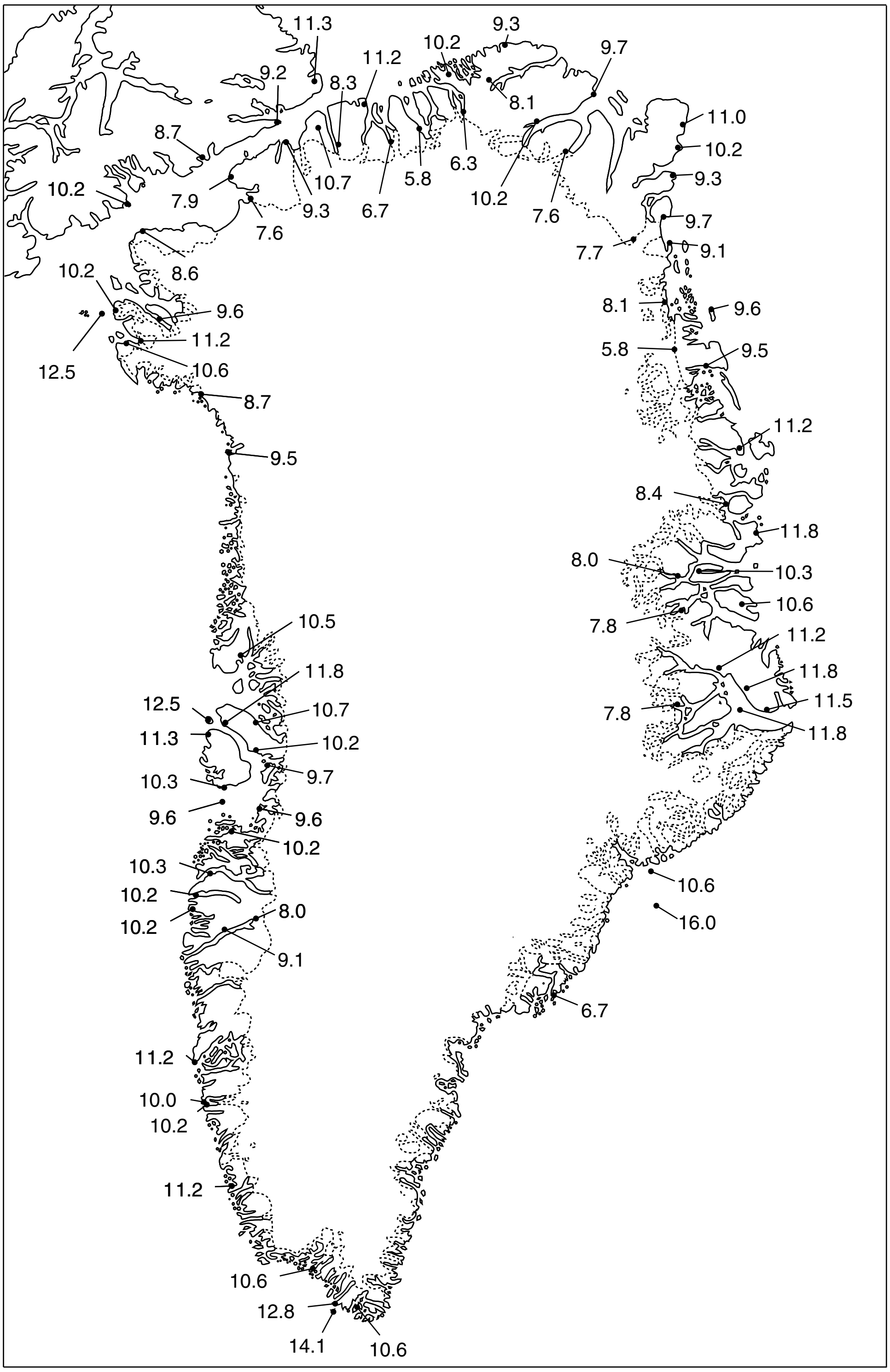

Figure 1 Distribution of oldest radiocarbon dates pertaining to the last deglaciation of the ice-free parts of Greenland, the continental shelf and eastern Ellesmere Island. Dates are given in cal. kyr BP (calibrated thousand years before present). For details, see Table 1

This was followed by calibration into calendar years before present (cal. yr BP) using the INTCAL98 data set and the 10-yr terrestrial calibration curve (Stuiver *et al.*, 1998). A standard reservoir age of 400 yr has been used for west Greenland, which is influenced by the West Greenland Current, and an age of 550 yr has been used for north and east Greenland and northern Ellesmere Island, which are influenced by the Transpolar Drift and the East Greenland Current (Tauber and Funder, 1974; Funder, 1982; Mörner and Funder, 1990). These figures commonly have been adopted by Quaternary scientists working on marine dates from Greenland, but it is clear that spatial and temporal differences are to be expected.

