

Benthic foraminifera in an Arctic fjord: recent distribution and fauna of the last two millennia



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A dissertation for the degree of Philosophiae Doctor

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Preface

This thesis is the result of a four-year PhD study within the research project ‘*Assessment of benthic foraminifera as environmental proxy in the Arctic region*’ (*ForArc*), financed by the Research Council of Norway. The overall goal of the project was to advance our knowledge about the ecology and distributions patterns of benthic foraminifera to improve the application of benthic foraminifera as proxy indicators of modern and past environments in the fjords and shelves of Svalbard, the Barents Sea and Northern Norway. The project was a joint project between the Norwegian Polar Institute (NP) in Tromsø and the Department of Geology, University of Tromsø (UiT). Most of the work was carried out at NP. However, 25 % of the education was financed by the UiT and, thus, assigned to “duty work” at the Department of Geology. This included teaching activities (assistant during educational cruises), assistance during marine-geological and geophysical cruises arranged by the Department of Geology (co-chief scientist during one cruise), preparations and presentations of activities during the “National Science Week” in Norway (Forskningdagene), contribution to the compilation of a data base of benthic foraminiferal species, introduction and application of a new method for staining live foraminifera (CellTracker Green (CMFDA)) at NP and UiT, and participation in the expedition ANT XXVI/3 on R/V *Polarstern* to the Amundsen Sea and Pine Island Bay, Antarctica (Jan. – April 2010). In the context of the PhD education, I prepared and participated in ten marine-geological and geophysical cruises on the research vessels *Lance* (NP) and *Jan Mayen* (now *Helmer Hanssen*, UiT).

Results of this PhD thesis were presented in eight oral and poster presentations (six as first author) during national and international workshops and conferences. The doctoral thesis resulted in four scientific papers that contribute with new knowledge on the distribution of modern and past benthic foraminiferal faunas from the Arctic region. The scientific papers are:

Paper I

Jernas, P., Klitgaard-Kristensen, D., Husum, K., Koç, N., Tverberg, V., Loubere, P., Prins, M., Dijkstra, N. **Response of modern Arctic benthic foraminiferal fauna to annual environmental changes; evidence from Kongsfjorden, Svalbard.**

In revision for Marine Micropaleontology

Paper II

Jernas, P., Klitgaard-Kristensen, D., Husum, K., Wilson, L., Koç, N. **Paleoenvironmental changes of the last two millennia on the western and northern Svalbard shelf.**

Re-submitted to Boreas

Paper III

Jernas, P., Husum K., Klitgaard-Kristensen D., Forwick, M., Koç, N. **Seasonal composition of recent benthic foraminifera in the surface sediments of Kongsfjorden, Svalbard.**

To be submitted to Polar Research

Paper IV

Loubere, P., Jacobson, B., Klitgaard-Kristensen, D., Husum, K., Jernas, P., Richaud, M., 2011. **The structure of benthic environments and the paleochemical record of foraminifera.** *Deep Sea Research, Part 1: Oceanographic Research Papers*, vol. 58, Issue 5, p. 535-545.

1. Introduction and objectives

Reconstructions of paleoenvironments and past climate conditions in marine sediment records aim to provide knowledge about the past climate history to better understand the forcing mechanisms behind natural variability. Further, this knowledge is of great importance to validate and improve the reliability of climate models predicting scenarios for future climate development. McCarroll (2010) argues that the boundary conditions of the last 2000 years are closest in resembling present conditions and presumably the conditions of the near future. Therefore, palaeoclimate data obtained from marine and terrestrial archives covering the last two millennia are highly appropriate for testing and validating climate models. The last 2000 years are characterised by some remarkable climate fluctuations including the prominent warming of ‘Roman Warm Period’ (c. 50 BC – AD 400) ‘Medieval Climate Anomaly’ (c. AD 900-1500) and the cooling of the ‘Dark Ages’ (c. AD 400-800) and the Little Ice Age (c. AD 1500-1900) (e.g., Lamb, 1977; Grove, 1988; Bradley, 2000; Jiang et al., 2002; Bengtsson et al., 2004; Eiriksson et al., 2006; Overland, 2008; Berner et al., 2011). During the last 100 years climate has warmed in the Northern Hemisphere, termed the ‘Modern Warming’ (Moberg, 2005; Mann, 2008; Kaufman et al., 2009). The climatic changes attributed to the ‘Modern Warming’ are even stronger in Polar Regions, particular the Arctic as shown by the ongoing warming and decreasing sea ice extent in this region (Stroeve et al., 2007). Models predict that this region will experience the strongest temperature increases in the future due to polar amplification (ACIA, 2004; IPCC, 2007).

The main oceanic heat source for the Arctic is the northward flowing warm and saline North Atlantic Current (Fig. 1). The warm and saline Atlantic surface water submerges around 78°N and continues as a subsurface flow into the Arctic Ocean, but also enters the fjords of west Svalbard (e.g., Cottier et al., 2005; 2010). Since this current is the major contributor of heat, salt and nutrients to the European Arctic region its variations at present and in the past are of strong relevance to past variations in climate and the ecosystem of the Arctic. Understanding this is necessary in terms of predicting future climatic and ecosystem changes. Therefore records that can provide very detailed information on variability in Atlantic Water are necessary in order to portray the full scale of natural environmental and climate changes. Obtaining detailed paleorecords also requires sediment cores with highest time resolution possible. Fjords have been shown to be both suitable and valuable in terms of providing high-resolution records (Howe et al., 2011) due their often high sedimentation rates compared to the open ocean (Howe et al., 2011). Fjords located at western Svalbard that is influenced by Atlantic Water and with high sedimentation rates can thus provide detailed studies of spatial and temporal variations of past Atlantic Water flow into the Arctic.

