Interaction between subsurface ocean waters and calving of the Jakobshavn Isbræ during the late Holocene

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Abstract

A marine sediment core from Vaigat in Disko Bugt, West Greenland, has been analysed in terms of lithology, dinoflagellate cysts and foraminifera in order to evaluate the influence of oceanographic variability on West Greenland glacier stability. The data show that during the past 5200 years the Atlantic foraminiferal abundance in the subsurface waters of the West Greenland Current (WGC) episodically increased, indicating periods of increases in the inflow of subsurface warm Atlantic water at 2000–1500 cal yr BP and 1300 cal yr BP as well as less pronounced periods of increased bottom-water temperatures around 4700-4000 cal yr BP, 3100–2800, 2600, 1000-800, 500–400, and at 200 cal yr. The sedimentological and dinoflagellate cyst data indicate that these episodes with enhanced advection of Irminger Sea-derived waters are accompanied by increased iceberg rafting, which we link to increased iceberg calving in relation to destabilization of the Jakobshavn Isbrae.

The long term trend in the data documents the end of a Late Holocene Thermal Maximum between 5200 and 4300 cal yr BP and a final onset of the Neoglaciation at 3500 cal yr BP. Increased responses of the iceberg rafting after 3500 cal yr BP, reflects a westward/seaward advance of the glacier margin in relation to onset of Neoglaciation and a development of the glacier into a floating tongue after 2000 cal yr BP.

A comparison of our record with a record from the eastern North Atlantic indicates that a NAO-like anomaly pattern between subsurface waters in West Greenland and atmospheric temperature in the Eastern North Atlantic may have been operating during most of the late Holocene. However, during the past 1000 years the NAO signal may have weakened as some other mode of climate variability overprints the anti-phase climate signal in this region.

Keywords: West Greenland Current, Late Holocene climate variability, iceberg calving, foraminifera, dinoflagellate, Jakobshavn Isbrae

A. Introduction

It is becoming increasingly clear that the cryosphere is responding quickly to the atmospheric temperature increase observed over recent decades (Box *et al*., 2006; Fettweis, 2007; Hanna *et al.*

2008; Mernild *et al.* 2008a). However, prediction of the contribution of the Greenland ice sheet to global sea-level rise is complicated by the lack of detailed knowledge on mechanisms behind ice sheet change. In particular ice streams and their interaction with the atmospheric and oceanic systems needs further investigation in order to make more realistic models of future sea-level rise.

In this study the Late Holocene climate history of the Jakobshavn Isbræ region (Fig. 1) was reconstructed on the basis of a marine sediment core from Disko Bugt in West Greenland in order to evaluate the influence of oceanographic variability on West Greenland glacier stability. The Disko Bugt embayment is particularly influenced by melt-water flux and icebergs from the Jakobshavn (Illulisat) Isbræ, which is a fast-flowing tide water outlet glacier draining 7% of the Greenland Ice Sheet (Kanagaratnam *et al.*, 2006) and the most prolific exporter of Greenland ice into the ocean mainly through calving. Holland *et al.* (2008) argued for a connection between a pulse of warm water in the West Greenland Current propagating up the West Greenland coast and entering Disko Bugt in 1997 and thinning, retreating and doubling of flow velocity of the Jakobshavn Isbræ at that time. Subglacial melting due to ocean subsurface warming has previously also been proposed as a crucial mechanism triggering ice sheet destabilisation and large-scale iceberg surges during glacial periods (Moros *et al*., 2002). Following these observations we aim at evaluating if intrusion of relatively warmer waters into Disko Bugt occurred on multi-decadal to centennial timescales and if so how these incursions affected the calving of icebergs. This may shed light on whether the modern acceleration of the Jakobshavn Isbrae is one of a kind and whether ocean-ice-sheet interaction is an important component of the climate-cryosphere system that needs to be assessed in details in climate models.

Variability of the subsurface and surface water is reconstructed by analysis of the benthic foraminiferal and dinoflagellate assemblage, respectively, and the production of icebergs and sea-ice is reconstructed on the basis of the ice-rafted debris in the sediment core.

A. Study area

B. Bathymetry and geology

Disko Bugt is a large marine embayment with water depths mainly between 200-400 m (Fig.1). The Vaigat Strait is a major channel exiting to the north bounded by Disko Island and the mainland carrying a large proportion of the iceberg flux that enters Disko Bugt from major tidewater glaciers to the north into Baffin Bay. The strait is c. 130 km long and 20-25 km wide and has water depths down to 600 m. It is believed that the passage acted as a northern conduit of an ice lobe extending to the mouth of the strait during the Last Glacial (Weidick and Bennike, 2007). At the head of Jakobshavn Isfjord the present day Jakobshavn Isbræ terminus is located ca. 40 km inland of the eastern coastline of Disko Bugt (Fig. 1). In the southwestern part of Disko Bugt a distinct trough up to 1000 m deep, Egedesminde Dyb, extends in a southwest-northeast direction cutting offshore banks. It has been suggested that during glacial times this trough acted as a drainage route of a high arctic ice stream (the Jakobshavn Isbræ) as well as melt water from the Greenland Ice Sheet (Long and Roberts, 2003).

The geology of the surface bedrock is composed mainly of Paleogene plateau basalts on Disko Island and the Nuussuaq Peninsula north of Disko Bugt, while the coastal regions facing Vaigat is composed of Upper Cretaceous and Paleogene sediments (Fig. 1). In contrast, lowlands of mainland West Greenland east of Disko Bugt are composed of Precambrian crystalline rock such as orthogneisses, granites, metavolcanic and metasedimentary rocks (Larsen and Pulvertaft, 2000).

B. Oceanography and glaciology

The modern surface hydrography in Disko Bugt is characterised by the West Greenland Current (WGC), which is a mixture of the warm and saline Irminger Current (IC) water of Atlantic origin overlain by the cold and less saline East Greenland Current (EGC) transporting Polar water to the region (Fig. 1) (Andersen, 1981). After passing Kap Farvel these currents increasingly mix on their northward path along the West Greenland shelf. When entering Disko Bugt the water mass below 200 m depth reaches 3-4°C and has a salinity of 34.2-34.4 psu (Cuny *et al.* 2002, Tang *et al.* 2004), whereas the upper part of the water column as well as conditions further offshore are characterised by a water mass with a temperature of 0-2°C and a lower salinity. In addition to the influence of Polar Water derived from the EGC the upper water mass is also highly influenced by surface run off from Greenland as well as by melt water from the ice sheet and melt water produced in conjunction with melting of icebergs in the ice fjord and Disko Bugt (Andersen, 1981). The Vaigat Strait acts as a major exit route of these waters entering Disko Bugt as well as for melt-water and icebergs produced by, among others, the Jacobshavn Isbræ.

The modern day climate of the Disko Bugt region is low arctic maritime with a mean annual temperature of -5.2°C, a summer mean of 4.8°C (Fredskild, 1996) and high precipitation. The bay is typically covered by land-fast sea-ice from mid-January to mid-April with a mean thickness of 0.7 m (Buch, 2000). During spring and summer a strong pycnocline is developed due to increased solar heating and large amounts of melt water from land and melting sea-ice. From September increased winds and cyclone activity break down the stratification resulting in winter hydrographic conditions dominated by uniform salinity and low temperatures (Andersen, 1981).

A. Methods

The 4.46 m long gravity core DA06-139G was collected in 2006 from Vaigat Strait during a cruise of the Danish research vessel *Dana* (Dalhoff and Kuijpers, 2007). The core site (70°05.486'N, 52°53.585'W) is located in the middle of the southern end of the strait at 384 m water depth. The split cores were visually logged and X-rayed in order to detect large clasts and the number of grains larger than 2 mm and 5 mm, respectively, was counted in 2 cm increments using the X-ray photographs. Sampling was carried out at 8, 4 and 2 cm intervals with regard to foraminiferal analysis and at 5 cm intervals with regard to sedimentological, petrologic and dinocyst analyses. The grain-size distribution (dry weight percentage) was determined by wet-sieving of dried, weighed and dispersed samples using 63 μm and 150 μm sieves. Subsequently, the same samples were dry-sieved on a 500 μm sieve, the number of grains was counted under a microscope and the petrologic composition determined. The petrologic composition was divided into basaltic grains and non-basaltic grains (i.e. k-feldspar, large aggregates of plagioclase, quartz and more).

The 90 samples for dinoflagellate cyst analysis (each sample consisting of 5 cm^3) were packed within an 11 μm nylon filter together with citric acid and washed for 1-2 hours in a household washing mashing at 70°C in order to remove the fine sediment fraction and carbonate. *Lycopodium* tablets were added during the washing process in order to calculate concentrations of dinocysts. After washing the samples were dried and subsequently placed in hydrofluoric acid for 2-3 days to remove silica before excess carbonate was removed using hydrochloric acid. Finally the dinoflagellate cysts were concentrated using $ZnCl_2$ (specific gravity 2.0). Due to the high content of sediment grains, which could not be removed through HF and HCl, swirling was carried out on some samples; tests showed that this did not affect the dinocyst composition. A minimum of 300 cysts were counted in each sample and identified following the nomenclature of Rochon *et al.* (1999) and Head *et al.* (2001) on a transmitted light microscope at x400 magnification. *Spineferites* spp. includes *S. elongatus*, *S. ramosus* and specimens not identified to species level. The relative frequency of dinoflagellate cyst species is calculated based on the total assemblage of dinocysts, whereas the percentage of the acritarch genus *Halodinium* sp. is calculated relative to the combined assemblage of dinocysts and acritarchs.