Description of selected regions

Nioghalvfjerdsfjorden

This fjord in northeast Greenland is covered presently by a floating outlet glacier 80 km long, but the presence of raised

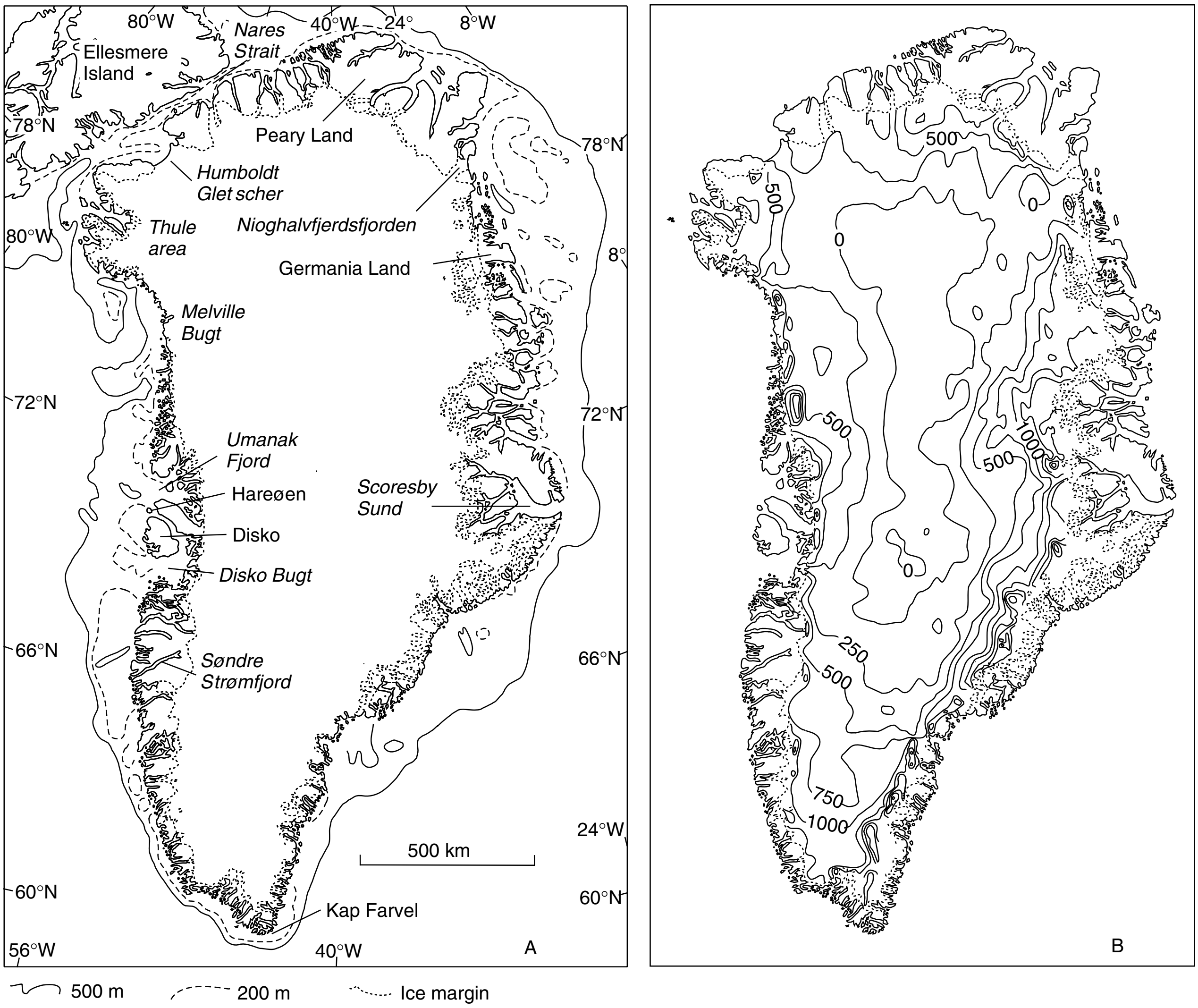

Figure 2 (A) Map of Greenland showing the location of place names mentioned in the text, and the 200 and 500 m depth contours on the shelf offshore Greenland. (B) Map of Greenland showing the topography of the terrain below the ice sheet based on airborne radar ice-thickness data (without any isostatic adjustment). Contour interval 250 m. Modified from Escher and Pulvertaft (1995)

marine deposits along the shores of the fjord shows that it was formerly ice-free. Numerous radiocarbon dates have been obtained from this region, and they show that the outer part of the fjord was free of glacier ice prior to 9.7 cal. kyr BP (Fig. 1), whereas the inner part of the fjord was deglaciated prior to 7.7 cal. kyr BP, corresponding to a mean recession rate of 30–40 m yr^{-1} (Bennike and Weidick, 2001). The deglaciation of the outer part of the fjord is late compared with other outer coast sites of Greenland, which may result from the fact that the shelf is unusually broad. If the shelf, or at least a major part of it, was glaciated during marine oxygen isotope stage 2, it could take a long time before frontal recession brought the ice margin close to the outer coast. This late deglaciation of the outer coast is also apparent for the region south of Nioghalvfjerdsfjorden (Fig. 1), in contrast to the region further north, where the shelf is much narrower (Hjort, 1997). South of Nioghalvfjerdsfjorden, Germania Land became an island during the mid- to late Holocene, when the glaciers west of the land were replaced by a strait (Weidick *et al.*, 1996).