Assessment of past natural environmental changes beyond the instrumental time series can only be estimated by using proxies (Stein, 2008 for review). One key proxy for paleoenvironmental reconstructions in the Arctic is benthic foraminifera. They are highly relevant due to their high abundance and diversity in shelf areas and in fjords (e.g., Schröder-Adams et al., 1990; Jennings et al.1994; Korsun et al, 1995; Hald and Korsun, 1997; Pogodina, 2001; Polyak et al., 2002; Murdmaa et al., 2004; Lloyd, 2006; Wollenburg et al., 2007; Bubenshchikova et al., 2008; Scott et al., 2008; Ivanova et al., 2008; Rasmussen and

Thomsen, 2010). These studies show that benthic foraminiferal fauna and abundance, in addition to stable oxygen and carbon isotopes, are capable of capturing paleoenvironmental variability in the region. But extracting more precise information about past variability of the subsurface flow of Atlantic water into the Arctic using benthic foraminifera is hampered by the lack of modern faunal analogues and a thorough understanding of how these relate to the environment (e.g., Ślubowska et al., 2005; 2008, Koç et al., 2002, Lubinski et al., 2001). Therefore more in depth knowledge on the relation between the responses of the benthic foraminiferal fauna to various environmental changes are needed.

Paleoclimate reconstructions of detailed high-resolution records also require a sensitive proxy with short response time to the changing environmental conditions. Many studies on modern benthic foraminifera assemblages focus only on the distribution patterns of the fauna under prevailing conditions during a length of time often restricted to a sampling interval that represents a 'snap-shot' (e.g. Mackensen et al., 1989; Schroder-Adams et al., 1990; Hald and Korsun, 1997; Wollenburg, 1998; Rytter et al., 2002; Bergsten 2004; Jennings 2004; Lloyd 2006; Bubenshchikova et al., 2008; Scott et al., 2008). Reconstructing high-resolution paleoclimate records in the Arctic using benthic foraminiferal, however, require more knowledge about temporal variability on annual and seasonal scale. Such studies are limited in the Arctic region (Korsun and Hald, 2000). Therefore more knowledge of ecological changes on short time scales (e.g., inter-annual, annual and even seasonal) is needed to improve the interpretation and understanding of the environmental signals archived in benthic foraminifera faunas in sediment cores and, thus, to contribute to more reliable and precise reconstructions of past and present environmental changes in the Arctic.

Benthic foraminifera possessing a carbonate test can also provide geochemical proxies, such as stable oxygen and carbon isotope and Mg/Ca measurements (e.g., Hald et al., 2001, Zajączkowski et al., 2010; Aagaard-Sørensen et al., 2012). Since these parameters can be strongly influenced by the microhabitat in which the faunas live (Rohling and Cooke, 1999 for a review), understanding of the distribution of the living benthic foraminifera within different microhabitats, e.g., different living depths in the sediment, will help to identify the environmental properties being reflected in the geochemical compositions of the tests. Such studies from Arctic fjords and shelves are still needed.

Benthic foraminifera species and faunas have been used as a proxy of paleoenvironmental conditions in studies from Svalbard fjords and shelf areas (Skirbekk et al., 2010; Ślubowska et al., 2005; Rasmussen et al., in press, Hald et al., 2004; Majewski et al., 2009; Kubischta et al., 2011,) covering mainly the Holocene and the deglaciation including the Younger Dryas cold period. Paleorecords with high resolution and covering the last two millennia in the marine environments is still sparse (Majewski et al., 2009) although as pointed out by McCarroll (2010) these may be particular useful in validating and testing climate models.

The overarching main objective of this thesis is to improve our knowledge about the ecology and distribution of the benthic foraminiferal faunas to increase the value of benthic foraminifera as a useful proxy for modern and past environmental conditions. The focus of this study is fjord and shelf environments on northwest Spitsbergen, Svalbard archipelago, European Arctic. These areas are influenced by northward-flowing warm and saline Atlantic

Water, as well as local influences of e.g., tidewater glaciers. Several sub-objectives were established in order to advance the knowledge of benthic foraminiferal ecology and their application down-core by the following; 1) perform analyses of living (stained) benthic foraminiferal assemblages, total abundances and diversity in surface samples (upper two centimetres in multicorer) covering inter-annual and seasonal sampling intervals; 2) measure environmental factors using different methods (oceanography, sedimentologic properties, and organic matter content); 3) relate the modern fauna to the environmental changes (i.e., variations in hydrography, food supply, light conditions, sea-ice distribution, and sediment supply); 4) investigate the benthic foraminiferal microhabitat and its influence on the faunal distribution and geochemical characteristics of the tests by down-core oxygen profiling and discrete subsampling of foraminifera and pore-water in multicorer samples; 5) reconstruct paleoenvironments using benthic foraminifera compositions, abundance and diversity in shelf records from northwestern Svalbard over the last 2000 years.

2. Study area

This study is based on the analyses of sediment samples from Kongsfjorden and the Hinlopen Trough on Svalbard (Fig. 1). Even though the areas are affected by the inflow of warm and saline Atlantic Water, regional differences with regard to their local oceanography, proximity to sediment sources and primary productivity occur.

