Late-Holocene diatom inferred reconstruction of temperature variations of the West Greenland Current from Disko Bugt, central West Greenland

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Abstract

The diatom flora from a high-resolution core collected from Disko Bugt, central West Greenland, records variations in surface water temperature for the Late Holocene (1600 – 300 cal. BP). Our data support the existence of a previously identified anti-phase relationship between the surface water temperature from West Greenland and climate events recorded in the NE Atlantic and between surface and subsurface waters (identified from benthic foraminifera) of the West Greenland Current (WGC). The diatom flora record relatively cool surface water conditions during end of the Roman Warm Period and Medieval Warm Period (MWP), and relatively warmer surface water conditions during the Dark Ages Cold Period and Little Ice Age (LIA). This is particularly pronounced during the MWP, experiencing the coldest conditions, and the LIA experiencing the warmest conditions through the whole sequence studied. The most likely explanation for this anti-phase relationship is linked to the flux of meltwater delivered to the WGC from sea-ice and the Greenland ice sheet off the West Greenland margin. The generally warmer conditions of the MWP resulted in increased melting of sea-ice and the Greenland ice sheet producing an increased meltwater flux and cooling of the surface waters of the WGC. In contrast, reduced meltwater flux during the relatively cold LIA resulted in reduced meltwater flux to the WGC producing a relative warming of the surface waters recorded by the diatom flora.

Key words: West Greenland, Disko Bugt, Late Holocene, West Greenland Current, North Atlantic, high-resolution diatom record

Introduction

The Disko Bugt area of central West Greenland has seen significant research interest in recent years investigating both the marine evidence of oceanic variability (e.g. Lloyd *et al.*, 2005; Moros *et al.*, 2006; Seidenkrantz *et al.*, 2008) and also recent fluctuations in tidewater based ice streams such as Jakobshavns Isbrae (e.g. Joughin *et al.*, 2004, 2008; Joughin, 2006; Rignot and Kanagaratnam, 2006). The driving mechanisms behind the major variations in ice stream activity are still uncertain, in particular the role of oceanic and/or atmospheric warming (Holland *et al.*, 2008). This uncertainty highlights the need for greater understanding of the links between ocean circulation, climate and ice sheet stability along the West Greenland margin.

Recent studies have identified significant Late-Holocene oceanographic variability along the West Greenland margin (e.g. Jensen *et al.*, 2004; Lloyd, 2006; Moros *et al.*, 2006; Møller *et al.*, 2006; Lloyd *et al.*, 2007; Seidenkrantz *et al.*, 2007, 2008). The link between such variability and broader North Atlantic climate variability (such as the 'Medieval Warm Period', MWP, and 'Little Ice Age', LIA) is, however, still rather unclear. Previously studied, benthic foraminiferal evidence from Disko Bugt, central West Greenland, suggests an in phase link between the subsurface water circulation component of the West Greenland Current (WGC) and established North Atlantic climate events such as the MWP and LIA (Lloyd, 2006). However, diatom and dinoflagellate cyst studies from outer Disko Bugt do not identify such a clear link in the uppermost surface waters of the WGC and North Atlantic climate variability (Moros *et al.*, 2006; Seidenkrantz *et al.*, 2008). Indeed several studies from the margins of the Labrador Sea to the south have suggested a climate seesaw during the Late Holocene with colder subsurface conditions during periods of relative warmth in the eastern North Atlantic ('Roman Warm Period' - RWP, and MWP) and vice versa during the colder periods ('Dark Ages Cold Period' - DACP, and LIA) with a suggestion of increased influx of Atlantic water masses during the LIA (Keigwin and Pickard, 1996; Seidenkrantz *et al.*, 2007, 2008). This has been linked to the atmospheric seesaw between West Greenland and northern Europe suggested by Dawson *et al.* (2003).

In this paper we present a high-resolution diatom record for the past 1600 years from a core collected from outer Disko Bugt covering several climate oscillations. This will allow further investigation of the link between oceanic and atmospheric circulation along the West Greenland margin, and also the phase relationship between West Greenland and the broader North Atlantic climate system. The diatom data presented here provide information on the uppermost hydrographic conditions of the WGC.