Scoresby Sund

This huge fjord and surroundings have been subject to detailed studies over the past decade (Funder *et al.*, 1998). Although these concentrated on the last interglacial—glacial cycle, the chronology of the last deglaciation also has been investigated. Remains of terrestrial plants sampled from sequences along the north coast of the fjord have given early Holocene dates. The oldest date is 11.8 cal. kyr BP (Table 1), which is pre-Holocene. However, if the standard deviation is taken into account, a Holocene age cannot be excluded. The macroflora from this sample is similar to earliest Holocene floras from the area, and we favour an earliest Holocene age (Bennike *et al.*, 1999). Lake Boksehandsken, an isolation basin north of Scoresby Sund, contains a complex stratigraphy (Björck *et al.*, 1994a). Although the chronology of this succession is uncertain, it was concluded that the deglaciation of the area could not be much older than 11 500 cal. yr BP.

A marine sediment core raised from the bottom of the Scoresby Sund fjord has given a date of $10\,760 \pm 180$ ^{14}C yr BP (AAR-202; Marienfeld, 1991). If corrected for the standard marine reservoir effect of 550 yr this also could indicate a pre-Holocene age ($10\,210 \pm 180$ ^{14}C yr BP, or ca. 11.8 cal. kyr BP, Table 1). However, it has been demonstrated that the reservoir effect in the eastern Greenland Sea was larger than today during the Younger Dryas and the early Holocene (Haflidason *et al.*, 2000). In addition, when taking the precision of the dating into account, an earliest Holocene age cannot be excluded. Another marine