Foraminifera samples were analyzed at 8 cm intervals in the upper part of the core and at 16 cm intervals below 3 m core depth. A measured volume of sediment was soaked in water overnight then sieved to retain foraminifera larger than 63 µm. Picking and counting foraminifera from wet residues minimised losses of fragile agglutinated specimens. At least 300 specimens, including at least 100 agglutinated and calcareous foraminifera, were counted where possible. Down-core variations in the abundance of agglutinated and calcareous foraminifera suggest there are significant changes in preservation. Therefore, separate percentage calculations are made for the agglutinated and calcareous species based on the sum of counts for these two components of the foraminifera dataset. The species were subsequently grouped according to their ecological requirements in Atlantic and Polar species. A final group consists of species with no or unknown ecological requirements.

The chronology of gravity core DA06-139G is constrained by 10 AMS ^{14}C dates on molluscs, marine plant (sea grass) fragments and one sample of mixed benthic foraminifera (Table 1). The ^{14}C dates were calibrated using the marine calibration model curves, with a marine reservoir age set to 400 years (ΔR=0) (MARINE04, Hughen *et al.* 2004; Stuiver and Braziunas, 1993) using the Oxcal 3.10 programme with the probability method. As the present day bottom water in Disko Bugt is characterised by Atlantic source water, the appliance of a marine reservoir correction of 400 years on all samples is plausible although the input of glacier melting can be expected to have a significant influence. The modern reservoir age (see Reimer & Reimer, 2001) of surface waters shows a large variation with ΔR varying from -95 to 260, albeit with lowest ΔR values closest to our study site (M. Moros, pers. comm.). In order to facilitate a better comparison with previous studies from the area (e.g. (Moros *et al.,* 2006; Lloyd 2006b; Lloyd et al., 2007; Seidenkrantz *et al.* 2008), which have all used ΔR=0, we have thus followed the same procedure. The age model (Fig. 2) is based on the median values of calibrated dates and linear interpolation (Telford *et al.* 2004).

A. Results

B. Sedimentology

The sediment in core DA06-139G consists of an olive gray, clayey sandy silt with occasional larger clasts. During visual inspection the sediment appears homogenous; however, X-ray photography reveals occasional layers with a high content of sand and large clasts up to several centimetres size. Sand and clasts are used as indicators of mainly iceberg, but also sea-ice, rafted debris (IRD). In the time period from 5000 to 2000 cal yr BP the sediment is characterised by occasional episodes with coarser sediment deposition as evidenced in the occurrence of IRD layers and number of pebbles >5 mm and >2 mm (based on X-ray photography), the wt% of grains >150 µm and in the concentration of non-basaltic grains >500 µm (Fig. 3A-F). Many of these events are reflected in most of the grain size parameters; e.g. the concentration of non-basaltic grains larger than 500 µm increase from background values of around 10 grains/g sediment to values ranging between 25-40 grains/g sediment (Fig. 3E). After c. 3000 yr BP the influx of IRD (mainly the >2mm fraction) become consistent and after 2000 cal yr BP the number of coarse grained events increases markedly and the events become clustered. The concentration of basaltic grains >500 µm (Fig. 3F) is much more stable with background values of 1 grains/g sediment in the time period from 5000 to 2000 cal yr BP except for four peaks centred at 5000, 3700, 2300 and 2100 cal yr BP with values between 2 and 15 grains/g sediment. These short-lived peaks are also evident in the non-basaltic grain concentration >500 µm (Fig. 3E), the >150 µm fraction (Fig. 3D), but not discernible in the larger fraction; i.e. no of pebbles > 5 mm and 2 mm and the IRD layers (Fig. 3A-C). After 2000 cal yr BP the concentration of basaltic grains >500 µm increases slightly with generally higher values fluctuating between 1 and 2 grains/g sediment.

B. Dinoflagellate cysts

A total of 14 different marine palynomorphs (13 dinoflagellate cysts and one acritarch) taxa were identidied. All palynomorphs observed in core DA06-139G belong to taxa living in the area today (Rochon *et al.*, 1999), and in general only minor changes in the assemblage characterise the record. Nevertheless, these albeit minor changes in dinocyst assemblage allow the recognition of important changes in surface-water conditions.

The palynomorph assemblage of core DA06-139G is mainly dominated by the dinoflagellate cysts *Operculodinium centrocarpum*, *Pentapharsodinium dalei* and *Islandinium minutum* s.l. (incl. *Islandinium* ? *cezare*) while *Brigantedinium* spp., *Spiniferites* spp. and (incl. *S. elongatus* and *S. ramosus*) as well as the acritarch *Halodinium* sp. are important assessory taxa (Fig. 4). The core is mainly characterised by highly fluctuating alternations between *I. minutum* and *I.* ? *cezare* on one side and *O. centrocarpum* and *P. dalei* on the other, thus indicating highly variable surface-water conditions. However, by applying a five point running mean to the data, centennial changes in the variability is apparent with maxima in *I. minutum* s.l. and lower values of *O. centrocarpum* and *P. dalei* centered around 4400, 3600, 2500, 1800, 900 and 200 cal. yrs BP. The dinoflagellate cyst concentration also fluctuates highly and likewise a five point running mean applied to the data demonstrates a centennial to millennial variability with higher values of concentration broadly centred around 4500, 3600, 3000, 2300, 1500, 700 and 200 cal. yrs BP; thus there is no clear connection between increases in particular taxa and concentration.

O. centrocarpum is found widespread in the North Atlantic and Arctic Ocean today but it seems to have its highest frequencies in areas influenced by Atlantic waters (de Vernal *et al.*, 1993; Rochon *et al.*, 1999). *P. dalei* is common in polar and subpolar regions (Dale, 1996; Rochon *et al.*, 1999) and has especially been found connected to spring blooms (Dale, 1977; Harland *et al.*, 2004a). In contrast, *Islandinium minutum* thrives in areas of extensive seasonal sea-ice cover and/or polar surface water conditions (e.g., Rochon *et al.*, 1999; de Vernal *et al.*, 2001; Head *et al.*, 2001; Kunz-Pirrung, 2001; Hamel *et al.*, 2002; Marret and Zonneveld, 2003; Grøsfjeld *et al.*, 2006) while *I.* ? *cezare* is common en areas with sea-ice cover for 6-12 month per year (Rochon et al., 1999; Head et al. 2001). *Halodinium* sp. may indicate a strong fluvial influence (de Vernal *et al.*, 1989; Head, 1993) and has been found in high frequencies near glacier melt water plumes (Mudie, 1992). *Brigantedinium* spp. may be linked to a relatively high primary productivity and high nutrient availability (e.g., Wall *et al.*, 1977; Rochon *et al.*, 1999; Kunz-Pirrung, 2001). It feeds on plankton, including sea-ice algae and is highly successful in sea-ice covered regions (Solignac *et al.* accepted). Finally, *Spiniferites elongatus* is today found relatively evenly distributed in most of the North Atlantic from mid to high latitudes (Rochon *et al.*, 1999), while *Spiniferites ramosus* is found in inner to outer neritic, tropical to subpolar environments (Rochon *et al.*, 1999; Zonneveld *et al.*, 2001) and *Selenopemphix quanta* is mainly found in near-coastal, tropical to subpolar regions, generally being absent in high arctic areas (Rochon et al. 1999). Further information on environmental data and the modern dinocyst assemblage has been compiled by Radi and de Vernal (2008) and are available at http://www.unites.uqam.ca/geotop/paleoceanographicDatabase/monographie_n1171/eng/index.shtml.

