JOURNAL OF QUATERNARY SCIENCE (2001) **16** (4) 353–363

DOI: 10.1002/jqs.614

Sea-surface conditions in northernmost Baffin Bay during the Holocene: palynological evidence

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Levac E., de Vernal A. and Blake, W. Jr. 2001. Sea-surface conditions in northernmost Baffin Bay during the Holocene: palynological evidence. *J. Quaternary Sci.*, **Vol. 16**, pp. 353–363. ISSN 0267-8179.

Received 26 July 2000; Revised 15 December 2000; Accepted 9 January 2001

ABSTRACT: The analysis of cores collected in northernmost Baffin Bay, from within the area of the North Water Polynya, permits definition of a composite sedimentary sequence ca. 12 m thick spanning the last 10 000 ^{14}C yr, with only a few discontinuities. Palynological analyses were performed in order to reconstruct changes in surface water conditions and biogenic production. Transfer functions, using dinocyst assemblages, were applied to estimate sea-surface temperature (SST) and salinity, as well as the seasonal duration of sea ice cover. At the base of the record, prior to 9300 ^{14}C yr BP, dinocysts and organic linings of benthic foraminifers are sparse, indicating harsh conditions and low productivity. After ca. 9300 ^{14}C yr BP, the increased concentration of benthic foraminifers (up to 10^3 linings cm^{-3}) and dinocyst fluxes (10^2–10^3 cysts cm^{-2} yr^{-1}) reveals high biological productivity related to open-water conditions. The early to middle Holocene, from ca. 9000 to ca. 3600 ^{14}C yr BP, is marked by relatively high species diversity in dinocyst assemblages and the significant occurrence of autotrophic taxa such as *Spiniferites elongatus*, *Pentapharsodinium dalei* and *Impagidinium pallidum*. This assemblage suggests conditions at least as warm as at present. From ca. 6400 to ca. 3600 ^{14}C yr BP, transfer functions indicate warmer conditions than at present, with SST in August fluctuating up to 5.5°C. After 3600 ^{14}C yr BP, the dinocyst record suggests a trend of decreasing temperature toward modern values, marked by recurrent cooling events. Copyright © 2001 John Wiley & Sons, Ltd.

Journal of Quaternary Science

KEYWORDS: sea-surface; Baffin Bay; Holocene; polynya; palynology; transfer function.

Introduction

Polynyas constitute marine ecosystems of polar seas that experience seasonal or year-round ice-free conditions within areas usually covered by sea ice (Schledermann, 1980). Polynyas are characterized by a high primary productivity (e.g. Pesant *et al.*, 1996) and might constitute sinks for atmospheric CO_2 (Smith *et al.*, 1997). They provide a feeding source for zooplankton, and are generally characterised by abundant and diverse fauna, including nekton, marine birds and mammals (Stirling, 1980). The faunal resources of polynyas probably played a determinant role with regard to the location of Inuit settlement in the Canadian Arctic (Schledermann, 1980).

The North Water Polynya occupies Smith Sound between Ellesmere Island and Greenland, and extends throughout most of northern Baffin Bay (see Fig. 1). It represents an area of open water of about 80 000 km^2 in summer and constitutes the largest polynya in the Canadian Arctic (Stirling, 1980; Ito, 1982; Steffen and Ohmura, 1985). It was first reported by William Baffin in 1616, and its name was given by the whalers (cf. Dunbar and Dunbar, 1972). Based on instrumental and historical observations, the position of the northern edge of the polynya is relatively stable; in the spring it is situated in southern Kane Basin (Fig. 1). The position of the southern edge varies from year to year. Its geographical limit is difficult to define because there is no clear boundary between the polynya and the gradually

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Contract grant sponsor: Natural Sciences and Engineering Research Council (Canada).
Contract grant sponsor: Fonds pour la Formation de Chercheurs et l'aide à la Recherche (Quebec)
Contract grant sponsor: Stiftelsen Ymer-80 (Stockholm)

(a)