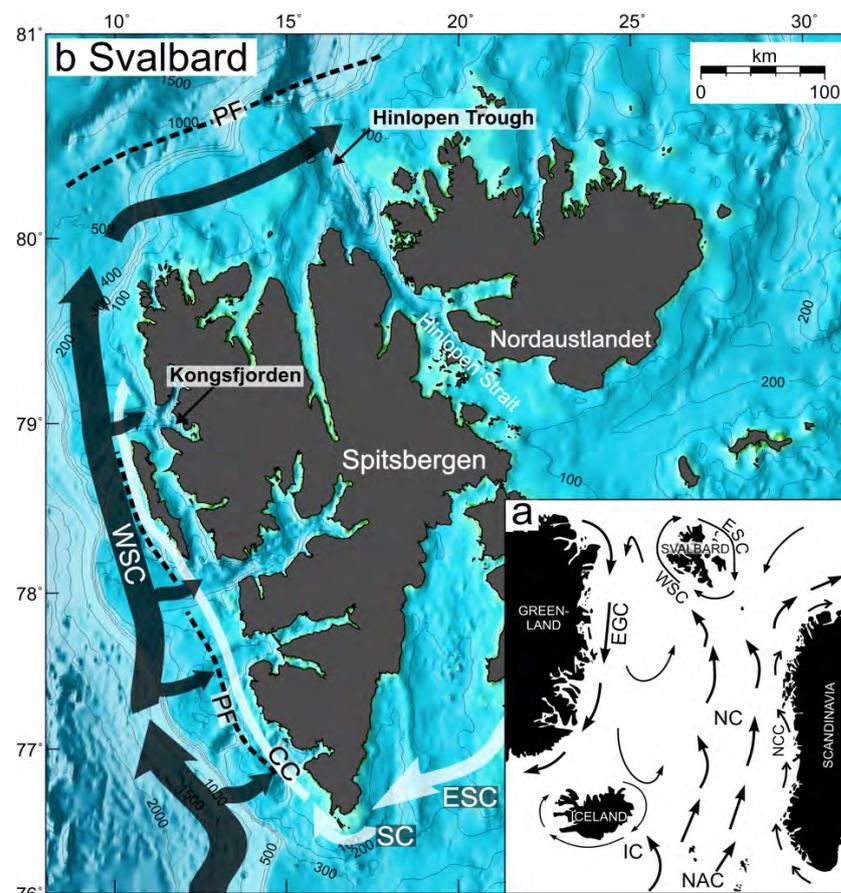


Figure 1. a) Overview map showing the location of Svalbard and the main surface and subsurface currents in the northern North Atlantic: the Atlantic-derived North Atlantic Current (NAC), Irminger Current (IC), Norwegian Current (NC), Norwegian Coastal Current (NCC), West Spitsbergen Current

(WSC) and Arctic-derived East Greenland Current (EGC) and East Spitsbergen Current (ESC). **b)** Map of Svalbard showing the approximate path of the WSC and the ESC: Sørkapp Current (SC) and Coastal Current (CC) as well as Polar Front (PF). The locations of the Hinlopen Trough and Kongsfjorden Trough are indicated with black arrows.

Kongsfjorden

Kongsfjorden is the southern branch of the Kongsfjorden-Krossfjorden fjord system on north-western Spitsbergen. It is c. 20 km long, 4-10 km wide and maximum 394 m deep. Kongsfjorden is a glacial trough that was excavated by grounded ice streams and the present seafloor comprises an irregular topography that still reveals imprints of the grounded ice (e.g., Howe et al., 2003; Ottesen et al., 2005, 2007; MacLachlan et al., 2010). At present two retreating tidewater glacier termini (Blomstrandbreen, as well as Kongsbreen comprising the glaciers, Kongsvegen, Kronebreen and Conwaybreen) reach into the fjord, and several of these are surge glaciers (Hagen et al., 1993).

Water masses of external and internal origin, as well as mixtures of these occur in Kongsfjorden (Svendsen et al., 2002; Cottier et al., 2005). An overview about their definitions and properties is provided in Table 1.

Table 1. Definitions and properties of water masses in Kongsfjorden (modified from Cottier et al., 2005).

Water Mass/origin	Abbreviation	Temperature [°C]	Salinity
<u>External origin</u>			
Atlantic Water	AW	>3.0	>34.65
Arctic Water	ArW	-1.5 - +1.0	34.30-34.80
<u>Internal origin</u>			
Winter-Cooled Water	WCW	<-0.5	34.40-35.00
Local Water	LW	-0.5 - +1.0	34.30-34.85
Surface Water	SW	>1.0	<34.00
<u>Mixed</u>			
Transformed Atlantic Water	TAW	1.0 - 3.0	>34.65
Intermediate Water	IW	>1.0	34.00-34.65

The Atlantic Water (AW) is transported by the northward-flowing West Spitsbergen Current (WSC) and the Arctic Water (ArW) is carried by the Sørkapp Current (SC) and the Coastal Current (CC; Fig. 1; Svendsen et al., 2002; Cottier et al., 2005). The internal and mixed water masses are described in detail in papers I and III.

The water column in Kongsfjorden experiences typically a seasonal cycle of stratification (Svendsen et al., 2002; Cottier et al., 2005, 2010). This cycle includes 1) well-developed stratification during summer resulting from solar radiation, fresh-water supply, as well as the inflow of AW and ArW due to the absence of a marked sill at the fjord mouth; 2) disappearing stratification in late summer and autumn due to surface cooling and convection;

3) haline convection of fjord-internal water masses during winter; 4) re-stratification during spring.

The inner parts of Kongsfjorden are typically covered with fast sea ice during winter. The ice breaks up between April and July (Svendsen et al., 2002). However, marked inter-annual variations of sea-ice extent and timing of melting and break-up occur (Gerland et al., 1999; Svendsen et al., 2002; Gerland and Renner, 2007).

Sediment supply to the fjord occurs mainly from the tidewater glaciers (iceberg rafting, meltwater runoff), as well as from rivers and sea ice. However, large lateral gradients from the fjord head towards the fjord mouth are found (highest sediment fluxes and generally coarsest composition at fjord head (e.g., Elverhøi et al., 1980, 1983; Hop et al., 2002; Svendsen et al., 2002; Zajaczkowski, 2008; Trusel et al., 2010). Marine organic matter from productivity of algae dominates the organic carbon content of the surface sediments (Winkelmann and Knies, 2005; Peterse et al., 2009). It increases towards the fjord mouth and inter-annual variations appear to be insignificant (Peterse et al., 2009). The penetration of oxygen into the sediments decreases from 10 mm in innermost Kongsfjorden to approx. 6-7 mm in the outer fjord (Loubere et al., 2011).