Table 1 Radiocarbon ages from Greenland and Ellesmere Island

Age, ^{14}C yr BP	Reservoir corrected yr BP[a]	Calibrated age, kyr BP[b]	Laboratory reference	Material[c]	Latitude	Longitude	Reference
Greenland, starting in eastern north Greenland and moving clockwise around Greenland							
9160 ± 95	9010	10.2	K-4031	Pa	82°09′	29°38′	Bennike, 1987
7280 ± 90	6730	7.6	HAR-3563	Mt	81°34′	27°14′	Funder, 1982
8890 ± 120	8740	9.7	K-4125	Ha	82°24′	21°10′	Funder and Abrahamsen, 1988
10 100 ± 90	9550	11.0	Lu-2574	Ha, Mt	81°10′	14°	Håkansson, 1987; Hjort, 1997
11 350 ± 100[d]	10 800	12.9	Lu-2569	Ha, Mt	81°10′	14°	Håkansson, 1987; Hjort, 1997
9080 ± 110	9080	10.2	Lu-3782	Shells	80°55′	15°	Hjort, 1997
8290 ± 80	8290	9.3	Lu-3702	Shells	80°25′	16°	Hjort, 1997
7810 ± 55	7260	8.1	T-11 769	Mt	82°54′	36°09′	Landvik *et al.*, 2001
6030 ± 80	5480	6.3	Ua-4587	Ha	82°16′	39°59′	Landvik *et al.*, 2001
7480 ± 170	6930	7.7	Ua-10 557	Ha	79°35′	21°41′	Bennike and Weidick, 2001
9280 ± 55	8730	9.7	AAR-3840	Pa	79°45′	18°52′	Bennike and Weidick, 2001
8700 ± 70	8150	9.1	AAR-3841	Mt	79°14′	19°06′	Bennike and Weidick, 2001
7855 ± 65	7305	8.1	AAR-4703	Pa	77°59′	21°27′	Bennike and Weidick, 2001
8765 ± 100	8655	9.6	T-9365	Mt	77°50′	17°38′	Landvik *et al.*, 1994
5180 ± 95	5030	5.8	K-6098	Mt, Ha	77°10′	21°59′	Weidick *et al.*, 1996
8605 ± 90	8495	9.5	Tua-124	Np	76°56′	20°15′	Landvik *et al.*, 1994
10 260 ± 105	9710	11.2	Ua-2787	Pa	75°20′	*c.* 20°	Björck *et al.*, 1994b
7795 ± 125	7645	8.4	I-9659	Mt, Ha	74°21′	21°52′	Weidick, 1978
10 720 ± 150	10 170	11.8	Lu-882	Mt, Ha	73°33′	20°45′	Håkansson, 1975
10 280 ± 130	9730	10.3	UtC-7465	Shells	73°20′	25°12′	Wagner, 2000
7360 ± 115	7210	8.0	I-9104	Mt, Ha	73°21′	26°28′	Weidick, 1977
7530 ± 75	6980	7.8	Lu-1070	Ha	72°43′	26°50′	Håkansson, 1976
9980 ± 95	9430	10.6	Lu-712	Ha	72°30′	23°05′	Håkansson, 1974
9900 ± 120	9750	11.2	K-1915	Ha, Mt	71°21′	24°50′	Funder, 1978
10 130 ± 130		11.8	AAR-2540	Po	70°51′	24°01′	Bennike *et al.*, 1999
10 160 ± 145	10 010	11.5	K-3109	Mt	70°30′	23°27′	Funder, 1990
10 760 ± 180	10 210	11.8	AAR-202	Forams	70°41′	25°00′	Marienfeld, 1991
7140 ± 130	6990	7.8	I-5421	Mt	70°57′	28°09′	Funder, 1978
9975 ± 100	9425	10.6	AA-1158	Forams	68°07′	31°26′	Manley and Jennings, 1996
13 830 ± 270	13 280	16.0	AA-29204	Forams	67°17′	30°58′	Smith and Licht, 2000
5905 ± 65		6.7	GrN-7027	Peat	65°36′	37°39′	Bick, 1978
9210 ± 140		10.6	K-1872	Lake gyttja	59°58′	44°21′	Fredskild, 1973
11 995 ± 130		14.1	Ua-14 845	Marine algae	59°58′	44°58′	Bennike *et al.*, in press
10 745 ± 100		12.8	Ua-14 888	Bryophytes	60°05′	45°09′	This study
9410 ± 125		10.6	I-7664	Driftwood	60°56′	46°03′	Weidick, 1975b
9840 ± 170		11.2	K-1149	Lake gyttja	62°06′	49°37′	Tauber, 1968
9030 ± 125	9030	10.2	I-7616	Mt	63°26′	51°12′	Weidick, 1975b
13 380 ± 175[d]	13 380	16.1	I-7624	Mt	63°31′	51°19′	Weidick, 1975a
9320 ± 90	8920	10.0	AAR-6827	Mt	63°31′	51°19′	This study
9860 ± 140	9860	11.2	I-8565	Ha	64°18′	52°04′	Weidick, 1976
8150 ± 60		9.1	UtC-5618	En, Ca	66°40′	51°58′	Willemse, 2000
7140 ± 130	7140	8.0	K-1664	Bb, Mt	67°00′	50°41′	Weidick, 1972
9070 ± 160	9070	10.2	K-1377	Mt	66°57′	53°41′	Weidick, 1972
9090 ± 140	9090	10.2	K-1549	Bb	67°19′	53°49′	Kelly, 1973
9180 ± 195		10.3	I-10288	Lake gyttja	67°26′	53°38′	Kelly, 1979
8970 ± 170	8970	10.2	Hel-362	Ha	68°36′	52°34′	Donner and Jungner, 1975
11 320 ± 140[d]		13.2	K-5133	Lake gyttja	68°26′	52°57′	Fredskild, 2000
8680 ± 130	8680	9.6	K-2023	Cc, Pa, Mc	69°01′	51°08′	Weidick, 1974
8820 ± 100		9.7	Beta-107 879	Lake gyttja	69°46′	51°15′	Long *et al.*, 1999
8940 ± 170	8940	10.2	K-994	Ha	70°04′	52°06′	Weidick, 1968
9090 ± 90	8690	9.6	RCD-21	Ha, Mt	68°59′	53°19′	Bennike *et al.*, 1994
9650 ± 250	9240	10.3	AAR-5	Shells	69°17′	53°28′	Ingólfsson *et al.*, 1990
9920 ± 150	9920	11.3	I-16393	Ha, Mt	70°16′	54°37′	Bennike *et al.*, 1994
10 470 ± 130	10 470	12.5	Ua-1789	Mt	70°23′	54°57′	Bennike *et al.*, 1994
10 160 ± 75[e]		11.8	AAR-3496	Bryophytes	70°28′	54°02′	Bennike 2000
9510 ± 150	9510	10.7	K-1547	Ha	70°40′	52°25′	Śimonarson, 1981
9730 ± 60	9330	10.5	AAR-3131	Pa	71°46′	50°53′	Bennike 2000
8540 ± 120		9.5	K-3276	Lake gyttja	75°22′	58°36′	Fredskild, 1985
7910 ± 90	7510	8.7	HAR-2950	Mt, Ha	76°16′	62°14′	Kelly, 1980
9385 ± 145	9385	10.6	I-9663	Mt	76°27′	69°35′	Weidick, 1978
9880 ± 500	9880	11.2	M-273	Mar. algae	76°39′	67°60′	Crane and Griffin, 1959
10 930 ± 105	10 530	12.5	Ua-3366	Forams	76°48′	71°52′	Blake *et al.*, 1996
9150 ± 60	9150	10.2	T-8722	Ha	76°32′	68°55′	Kelly *et al.*, 1999
8715 ± 140	8715	9.6	I-9691	Ha	77°10′	67°01′	Weidick, 1978
7800 ± 200	7800	8.6	L-1091E	Shells	78°35′	70°46′	Nichols, 1969