B. Foraminiferal analysis

The benthic foraminiferal dataset has been divided into calcareous and agglutinated taxa. Species are then grouped based on their ecological preferences, in particular their relationship to Atlantic sourced water of the WGC and colder, less saline, melt water influenced Polar Water. These groupings are based on the modern distribution of foraminifera in Disko Bugt (Lloyd, 2006a) and also other ecological studies from the Arctic (e.g. Vilks 1964, 1981; Mudie *et al.* 1984; Madsen & Knudsen 1994; Hald & Steinsund 1992; Jennings & Helgadottir 1994; Seidenkrantz, 1995; Hald & Korsun 1997; Korsun & Hald 1998). The Atlantic water assemblage comprises foraminifera that are abundant at the present day in areas strongly influenced by the WGC water mass in Disko Bugt, or diluted/chilled Atlantic water elsewhere in the Arctic including the following species: *Adercotryma glomerata, Ammotium cassis, Portatrochammina bipolaris* (agglutinated taxa) and *Buccella frigida, Buccella tenerrimma, Cassidulina neoteretis, Globulina inaequalis, Melonis barleeanum, Nonionellina labradorica* (calcareous taxa). Many of the calcareous species in this group (particularly *N. labradorica* and *M. barleeanum*) are commonly associated with high productivity and, hence, high levels of organic material. Indeed the abundance of these species in Disko Bugt has been shown to be linked to high levels of organic material, but this is also associated with strong influx of WGC waters (Lloyd, 2006a) hence their grouping in the Atlantic water group. The Polar Water group includes species commonly found in areas with no Atlantic water influence dominated by colder less saline waters and includes: *Cuneata arctica, Spiroplectammina biformis* (agglutinated taxa), *Cassidulina reniforme* and *Elphidium excavatum* f. c*lavata* (calcareous taxa). In this study we only present the total calcareous and agglutinated Atlantic water influenced assemblage (Fig. 6A). The majority of the species belong to the agglutinated taxa. The long-term down-core trends may thus be somewhat affected by post-mortem destruction, but we believe the short-term variability to be reliable. The relative proportion of Atlantic water fauna shows marked variability over the last 5200 cal yrs BP varying from a minimum abundance of 1% to a maximum of 25%. This variability reflects changes in the relative warmth of bottom waters at the core site associated with changes in the balance between WGC waters, Polar Water and melt waters to the surrounding area. There are two periods of significantly increased Atlantic faunal abundance at 2000–1500 cal yr BP and a brief period at 1300 cal yr BP indicating warmer bottom waters (relatively warmer periods of the record are shaded in Fig. 6). Other less pronounced periods of increased bottom water temperatures are also recorded from 4700-4000 cal yr BP, 3100–2800, 2600, 1000-800, 500–400, and at 200 cal yr BP.

A. Discussion

B. Surface water variability

In this study we use marine palynomorph assemblages in order to document changes in environmental conditions of surface water. A principal component analysis (PCA) using Canoco 4.5 (ter Braak and Šmilauer 2003) was performed on square root transformed percentage data in order to evaluate the inter-relationships between the different taxa. The eigenvalue of the 1st axis is 57%, which means that a moderate part of the variance in the dataset is explained by this axis. A biplot of the 1st and 2nd axis scores of the variables demonstrate that variability in the dinoflagellate cyst assemblage is largely related to changes between *O. centrocarpum*, *P. dalei* and *I. minutum*, with the rest of the taxa in-between (Fig. 5). It is important to note that the interpretation of dinoflagellate cyst assemblage variability in a highly glacier-influenced marine setting is not readily comparable with interpretations from more open water settings – caution should therefore be taken before applying the inferred environmental conditions directly to the Jakobshavn setting. We suggest that the marine palynomorph assemblage variability in Vaigat Strait is mainly controlled by the input of fresh and cold water from the Greenland ice-sheet. As demonstrated on the biplot relatively high negative scores reflects higher input of fresh and cold waters whereas positive values reflects increasing influence of relatively warmer and more saline Atlantic water component in the WGC (*O. centrocarpum* and *P. dalei*). This implies that maxima in *I. minutum* and *I. ? cezare* reflect periods with increased production of cold and fresh water from the Greenland ice-sheet carrying plenty of icebergs and sea-ice. However, it is important to note that sea-ice may also form in periods characterised by decreased melt water production. As *I. minutum* and *I. ? cezare* among other thrives in areas of extensive sea-ice cover (e.g. Rochon et al. 1999), we hesitate to use *I. minutum* and *I. ? cezare* as a direct proxy for Greenland ice-sheet melt water production - it is likely a proxy for both melt water production and sea-ice production. In contrast, we consider *Halodinium* sp. a relevant candidate for reconstruction of iceberg calving and melt-water production as this species is known to thrive by glacial melt-water plumes (Mudie, 1992). In periods of extensive iceberg calving, melting of these icebergs in Vaigat Strait may be expected to create a relatively turbid layer of fresh water for *Halodinium* sp. to thrive in.

The palynomorph assemblages indicate that during most of the mid to late Holocene, the southern Vaigat Strait was characterised by fluctuating iceberg drift on a centennial time-scale. A division of the dinoflagellate cyst dataset into five major Palynomorph Zones (PalynoZones; Fig. 4 and Fig. 5) provides some additional information. In PalynoZone I, which spans the time interval 5200-4300 cal. yrs BP, *I. minutum* and *Halodinium* sp. are important taxa, which may indicate an environment dominated by relatively high influence of glacial melt from the Greenland ice-sheet. The relatively low values of *Brigantedinium spp.,* however, suggest that the melt water was relatively sparse of sediment. The high palynomorph production indicates warm summers at this time. In PalynoZone II (4300-3500 cal yr BP) frequencies of *Halodinium* sp. decrease indicating decreased melt water production from Greenland glacial melting. The still high frequencies of *I. minutum* and *I.? cezare* may indicate that at least part of this increased level could be related to sea-ice occurrence, thus indicating an onset of cooling around 4300 cal yr BP. In PalynoZone III (3500-2100 cal yr BP) *I. minutum* and *I.? cezare* also starts to decrease indicating decreased polar water influence and as a result the Atlantic species *P. dalei* becomes more important. PalynoZone IV (2100-1500 cal yr BP) is characterised by a renewed increase in *Halodinium* sp. and *Brigantedinium* spp. along with slightly decreasing values of the Atlantic species *O. centrocarpum* and *P. dalei*; this may indicate a return of cold and fresh melt water carrying icebergs from the Greenland ice-sheet. The increase of *Brigantedinium* spp. may reflect the high nutrient availability associated with melting of sediment-carrying icebergs in Vaigat. In PalynoZone V (1500-0 cal yr BP) *I. minutum* and *I.* ? *cezare* increases, whereas *Halodinium* sp. and *O. centrocarpum* decrease. The sudden anti-correlation between *Halodinium* sp. and *I. minutum* in the time period 1500-0 cal yr BP (before this time interval they roughly correlate except in PalynoZone II) suggest that at least some of the *I. minutum* and *I.* ? *cezare* increase after 1500 cal yr BP could be related to increased sea-ice occurrence, indicating a general surface-water cooling with decreased melt water production. As a result of the decreased polar melt water influence the Atlantic *Spiniferitis* spp. (mainly the eutrophic species *S. elongatus*) increases.

B. WGC variability and influence on iceberg calving

The grain-size data are used as indicators of iceberg and sea-ice rafting and the petrology can provide information on the provenance of the IRD and thus of the ice. Basaltic material originates from Disko Island and the Nuussuaq Peninsula bordering Vaigat (Fig. 1). As both areas are devoid of marine based glaciers basaltic material can only be transported to the core site incorporated into coastal (grounded) sea-ice. In contrast, the West Greenland region with its Precambrian basement provides granitic material to the site incorporated into both sea-ice and icebergs. The data from core DA06-139G show that from 5200 to 2000 cal yr BP iceberg rafted material was predominantly composed of granitic material from the West Greenland mainland coast, documenting the output of icebergs from Jakobshavn Isbræ and as well as from the Sermeq kujatdleq and Sermeq avangnardleq glaciers draining into Torsukattaq (Fig. 1). The contribution of basaltic material from sea-ice is minor except for the four episodes at 5000, 3700, 2300 and 2100 cal yr BP; all of which are accompanied by short lived peaks in concentration of non-basaltic material larger than 500 μm (Fig. 3E). After 2000 cal yr BP iceberg rafting increased markedly and the overall concentration from sea-ice (basaltic material) also increased.

By comparing the concentration of non-basaltic grains >500 μm with the warm water foraminifera assemblage (Fig. 6A and B) there is a moderate correlation between warmer subsurface waters and increased IRD except for four short-lived episodes of increased IRD at 5000, 3700, 2300 and 2100 cal yr BP (these episodes are discussed in detail later). We suggest that iceberg rafting episodes generally coincide with subsurface warming of the WGC and we speculate that the mechanism linking this correlation could be explained by analogy to the study of Holland *et al.* (2008). In their study Holland *et al.* (2008) suggest that the rapid increase in velocity of Jakobshavn Isbræ and the break up of the floating tongue from 1997 was linked to recent oceanographic warming of the subsurface WGC causing rapid basal melt-induced thinning. As a result the longitudinal stretching and thereby velocity of the glacier tongue increases, suggesting that the water temperature in the ice fjord controls the glacier velocity and subsequent calving. Thus the increased iceberg rafting in Vaigat is interpreted to be related to increased iceberg production.

Contrastingly, periods of decreased iceberg calving may reflect extensive and long-lasting sea-ice cover shortening the summer iceberg calving season by stabilizing the glacier margin.

By comparing the warm water benthic foraminiferal record, with the IRD and *Halodinium* sp. record the interaction between warm subsurface currents and melt water production from the Greenland ice-sheet during the past 5200 years is following evaluated (Fig. 6).