The benthic ecosystem in the fjord is influenced by the marine productivity in the upper water masses that undergoes large seasonal fluctuations depending on e.g., seasonal light variations (polar night vs. midnight sun), sea ice break-up and water mass stratification (Hop et al., 2002, Svendsen et al., 2002; Hegseth et al., 2009; Hodal et al., 2011). Other factors affecting the organic matter flux to the fjord floor are grazing zooplankton as well as the large amounts of faecal pellets (Wassmann et al., 1996; Hop et al., 2002 for review).

Hinlopen Trough

Hinlopen Trough off northern Svalbard is a glacially eroded trough and the northward continuation of the Hinlopen Strait separating the islands of Spitsbergen and Nordaustlandet (Fig. 1). The trough is approx. 70 km long and generally 200-400 m deep (Batchelor et al., 2011). The oceanography in the Hinlopen Trough and Strait is presented in detail in paper II. The core of the AW in the Hinlopen Trough is typically located between approx. 80-500 m (e.g., Ślubowska et al., 2005; Ślubowska-Woldengen et al., 2007). However, it should be noted that marked inter-annual variations in the vertical and horizontal extents, as well as the temperatures of the AW around Svalbard occur (e.g., Cottier et al., 2007; Polyakov et al., 2011).

Due to its location at the margin of the Arctic Ocean, the Hinlopen Trough is exposed to highly variable fluctuations in sea-ice cover during the year (marginal ice zone; Cokolet et al., 2008). This proximity to the marginal sea ice zone generally results in high primary biological production (Sakshaug and Skjoldal, 1989; Falk-Petersen et al., 2000a). The present sedimentary environment is characterised by hemipelagic sedimentation within a low-energy, ice-distal environment (Batchelor et al., 2011).

3. Material and Methods

This thesis comprising the papers I to IV are based on analyses of benthic foraminifera faunas from surface and sub-surface sediments from Kongsfjorden and from cores from Kongsfjorden Trough and the Hinlopen Trough, complemented with oceanographic, lithological, geochemical and published data. In this chapter, the material and methods for papers I to III will be described, as the candidate is the first author. A description of the methods for paper IV (where the candidate is co-author) can be found in Loubere et al. (2011).

3.1. Seafloor and sub-seafloor samples

3.1.1. Sediment cores

Multicorer samples retrieved in Kongsfjorden provide the samples analysed and presented in papers I and III. The multicorer contained 6 transparent barrels of 80 cm length and 10.4 cm inner diameters. For paper I, the samples were collected along a transect of six stations in Kongsfjorden using *R/V Lance*. The material was retrieved annually in the late summers (August/September) of 2005 to 2008. The material providing the basis for paper III was collected along a transect of four stations and was collected in April, August and October 2008, as well as in May 2009 using the research vessels *R/V Lance* and *R/V Jan Mayen* (now *R/V Helmer Hanssen*).

The study in paper II was based on composite stratigraphies of gravity core NP94-51GC and box core NP94-51BC from Hinlopen Trough, as well as gravity core NP05-21GC and multi core NP05-21MC from Kongsfjorden Trough, respectively. The cores were retrieved in the summers of 1994 and 2005 with *R/V Lance*. The cores NP94-51GC, NP94-51BC and NP05-21GC have previously been sub-sampled and analysed by Ślubowska et al. (2005) and Skirbekk et al. (2010) (Table 2). For this thesis the sample resolution was increased to 1 cm in the upper part of gravity core NP05-21GC.

Table 2. Information on sediment cores used in paper II and references to the previous studies of the cores.

Core	Type of core	Latitude	Longitude	Water depth (m)	Core length studied (cm)	Previous Studies
Hinlopen Trough						
NP94-51BC	Box	80°21.4 N	16°18.1 E	398	32	Ślubowska et al. (2005)
NP94-51GC	gravity	80°21.4 N	16°17.9 E	399	115	Ślubowska et al. (2005)
Kongsfjorden Trough						
NP05-21MC	multi	79°03.0 N	11°05.5 E	326	24	
NP05-21GC	gravity	79°03.0 N	11°05.4 E	327	63	Skirbekk et al. (2010)

3.1.2. Sub-sampling

For the studies of living foraminifera the uppermost two cm of one barrel from the multi corer, with apparently undisturbed sediments, was subsampled at each station immediately after core retrieval. The samples used for paper 3, as well as the samples from 2005 and 2006 used for paper I were 1 cm thick, while the samples retrieved in 2007 and 2008 (paper I) were 0.5 cm thick. Immediately after subsampling, the samples were stained with a solution of ethanol and Rose Bengal (1g/ 1 litre ethanol; Boltovskoy and Wright, 1976) to preserve and stain the living foraminifera. Stained samples were subsequently stored at +4 °C until further laboratory processing. The gravity, multicorer and box cores analysed for paper II were sub-sampled in 1-cm thick slices prior to the initiation of this study. While the multicorer and boxcores were sub-sampled entirely, the gravity cores were sub-sampled to depths dating back to c. 2000 years, i.e. 115 cm (Hinlopen Trough) and 63 cm (Kongsfjorden), respectively.

3.1.3. Laboratory work – granulometric analyses and preparation for foraminifera

Sample preparation was performed in multiple ways for the different papers. The material for papers I and III was wet sieved using mesh sizes of 63 µm and 106 µm. Sub-samples from the cores analysed for paper II were sieved prior to the start of this Ph.D. study. The mesh sizes 63 µm, 125 µm and 500 µm were used for the gravity core and the box core from Hinlopen Strait. The gravity core from Kongsfjorden was sieved with mesh size of 63 µm, 100 µm and 1 mm whereas for the multi corer the mesh size of 100 µm was substituted with a sieve of 106 µm. The use of 106 µm and 100 µm is due to samples being processed at NP and UiT, respectively.

Grain-size distributions presented by Ślubowska et al. (2005) and Skirbekk et al. (2010) were adapted for this study and extended to higher resolution within this study. Grains >1 mm are regarded as ice-rafted debris (IRD) (Lisitzin, 2002 and references therein) and were counted at station NP05-21.