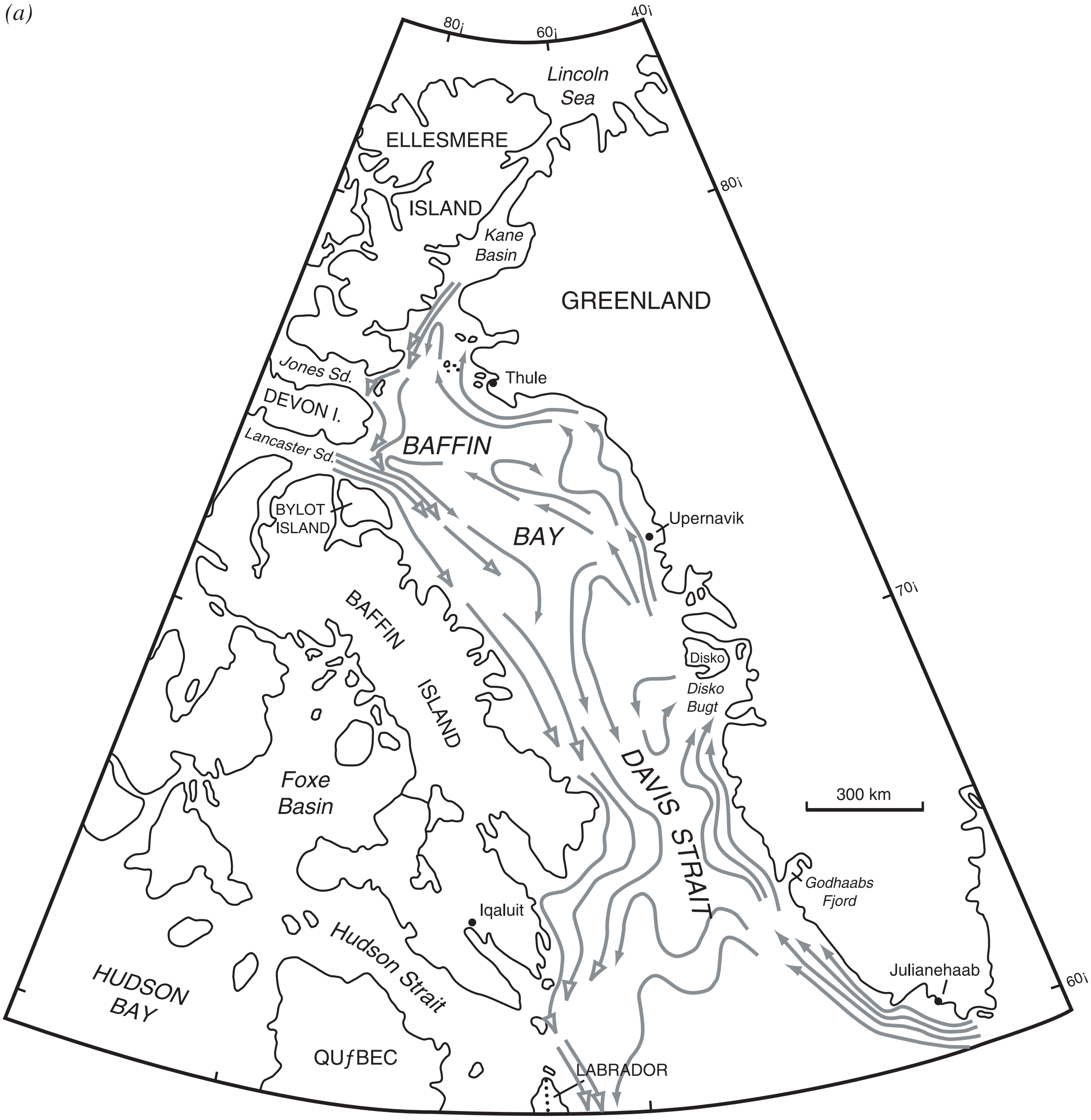

Figure 1 (a) Map of Baffin Bay. Surface water circulation patterns are indicated by arrows, with solid-tipped arrows for the warm West Greenland Current and open-tipped arrows for the cold Baffin Current.

thicker sea ice cover of Baffin Bay (Dunbar and Dunbar, 1972).

The mechanisms responsible for the formation of polynyas are complex (Muench, 1990). In the North Water Polynya, the cells of elevated temperature that are detected by remote sensing appear related to wind-driven upwelling providing heat from deeper waters. In winter, the polynya is occupied by thin and newly formed ice, which is removed regularly by the southward-flowing current and prevailing northerly winds (Stirling, 1980). This causes a deep vertical water convection, and also the thickening of pack ice to the south, in Baffin Bay (Dunbar and Dunbar, 1972). The polynya is truly open by May or June, when the southern limit of open water reaches Bylot Island to the west, and Melville Bay to the east (Dunbar and Dunbar, 1972; cf. also Ito, 1982). In summer, surface temperatures in the polynya reach up to 2.5°C in August, and salinity is established at 32 on average (cf. NODC, 1994).

The biological activity in polynyas has been studied intensively during the past few years through international research programmes, including the North Open Water (NOW) project in the North Water Polynya (cf. NOW Website, 2000). Although the modern ecosystems of polynyas are relatively well documented, little is known concerning their temporal evolution and their stability on secular or millenial scales. Palynological analyses were performed on marine cores collected in northernmost Baffin Bay in order to document the sea-surface conditions in the North Water Polynya region during the Holocene. Palynological assemblages also include different types of marine protist remains, notably organic-walled cysts of dinoflagellates (dinocysts), which relate to primary productivity in the upper water column (e.g. Taylor, 1987). Dinocysts that are composed of highly resistant organic compounds (e.g. Traverse, 1994) are recovered in high numbers in recent sediments of subpolar and polar seas (e.g. Mudie and Short, 1985; Mudie, 1992; Matthiessen, 1995; de Vernal *et al.*, 1997; Kunz-Pirrung, 1998). The distribution patterns of dinocyst assemblages in high-latitude marine environments show close relationships with sea-surface temperature, salinity and sea ice cover. This

(b)

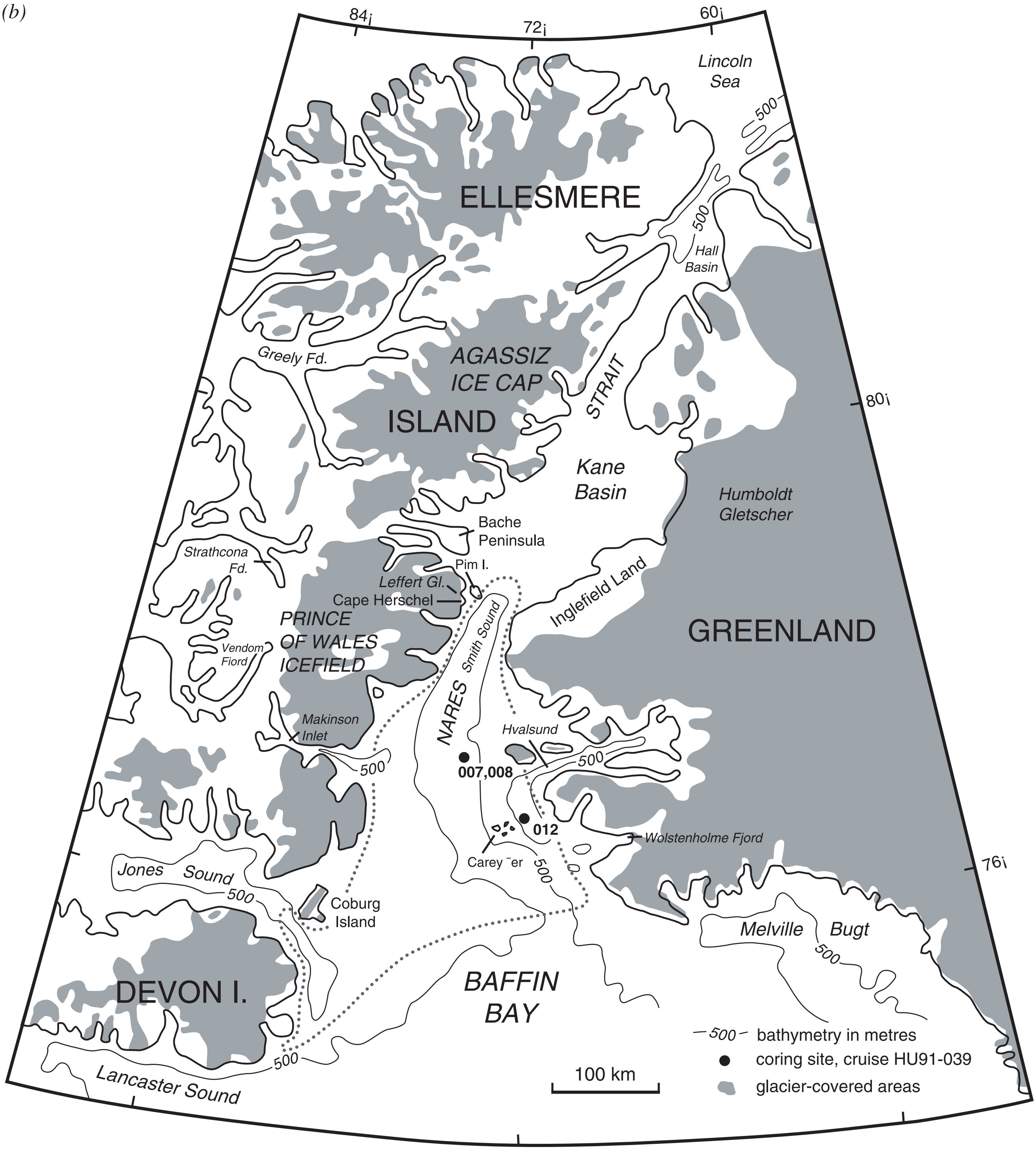

Figure 1 Continued. (b) Location of the coring sites in the northernmost Baffin Bay. The dotted line indicates the modern extent of the North Water Polynya in May after Dunbar and Dunbar (1972).

allows the development of transfer functions for quantitative estimates based on analyses of fossil assemblages (e.g. Rochon *et al.*, 1999). In the present study, emphasis is focused on the dinocyst assemblages, which are used as proxies to reconstruct sea-surface conditions in the northern part of Baffin Bay during the past ten millenia.