B. Late Holocene Thermal Maximum: 5200 to 3500 cal yr BP

Provisional reconstructions of the ice margin position of the Jakobshavn Isbræ show that the ice margin was positioned east of its present position until c. 2200 years ago with optimum Holocene climate conditions (and maximum eastward glacier margin position) around 4000-5000 years ago (Fig. 7) (Weidick *et al.* 1990; Weidick 1992a, Weidick and Bennike, 2007). This could imply that in the time span 5000/4000 to 2200 years ago the glacier margin moved progressively westward towards Disko Bugt. The glacier margin response to increased warming of the WGC (Fig. 6A) 4700 to 4000 cal yr BP was characterised by almost no increase in the iceberg calving (Fig. 6B). However the relatively high *Halodinium* sp. and *Islandinium* spp. values around the same time (PalynoZones I-II, 5200-3500 cal yr BP) indicate that significant amounts of melt water was present in the Vaigat Strait, suggesting that most sediment material had already melted out from the icebergs before entering the Vaigat Strait. The relatively low content of suspended sediment in the water is also documented by the relatively low *Brigantedinium* spp. values in PalynoZone I, (Fig. 4). PalynoZone I thus probably corresponds to a late Holocene Thermal Maximum, while PalynoZone II corresponds to the following gradual cooling prior to the Neoglaciation as indicated by relatively high *I. minutum and I. ? cezare* values along with lowered *Halodinum* sp. values. This is in agreement with prior studies from Disko Bugt by Moros *et al.* (2006). Based on diatom and lithological analysis on a sediment record from Kangersuneq Fjord (Fig. 1) they have documented a late Holocene Thermal Maximum beginning at 4800 cal yr BP and ending between 3500 and 3100 cal yr BP. A late Holocene Thermal Maximum lasting until around 4-3000 cal. yr BP in the Labrador Sea – Baffin Bay region is in agreement with marine sediment studies from southwest Greenland (Møller *et al.* 2006; Seidenkrantz *et al.* 2007; Ren *et al.*, 2009) and the Nares Strait (Knudsen *et al.* 2008) as well as from terrestrial studies from Baffin Island, NE Canada and West Greenland (Fredskild, 1974, 1988; Willemsee and Törnquist, 1999; Kaplan *et al.* 2002; Kaufman *et al.*, 2004). Also, based on dinoflagellate cyst studies from a sediment core offshore Newfoundland, Solignac *et al.* (accepted) suggest that arctic melt-water export from Baffin Bay decreased after 4000 cal yr BP as a result of the termination of the Holocene Thermal Maximum. Lloyd *et al.* (2007) document WGC variability based on benthic foraminiferal record in the same core as Moros *et al.* (2006) in Kangersuneq Fjord. However, these authors found a Holocene Thermal Maximum in subsurface (Irminger Sea derived) waters between 6000 and 5000 cal yr BP with the onset of gradual cooling hereafter.

B. Neoglacial cooling: 3500 to 2000 cal yr BP

The onset of a general cooling in the West Greenland region is reflected in colder subsurface water masses in Vaigat Strait between 3500 and 2000 cal yr BP except for two minor warm peaks centered at 3000 and at 2600 cal yr BP (Fig. 6A). This cooling of subsurface waters possibly resulted in relatively decreased iceberg and melt water production from Greenland as was also documented in PalynoZone III (3500-2100 cal yr BP) by decreased *I. minutum*, *I.? cezare* and *Halodinium* sp. (Fig. 4 and Fig. 6C).

In contrast to the almost lack of a response in iceberg rafting in Vaigat Strait during the Holocene Thermal Maximum due to the further inland position of the West Greenland Ice Sheet margin, the short lived WGC warming centered at 3000 cal yr BP in our record coincide with increased iceberg rafting as documented in the sedimentological data as well as by a minor increase in *Halodinium* sp. (Fig. 6A-C). This may be the consequence of the increased westward/seaward advance of the Jakobshavn Isbræ glacier margin (Fig. 7), perhaps accompanied by the development of a small floating ice tongue, making it more sensitive to warm pulses in the subsurface waters.

It should be noted that the four episodes of short-lived iceberg rafting at 5000, 3700, 2300 and 2100 cal yr BP differ from other iceberg rafting episodes in our record, in that they **1)** occur during relatively colder subsurface water conditions (according to the foraminiferal record (Fig. 6A)) and decreased melt water production (according to *Halodinium* sp. (Fig. 6C)) and **2)** are accompanied by a marked peak in *sea-ice* rafting according to the basaltic grain record (Fig. 3F). This supports the idea that periods of decreased iceberg calving are accompanied by extensive and long-lasting sea-ice cover shortening the summer iceberg calving season by stabilizing the glacier margin. An increased wind regime at the same time may also have played a role in transporting larger amounts of sediment-carrying sea-ice from the shores of Disko Island and Nussuaq Peninsula to the core site. Indeed records from West Greenland document increased aeolian activity during the Middle Holocene (Willemse *et al.* 2003), which is supported by pollen studies of marine sediment cores from the Labrador Sea region (Jessen *et al.* submitted). However, apart from wind-induced sea-ice transport to the site, apparently the iceberg rafting also must have increased as reflected in the increased concentration of non-basaltic grains >500 μm and the occurrence of IRD layers and pebbles (Fig. 3. 3A-E). Increased iceberg rafting at this time (with overall colder subsurface waters and decreased melt water production (Fig. 6A and C)) is in contradiction to our postulation of a general connection between warmer subsurface waters and iceberg calving.

Although speculative, the increase in non-basaltic IRD during these four events may also be related to the increased wind-regime transporting more sea-ice of non-basaltic material from the west coast of the main land (Fig. 1) to the site.

B. Floating ice tongue advance: 2000 cal yr BP and onwards

The general increase in iceberg rafting after 2000 cal yr BP according to our record may mark a further advance of Neoglacial conditions, as the glacier margin developed into a regular floating ice tongue and advanced further west into the ice fjord (Fig. 7) (Weidick & Bennike, 2007). This relatively advanced position would have made the floating ice tongue even more sensitive to bottom melting due to incursions of relatively warmer WGC waters into the ice fjord, favouring enhanced iceberg calving. In South Greenland the Narssarssuaq moraine system estimated to c. 2000 cal yr BP (Weidick *et al.* 1994b; Bennike & Sparrenbom, 2007) also document increased Neoglacial conditions at this time. Apart from Greenland glacier growth the atmospheric climatic conditions also must have deteriorated as the concentration of basaltic grains generally is a little higher indicating that sea-ice production and/or transport increased after 2000 cal yr BP. PalynoZone V (1500-0 cal yr BP) also indicated increased sea-ice occurrence perhaps along with increased wind-regime. In spite of the cooler atmospheric conditions with increased winter sea-ice occurrence which is presumed to stabilize the glacier margin, the response in iceberg calving during summer to even small warm subsurface water incursions was relatively marked – this may be due to the floating ice tongue.

Marked episodes of warmer subsurface waters in Vaigat Strait occur around 2000-1500 cal yr BP, 1300 cal yr BP, and minor episodes around 1000-800 cal yr BP, 500 cal yr BP and 200 cal yr BP and they are all accompanied by increases in IRD linked to increased iceberg calving (Fig. 6A and B) and increases in melt water as indicated by *Halodinium* sp. The particularly marked incursion of warm subsurface waters around 2000 to 1500 cal yr BP corresponds to PalynoZone IV (2100-1500 cal yr BP) which also indicates increased melt water influence. Lloyd *et al.* (2007) also find marked subsurface warming in outer Disko Bugt at 2000-1400 cal yr BP and Moros *et al.* (2006) and Seidenkrantz *et al.* (2008) find surface warming in outer Disko Bugt at 2200-1500 cal yr BP and 2000-1500 cal yr BP, respectively. The minor subsurface warming in Vaigat around 1000-800 cal yr BP may correspond to a minor, short-lived subsurface warming of the WGC around 1000 cal yr BP found in outer Disko Bugt and a longer-lived subsurface warming around 1600-500 cal yr BP in inner Disko Bugt (Lloyd *et al*. 2006b, 2007). In spite of this very small increase in subsurface warming in Vaigat, the corresponding melt-water and iceberg production was relatively marked according to the *Halodinium* sp. and IRD increases (Fig. 6A-C). This could explain why Moros *et al.* (2006) and Seidenkrantz *et al.* (2008) find cooling of surface water all the way into outer Disko Bugt at this time.

The large peak in IRD corresponding to a minor incursion of warm subsurface waters around 200 cal yr BP could reflect the maximum LIA extension of the protruding Jakobshavn marine-based glacier (Fig. 7) as well as maximum extension of the glaciers draining into Torsukattaq.