Study Site and oceanographic setting of Disko Bugt

Disko Bugt is a large marine embayment (68°30' N and 69°15' N and 50°00' W and 54°00' W, Figure 1) in central West Greenland. The core analysed here, DA00-02, was collected from a deep water trough, Egedesminde Dyb, with water depths of up to 900 m on the western (outer) part of Disko Bugt. This trough marks the palaeochannel of a major ice stream, Jakobshavns Isbrae, which at the last glacial maximum would have discharged across Disko Bugt onto the continental shelf to the west (Long and Roberts, 2003). Disko Bugt has a polar maritime climate and is typically covered by land-fast sea ice from January to April with a mean thickness of 0.7 m (Buch, 2000). Increased insolation in spring forms a pycnocline due to significant meltwater from land and from surrounding sea ice. A strongly stratified water column is maintained until September when increased winds and cyclone activity leads to increased mixing (Andersen, 1981b).

The hydrography of Disko Bugt and West Greenland in general is strongly influenced by the northward flowing West Greenland Current (WGC, Figure 1). The WGC entrains relatively warm and saline Atlantic water from the Irminger Current (IC) as well as cold, low salinity Arctic water from the East Greenland Current (EGC) (Tang *et al.*, 2004). On rounding the southern tip of Greenland these two components of the WGC start to mix, but the relatively cold and fresh Arctic component tends to dominate the upper 200 m and in coastal areas, while the warmer more saline Atlantic water component has a core from 200 to 500 m (Andersen, 1981a; Cuny *et al.*, 2002). These components of the WGC gradually mix northwards and are also complemented by significant meltwater flux from the Inland Ice, but are still distinguishable immediately south of Disko Bugt (Andersen, 1981a).

Materials and methods

The piston core DA00-02 was retrieved from a water depth of 840 m in the deepwater trough (Egedesminde Dyb) on the western edge of Disko Bugt during a cruise of the R/V Dana in August 2000 (Figure 1) (Kuijpers *et al.*, 2001). The exact location of the core site was

68º51’88” N, 53º19’72” W (Figure 1) and while the full core was 861 cm long results from only the upper 415.5 cm are presented here. A total of 222 samples were prepared for microscopic analysis at a resolution of approximately 2 cm. The age model used here was developed by Seidenkrantz *et al.* (2008) covering the full 3300 cal years of the core. Only the time interval from 1600 to 300 cal. years is presented here (see Seidenkrantz *et al.*, 2008, for full details of age model and lithological description of the core).

For diatom analysis 0.5 to 1 g of dry sediment was treated with 10% HCl and washed with distilled water. Samples were then boiled in hydrogen peroxide and washed several times in distilled water. Several drops of the final suspension were then allowed to dry on a cover slip and mounted in Naphrax® for subsequent diatom identification. In some cases identification was aided by scanning electron microscope (SEM). For each sample over 300 valves were counted excluding unidentifiable *Chaetoceros* spp. resting spores (r.s.) which are used as productivity indicators and were found in numbers equivalent to 100-200% of the actual diatom flora counted. Identification of diatom species was based on Fryxell (1975), Hasle and Syvertsen (1996), Metzeltin and Witkowski (1996), Witkowski *et al*. (2000), Von Quillfeldt (2001, 2004).

Results and Interpretation

A total of 308 diatom species were identified from 44 genera (13 centric, 31 pennate). The dominant taxa identified are *Fragilariopsis cylindrus*, *Thalassiosira kushirensis* r.s. and *Chaetoceros furcellatus* r.s.; these species along with the other selected abundant species are plotted in Figure 2. Diatoms have been used extensively in reconstructions of surface water mass characteristics (e.g. Koç Karpuz and Schrader, 1990; Jiang *et al*., 2002; Justwan and Koç, 2008). Studies have shown that they are particularly sensitive to changes in surface water temperature and have been used for quantitative reconstructions based on transfer functions (e.g. Koç *et al.*, 1993; Zieliński and Gersonde, 1997; Zielinski *et al*., 1998) and recently for reconstruction of sea ice concentrations in the North Atlantic (Justwan and Koç, 2008). The diatom species identified in this study are part of the Marginal Ice Zone group (MIZ; Justwan and Koç, 2008). However we sub-divide the diatoms into groups based on their ecological tolerance to water temperature in order to reconstruct changes in surface water temperature over the past 1600 years. Three groups have been distinguished: a sea-ice group - cryophilic, Arctic forms associated with ice margin habitat and sea-ice brine channels; northern cold water group - with neritic species, typical for open water conditions; warm/temperate water group – with neritic species, typical for waters of Atlantic origin (classification based on: Hasle and Syvertsen, 1996; Wiktor and Szymelfenig, 2002; Jensen, 2003; Justwan and Koç, 2008; Mikkelsen and Witkowski, 2010). The full list of species included in these groupings is given in Appendix 1. The most abundant species within the sea-ice group include *Fragilariopsis cylindrus, Fragilariopsis reginae-jahniae, Fragilariopsis oceanicus, Bacterosira bathyomphala* r.s. and *Fossula arctica* (species belonging to *Fragilariopsis* appear in plankton after ice break up e.g. Jensen, 2003; Figure 2). Species representing northern cold waters include *Chaetoceros furcellatus* r.s. and *Thalassiosira antarctica* var. *borealis* (both r.s. and vegetative cells) (Figure 2). The third group consists of warm/temperate taxa such as *Thalassiosira kushirensis* r.s., *Navicula distans* and *Thalassiosira oestrupii* (Hasle and Syverstsen, 1996; Witkowski *et al.*, 2000) (Figure 2). Sporadically abundant are species such as the littoral form *Fragilaria investiens* and the freshwater *Fragilaria* spp. Occurrence of these taxa is thought to be connected to melt water inflow from the inland ice (Jensen, 2003).