3.1.4. Benthic foraminiferal analyses

For papers I and III, the living (stained) benthic foraminifera fauna was identified and quantified in wet samples of material >106 µm. The analyses were performed on wet samples to increase the transparency of the tests and, thus, easier detection of the Rosa Bengal colourization. Calcareous and agglutinated foraminifera were examined, quantified and identified to species level in each subsample. Calcareous species were regarded as living if at least one chamber was completely filled and evenly coloured. However, agglutinated foraminifera were in addition examined for colouration of the aperture, except for *Hyperammina subnodosa* tests that were crushed to examine their internal content for the eventual presence of a stained cell. Typically c. 300 specimens are identified in foraminifera samples (Patterson and Fishbein, 1989). However, due to the dominance of *Nonionellina labradorica* (up to 90 %), all living specimens were counted in order to ensure the identification of each available species in the samples. Following the examinations (within 12 h), all specimens were stained again with a mixture of ethanol and Rose Bengal and stored at 4 °C. For paper II, the benthic foraminifera were analysed in size fractions >0.125 mm in core

NP94-51, and >0.106 mm in core NP05-21, respectively. Cronin et al. (2007 and references therein) point out that the use of sieves with mesh sizes of 0.063 and 0.125 mm influences the species composition. However, since sieves with significantly smaller differences in mesh sizes were used in this study, it is reasonable to assume that the species differences are negligible. At least 300 specimens were dry picked and identified to species level when possible. For all papers, the species were identified based on the classifications in Höglund (1947), Loeblich and Tappan (1953), Feyling-Hanssen (1964) and Feyling-Hanssen et al. (1971).

3.1.5. Presentation of results - foraminifera

The results from the foraminiferal counts are presented in several ways that are explained below:

- *Relative abundances* as percentages of each foraminiferal species in relation to all specimens in a sample (papers I, III) or in relation to the calcareous fauna (paper II)
- *Absolute abundance* of stained individuals based on a standardization for a sediment volume of 100 ml (papers I, III)
- *Species diversity* using the Shannon-Wiener \log_e -based index (Buzas and Gibson, 1969; papers I, II, III)
- *Evenness* calculated with the Pielou index (J; papers I, II, III)
- *Flux* of calcareous benthic foraminifera (paper II)
- *Ordination methods* Redundancy analysis (RDA) and Principal Component Analysis (PCA; ter Braak and Smilauer, 2002) were performed on the faunal data. The Redundancy analysis (RDA; ter Braak and Smilauer, 2002) constrained ordination technique was performed on the total counts of specimens and was used to correlate the general preferences of the species to the sediment depth. The technique was chosen prior to the preliminary results of the de-trended correspondence analysis (DCA). In order to group the benthic foraminifera according to their similarities/differences in dominance in the fjord over the studied seasons, the Principal Component Analysis (PCA; Parker and Arnold 1999) was performed. The database for the PCA consists of the mean occurrence of the most abundant species ($\geq 2\%$ in at least one sample) for each season. The data were square-root transformed prior to analysis. The ordination techniques (PCA and RDA) were performed with software CANOCO v.4.5 software (ter Braak and Smilauer, 2002) (paper III).

In papers I and III, dealing with surface samples, the above mentioned parameters have been applied on both calcareous and agglutinated foraminiferal species. However, due to generally low numbers of agglutinated foraminifera in the cores analysed for paper II, probably caused by their low preservation potential down core (e.g., Ślubowska et al., 2005), only the results of the calcareous fauna are presented.

3.1.6. Additional environmental parameters

Paper I

Additional environmental parameters included into paper I are:

- *Grain-size distribution* of the uppermost 1 cm from 2007 and 2008 (provided by Dijkstra, 2009);
- *CTD (conductivity-temperature-depth) survey along the fjord transect* performed with seabird (SBE 911 *plus*)
- *Organic-matter content* of the uppermost 1 cm of the sediment. Samples retrieved in 2005, 2006 and 2008 were measured for total organic carbon (wt. %TOC) using a Leco CS-200 induction furnace at the Department of Geology, University of Tromsø. Prior to the measurement the inorganic carbon was removed from the bulk sediment with HCl (10%) at room temperature (Espitalié et al., 1997). Furthermore, the C_{org}, C/N ratio and marine organic carbon (% MOC) from 2007 were adapted from Peterse et al. (2009) and Kim et al. (2011).
- *Oxygen profiles* from surface sediments (0-1 cm) adapted from Loubere et al. (2011).

Paper III

- Additional environmental parameters included into paper III is the *CTD survey along the fjord transect* performed with seabird (SBE 911 *plus*) with attached fluorometer (type Wetlab ECO-AFL/FL, calibrated on April 19, 2007) that provided *in situ fluorescence profiles* used to estimate the phytoplankton concentration over the seasons.

3.2. Chronology (paper II)

The chronologies for the investigated sites in paper II was obtained from published radiocarbon dates (Ślubowska et al., 2005; Skirbekk et al., 2010), complemented with new radiocarbon dates together with ²¹⁰Pb and ¹³⁷Cs analyses. The new radiocarbon ages were derived from ¹⁴C AMS (accelerator mass spectrometry) performed at the AMS ¹⁴C Dating Centre, University of Aarhus (AAR), Denmark. All radiocarbon ages were calibrated into calendar years using the calibration program OxCal version 4.1 (Bronk Ramsey, 2009) using a marine reservoir age of 405 +/-22 ¹⁴C years that was incorporated within the Marine09 calibration curve (Reimer et al., 2009). A regional reservoir age correction ΔR of 105±24 for Svalbard was applied (Mangerud et al., 2006). The age models were constructed based on the calibrated ages obtained from the peaks of the probability curves within the 2σ range for each dating. In the uppermost part of NP05-21MC ²¹⁰Pb and ¹³⁷Cs measured at the Gamma Dating Center, Copenhagen University, Denmark. The ages were assigned using CRS modelling (Constant Rate of Supply; Appleby, 2001).