Methods

Five cores collected in Greenland waters during C.S.S. *Hudson* cruise 91-039, at sites selected by the third author, were analysed for their palynological content (see Fig. 1b). Piston core 91-039-008P and box core 91-039-007B(C) were obtained at 77°16.0′N, 74°19.9′W in a water depth of 663 m. Trigger weight and piston cores 91-039-012TWC/012P, plus box core 91-039-011B(I) were collected at 76°48.3′N, 71°51.5′W in a water depth of 823 m. Of the two piston cores, 91-039-008P was dominantly a fairly homogeneous olive grey to dark olive grey mud throughout. Core 91-039-012P was composed of similar material down to 180 cm, with a number of clasts below 95 cm. From 190 to 205 cm, it was composed of laminated dark grey clay, with sharp contact to a dark reddish grey diamicton at 205 cm. This unit extended to the base of the core at 233 cm.

Core 91-039-008P and the upper 120 cm of core 91-039-012P were sampled at 20 cm intervals, whereas the lower part of core 91-039-012P and box core 91-039-007B(C) were sampled at 10-cm intervals. Sediment samples of 5 cm^3 were processed for palynological analyses following the standard procedure used at GEOTOP (de Vernal *et al.*, 1996; Rochon *et al.*, 1999). The addition of a calibrated suspension of *Eucalyptus globulus* permitted the evaluation of palynomorph concentrations based on the marker-grains method (Matthews, 1969), which yields results accurate to about 10% for a 0.95 confidence interval (de Vernal *et al.*, 1987). Wet sieving through 10 and 120 μm mesh sieves was done in order to remove coarse sand, fine silt and clay particles. Repeated treatments with HCl (10%) and HF (49%) on the 10-120 μm fraction were carried out to dissolve carbonate and silica particles. Immersion for less than 10 min in KOH (10%) was necessary in order to deflocculate the organic matter. After a last sieving at 10 μm, the residue was mounted between slide and cover slide in glycerine gel.

All palynomorphs recovered in the samples were identified and counted on a transmitted light microscope under ×400 or ×1000 of magnification. They include mainly dinocysts, pollen grains and spores, organic linings of benthic foraminifers and *Halodinium*, which probably belongs to thecamoebiens (cf. de Vernal *et al.*, 1989). Reworked palynomorphs include spores (e.g. *Cicatricosisporites*), pollen (bisaccate and triporate being dominant) and a few dinocysts and acritarchs. These palynomorphs are characterised by a strong diagenetic alteration of the sporopollenin, and they probably are derived from the erosion of Mesozoic and/or Tertiary formations of the surrounding land areas.

Dinocysts were identified to species level using the taxonomical nomenclature described in Rochon *et al.* (1999). In most samples, 300 dinocysts were identified and counted for the calculation of taxa percentages. The dinocyst assemblages allow reconstruction of sea-surface conditions using both modern analogue techniques (see Guiot, 1990) and a reference data base of the middle to high latitudes of the North Atlantic and adjacent subpolar and polar seas (de Vernal *et al.*, 1997; Rochon *et al.*, 1999). The data base, updated in February 2000, includes 540 modern sites representative of a wide range of sea-surface (0 m) conditions, notably with respect to salinity (15 to 36) and sea ice cover (0–12 months yr^{-1}). The environmental parameters that are estimated include: the surface temperature and salinity in August (compiled after the *World Ocean Atlas*, 1994 data set documentation; see NODC, 1994); the seasonal duration of sea ice cover, expressed as the number of months per year with more than 50% of sea ice coverage, after data from Markham (1980) and from the 1953–1960 data set provided by the National Climate Data Center (NCDC) in Boulder. The validation tests yielded accurate results: coefficients of correlation between estimates and instrumental values are greater than 0.93 for all parameters, with more than 95% of reconstructions included within one standard deviation around instrumental data averages. The residuals (i.e. the differences between reconstructions and observations) permit calculation of the degree of accuracy of estimates, which is ±1.7°C for the sea-surface temperature in August, ±0.8 for the salinity (in the $>$25 salinity domain), and ±1.1 month/year for the sea ice cover (see also de Vernal and Hillaire-Marcel, 2000).

Chronostratigraphy of the composite record

Radiocarbon dating of individual pelecypod shells and mixed benthic foraminiferal populations by accelerator mass spectrometry (AMS) provides a chronostratigraphical framework (see Table 1 and Fig. 2). The ^{14}C ages were normalised for a $\delta^{13}C$ of −25‰ and corrected by Kyr^{-1} to account for the air–sea reservoir difference (see Bard, 1988). However, the ages remain approximate because of uncertainties concerning the actual air–sea reservoir difference on a regional scale (see, e.g. Mörner and Funder, 1990; Bard *et al.*, 1994; Austin *et al.*, 1995; Barber *et al.*, 1999; Haflidason *et al.*, 2000). Calibration to calendar years (see Table 1 and Fig. 2) was made using the software CALIB 4.3 for marine carbonate (see Stuiver *et al.*, 1998, 2000) without additional correction for local marine reservoir (i.e., Delta R = 0). Calibrated ages were used to calculate sedimentation rates and reported in Table 1 in order to facilitate comparison with the ice-core chronology. Throughout the present paper, however, we refer to corrected ^{14}C ages in years BP (Figs 3–5), and reference to calendar ages (in ka) is made only for ice-cap core data.