B. Causal mechanisms behind variability in the WGC

Holland *et al.* (2008) suggested that the increased temperature of the WGC in Disko Bugt in 1997 was related to a warming in the mid-1990s of the subpolar gyre (Stein, 2005; Holliday *et al.* 2008) and the northern Irminger Basin (Mortensen and Valdimarsson, 1999), presumably in relation to a prolonged positive phase of the North Atlantic Oscillation (NAO) index associated with strong westerlies. In 1995-1996 the NAO switched to a negative phase characterised by weaker winds

(Flatau *et al.*, 2003) and as a result the subpolar gyre weakened thereby moving the subpolar frontal system from an easterly position to a more westerly position, spreading the warm subpolar waters westward (Hatun *et al.* 2004; Flatau *et al.*, 2003). This observation makes it interesting to investigate if the mechanisms behind the 1997 event are also responsible for the reconstructed late Holocene warm WGC pulses of centennial duration; i.e. did a NAO type pattern play a significant role in late Holocene centennial to millennial-scale climate fluctuations in the Labrador Sea region as suggested by Seidenkrantz *et al.* (2007, 2008)? We compared our record with the Crag Cave CC3 record from southwest Ireland (Fig. 6D), which infers air temperature on basis of $\delta^{18}O$ values in speleothem (McDermott *et al.* 2001) assuming that changes in the North Atlantic Drift generally influences atmospheric climate in that region. There is a tendency for anti-phase relationship between West Greenland and the eastern North Atlantic in the time period 5000 to around 1000 cal yr BP, for example the European Roman Warm Period (RWP) lasted from around 3000 to 2000 cal yr BP according to the speleothem data and at this time the WGC was relatively cold and iceberg rafting relatively reduced. Furthermore, our record and the outer Disko Bugt records (Lloyd *et al.*, 2007) show a significant warming of the WGC between 2000 and 1500 cal yr BP at a time when Europe was suffering the harsh climate of the Dark Ages Cold Period (DA) according to the speleothem record. However, the Medieval Climate Anomaly (MCA) (1200-800 cal yr BP) seems to have been associated with warming of subsurface waters of the outer Disko Bugt (Lloyd *et al.* 2007), although the coastal regions of SW Greenland were subject to a decrease in the Atlantic water component of the WGC (Lassen *et al.*, 2004; Seidenkrantz *et al.*, 2007). Also in Vaigat Strait the benthic foraminifera indicate a minor warming of subsurface waters along with iceberg rafting and associated cooling of surface waters in both Vaigat Strait and the outer Disko Bugt (Moros *et al.* 2006, Seidenkrantz *et al.* 2008). During the Little Ice Age the WGC generally cooled in Vaigat, but with minor warm fluctuations. As found by Moros *et al*. (2006) and Seidenkrantz *et al.* (2007, 2008), this period was also characterised by relatively cool surface-water conditions in outer Disko Bugt despite increased WGC influx along West Greenland (Lassen et al. 2004; Seidenkrantz et al. 2007). The NAO dipole anomaly pattern between West Greenland and the Eastern North Atlantic thus seem to have persisted during the past but was significantly weaker during the last 1000 years. This indicated that also other factors than NAO 'climate seesaw' has dominated West Greenland climate variability for the last millennium. This could, for instance, be an increasingly larger melt water component from melting of West Greenland glaciers received by the WGC on its way north. Atmospheric variability in the Barents Sea and Arctic Ocean modulating the outflow of sea-ice must also have played an important role for variability in the North Atlantic Ocean in the form of centennial long periods characterised by extensive 'Great Salinity Anomalies' (Andrews *et al.* 2001a, b, c; Andrews and Giraudeau 2003; Bond *et al.* 2001; Jennings *et al.* 2002, Andresen *et al.*, 2004; Andresen and Björck, 2005). The influence from sea-ice transported from the Arctic Ocean may have increased during the past 1000 years modulating the East Greenland Current and affecting the North Atlantic and West Greenland region in a similar manner (in-phase relationship), likewise, melt water from a growing Inland ice-sheet may potentially have altered surrounding water masses. This implies that the Little Ice Age was probably the most severe of the recorded Holocene coolings in the entire North Atlantic region as also supported by other studies (Stötter *et al.*, 1999; Jiang *et al.*, 2002 and many more).

A. Conclusions

By analysing the lithology, dinoflagellate cyst and foraminiferal content in a sediment record from Vaigat in Disko Bugt we conclude that during the past c. 5000 years there have been a number of centennial long episodes of (subsurface) warming of the West Greenland Current. These episodes with enhanced advection of Irminger Sea-derived waters were accompanied by increased iceberg rafting and we link them to increased iceberg calving in relation to warming of subsurface waters in the WGC. Between 5200 and 4300 cal yr BP the data are interpreted to document the end of a late Holocene Thermal Maximum in West Greenland with final onset of the Neoglaciation around 3500 cal yr BP. An increased response of the iceberg rafting during warm pulses of WGC in the time period 3500 to 2000 cal yr BP is interpreted as the consequence of a westward/seaward advance of the glacier margin in relation to onset of Neoglaciation. A further increase in response of iceberg rafting to warm-water incursions after 2000 cal yr BP may document the advanced, westward position of the floating glacier tongue, making it more sensitive towards warm WGC subsurface waters from Disko Bugt.

Our data provide evidence that the 1997 acceleration of the Jakobshavn Isbræ may be comparable to a recurrent phenomenon characterising the Holocene on multi-decadal to centennial time-scales. The modern acceleration was associated with multidecadal-scale warming of the North Atlantic subpolar gyre and a change in the NAO index. A comparison of our West Greenland record with a record from the Eastern North Atlantic indicates that a NAO-like anomaly pattern may have been operating during most of the late Holocene. However, during the past 1000 years some other mode of climate variability may have overprinted the ‘climate seesaw’ signal.

Thus intrusion of relatively warmer waters to Greenland fjords and embayment occurring on multi-decadal and centennial timescales play a significant role in controlling the stability of the Greenland ice sheet and predictive climate models needs to asses this influence in order to make realistic scenarios of future sea level rise.

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Figure captions

Fig. 1. Seabed contour map of Disko Bugt from Lloyd *et al.* (2005) based on an adaption from Long and Roberts (2003). Also shown geological map adapted from Weidick & Bennike (2007).

Fig. 2. Age model of core DA06-139G based on calibrated ^{14}C-ages (BP 1950) shown with 2 sigma error.

Fig. 3. Grain size data. A. IRD layers on basis of x-ray photography. B. Number of grains > 5 mm (on basis of x-ray photography). C. Number of grains > 2mm (on basis of x-ray photography). D. Grains >150 µm (dry weight %). E. Non-basaltic grains >500 µm (dry weight %). F. Basaltic grains >500 µm (dry weight %).

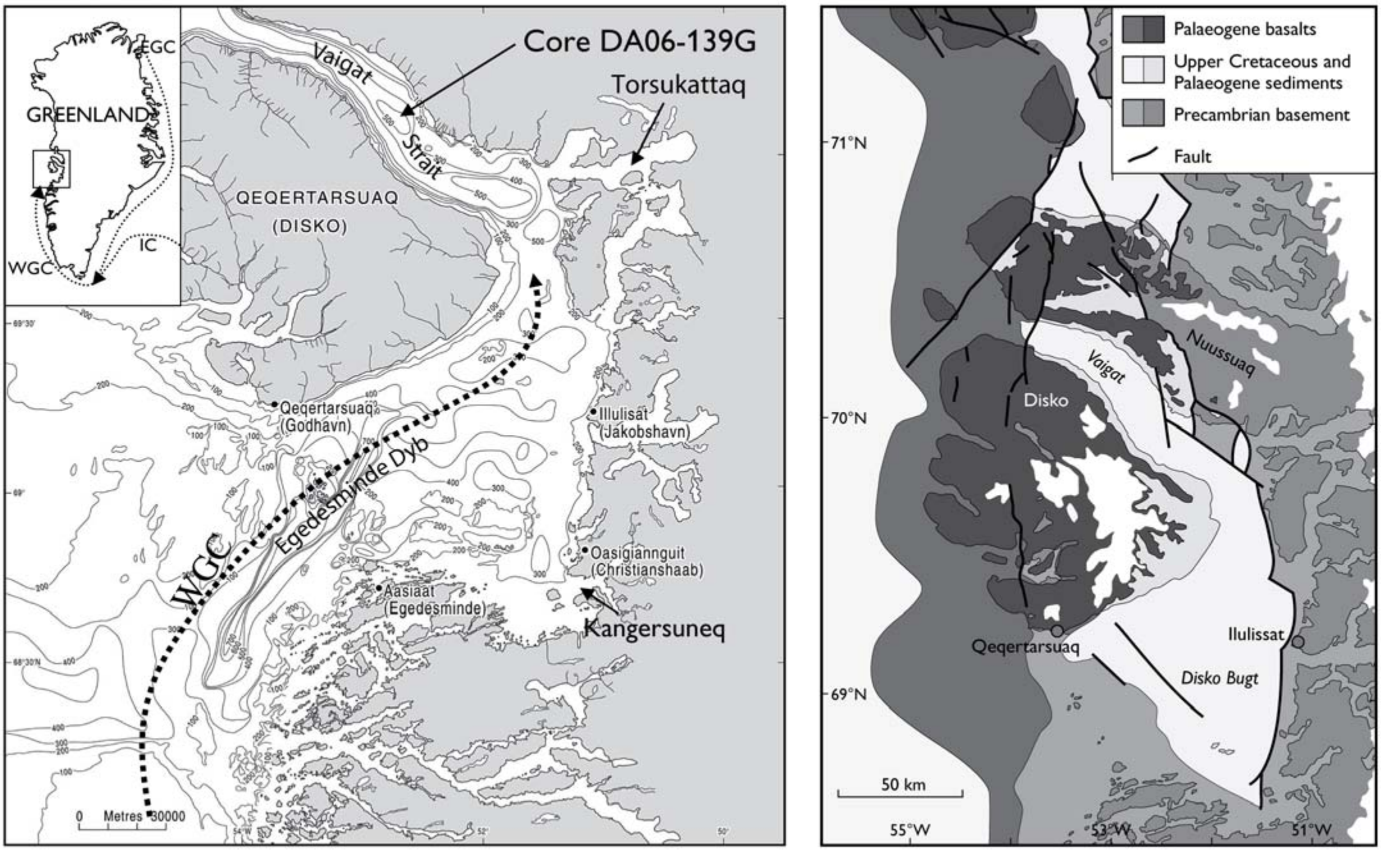
Fig. 4. Relative abundance (%) of selected dinoflagellate cyst and one acritarchs taxa calculated based on the total marine palynomorph assemblage as well as the total concentration (no./g sediment) of marine palynomorphs in core DA06-139G. Note different percentage scale for the different taxa. The red line shows a five point running mean.