4. Summary of papers

Paper I

Jernas, P., Klitgaard-Kristensen, D., Husum, K., Koç, N., Tverberg, V., Loubere, P., Prins, M., Dijkstra, N. **Response of modern Arctic benthic foraminiferal fauna to annual environmental changes; evidence from Kongsfjorden, Svalbard**

In revision for Marine Micropaleontology

The purpose of this study is to investigate the response and sensitivity of the live benthic foraminiferal species to annual shifts in environmental conditions in the glacio-marine Kongsfjorden. A multi-year (2005-2008) seabed sampling along the fjord transect covering four consecutive summer seasons was performed concurrent with an extensive CTD survey. Along with the CTD survey providing oceanographic properties sediment composition, organic carbon (Corg) were analysed in order to compare to the variations in benthic foraminiferal composition, abundance and diversity. Our oceanographic observations indicate that the overall fjord conditions are strongly influenced by the annual variability in the advection of warm and saline Atlantic Water (AW) into the fjord. This allows us to determine the shifts from AW dominated 'warm years' to less influence from AW in 'cold years' based on a concept established by Cottier et al. (2007). The benthic foraminiferal faunas respond rapidly by changing composition, absolute abundance and diversity inter-annually. The strongest faunal response is attributed to the variability of primary production that shifts concomitantly with the change in fjord hydrology. For example, the summer advection of AW seemed to have a stimulating effect on the overall fjord productivity, whereas the continuous presence of AW over the large part of the year (winter to early spring) may have an opposite effect. The latter situation results in limited food supply, which apparently can explain the decrease in absolute abundance of the benthic foraminiferal fauna and the distinct reduction in relative abundance of the dominant species *Nonionellina labradorica*. The strong intrusions of AW also changed the salinity of the fjord and reduced the occurrences of the glacio-marine species *Elphidium excavatum* f. *clavatum* and *Cassidulina reniforme*.

Paper II

Jernas, P., Klitgaard-Kristensen, D., Husum, K., Wilson, L., Koç, N. **Paleoenvironmental changes of the last two millennia on the western and northern Svalbard shelf.**

In revision for Boreas

The purpose of this study is to reconstruct paleoenvironmental changes during the last two millennia in cores presently underlying the inflow of Atlantic Water along northwest Svalbard. The study is based on two sediment cores retrieved from Kongsfjorden Trough and Hinlopen Trough, respectively. Both records have decadal to multi-decadal temporal resolution. The reconstruction is based on the benthic foraminiferal faunas, including species composition, relative and total abundances, diversity, and fluxes, as well as on lithological parameters. The results suggest that the inflow of Atlantic Water generally increased during

the last 2000 years, resulting in development of generally warmer and less glacially influenced conditions as indicated by the overall gradual decrease of *Elphidium excavatum* f. *clavatum*. Synchronous faunal and sedimentary shifts in both study areas occurred at centennial time scales and are interpreted to reflect variations in the inflow of Atlantic Water. The general increase in inflow of the Atlantic Water exerted a strong control on the foraminiferal productivity at both sites. In Hinlopen Trough the productivity was reduced due to the retreat of the high-productive seasonal sea-ice margin towards the north. In Kongsfjorden the productivity increased due to the advection of nutrient-rich water. Five time intervals are distinguished: 50 BC – AD 300; AD 300-700; AD 700-1200; AD 1200-1500; AD 1500-1900 and AD 1900 to present. The most distinct faunal signal in both records is evident by very high foraminiferal productivity from AD 1200-1500. It is attributed to the development of highly productive oceanographic fronts along the western and northern Svalbard shelf. The interval is followed by reductions in benthic foraminiferal productivity from AD 1500-1900, and a shift to particularly harsh conditions and most likely close to perennial sea ice cover at the Hinlopen Trough core site, whereas less severe conditions in Kongsfjorden are indicated by still moderate productivity of the benthic fauna and faunal composition that suggests continued advection of Atlantic Water.

The overall synchronous changes in the benthic foraminiferal composition and abundance at the two core sites suggest that the inflow of Atlantic Water is the common driving force behind the environment variability of the NW Svalbard shelf. In addition, local factors such as the distance to the sea-ice margin, degree of glacial activity, and primary productivity associated with sea ice margin and the inflow of Atlantic Water also affected the faunas differently at the core sites.

Paper III

Jernas, P., Husum K., Klitgaard-Kristensen D., Forwick, M., Koç, N. **Seasonal composition of recent benthic foraminifera in surface sediments of Kongsfjorden, Svalbard.**

To be submitted to Polar Research

The purpose of this paper is to investigate the seasonal variability of the live benthic foraminiferal faunas from the uppermost two centimetres of the seafloor in Kongsfjorden, and secondly, identify environmental factors that control the distribution of benthic foraminiferal species. Species composition, abundance and distribution were studied in samples retrieved in early spring, summer to autumn of 2008 and spring of 2009. The results were compared to the seasonal development of the fjord hydrology and the pelagic production. Eighteen species occur in relative abundances of $\geq 2\%$ during at least one season. The dominant benthic foraminifera *Nonionellina labradorica* constitutes 17-69 % of the fauna in the upper 2 cm of surface sediments during the investigated seasons. Our results indicate that primary factors influencing the seasonal variability in benthic foraminiferal composition and abundance are the bottom and overall fjord water temperature in combination with the enhanced sediment supply from glacial melt and the food supply.

In summer and autumn the high bottom temperatures and higher sediment accumulation result in decreasing abundance of agglutinated benthic foraminifera indicating their sensitivity to the higher temperatures and sediment load.