Six age determinations in piston core 91-039-008P reveal a stratigraphy spanning about 6400 to 2400 ^{14}C yr BP (i.e. ca. 7.3 to 2.6 ka). They allow calculation of very high sedimentation rates of about 150 cm kyr^{-1} at the coring site. Seven other ages from core 91-039-012P indicate that deposition commenced at about 10 500 ^{14}C yr BP and continued to 7300 ^{14}C yr BP (i.e. ca. 12.0 to 8.2 ka), with sedimentation rates of about 50 cm kyr^{-1}. Piston cores 91-039-008 and 91-039-012 together comprise a composite record spanning 10 500 to 2400 ^{14}C yr BP, with a possible hiatus between 7300 and 6400 ^{14}C yr BP. A part of the past 2400 ^{14}C yr may be missing from this composite record. Box core 91-039-007, which yielded an age of 320 ^{14}C yr BP at a depth of 14–22 cm, however, represents the latest part of the Holocene. The top of box core 91-039-007 can be assumed to provide a picture of 'recent' palynological assemblages.

Results of palynological analyses

Palynomorph concentration

Palynomorphs are abundant throughout the composite sequence, except in the lower part of core 91-039-012P (Fig. 3). The most abundant palynomorphs in the sediments are dinocysts (up to 30 000 cysts cm^{-3}), organic linings of foraminifers (up to 6000 linings cm^{-3}) and *Halodinium* (up to 7000 individuals cm^{-3}). Reworked palynomorphs of pre-Quaternary age reach maximum concentrations of 2500 individuals cm^{-3}. Pollen and spores are relatively sparse ($<$500 pollen grains cm^{-3} and $<$150 spores cm^{-3}).

The number of pollen grains counted was too low for the calculation of percentages and for an assessment of the regional vegetation. The assemblages include input from the regional vegetation (*Salix*, Ericaceae, Cyperaceae, Poaceae and other vascular plants plus *Sphagnum*), in addition to long-distance contributions from forest or shrub tundra vegetation (*Picea*, *Pinus*, *Betula* and *Alnus*). Such inputs are comparable to the airborne pollen influxes recorded in snow from ice caps in the Canadian Arctic (Lichti-Federovich, 1975; Bourgeois *et al.*, 1985).

Table 1 Radiocarbon age determinations for the composite record of cores 91-039-007, 91-037-008 and 91-039-012

Core	Depth (cm)	Material dated[a]	Apparent ^{14}C ages (yr BP)[b]	Laboratory numbers[c]	Corrected ^{14}C ages (yr BP)[d]	Calibrated ages (ka)[e]
91-039-007C	14–22	Benthic foraminifers	720 ± 85	Ua-10256	320	0.44–0.29
91-039-008P	72–73	*Megayoldia thraciaeformis*	2885 ± 60	Ua-2832	2485	2.73–2.58
91-039-008P	461–464	*Megayoldia thraciaeformis*	4065 ± 50	Ua-2833	3665	4.15–4.00
91-039-008P	527–529	*Megayoldia thraciaeformis*	4190 ± 60	Ua-4118	3790	4.36–4.19
91-039-008P	704–705	*Clinocardium ciliatum*	5110 ± 55	Ua-4450	4710	5.56–5.43
91-039-008P	831–834	*Clinocardium ciliatum*	6675 ± 75	Ua-2834	6275	7.29–7.13
91-039-008P	832–834	Benthic foraminifers	6800 ± 60	Ua-4119	6400	7.37–7.27
91-039-012T	148–153	Benthic foraminifers	4540 ± 65	Ua-11796	4140	4.82–4.65
91-039-012P	15–18	Benthic foraminifers	7755 ± 100	Ua-11797	7355	8.32–8.12
91-039-012P	24–27	Benthic foraminifers	8230 ± 70	Ua-4447	7830	8.81–8.62
91-039-012P	105–108	Benthic foraminifers	9675 ± 110	Ua-4448	9275	10.66–10.24
91-039-012P	117–120	Pelecypod fragments	9885 ± 115	Ua-4449	9485	10.83–10.57
91-039-012P	184–188	Benthic foraminifers	10 930 ± 105	Ua-3366	10 530	12.64–12.27
91-039-012P	188–194	Benthic foraminifers	10 805 ± 145	Ua-3367	10 405	12.37–11.90
91-039-012P	190–195	Benthic foraminifers	10 815 ± 130	Ua-4998	10 415	12.37–11.90

[a]Pelecypods were identified by W. Blake, Jr. Foraminiferas were identified and extracted for dating by K.-L. Knudsen and M.-S. Seidenkrantz, Geological Institute, Aarhus University, Denmark.
[b]This column lists the ^{14}C ages as reported from the laboratory after normalisation for a $\delta^{13}C$ value of −25‰.
[c]AMS dating was carried out at the Tandem Accelerator Laboratory, Uppsala, Sweden, under the direction of G. Possnert.
[d]A correction of 400 yr has been applied to account for the air–sea reservoir difference (see Bard, 1988). Although a reservoir correction of as much as 800 to 1100 yr has been suggested for samples of Younger Dryas age in several areas of the North Atlantic (Bard *et al.*, 1994; Austin *et al.*, 1995; Haflidason *et al.*, 2000), data to permit such correction are not available in northernmost Baffin Bay. In Makinson Inlet, on Ellesmere Island side of the northernmost Baffin Bay, there is excellent agreement between the ages of the marine shell samples and terrestrial *Salix* wood at 8000 ^{14}C yr BP (Blake, 1979).
[e]Calibrations to calendar ages in ka were made using the software CALIB 4.3 for marine carbonate (Stuiver *et al.*, 1998, 2000) with no Delta R reservoir correction. The calibrated ages range is reported after the probability approach taking into account one standard deviation (one sigma; i.e. a confidence interval of 68.3%). Note that calibrated ages reported here differ somewhat from those reported by Blake (1998), which were produced by R.P. Beukens (IsoTrace Laboratory). The earlier calibrations used a Delta R reservoir correction of 328 ± 19 yr according to data sets from Stuiver and Reimer (1993) and Stuiver and Braziunas (1993).

In the lowest part of the sequence (> 9300 ^{14}C yr BP), the palynomorph concentrations are low, suggesting limited biogenic inputs, probably because of harsh environmental conditions with extensive sea ice cover. Presence of clasts in the lowest part of the core also suggest ice-rafting deposition. The early Holocene is characterised by increased concentration of palynomorphs. In particular, concentrations of dinocysts and organic linings of foraminifers increased by about one order of magnitude, indicating significant pelagic and benthic productivity no doubt related to seasonal open-water conditions. Particularly high dinocyst concentrations (10^4 cysts cm^{-3}) and fluxes (> 10^3 cysts cm^{-2} yr^{-1}) are recorded in core 91-039-008, which spans about 6400 to 2400 ^{14}C yr BP. The maximum abundance of dinocysts, recorded between 3600 and 3000 ^{14}C yr BP, coincides with a peak occurrence of *Halodinium*.