Table 1 (*Continued*)

Age, ^{14}C yr BP	Reservoir corrected yr BP[a]	Calibrated age, kyr BP[b]	Laboratory reference	Material[c]	Latitude	Longitude	Reference
7240 ± 65	6690	7.6	AAR-5762	Mt	79° 56	67°17′	Bennike, in press
7580 ± 55	7030	7.9	AAR-5760	Ha	80°19′	67°24′	Bennike, in press
8820 ± 75	8270	9.3	AAR-5768	Ha	81°11′	63°21′	Bennike, in press
9580 ± 140	9430	10.7	GSC-3744	Shells	81°42′	59°36′	England, 1985
8060 ± 170	7510	8.3	HAR-6294	MtHa	81°33′	58°02′	Kelly and Bennike, 1992
10 030 ± 175	9880	11.2	K-4339	Pa	82°18′	55°04′	Kelly and Bennike, 1992
6480 ± 100	5930	6.7	HAR-6287	Mt	81°31′	51°05′	Kelly and Bennike, 1992
5180 ± 90	5030	5.8	K-4381	HaMt	81°50′	46°56′	Kelly and Bennike, 1992
9700 ± 100	9150	10.2	Ua-260	Ha	83°03′	43°24′	Kelly and Bennike, 1992
6030 ± 80	5480	6.3	Ua-4587	Ha	82°16′	39°59′	Landvik *et al.*, 2001
8450 ± 120	8300	9.3	K-3287	Mt, Ha	83°39′	33°31′	Funder, 1982
7260 ± 55	7810	8.1	T-11 769	Mt	82°54′	36°09′	Landvik *et al.*, 2001
5480 ± 80	6030	6.3	Ua-4587	Ha	82°16′	39°59′	Landvik *et al.*, 2001
Eastern Ellesmere Island, south to north							
9010 ± 150	9010	10.2	TO-226	Mc	78°36′	74°45′	Blake, 1992
8050 ± 90	7900	8.7	TO-3450	Shells	80°10′	71°11′	England, 1996
8380 ± 105	8230	9.2	DIC-737	Shells	81°33′	64°30′	England, 1983
10 100 ± 210	9950	11.3	GSC-1815	Pa	82°27′	62°40′	England, 1977

[a] Shell dates from the laboratories K, T, Tua, I, Hel, L, GSC, TO and DIC are corrected for isotopic fractionation by normalising to $\delta^{13}C = 0.0$‰ on the PDB scale, whereas shell dates from the other laboratories, are normalised to a base of $\delta^{13}C = -25$‰ PDB. The seawater reservoir corrections used for the two data sets are 0 and −400 yr in west Greenland and −150 and −550 yr in north and east Greenland and northeast Ellesmere Island.
[b] Calibrated according to CALIB 4.0 (Stuiver *et al.*, 1998).
[c] Pa = *Portlandia arctica*, Mt = *Mya truncata*, Ha = *Hiatella arctica*, Np = *Nuculana pernula*, Po = *Polytrichum* sp., En = *Empetrum nigrum*, Ca = *Carex* sp., Bb = *Balanus balanus*, Cc = *Clinocardium ciliatum*, Mc = *Macoma calcarea*, Sg = *Serripes groenlandicus*, Am = *Astarte montagui*.
[d] Considered dubious and thus not included in Fig. 1.
[e] Perhaps subject to some hard-water effect.

core yielded a date some hundred years younger (Marienfeld, 1991).

These are the only two radiocarbon dates from the Scoresby Sund area that could provide direct dating evidence for a pre-Holocene age of the last deglaciation. However, the dated interval from the marine cores from Scoresby Sund is underlain by a unit of laminated sediments, and Marienfeld (1991) suggested that this unit was formed during an extended time period of perennial sea ice, which he correlated with the Younger Dryas cooling. The laminated sediments are underlain by homogeneous sediments, which were referred to the Allerød. Thus it was suggested that the outer part of the fjord was deglaciated during the Allerød (Marienfeld, 1991; Dowdeswell *et al.*, 1994; Funder *et al.*, 1998). It should, however, be stressed that there is no solid dating evidence for such an early deglaciation.