Fig. 5. Biplot of 1st (eigenvalue 57%) and 2nd (16%) axis scores of variables obtained from a principal component analysis of dinoflagellate cyst and one acritarchs taxa (%). The data were square root transformed before analysis. Also shown the mean value of 1st and 2nd scores of the dataset in four Zones: PalynoZone I (5200-4300 cal yr BP), PalynoZone II (4300-3500 cal yr BP), PalynoZone III (3500-2100 cal yr BP), PalynoZone IV (2100-1500 cal yr BP) and PalynoZone V (1500-0 cal yr BP).

Fig. 6. Synthesis of selected data. A. Warm water foraminiferal assemblage. Shaded boxes indicate periods with relatively warm subsurface waters according to the foraminifera. B. Non-basaltic grains >500 µm (dry weight %) SI denotes sea-ice peaks discussed in text. C. *Halodinum* sp. percentages of the total marine palynomorph assemblage. D. CC3 $\delta^{18}O$ (VDBD) record from Irish stalagmite (McDermott *et al.* 2001) denoted with the European climate stages; the Little Ice Age (LIA), the Medieval Climate Anomaly (MCA), the Dark Ages Cold Period (DACP) and the Roman Warm Period (RWP).

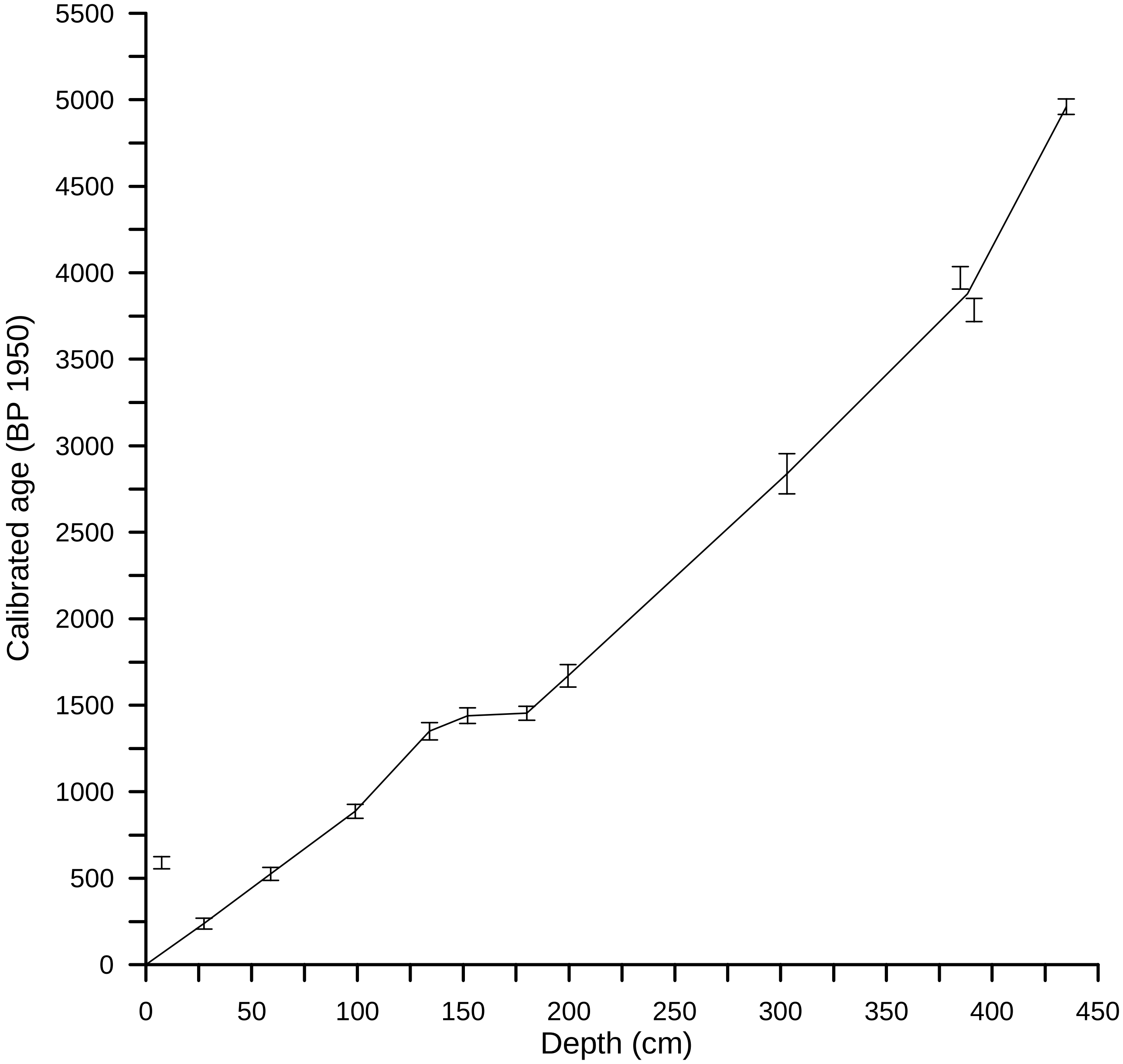
Fig. 7. Provisional reconstruction of ice margin. Also shown ice margin positions during the early Holocene. From Weidick and Bennike (2007).

Table 1. List of radiocarbon dates.



Core DA06-139G
Vaigat
Strait
Torsukattaq
GREENLAND
EGC
IC
WGC
QEQERTARSUAQ
(DISKO)
Qeqertarsuaq
(Godhavn)
Illulisat
(Jakobshavn)
Egedesminde Dyb
WGC
Oasigiannguit
(Christianshaab)
Aasiaat
(Egedesminde)
Kangersuneq
0 Metres 30000
Palaeogene basalts
Upper Cretaceous and Palaeogene sediments
Precambrian basement
Fault
71°N
70°N
69°N
Disko
Vaigat
Nuussuaq
Qeqertarsuaq
Ilulissat
Disko Bugt
50 km
55°W
53°W
51°W

Figure 1



5500
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
Calibrated age (BP 1950)
0
50
100
150
200
250
300
350
400
450
Depth (cm)