The absolute abundance of living benthic foraminifera fauna, both calcareous and agglutinated, is closely related to the deposition of fresh organic matter at the fjord floor in spring and can rise up to eight-fold in comparison to the abundances in other seasons. This situation is also reflected in the fauna composition and the overall highest dominance of *Nonionellina labradorica* (28-69%) in spring. During this season the species constitutes up to 50-69% of the fauna in samples containing the largest amount of organic matter aggregates, indicating that it strongly rely on fresh phytodetritus supply. Other species like *Globobulimina auriculata* and *B. pseudopunctata* seem to take advantage of the more refractory organic matter that is assumed to characterise the summer season and particularly in autumn.

In the summer season the diversity was low in the inner fjord and this was attributed to the glacial influence. The fauna was composed mostly of *Nonionellina labradorica* and *Globobulimina auriculata* which indicate that the species are most opportunistic in Kongsfjorden.

The vertical distribution of the foraminifera shows that most of the species occupy the uppermost centimetre of the sediment column, while *Nonionellina labradorica* and *Globobulimina auriculata* prefer the interval from 1-2 cm. *Robertinoides arctica* and *Stainforthia loeblichii* seem to change the habitat depth and migrate to shallower sediments during seasons of enhanced food supply, while they stay at greater depths in the remaining seasons. In this way, the two species remain less exposed to the competition and the predation in the settings of low food availability.

Paper IV

Loubere, P., Jacobson, B., Kritgaard-Kristensen, D., Husum, K., Jernas, P., Richaud, M., 2011. **The structure of benthic environments and the paleochemical record of foraminifera.** *Deep Sea Research, Part 1: Oceanographic Research Papers*, vol. 58, Issue 5, p. 535-545.

The aim of this study is to examine the influence of microhabitats on the distribution of benthic foraminiferal species and the geochemical composition of benthic foraminifera tests in fjord and shelf environments in the Arctic. During multi-year seabed sampling of the western continental margin of Svalbard and in Kongsfjorden, measurements of the pore-water oxygen gradients and dissolved inorganic carbon isotopes were performed concurrent with characterisation of the sediment bio-structures created by the activities of macro-/meio-fauna and analyses of the vertical distribution of living benthic foraminifera. Two staining techniques are used: Rose Bengal and CellTracker Green (CTG).

The pore-water oxygenation indicates that the organic carbon flux is higher in the fjord than over the slope. The sampled seabed shows a patchy distribution of the bio-structures. Oxygen profiles of the bio-structures reveal increased oxygen penetration into the

deeper sediments well below the depth of the average anoxic boundary in the surrounding sediment. Furthermore, the benthic foraminifera fauna associated with the bio-structures have higher absolute abundance than the non-biostructure fauna as well as higher biomass below the pore-water anoxic boundary. Our observations indicate that benthic foraminifera are selecting microhabitats associated with bio-structures in order to take advantage of the better ventilated micro-environments and exploit the organic matter stored in the subsurface sediment in the generally suboxic or even anoxic surroundings. The stable isotope values of the stained species *Nonionellina labradorica* and *Globobulimina* sp. show that the carbon isotope values are nearly constant with sediment depth, even though pore-water isotope gradients exist. This suggests that foraminifera may calcify within waters of the bio-irrigation system, which provides different pore-water conditions from the surrounding sediment mass. Thus, the stable isotope and trace element composition of benthic foraminifera may depend on how conservative species are in selecting micro-environments around bio-structures.

Authorship contribution to paper IV:

I was responsible for the CellTracker Green staining method (preparation and application of the chemical reagents, foraminiferal incubation). I also participated in species identification and discussion of the manuscript.

5. Synthesis

The primary objective of this study was to improve the understanding of living benthic foraminiferal faunal responses to environmental changes in an Arctic fjord environment in order to optimize benthic foraminifera as a proxy of past environmental changes. Secondly, the aim was to apply this new knowledge to interpret high-resolution (multi-decadal) paleoenvironmental changes on Svalbard during the past 2000 years. The carbonate tests of benthic foraminifera are extensively used as geochemical proxies but benthic foraminifera may select a certain microhabitat that in turn will influence the geochemical proxy signal. A third goal of this study was therefore to examine the effect of benthic foraminiferal selection of microhabitat and its possible influence on geochemical proxies.

The primary goal has been achieved through investigations of living (stained) benthic foraminifera assemblages in Kongsfjorden, Svalbard, from surface sediments along a transect of six (paper I) and four stations (paper III) retrieved on inter-annual and seasonal time scale, respectively. The fauna was subsequently compared to oceanographic data, sedimentologic properties, primary productivity and other environmental information, in order to identify the driving forces leading to the faunal variations. The second aim was achieved through down core analyses of two shelf records from northwestern Svalbard and utilizing the newly gained knowledge on benthic foraminifera and their relationship to recent changes in the environment (primarily oceanography and primary productivity) to interpret past paleoceanographic changes (paper II). Thirdly, the selection of benthic foraminifera of their habitat and the effect on geochemical proxies were investigated through down-core oxygen profiling, pore-water chemistry, bio-structure occurrences, foraminiferal abundances and geochemistry in multicorer samples in Kongsfjorden (paper IV). This study also adds to the

primary goal of further understanding of benthic foraminiferal behavior in the sediments and their ecology.

Based on the investigations in Kongsfjorden during this thesis project the main conclusions drawn are the following. The studies of living benthic foraminifera in Kongsfjorden, western Svalbard, show that presently *Nonionellina labradorica* dominates the fauna. The species reflects summer intrusions of warm, nutrient-rich Atlantic Water (AW), which results in high primary productivity in the fjord and overall favorable conditions for this species. The implication is that *N. labradorica* can be classified as an indicator of high seasonal productivity. In this specific setting of an Arctic fjord influenced by AW and with a highly variable hydrography the species can also be regarded as an indicator of summer inflow of AW.