Kap Farvel area

The southern tip of Greenland, at 60° north, is situated so far south in the Atlantic Ocean that it must have been strongly influenced by the marked warming that brought an end to Greenland stadial 2, GS-2 (Björck *et al.*, 1998b). In addition, the shelf here is narrow and the ice-free land area relatively small, which taken together would suggest that the area was free of glacier ice early. In 1999 we cored a number of softwater lake basins (Bennike and Björck, 2000), and subsequent extensive accelerator mass spectroscopy (AMS) radiocarbon dating, mainly on aquatic bryophytes, has shown that five of the basins contain late-glacial sediments. The oldest sequence was found in an isolation lake on a small island off the mainland coast, where sediments date back to 14.1 cal. kyr BP (Table 1). The other records are older than 10 ^{14}C kyr BP and extend back into the Younger Dryas cold period. This is the first time that late-glacial lake sediments have been securely demonstrated on Greenland, in spite of many previous attempts to locate such records.

Seven isolation basins have been sampled in this area, and an emergence curve has been constructed (Bennike *et al.*, in press). The glacio-isostatic rebound was around 110 m. Modelling of the sea-level data indicates that the margin of the Greenland Ice Sheet extended out to the edge of the shelf, and that the ice thickness was at least 1500 m over the outer coast.

Disko Bugt and West Greenland

This large bay in central West Greenland appears to have been deglaciated later than Umanak Fjord to the north and Scoresby Sund in east Greenland (Fig. 1). The oldest date from the mouth of the bay is 10.3 cal. kyr BP (Ingolfsson *et al.*, 1990), whereas from the inner part of the bay the oldest shell sample is 9.6 cal. kyr BP; and the oldest bulk sample of lake sediments is 9.7 cal. kyr BP (Long *et al.*, 1999). These dates are around 2000 yr younger than the oldest dates from Scoresby Sund and about 1000 yr younger than dates from Umanak Fjord. They are also much younger than shell dates from northwest Disko and Hareøen. A single shell sample from the latter site was dated by AMS to 12.5 cal. kyr BP. The reason for the apparently relatively late deglaciation of Disko Bugt could be that a threshold with some groups of islands is found at the entrance to the bay. This threshold may have functioned as a pinning point for the Disko Bugt glacier (Weidick, 1996). Funder and Hansen (1996) argued for an earlier deglaciation of the bay, and suggested that it was largely ice-free by 11.5 cal. kyr BP, but this scenario is not supported by radiocarbon dated material. Although such material provides only minimum dates for the deglaciation, the lack of dates from Disko Bugt, as compared with other regions, is explained most easily if the bay was deglaciated later.

A date of ca. 13.2 cal. kyr BP was reported from an island just south of Disko Bugt by Fredskild (2000). This surprisingly old date was obtained on basal lake gyttja from an isolation basin, and the lake sediments are underlain by marine clay. From what is known about the relative sea-level changes after the last deglaciation in west Greenland it appears that the marine clay is of early Holocene age (Kelly, 1985), and therefore it is highly unlikely that this date can be correct. Recent analyses of lakes below and above the lake investigated by Fredskild suggest that the original chronology requires revision (A. J. Long, University of Durham, personal communication, 2001).

South of Disko Bugt, some of the most extensive ice-free land in Greenland is found, and the fjords are relatively narrow. Therefore the recession of the ice front had to be mainly by ablation rather than calving, and this accounts for the late deglaciation of the inner part of this region. Thus the oldest date from the interior of Søndre Strømfjord is 8.0 cal. kyr BP, whereas a lake situated close to the middle part of the fjord yielded a gyttja date of ca. 9.1 cal. kyr BP (Willemse, 2000). Along the outer coast, the oldest dates are 10.2–10.3 cal. kyr BP. These dates correspond to a mean recession rate of 50–60 m yr^{-1}.

Further south in west Greenland, an old and aberrant date of ca. 16.1 cal. kyr BP has been obtained (Weidick, 1975a, I-7624: $13\,380 \pm 175$ ^{14}C yr BP). A recent AMS dating of a single *Mya truncata* shell from the sample (GGU 157315) yielded an age of 9320 ± 90 ^{14}C yr BP (Table 1), which is in good agreement with other dates from the outer coast of this region (Fig. 1). We suggest that the previous date is erroneous. Other erroneous dates were produced by Telydone Isotope (I-xx) on Greenland shell material in the 1970s (Funder, 1977).

Nares Strait

It has long been known that the northern entrance to Nares Strait was ice-free early, with the oldest shell dates from the Canadian and Greenland sides of 11.3 and 11.2 cal. kyr BP respectively (England, 1977, 1999; Kelly and Bennike, 1992, Fig. 1). From the southern entrance the oldest date from onshore deposits is 10.2 cal kyr BP (Blake, 1992).

The oldest date from the Thule area, south of Nares Strait, is ca. 11.2 cal. kyr BP, but this is an old date with a large standard deviation (Crane and Griffin, 1959). More recent radiocarbon dates show somewhat younger ages from this area (Weidick, 1978; Mörner and Funder, 1990).