The dinoflagellate cyst record

Dinoflagellate cysts assemblages are dominated by *Brigantedinium* spp. and *Algidasphaeridium*? *minutum*, including varieties *cezare* and *minutum* (Fig. 4). The co-dominance of these taxa is characteristic of polar environments marked by extensive sea ice cover (see Mudie and Short, 1985; de Vernal *et al.*, 1992, 1994, 1997; Rochon and de Vernal, 1994; Kunz-Pirrung, 1998; Rochon *et al.*, 1999; de Vernal and Hillaire-Marcel, 2000). The accompanying taxa include *Pentapharsodinium dalei* and species that belong to Gonyaulacales (*Operculodinium centrocarpum, Spiniferites elongatus* s.l., *Impagidinium pallidum* and *Pyxidinopsis reticulata*). The significant occurrence of these accompanying taxa in the early to mid-Holocene part of the record (about 9300 to 3600 ^{14}C yr BP) suggests relatively mild conditions, at least as warm as present, during the summer season. The upper part of the record, corresponding to the late Holocene (< 3600 ^{14}C yr BP), is marked by a diminution of the percentages of Gonyaulacales, and by increased proportions of the Arctic taxa *Algidasphaeridium*? *minutum* var. *cezare*, which together indicate a trend towards colder conditions and more extensive sea ice.

Reconstructions of sea-surface conditions

The quantitative estimates of sea-surface conditions, based on transfer functions using dinocyst assemblages, reveal significant hydrographical changes throughout the sequence (Fig. 5). The lowest part of the dinocyst record, dated before ca. 9300 ^{14}C yr BP and following an episode of almost nil productivity associated with harsh conditions, suggests the presence of an extensive sea ice cover (11–12 months yr^{-1}). Following this interval, from about 9300 to 3600 ^{14}C yr BP, ice-free conditions apparently prevailed for 4 to 5 months per year, with summer temperature at least as warm as present. Sea-surface temperatures of the warmest month

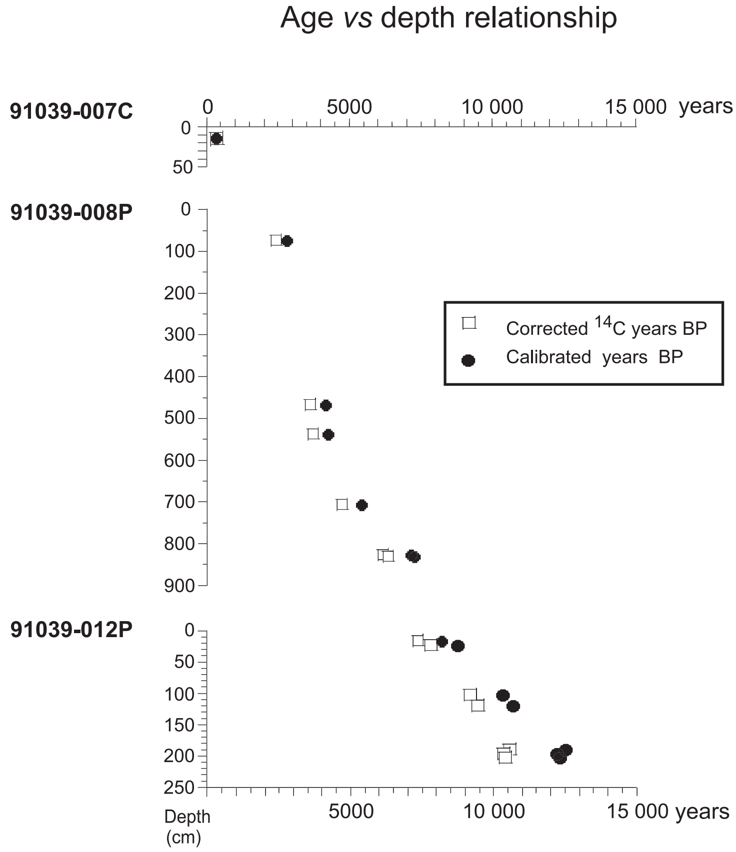

Figure 2 Age versus depth relationships in cores 91-039-08P and 91-039-012P (see Table 1). The ages are reported in conventional ^{14}C years after normalisation to $\delta^{13}C$ of −25‰, with a correction for air–sea reservoir difference of 400 yr. Corresponding calendar ages, calculated using the CALIB 4.2 software (Stuiver *et al.*, 1998, 1999), are reported in Table 1.

varied between 1.0 and 5.5°C. During this interval, salinity fluctuated between 27.0 and 32.0, which is slightly lower than at present, probably as a result of dilution with sea ice meltwater, combined with continued retreat and melting of tidal glaciers around northermost Baffin Bay.

After 3600 ^{14}C yr BP, a cooling towards modern values is recorded. High-frequency variations of temperatures and sea ice cover are superimposed on the cooling trend. For example, three major pulses of sea ice spreading for up to 10–11 months yr^{-1} with August temperature lower than 1°C are recorded between 3600 and 2400 ^{14}C yr BP.

Discussion

The onset of optimal conditions in the early to mid-Holocene

The reconstruction of low productivity in surface water and harsh climatic conditions prior to 9300 ^{14}C yr BP is consistent with results from other studies, which indicate glaciomarine conditions on a regional scale (e.g. Osterman and Nelson, 1989; Zarkhidse *et al.*, 1991; Blake, 1992; England, 1999; Kelly *et al.*, 1999). According to dinocyst assemblages, the amelioration of sea-surface temperatures towards present-day values occurred early during the Holocene, between about 9300 and 8000 ^{14}C yr BP. There are other lines of evidence to support such an early establishment of marine post-glacial conditions. Abundance peaks of planktonic foraminifers in southern Baffin Bay between 9000 and 6000 ^{14}C yr BP indicate an early Holocene penetration of subarctic water into Baffin Bay, in addition to relatively high pelagic productivity (Aksu, 1983). Benthic foraminiferal assemblages also reveal a penetration of relatively warm and saline bottom waters into Baffin Bay, from a southern origin, by about 8500 ^{14}C yr BP (Osterman and Nelson, 1989). Moreover, mollusc fauna collected along the west Greenland coastline indicate the onset of northward flow of the West Greenland Current by about 8400 ^{14}C yr BP (Funder and Weidick, 1991). In addition to evidence from the marine ecosystem, the ice-core record suggests an early warming over Ellesmere Island, as melt layers in Agassiz Ice Cap indicate maximum melting between 9.5 and 8.5 ka on a calendar scale, probably in response to warmer summers than today (Koerner and Fisher, 1990). Pollen concentrations in ice-core from Ellesmere Island also record maximum values during the early Holocene (Bourgeois *et al.*, 2000). This time interval coincides with the maximum summer insolation over high latitudes (Kutzbach and Webb, 1993).