We have also made one significant taxonomic change in this study based on detailed SEM research. The species identified here as *Thalassiosira kushirensis* r.s. (Takano, 1985), indicative of temperate waters of Atlantic origin, was included in recent studies (e.g. Jensen, 2003; Moros *et al*., 2006) as *Thalassiosira antarctica* var. *borealis*, which represents northern cold water conditions. The occurrence of *Thalassiosira kushirensis* r.s. in western Greenland sediments is most probably caused by transport activity of the WGC, encompassing waters of Atlantic origin, as it was not abundant in modern plankton analyses (Witkowski and Krawczyk unpublished data, 2010). This change in classification has an important influence on palaeoenvironmental reconstructions.

Based on our primary aim of investigating the link between surface water conditions in West Greenland and broader North Atlantic climate we have sub-divided our record based on both the diatom flora from the core and the approximate boundaries between four key climate events identified elsewhere. The following section provides a brief interpretation of water mass characteristics in West Greenland during these 4 climatic periods based on the diatom record presented in Figure 3.

End of the Roman Warm Period (RWP, 1610 – 1500 cal. BP; AD 340 – 450)

The sea-ice group constitutes approximately 45% of the diatom assemblage through this interval (ranging from 32 – 52%), dominated by *Fragilariopsis cylindrus, Fragilariopsis reginae-jahniae* and *Bacterosira bathyomphala* r.s. The northern cold water assemblage, with *Chaetoceros furcellatus* r.s. dominant, has a relatively high abundance, averaging 20 – 40% through this interval. The warm/temperate taxa show a relatively low but variable abundance averaging 5 – 25%. In general the diatom assemblage indicates relatively cold water conditions at the core site during this interval (particularly compared with the rest of the core).

The Dark Ages Cold Period (DACP, 1500 – 1300 cal. BP; AD 450 – 650)

Whilst the sea-ice forms are again dominant during this period there is a distinct decrease in abundance of northern cold water forms (average approximately 25%) compared to the RWP. This corresponds to a distinct increase in the warm/temperate water taxa, in particular *Thalassiosira kushirensis* r.s., reaching a peak of 40% at 1400 cal. BP. The diatom flora indicates a slight warming in surface water conditions in outer Disko Bugt during this interval, particularly at 1400 cal. BP.

The Medieval Warm Period (MWP, 1300 – 700 cal. BP; AD 650 – 1250)

The time period is marked by a significant increase in abundance of taxa representing sea-ice conditions such as *Fragilariopsis cylindrus, Bacterosira bathyomphala* r.s., *Fragilariopsis oceanicus* and *Fragilariopsis reginae-jahniae*. The abundance of this group rises from 50% at 1300 cal. BP to 60% at *c.* 1200 cal. BP, 1050 cal. BP and 950 cal. BP, before gradually falling to values around 25 - 30% by 700 cal. BP at the end of the period (Figure 3). The warm/temperate assemblage has a relatively low abundance through most of this period, below 30% from 1300 cal. BP to *c.* 950 cal. BP before gradually increasing to 40 – 50% by 700 cal. BP. Northern cold water diatom abundance remains relatively stable (averaging 20 – 30%). However, at *c*. 1150 cal. BP there is a peak (exceeding 40%), dominated by *Chaetoceros furcellatus* r.s. The diatom flora indicates cooling in surface waters from 1300 cal. BP reaching the coldest conditions found in this study at *c.* 1150 cal. BP followed by a gradual warming becoming more pronounced from *c.* 900 cal. BP.