The oldest date from the central part of Nares Strait comes from the Canadian side and is 8.7 cal. kyr BP (England, 1996; Fig. 1), and at this time the strait had begun to function. This estimate is in agreement with that arrived at by England (1999). On the Greenland side, recent field work in Washington Land failed to produce samples older than 7.9 cal. kyr BP (Bennike, in press, Fig. 1), and it appears that the region in front of Humboldt Gletscher was among the last to be deglaciated near the outer coast of Greenland. This may reflect the fact that Humboldt Gletscher is one of the largest outlet glaciers from the Greenland Ice Sheet. In central north Greenland, the inner parts of the fjords became ice free considerably later than in the Thule area (Fig. 1).

Peary Land

From northwestern and southern Peary Land, dates on marine shells of 10.2 cal. kyr BP provide minimum dates for the deglaciation of these areas. In southern Peary Land, evidence for a readvance or halt in the deglaciation is provided by a gap in the radiocarbon dates between 10.2 and 8.6 cal. kyr BP (Bennike, 1987). Along the north coast of Peary Land, the occurrence of erratic boulders and landforms has been interpreted as the result of an eastward moving ice shelf, either formed from local sources (Funder and Larsen, 1982), or formed by coalescent ice from Ellesmere Island and Greenland (Dawes, 1986). The oldest dates from the inner fjords of western Peary Land are 8.1 and 6.3 cal. kyr BP (Landvik *et al.*, 2001), which corresponds with other dates from the inner fjords of North Greenland (Funder, 1982; Kelly and Bennike, 1992).

The Greenland shelf

Information about the Quaternary deposits on the extensive shelf areas around Greenland is limited. However, a number of sediment cores have been collected off East Greenland. Several cores from the continental slope off northeast Greenland contain foraminiferal faunas from the late-glacial, whereas no late-glacial or glacial faunas have been recovered from the shelf (Nam *et al.*, 1995; Notholt, 1998). This could indicate that the grounded Greenland Ice Sheet margin reached out on the shelf during marine oxygen isotope stage 2.

Off southeast Greenland a larger number of sediment cores have been obtained from the fjords, continental shelf and slope, and ca. 125 radiocarbon dates are now available (Kaufman and Williams, 1992; Mienert *et al.*, 1992; Manley and Jennings, 1996; Andrews *et al.*, 1997; Smith and Licht, 2000). The oldest well-constrained basal date from a shelf core is 16.0 cal. kyr BP (Table 1; Smith and Licht, 2000), but none of the shelf cores penetrated secure till. However, the lack of older dates and sediments has been taken as an indication that the shelf was covered by an extended, grounded Greenland Ice Sheet prior to 17 cal. kyr BP (Mienert *et al.*, 1992). Only few radiocarbon dated sediment cores are available from the west Greenland shelf. Off Thule a marine sediment core (core 012P), which was collected at a water depth of 823 m, contains a laminated clay unit with foraminifers dated to ca. 12.5 cal. kyr BP, corresponding to the Younger Dryas cool period (Blake *et al.*, 1996; Levac *et al.*, 2001). The laminated clay unit overlies a compact diamicton.

Discussion and conclusion

According to different proxy records from around the North Atlantic, notably the oxygen isotope records from the Greenland ice-cores, very rapid and dramatic temperature increases occurred around 14.7 and 11.5 cal. kyr BP (Björck *et al.*, 1998b). Although this probably led to increased ablation of the Greenland Ice Sheet, it is uncertain how this warming influenced the deglaciation rate of this predominantly land-based ice sheet. It did, however, result in flourishing plant and animal life. It may, therefore, be that ages obtained on terrestrial plant remains, for example from the Scoresby Sund area that are dated to around 11.5 cal. kyr BP, reflect the spread of plant life over the terrain rather than large-scale deglaciation. Records from the continental shelf and slope off east Greenland, however, show the existence of fairly rich faunas and floras during the late-glacial (Williams, 1993; Nam *et al.*, 1995; Notholt, 1998), indicating a restricted impact on the marine biotas from the nearby ice-sheet margin.

The only unambiguous late-glacial sediments so far located in Greenland come from the Kap Farvel area in the far south. Earlier records of late-glacial sediments need to be confirmed. Conventional radiocarbon dating of marine shells is problematic, because many shells are required for one dating; and consequently shells dated by this method can represent a mixture of shells of different ages. Furthermore, dating of marine shells in general, including single shells, may be problematic owing to the unresolved temporal and spatial variations of the reservoir effect. These effects may be especially accentuated in glaciomarine environments, such as the Greenland fjords and continental shelf. Dates on bulk lake sediments from areas with old organic carbon or carbonate bedrock are often too old (e.g. Björck *et al.*, 1994a,b), and even lake sediments from softwater lakes can produce dates that are too old (Björck *et al.*, 1998a). Thus except for the Kap Farvel, there is no secure dating evidence for late-glacial deglaciation of the onshore parts of Greenland. However, it must be remembered that the dates provide only minimum ages for the deglaciation. The lack of reliable late-glacial dates could be explained, in part, if conditions were too harsh for plant and animal life. Maybe the glacial climate restricted biological productivity to such an extent that organic remains for radiocarbon dating are missing.