The dinocyst assemblages reveal the establishment of optimal conditions, with sea-surface temperatures 2–3°C warmer than at present by 6400 ^{14}C yr BP, if not earlier. Unfortunatly, a hiatus in the composite record prevents a precise age assessment of the onset of Holocene optimal conditions, which may be associated with the so-called 'Hypsithermal'. As mentioned above, there are other regional palaeoclimatic data indicating an early onset of optimal conditions in the marine ecosystem. However, uncertainties concerning the air versus sea reservoir difference in ^{14}C activities make it difficult to set an absolute chronology from marine carbonates (e.g. Bard, 1988; Barber *et al.*, 1999). The time slice during which optimum conditions prevailed on a regional scale also can be a matter of debate. According to Funder and Weidick (1991), boreal mollusc shells are recorded

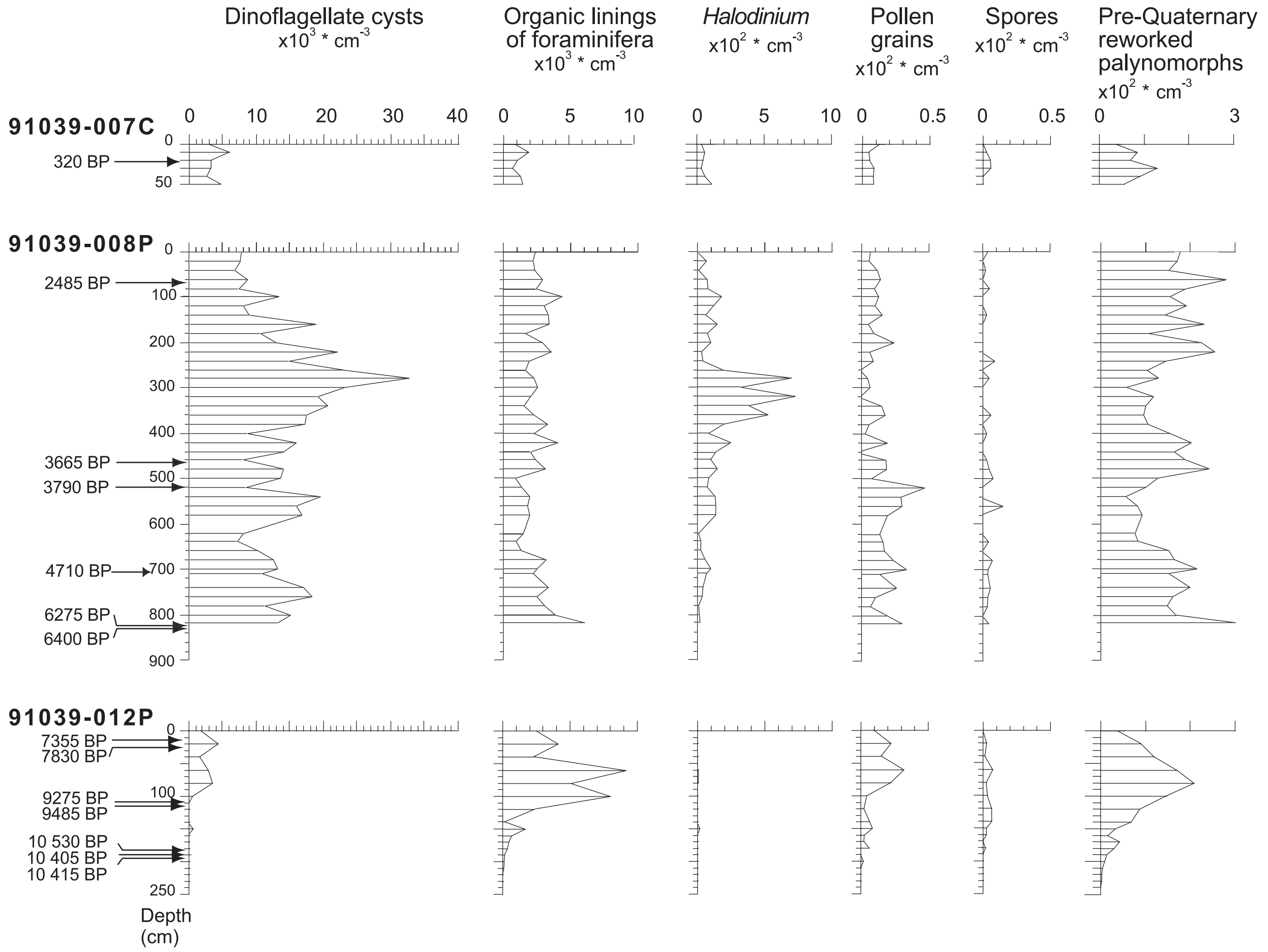

Figure 3 Palynomorph concentrations in the composite record of cores 91-039-007B, 91-039-008P and 91-039-012P. Corrected ^{14}C ages are reported in the left margin of the diagram (Table 1).

along the west coast of Greenland (66° to 69°N) from 8400 to 4900 ^{14}C yr BP, indicating summer surface temperatures 1–3°C higher than today. The occurrence of these taxa also suggests an increased northward flow of Atlantic waters. Despite indications for an early Holocene climate optimum in some Arctic regions, there are data suggesting delayed regional responses. Blake (1998) reported radiocarbon ages on the subarctic taxon *Chlamys islandica* from Smith Sound, at the northern end of Baffin Bay, only at 6500 to 3500 ^{14}C yr BP. Dyke *et al.* (1996) also argued that the access of bowhead whales to the Arctic channels was reduced by sea ice cover between 8500 and 6000 yr BP, but that access increased between 6000 and 5000 ^{14}C yr BP, and reached a maximum by 4000 ^{14}C yr BP, thus suggesting minimum sea ice cover during the mid-Holocene.

Data from the Devon Ice Cap also reveal maximum $\delta^{18}O$ values around 4.5 ka, in addition to a maximum concentration of marine salts, which together reflect longer seasons of open water conditions (cf. Koerner, 1989). In numerous terrestrial records there is evidence for the onset of optimum conditions during the mid-Holocene, as shown for example by inland ice retreat in central West Greenland starting after 7000 ^{14}C yr BP and culminating by 5000 ^{14}C yr BP, which indicates temperature 2°C higher than at present (Weidick *et al.*, 1990). On Baffin Island, local pollen also indicate a mid-Holocene warming after 7000 ^{14}C yr BP (Short *et al.*, 1994); transfer functions based on pollen led to the reconstruction of a warmer and wetter climate than present between 6000 and 4000 ^{14}C yr BP (Andrews *et al.*, 1980). Over northwest Greenland, pollen data also indicate optimum climatic conditions between 7000 and 3000 ^{14}C yr BP (Funder, 1978). Fredskild (1985a, b) interprets high influx of long-distance pollen at Melville Bugt (ca. 6600–2000 ^{14}C yr BP) and Qeqertat (ca. 6300–3300 ^{14}C yr BP) as the result of a milder, possibly more humid climate during a mid-Holocene interval.