The Little Ice Age (LIA, 700 – 350 cal. BP; AD 1250 – 1600)

This period is characterized by the lowest abundance of the northern cold water species found over the period studied, averaging approximately 15% with a significant decreasing trend through the period. The diatom flora is dominated by the warm/temperate group, in particular *Thalassiosira kushirensis* r.s., but it is also significant that the relatively warm, temperate water species *Navicula distans* occurs in moderate numbers for the first time during this period (Figure 2). Overall the warm/temperate group increases from approximately 40% at the beginning of the period to an average of 55% from 550 – 350 cal. BP. The proportion of this warm/temperate assemblage during the LIA is significantly higher than any period observed earlier in the record. The abundance of sea-ice diatoms is again highly variable in this period reaching a peak of 68% at *c.* 500 cal. BP and 55% at *c*. 400 cal. BP, but then decreasing from 35% to 25% by 350 cal. BP. Whilst this might indicate moderately high proportions of sea-ice during limited parts of the LIA, the diatom flora in general indicates significantly warmer surface water conditions during the LIA than during earlier periods investigated in this study.

Discussion

The most striking pattern identified from the diatom flora in DA00-02 is the general anti-phase relationship between surface water temperatures off West Greenland and atmospheric climatic conditions from the NE Atlantic. This is most pronounced during the relatively warm atmospheric conditions in the NE Atlantic of the MWP with the dominance of a sea-ice and northern cold water flora in West Greenland, followed by a dominance of warm/temperate surface water flora during the cold period of the LIA (Figure 3). There is also a clear anti-phase relationship between our diatom inferred surface water temperature from outer Disko Bugt and the atmospheric temperature as identified from the DYE-3 Greenland ice core record (Dahl-Jensen *et al.*, 1998) also shown in Figure 3, which shows warmer temperatures during the MWP and colder temperatures during the LIA. Moros *et al.* (2006) and Seidenkrantz *et al.* (2008) also identified significant surface water cooling during the MWP based on diatoms and dinoflagellate cysts respectively, from similar locations in outer Disko Bugt. However, evidence from benthic foraminifera show the opposite pattern with relatively warm subsurface water conditions during the MWP and colder conditions during the LIA from both inner and outer Disko Bugt (Lloyd, 2006; Lloyd *et al.*, 2005; 2007). Interestingly, benthic foraminifera from a location in SW Greenland, Ameralik Fjord, show increased advection of WGC water during the LIA (Møller *et al.,* 2006; Seidenkrantz *et al.*, 2007). The reason for this apparent difference is unclear, but could be linked to the different settings. Amerilik fjord has a relatively shallow sill, hence advection of subsurface water is influenced by processes such as stratification, local brine formation and strength of katabatic winds (Seidenkrantz *et al.* 2007). Such processes may not play such an important role in the more open marine environment of Disko Bugt. In general, glacial reconstructions suggest significant advance of Greenland glaciers during the LIA (Weidick *et al.*, 1990; Weidick, 1992). Relatively warm/milder conditions during the MWP are also suggested for SW Greenland based on a lacustrine record from Kaplan *et al.* (2002) and fjord records from Jensen *et al.* (2004) and Lassen *et al.* (2004). Ice wedge data from the Hudson Strait area also suggest milder conditions prior to the LIA extending through the MWP (Kasper and Allard, 2001). Kaufman *et al.* (2009), in a compilation of records covering the last 2000 years, report a long-term Arctic summer cooling trend encompassing the LIA – with only a slight warming during part of MWP (AD 900 – 1050). They suggest this trend is driven by orbital forcing.

Our data supports the identification of an anti-phase relationship between the surface water temperature in Disko Bugt and climate conditions in the NE Atlantic, identified by Seidenkrantz *et al*. (2008). However we also identify an anti-phase relationship between the surface and subsurface waters of the WGC in the Disko Bugt area. An anti-phase or climate 'seesaw' pattern has been suggested between West Greenland and the NE Atlantic region based on North Atlantic Oscillation type atmospheric conditions (Dawson *et al.*, 2003). This was suggested as a possible mechanism to explain the cold conditions during the MWP identified by Seidenkrantz *et al.* (2008). However, there is an alternative mechanism that could also account for the anti-phase relationship between surface and subsurface waters in Disko Bugt.

The diatom flora record changes in the surface water component while benthic foraminifera record changes in the subsurface water component of the WGC. During warm climatic periods (such as the MWP) higher atmospheric temperatures over Greenland will lead to increased melting of the ice sheet and earlier, more extensive melting of sea-ice. This would produce increased meltwater flux off the West Greenland margin diluting the surface waters of the WGC with colder, lower salinity waters leading to an increase in northern cold, open water assemblages and also increased release of sea-ice diatoms into the water. Both these processes are typical of the Arctic spring bloom and could combine to account for the diatom flora identified here during the MWP. An increase in cold water diatom flora in surface waters would occur at the same time as an increase in the warmer benthic foraminifera fauna due to subsurface warming linked to broader North Atlantic climate warming – producing increased IC influence in the WGC as suggested by Lloyd (2006).