Figure 2

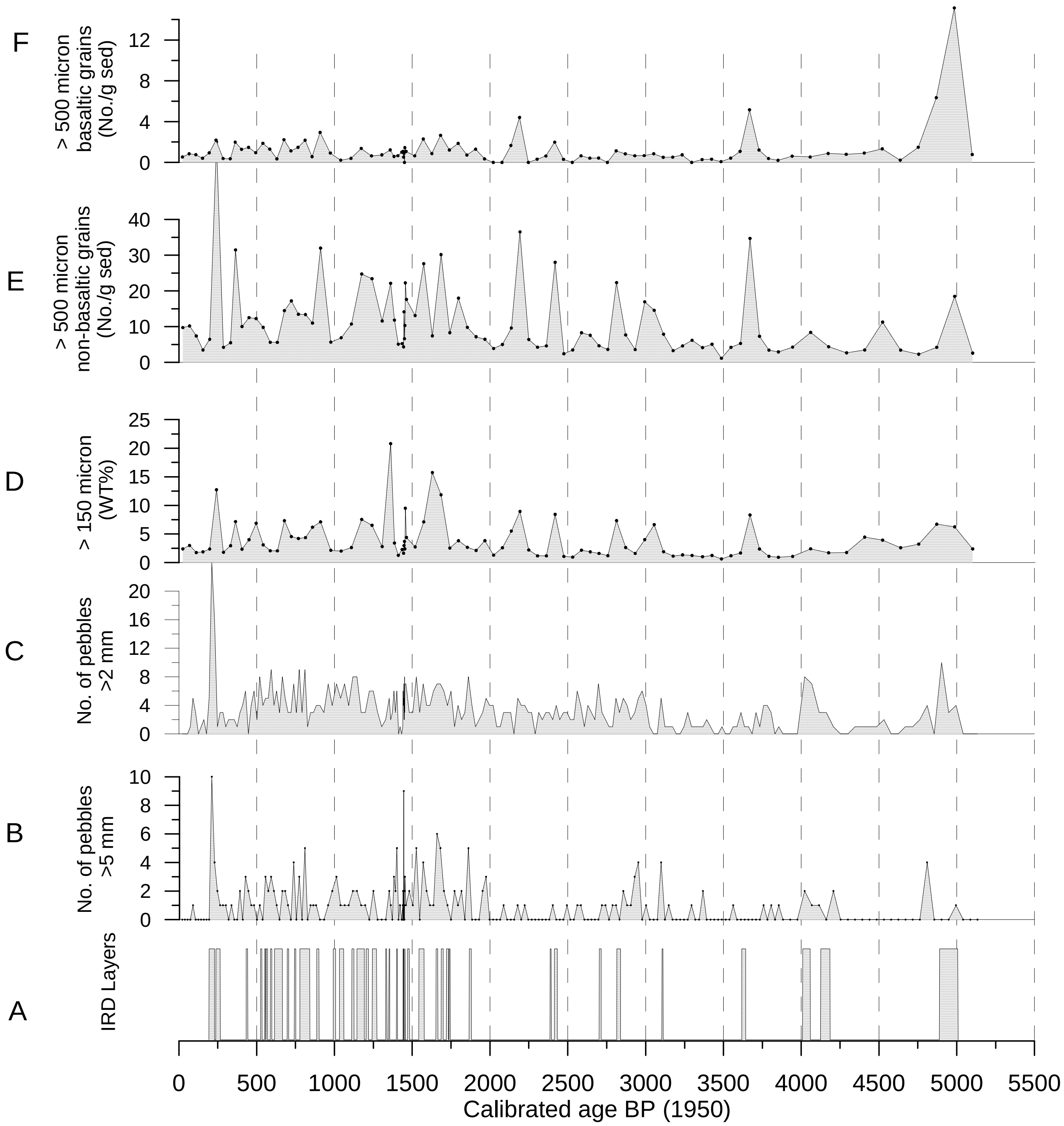

F
> 500 micron
basaltic grains
(No./g sed)
12
8
4
0
E
> 500 micron
non-basaltic grains
(No./g sed)
40
30
20
10
0
D
> 150 micron
(WT%)
25
20
15
10
5
0
C
No. of pebbles
>2 mm
20
16
12
8
4
0
B
No. of pebbles
>5 mm
10
8
6
4
2
0
A
IRD Layers
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
5500
Calibrated age BP (1950)

Figure 3

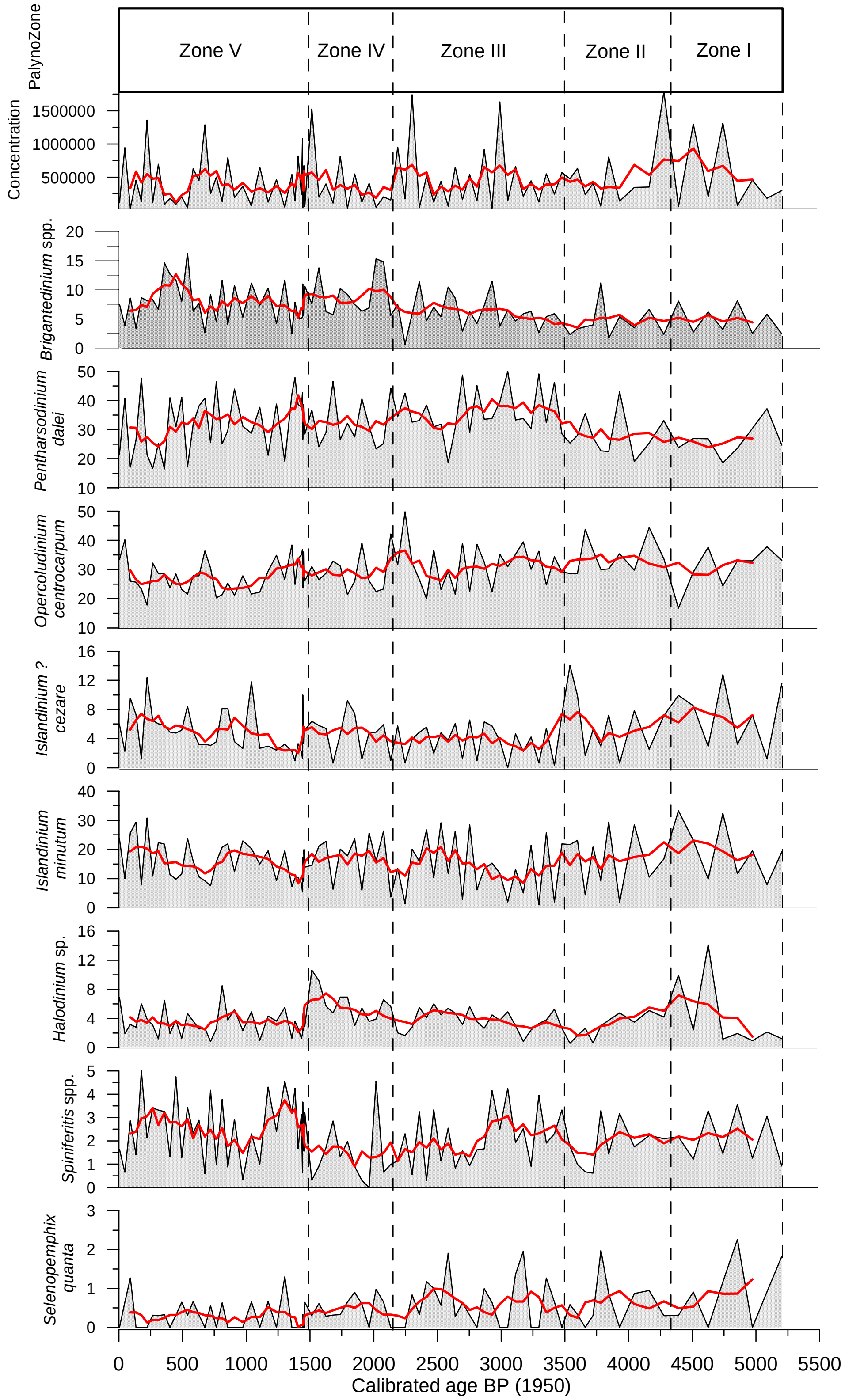
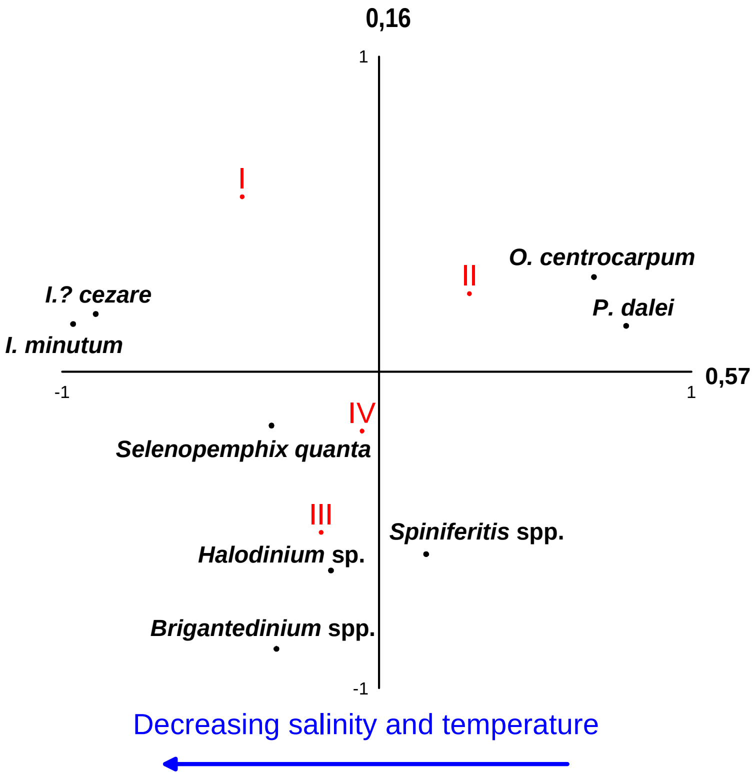

PalynoZone
Zone V
Zone IV
Zone III
Zone II
Zone I
Concentration
1500000
1000000
500000
Brigantedinium spp.
Pentharsodinium dalei
Operculodinium centrocarpum
Islandinium ? cezare
Islandinium minutum
Halodinium sp.
Spiniferitis spp.
Selenopemphix quanta
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
5500
Calibrated age BP (1950)

Figure 4



0,16
1
I
II
O. centrocarpum
I.? cezare
P. dalei
I. minutum
0,57
-1
1
IV
Selenopemphix quanta
III
Spiniferitis spp.
Halodinium sp.
Brigantedinium spp.
-1
Decreasing salinity and temperature