The late Holocene cooling

Both marine and terrestrial records indicate a significant cooling during the late Holocene. The dinocyst record suggests that the cooling trend in the northernmost Baffin Bay was marked by cold pulses with extensive sea ice cover. A late Holocene decline in diatom fluxes in northwestern Baffin Island (Short *et al.*, 1994), and near the coasts of Baffin and Devon Islands (Williams, 1990), could be the result of more important sea ice cover. On land, the mass balance of the Agassiz Ice Cap became positive during the past 3000 yr (Koerner and Fisher, 1990), and isotopic analyses of the Devon Ice Cap reveal a 3°C decrease in mean temperature after 4.3 ka, whereas a decrease in the sodium and magnesium content of the ice after 3.5 ka suggests reduced marine aerosols (Fisher *et al.*, 1995), probably related to more extensive sea ice over adjacent marine bodies (cf. Bradley, 1990). Ice readvances after 5000 ^{14}C yr BP also have been reconstructed over Greenland (Weidick *et al.*, 1990), and close to

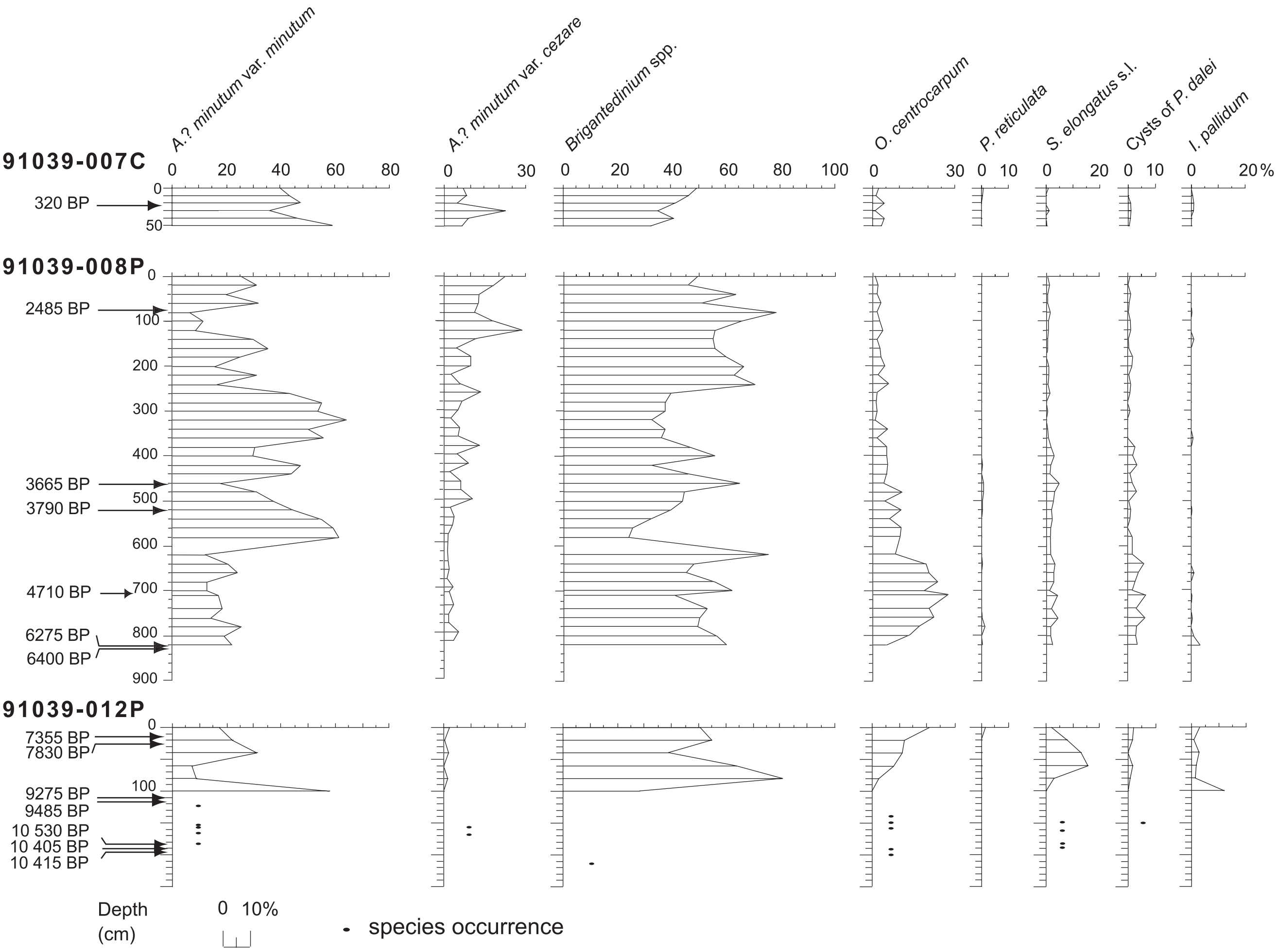

Figure 4 Diagram of dinocyst taxa percentages in the composite sequence of cores 91-039-007B, 91-039-008P and 91-039-012P. *Brigantedinium* spp. include cysts of *B. cariacoense* and *B. simplex*. In samples containing sparse assemblages (counts < 50 cysts), occurrences are reported by dots on the diagram. Corrected ^{14}C ages are reported in the left margin of the diagram (Table 1).

2000 ^{14}C yr BP along the Ellesmere Island coast of Smith Sound (Blake, 1989, 1995). At 'Kap Inglefield Sø', near Smith Sound, the ice on the lake became permanent around 4000 ^{14}C yr BP (Blake *et al.*, 1992), and on the summit plateau of the northwestern island in the Carey Øer group, within the area of the North Water Polynya, peat growth ceased between 4500 and 4000 ^{14}C yr BP (Brassard and Blake, 1978). Decreased influx of long-distance pollen at Melville Bugt after 2300 ^{14}C yr BP, and at Qeqertat after 3300 ^{14}C yr BP, is interpreted as the result of drier, and more northerly winds (Fredskild, 1985a, b). Pollen assemblages from Axel Heiberg Island also indicate a colder climate after 3000 ^{14}C yr BP (Hegg, 1963; Nichols, 1972). The local pollen in Agassiz Ice Cap core show some decline after 2.6 ka, and important fluctuations in pollen assemblages occur after 3.6 ka (Bourgeois *et al.*, 2000). The cooling trends and events mentioned in the literature and summarised above might well correspond to the climatic oscillation and cold pulses as recorded by dinocyst assemblages in the northernmost Baffin Bay during the past 4000 yr.