During colder intervals, such as the LIA, cooler atmospheric conditions over Greenland would lead to reduced melting and advance of the ice sheet and also reduced melting of sea-ice. A reduction in meltwater flux off the Greenland margin would reduce the dilution of the surface water of the WGC by colder lower salinity water leading to a relative increase in surface water temperature. Less melting of the sea ice would further decrease dilution from relatively cold freshwater, but would also reduce time available for the spring bloom and flux of sea ice diatoms to the surface waters. Combined, these processes would decrease the proportion of 'cold water' diatom flora and the increase in relatively warm/temperate water diatom flora identified during the LIA - with major dominance of *Thalassiosira kushirensis* r.s. – identified in DA00-02.

Conclusions

The high-resolution diatom record from outer Disko Bugt presented here records an anti-phase relationship between surface water temperatures off West Greenland and NE Atlantic climate. We also identify an anti-phase relationship between surface and subsurface water temperature within the WGC in Disko Bugt. The anti-phase relationship between West Greenland and the NE Atlantic has previously been linked to an NAO type climate seesaw. We present an alternative mechanism linked to meltwater flux from sea-ice and the Greenland ice sheet that is known to influence the WGC. During relatively warm intervals, such as the MWP, increased melting of sea-ice and the Greenland ice sheet would result in an increased flux of cold and low salinity meltwater to the surface waters of the WGC producing a diatom assemblage indicative of colder conditions. By contrast during colder intervals, such as the LIA, reduced melting of sea-ice and the Greenland ice sheet would reduce meltwater dilution of the WGC surface waters leading to a decrease in cold water diatom assemblage in favor of a warmer water diatom assemblage. This mechanism is also consistent with the anti-phase relationship between surface and subsurface waters (as suggested by published benthic foraminiferal records from Disko Bugt).

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Appendix 1. List of all species used in figure 3.

Sea-ice diatoms:

Bacterosira bathyomphala (Cleve) Syvertsen *et* Hasle in Hasle & Syvertsen

Chaetoceros socialis Lauder

Fossula arctica Hasle & Syvertsen *et* von Quillfeldt

Fragilariopsis cylindrus (Grunow) Krieger in Helmke & Krieger

Fragilariopsis oceanicus (Cleve) Hasle

Fragilariopsis reginae-jahniae Witkowski, Lange-Bertalot *et* Metzeltin

Navicula kariana Grunow var. *frigida* (Grunow) Cleve

Nitzschia frigida Grunow in Cleve & Grunow

Nitzschia promare Medlin

Pauliella taeniata Grunow

Northern cold water diatoms:

Chaetoceros furcellatus J. W. Bailey

Rhizosolenia borealis Sundström

Rhizosolenia hebetata Bailey f. *hebetata*

Rhizosolenia styliformis Brightwell

Thalassiosira antarctica Comber var. *borealis* Fryxell, Ducette *et* Hubbard

Thalassiosira baltica (Grunow) Ostenfeld

Thalassiosira bulbosa Syvertsen in Syvertsen & Hasle

Thalassiosira hyalina (Grunow) Gran

Thalassiosira levanderi van Goor

Thalassiosira nordenskioeldii Cleve

Warm/temperate water diatoms:

Actinocyclus circellus T. P. Watkins *in* Watkins & Fryxell (warm)

Actinocyclus vestigulus T. P. Watkins *in* Watkins & Fryxell (warm)

Navicula distans (W. Smith) Ralfs in Pritchard (temperate)

Thalassionema nitzschioides Grunow ex Hustedt (warm to temperate)

Thalassiosira angulata (Gregory) Hasle (temperate)

Thalassiosira kushirensis Takano (temperate)

Thalassiosira oestrupii (Ostenfeld) Hasle (warm to temperate)

Figure Captions

Figure 1. Location of the DA02 core site, Disko Bugt and an overall scheme of the circulation system in Greenland region. Relatively warm waters: IC-Irminger Current; WGC-West Greenland Current. Cold waters: BC-Baffin Current; EGC-East Greenland Current; LC-Labrador Current

Figure 2. Percentage plot of the dominant diatom species (>2%) in core DA02, Disko Bugt. Time intervals based on NW European system (Seidenkrantz et al., 2008)