Our findings are consistent with other studies from the Arctic. Thus, during the past decades, it has become clear that the Barents Sea–Svalbard region was covered by an ice sheet during marine oxygen isotope stage 2 (Landvik *et al.*, 1998). Another formerly debated region, the northern part of the Canadian Arctic Archipelago in northern Canada, was also covered by an ice sheet—the Innuitian Ice Sheet (Blake, 1992; England, 1999; Dyke, 1999). The latter ice sheet coalesced with the Greenland Ice Sheet, as indicated by the decreasing ages from the northern and southern entrances of Nares Strait to its central part, the large emergence, by surface exposure dating using cosmogenic ^{36}Cl (Zreda *et al.*, 1999), by fresh glacial sculptures and moraines along Nares Strait and the lack of dates between 19 and ca. 10 ^{14}C kyr BP (Bennike *et al.*, 1987; Blake *et al.*, 1992; Kelly and Bennike, 1992; England, 1999). The location of the margin of the southward glacier that drained Nares Strait is debated (Blake *et al.*, 1996, Kelly *et al.*, 1999). Baffin Island in the eastern Canadian Arctic also may have been glaciated more extensively than previously believed (Marsella *et al.*, 2000). Further south, studies of the submarine Quaternary geology off Newfoundland indicate that grounded ice extended to the shelf edge during the Last Glacial Maximum, in contrast to earlier reconstructions where the ice margin was placed just offshore from the coast (Shaw *et al.*, 2001).

One argument that has been used against such extensive glaciations in the far north is that these regions would be too arid for ice sheets to develop (e.g. England, 1976). However, data from the Nordic Seas now indicate that open water was more widespread than formerly believed during marine oxygen isotope stage 2 (e.g. Sarnthein *et al.*, 1995). Thus moisture and precipitation may have been rather high along the marginal parts of the ice sheet, which in combination with low air temperatures (Dahl-Jensen *et al.*, 1998) would enhance growth of glaciers.

Although few data are available from the Greenland shelf, we also suggest that this was rather extensively glaciated during the Last Glacial Maximum. Models for the extent of the Greenland Ice Sheet during the Last Glacial Maximum have, to a large degree, been based on weathering zones, but it is becoming increasingly clear that old landforms and deposits can survive glaciations by cold-based ice frozen to its bed (e.g Lagerbäck and Robertsson, 1988; Kleman and Stroeven, 1997; Kleman and Hattestrand, 1999). Thus in north east Greenland we feel inclined to place the Last Glacial Maximum off Nioghalvfjerdsfjorden at the continental shelf edge. In this context it may be mentioned that a small island was discovered recently on the shallow shelf off Nioghalvfjerdsfjorden (Bennike and Weidick, 2001). On this island, a small local ice cap occurs, and one can speculate that if local ice built up on the shelf, it might become confluent with the Greenland Ice Sheet. If unglaciated, parts of this shallow shelf area probably would be dry land during the low global sea-level of the Last Glacial Maximum. For this area we suggest a more extensive glaciation of the shelf than suggested by Funder and Hansen (1996), who place the Last Glacial Maximum limit offshore but close to the present outer coast. In central east Greenland, the Last Glacial Maximum limit was also placed close to the present outer coast by Funder *et al.* (1998). However, very large differences are seen both in the offshore bathymetry and in the subice topography between these regions. At Nioghalvfjerdsfjorden, the shelf is much broader and shallower than further south, and the substratum of the Greenland Ice Sheet situated at or below present sea-level, whereas central east Greenland is shielded from the present margin of the ice sheet by high mountains (Fig. 2). These differences may explain why older deglaciation dates have been obtained in central east Greenland than further north (Fig. 1).

Evidence from southernmost Greenland suggests that the ice margin reached the edge of the shelf during the Last Glacial Maximum, and along west Greenland a similar picture could well be envisaged. Only limited shallow seismic and coring data are available from the shelf off west Greenland, but new seismic data appear to support a scenario where grounded ice extended to the shelf edge during the Last Glacial Maximum (J.B. Jensen, personal communication, 2001).

Our compilation of radiocarbon dates suggests that the cover by glacial ice over Greenland during the later part of the last glacial stage and the early Holocene was more extensive than formerly suggested. We propose that the central east Greenland sector of the ice sheet may have behaved differently from that in southeast Greenland and in northeast Greenland, in part owing to topographical differences.

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