Figure 5

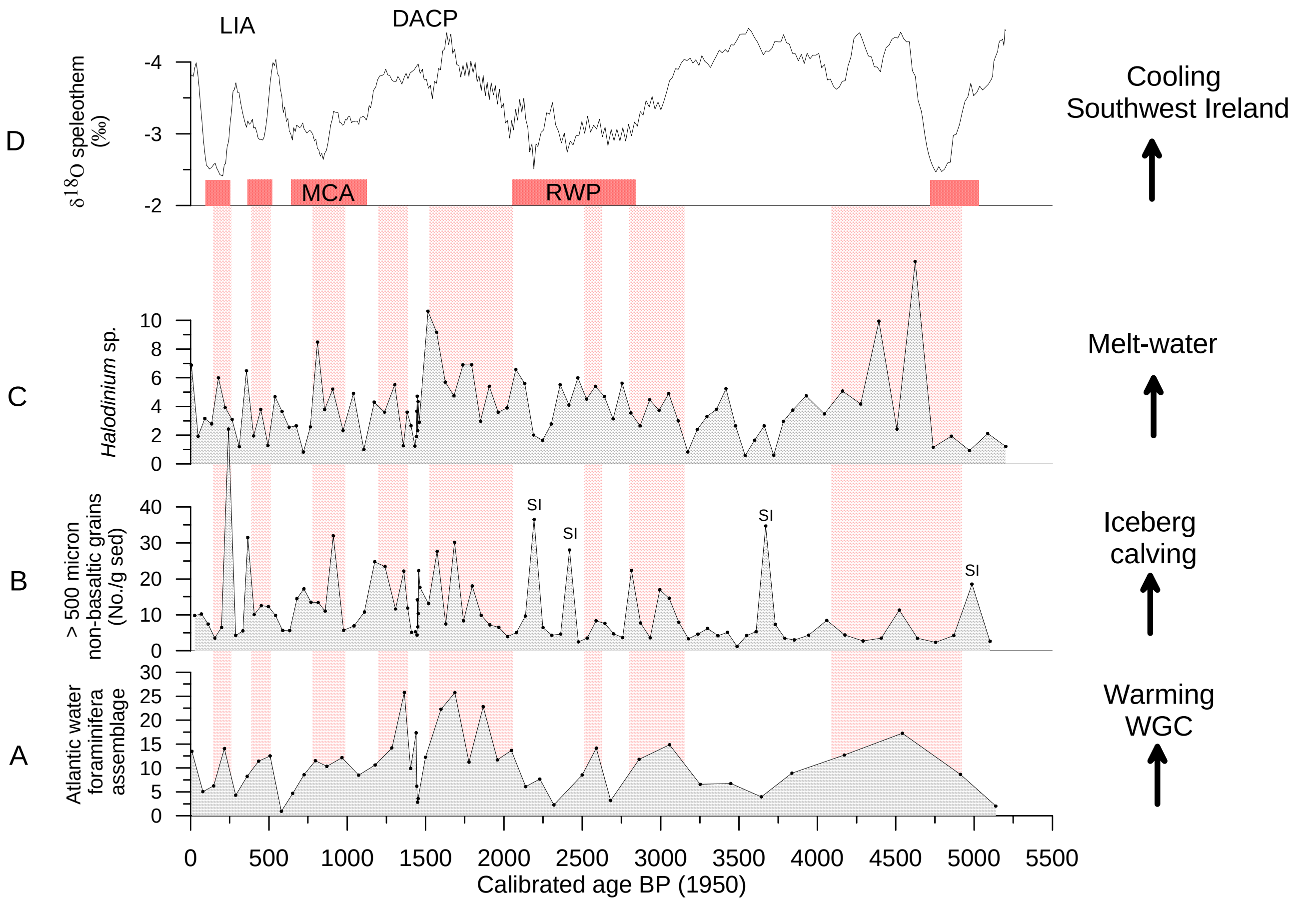

LIA
DACP
MCA
RWP
D
δ18O speleothem (‰)
-4
-3
-2
Cooling Southwest Ireland
C
Halodinium sp.
Melt-water
B
> 500 micron non-basaltic grains (No./g sed)
SI
SI
SI
SI
Iceberg calving
A
Atlantic water foraminifera assemblage
Warming WGC
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
5500
Calibrated age BP (1950)

Figure 6

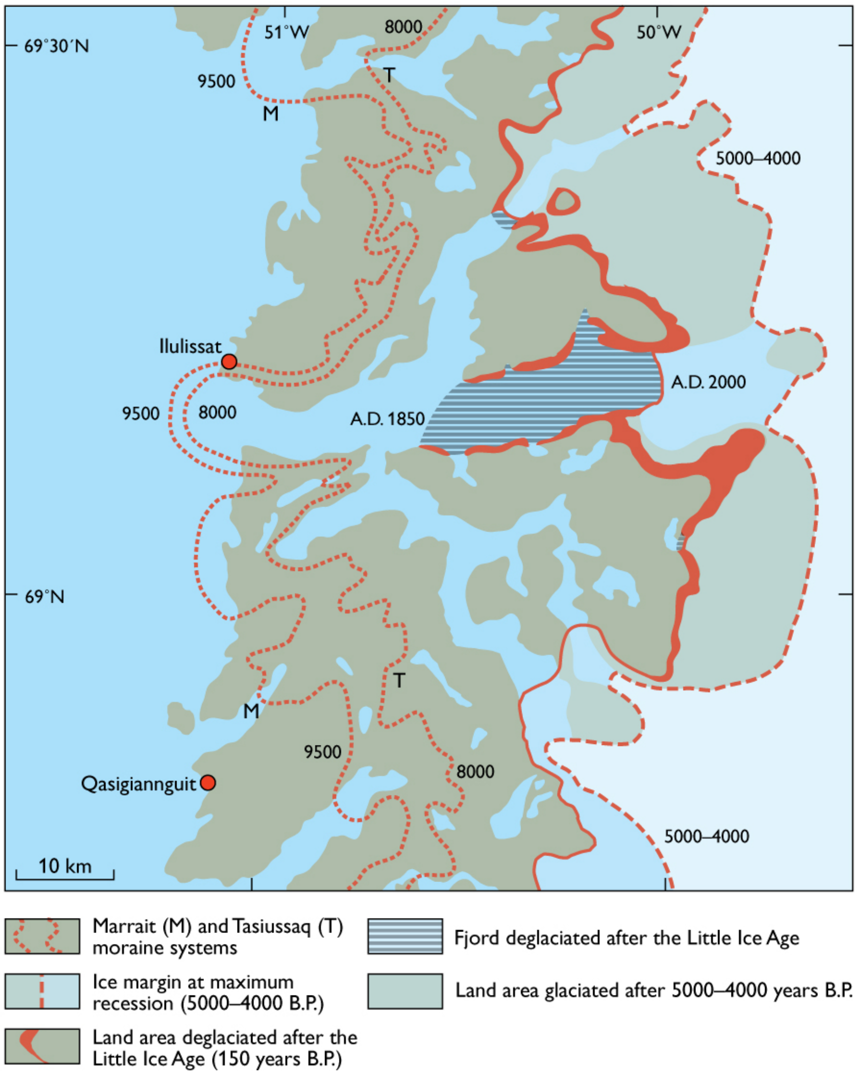

51°W
50°W
69°30′N
69°N
8000
9500
M
T
5000–4000
Ilulissat
9500
8000
A.D. 1850
A.D. 2000
T
M
9500
8000
Qasigiannguit
5000–4000
10 km
Marrait (M) and Tasiussaq (T) moraine systems
Ice margin at maximum recession (5000–4000 B.P.)
Land area deglaciated after the Little Ice Age (150 years B.P.)
Fjord deglaciated after the Little Ice Age
Land area glaciated after 5000–4000 years B.P.

Figure 7

Depth (cm)	Lab. no	Sample type	^{14}C age (BP)	Res. Corrected ^{14}C age (BP)	Calibrated age (BP) 2 sigma ranges	Median calibrated age (BP)
7-8	AAR 10953	Bivalve fragment	1013±35	613±35	660-520	590
27-28	AAR13060	Bivalve fragment	607±22	207±22	301-175	238
58-60	AAR 10952	Bivalve fragment	903±35	503±35	600-450	525
99	AAR13552	Marine plant fragm.	1356±27	956±27	805-969	887
132-136	AAR 10951	Marine plant fragm.	1797±40	1397±40	1450-1250	1350
152	AAR13553	Marine plant fragm.	1899±33	1499±33	1349-1529	1439
180	AAR13059	Marine plant fragm.	1913±27	1513±27	1535-1373	1454
199-200	AAR 10950	Marine plant fragm.	2090±42	1690±42	1800-1540	1670
302-304	AAR 13061	Benthic forams	3030±90	2630±90	3071-2605	2838
385	AAR 10949	Bivalve fragment	3976±38	3576±38	4100-3840	3970
390-393	AAR 10948	Marine plant fragm.	3833±43	3433±43	3920-3650	3785
435	AAR 10947		4709±40	4309±40	5050-4870	4960

Table 1