Figure 3. Disko Bugt (DA02) data: (A) relative abundance record of sea ice-associated diatoms; (B) relative abundance record of northern cold water diatoms and (C) relative abundance of warm/temperate water diatoms. In addition, in (D) the ice core borehole temperature reconstruction for DYE-3 by Dahl-Jensen et al. (1998). Time intervals based on NW European system (Seidenkrantz et al., 2008)

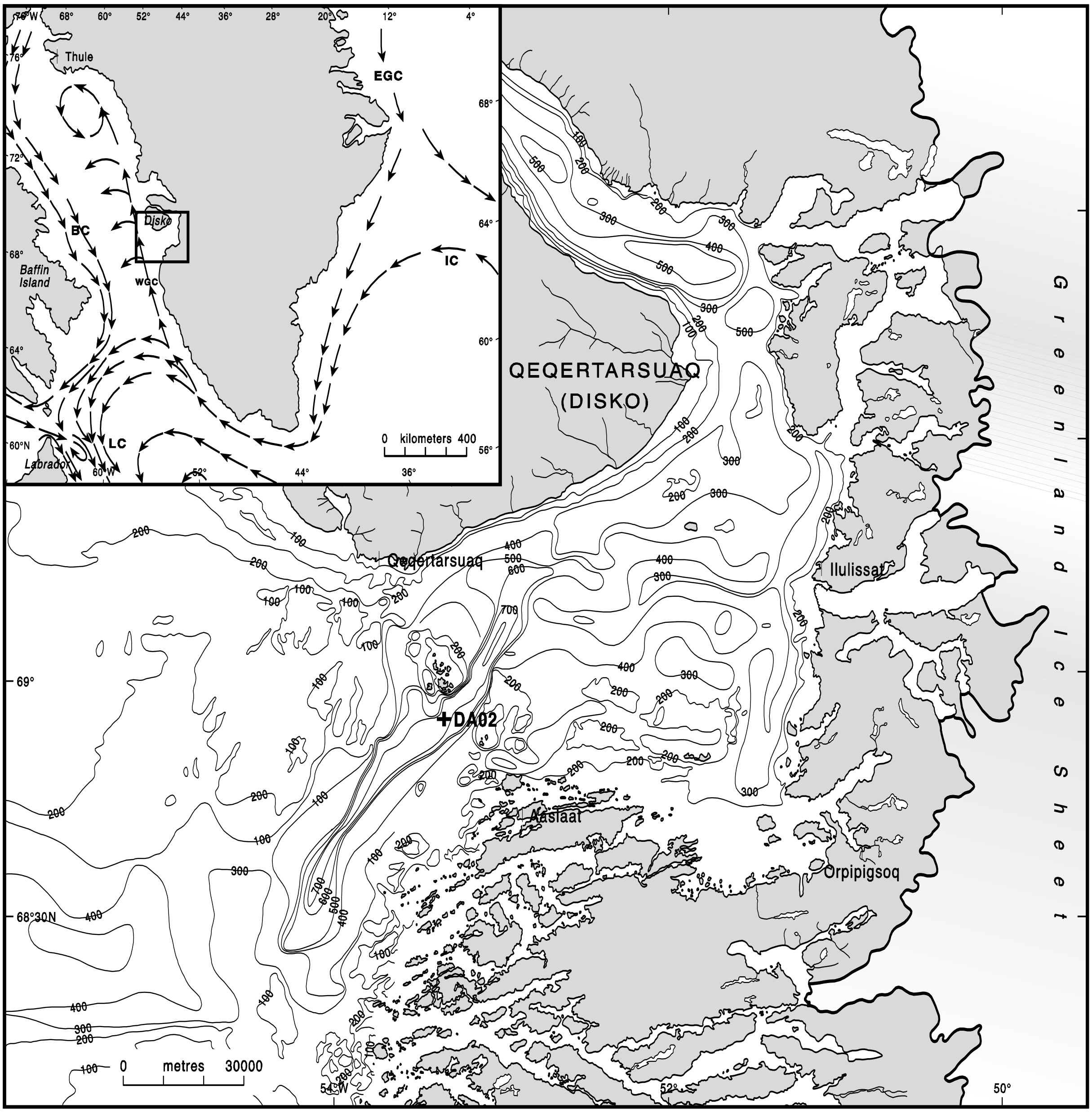
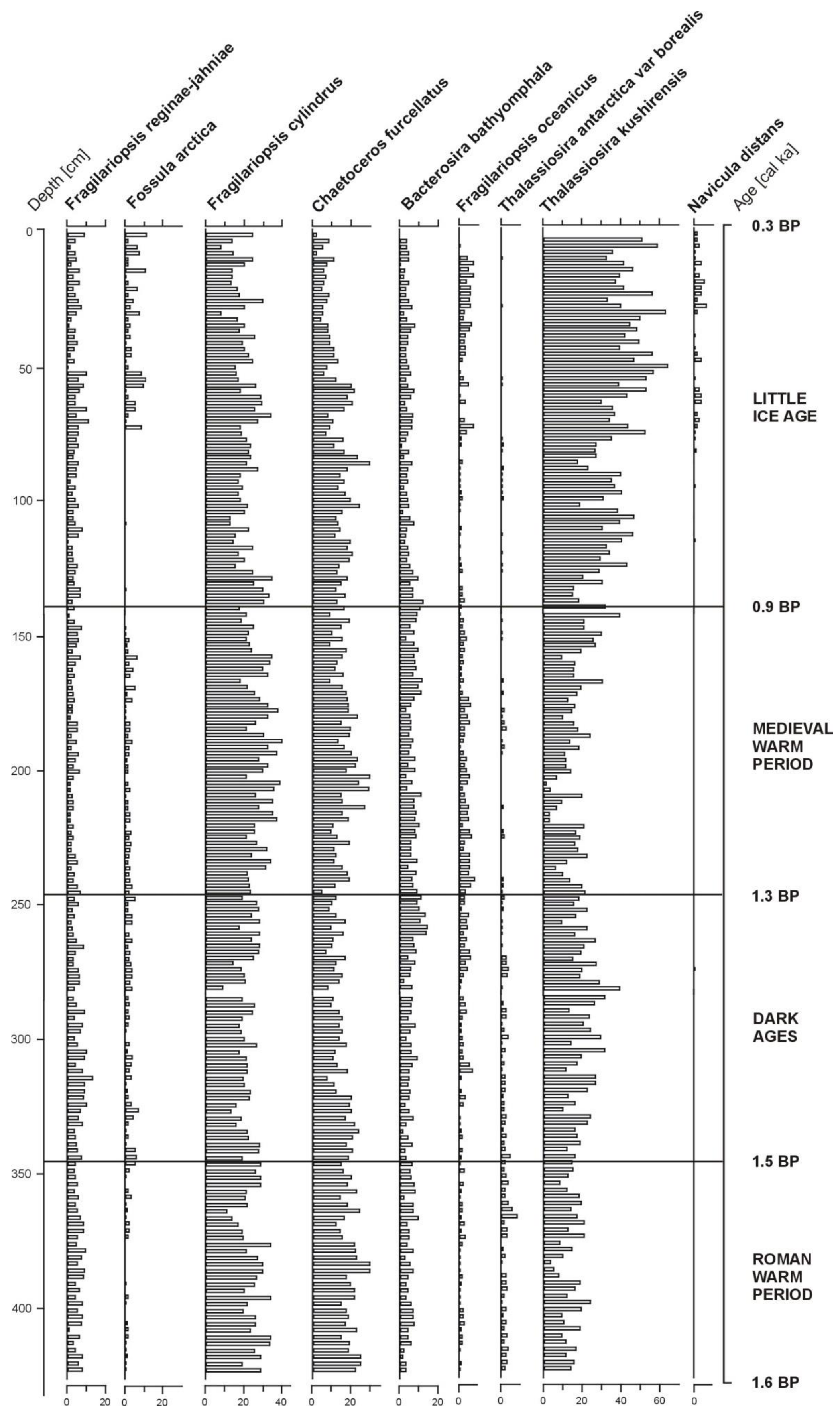