Conclusions

The palynological data indicate that seasonally ice-free conditions existed in the North Water polynya throughout most of the past 9000 yr. The abundance of dinocysts and organic linings of foraminifers indeed reflects a relatively high pelagic and benthic productivity. Reconstructions of sea-surface conditions based on dinocyst assemblages, however, reveal postglacial changes in sea-surface conditions of northernmost Baffin Bay as summarised below.

1. By about 9000 ^{14}C yr BP, after an extremely cold interval marked by low productivity and extensive sea ice cover, sea-surface temperature increased and conditions similar to those of the present were established.
2. By 6400 ^{14}C yr BP, and probably as early as 7800 ^{14}C yr BP, sea-surface temperatures reached maximum values. During an interval lasting until 3600 ^{14}C yr BP, ice-free conditions prevailed for 4–5 months per year, and, on average, sea-surface temperatures were significantly higher than at present. Peaks of temperature up to 3°C higher than at present occurred.
3. During the past 3600 yr, a general deterioration marked sea-surface conditions, with a succession of short-lived cold spells, accompanied by the development of very extensive sea ice cover.

On the whole, the dinocyst record from northernmost Baffin Bay strongly supports the existence of an early to mid-Holocene thermal optimum in the High Arctic.

Acknowledgements This study is a contribution to the Canadian research network 'Climate System History and Dynamics' (CSHD),

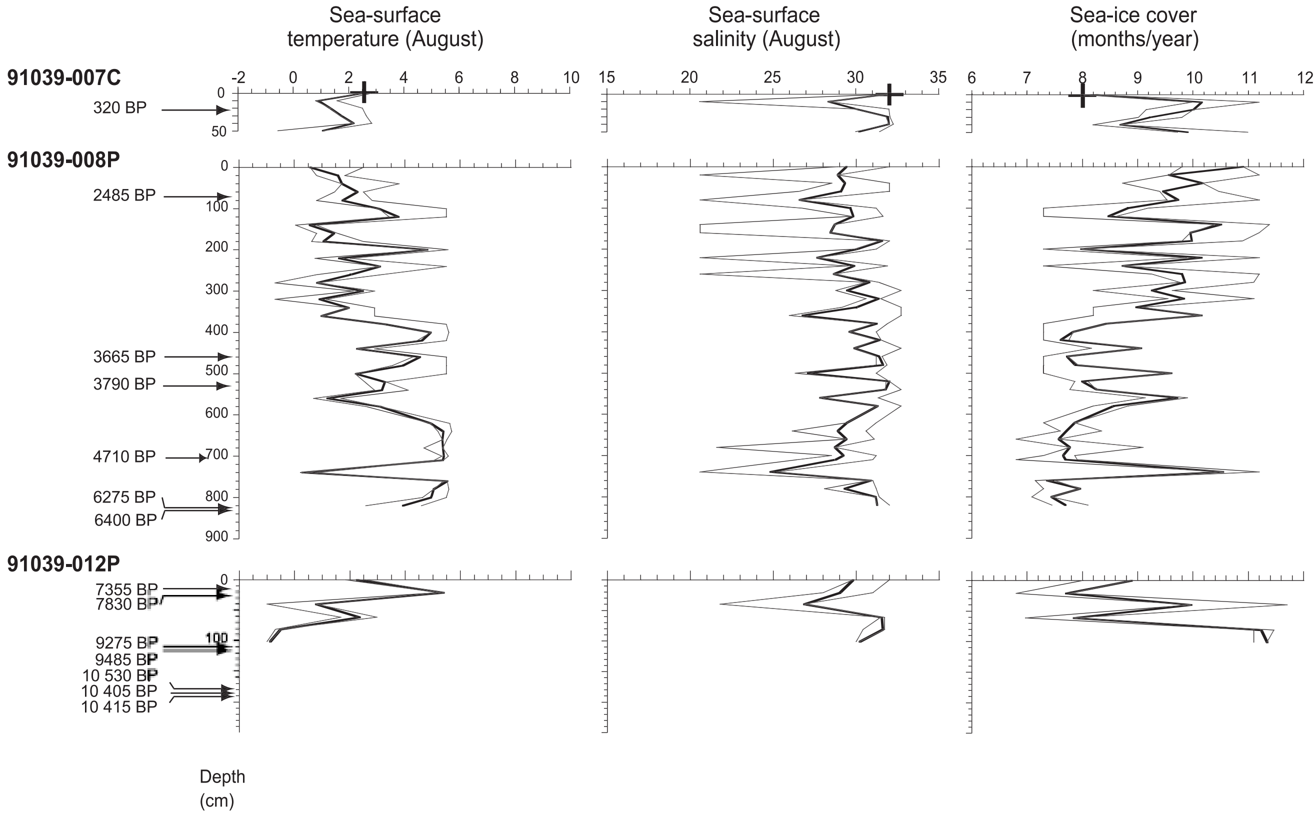

Figure 5 Reconstruction of sea-surface conditions from the composite record of cores 91-039-007B, 91-039-008P and 91-039-012P. The solid lines represent the most probable estimate based on the weighted average of the five best analogues. The thin lines correspond to maximum and minimum values possible according to the set of analogues. The '+' signs on the upper horizontal axis correspond to modern instrumental values. Corrected ^{14}C ages are reported in the left margin of the diagram (Table 1).

funded by the Natural Sciences and Engineering Research Council (NSERC) of Canada. We also benefited from the financial support to A. de V. from the *Fonds pour la Formation de Chercheurs et l'Aide à la Recherche (FCAR)* of Quebec. We thank Jocelyne Bourgeois, Jens Matthiessen and Fabienne Marret for their critical review of the manuscript and helpful comments. We acknowledge useful discussions with P. J. Mudie (GSC, Atlantic) and the contribution of André Rochon (GSC, Atlantic) and Virginie Loucheur (GEOTOP) for help with analyses, data treatment and drawing the figures. Tracy Barry (GSC, Ottawa) drew Fig. 1a and b. W. B., Jr. acknowledges with thanks the assistance of officers and crew aboard C.S.S. *Hudson* cruise 91-039 and the generous allocation of ship time to the marine geological programme by Chief Scientist H. Ruth Jackson. The entire ^{14}C AMS dating series was funded by grants to W. B., Jr. from Stiftelsen Ymer-80, Stockholm. Geological Survey of Canada Contribution 2000121; Cape Herschel Contribution No. 65.

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