Thule
EGC
BC
Disko
Baffin Island
WGC
IC
LC
Labrador
0 kilometers 400
QEQERTARSUAQ
(DISKO)
Qeqertarsuaq
Ilulissat
DA02
Aasiaat
Orpipigsoq
Greenland Ice Sheet
0 metres 30000
69°
68°30N
54°W
52°
50°

Figure 1



Depth [cm]
Fragilariopsis reginae-jahniae
Fossula arctica
Fragilariopsis cylindrus
Chaetoceros furcellatus
Bacterosira bathyomphala
Fragilariopsis oceanicus
Thalassiosira antarctica var borealis
Thalassiosira kushirensis
Navicula distans
Age [cal ka]
0.3 BP
LITTLE ICE AGE
0.9 BP
MEDIEVAL WARM PERIOD
1.3 BP
DARK AGES
1.5 BP
ROMAN WARM PERIOD
1.6 BP
0
50
100
150
200
250
300
350
400
20
40
60

Figure 2

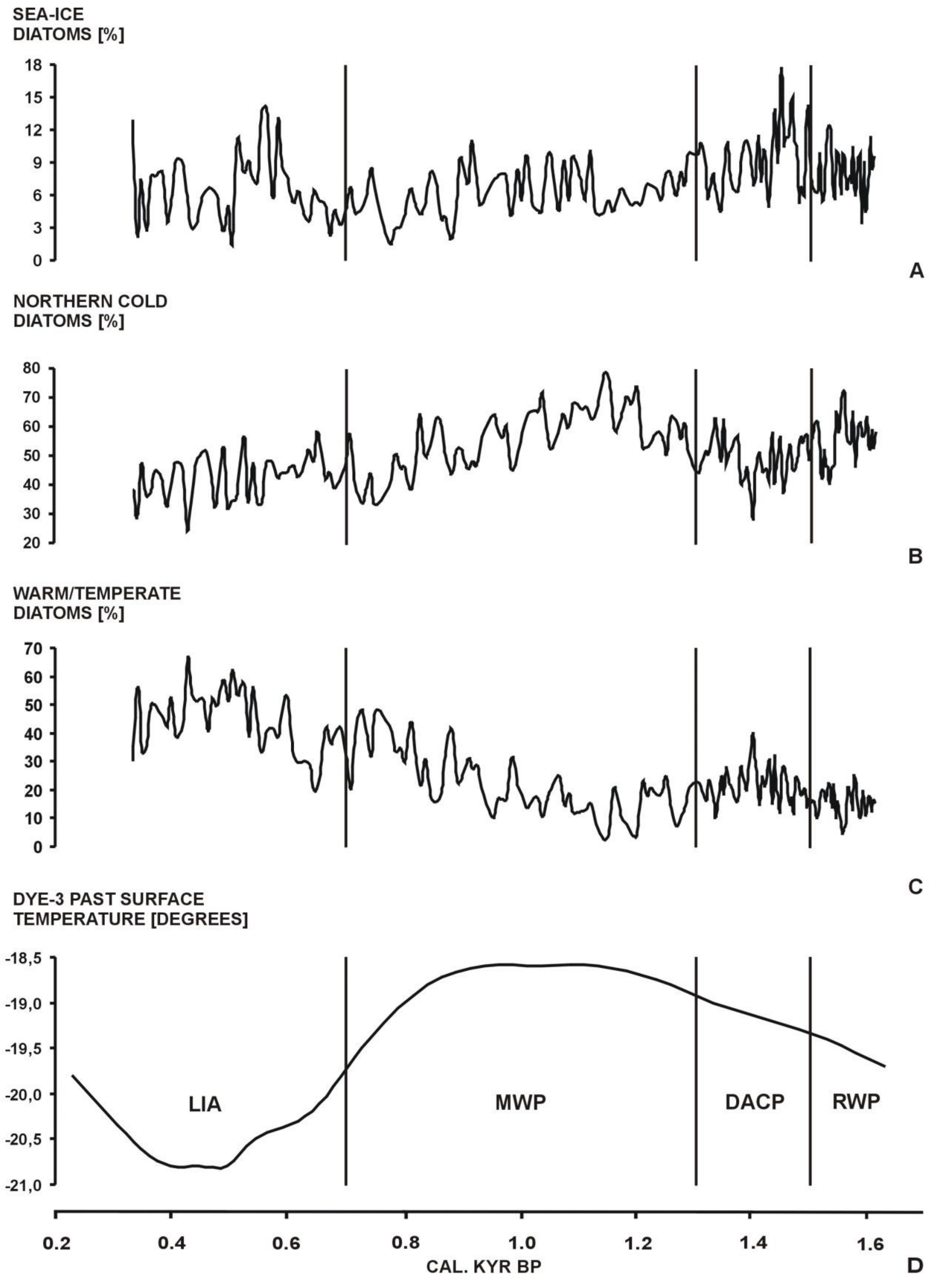

SEA-ICE
DIATOMS [%]
18
15
12
9
6
3
0
A
NORTHERN COLD
DIATOMS [%]
80
70
60
50
40
30
20
B
WARM/TEMPERATE
DIATOMS [%]
70
60
50
40
30
20
10
0
C
DYE-3 PAST SURFACE
TEMPERATURE [DEGREES]
-18,5
-19,0
-19,5
-20,0
-20,5
-21,0
LIA
MWP
DACP
RWP
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
CAL. KYR BP
D

Figure 3