Overall, the annual and seasonal studies of the live benthic foraminiferal fauna indicate that their response is mainly controlled by AW that affects the pelagic production and temperature and salinity of the fjord between years and on seasonal time scale. This relates to the timing of AW inflow into the fjord, the amount of AW being advected and the length of time that AW can be retained in the fjord. Further, turbid meltwater from the surrounding glaciers are also of importance to the composition of the benthic foraminiferal fauna. The absolute abundance of benthic foraminifera is strongly controlled by pelagic production in the upper water column that delivers fresh phytodetritus to the sea bed. The diversity of foraminifera along the sampled transect shows strongest responses at the outer and inner part of the transect. The factors affecting the diversity mostly is the turbid meltwater from the glaciers at the inner part of the transect. At the outer most part of the transect in Kongsfjorden the highest amplitudes in temperature and salinity affect diversity. The benthic foraminifer micro-environment can be significantly affected by the patchy distribution of the biostructures e.g. tubes, burrows and other features made by benthos in the sediment substrate. The benthic foraminifera seem to develop a colonization strategy by inhabiting micro-environments in proximity to the bio-irrigation system. This allows them to use the available oxygen and labile organic matter well below the pore-water anoxic boundary. Moreover, the geochemistry of the pore-water related to the bio-structures and the irrigation-system differs from the general sediment pore-water. Thus, the elemental ratios of foraminifera test associated with bio-structures and the irrigation-system is influenced by this and thereby reflects the bottom-waters properties.

Based on the results presented in papers I, III, and partly IV a schematic outline of the interplay of environmental factors and responses of benthic foraminifera in the fjord during a year, divided into seasons, is shown in Figure 2. Generally, the interaction of environmental components in Kongsfjorden develops through the seasons. It is initially started by the increasing solar insolation following the polar nights and secondly, by temporal intrusions of warm and saline AW. The subsequent results of the AW inflow into Kongsfjorden may, however, vary due to differences in timing of the year of these inflows.

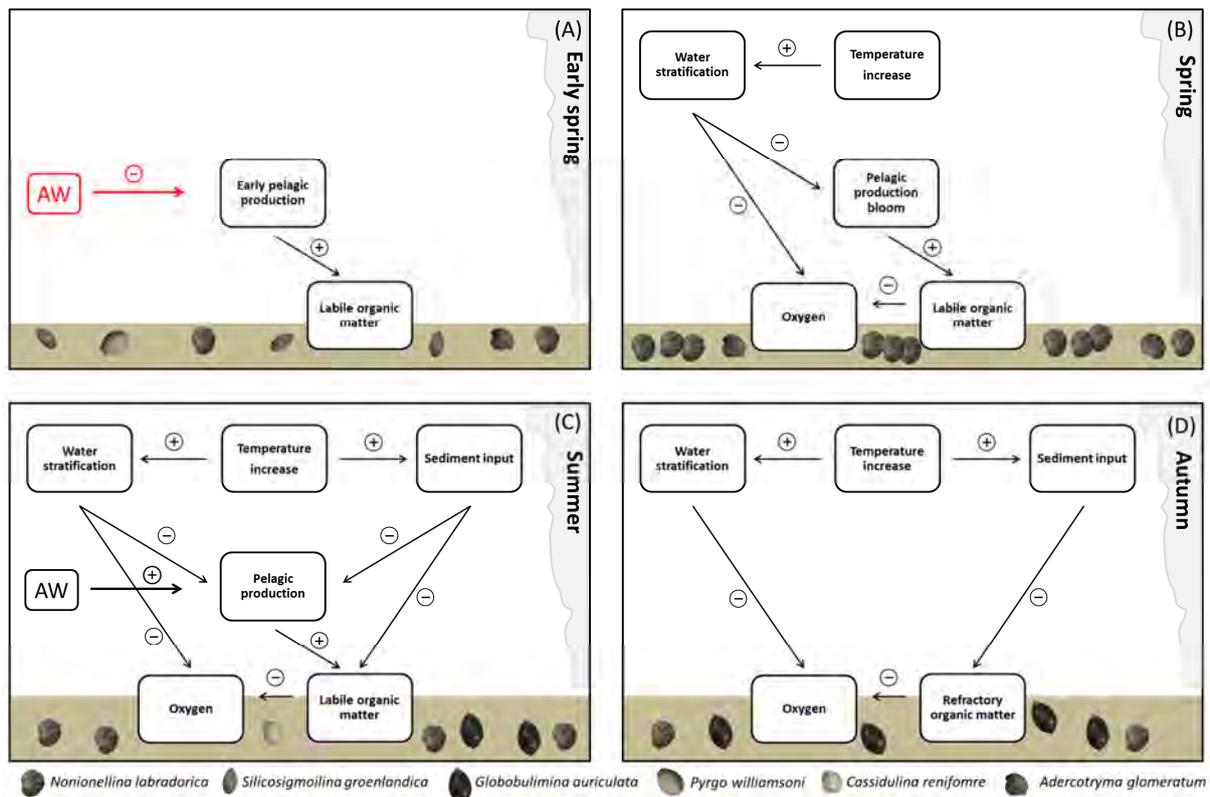


Figure 2. Schematic model of the environmental development in Kongsfjorden during consecutive seasons (A-D) and the influence on and responses of the living benthic foraminifera to this. The figure shows both typical and atypical (marked in red) hydrological situations related to the inflow of AW into Kongsfjorden. The arrows with ‘plus’ indicate positive effect, while ‘minus’ indicate negative effect; AW- inflow of Atlantic Water. (A)- early spring; (B)- spring; (C)- summer; (D)- autumn.

In early spring the return of the light and the water convection provide appropriate conditions enabling the initiation of the pelagic production. After the non-pelagic productive winter season, the very first supply of labile organic matter is exploited by the early spring year species like *Silicosigmoilina groenlandica* and *Pyrgo williamsoni* (Fig. 2 A).

In hydrological situations typical of spring (Fig. 2 B) the bloom of primary production develops completely and provides the largest amounts of fresh phytodetritus to the bottom habitat. In response to this the absolute abundance of benthic foraminifera increases several magnitudes and the Kongsfjorden fauna is dominated by one species, *N. labradorica* (Fig. 2 B).

A deviation from the typical spring hydrological situation in Kongsfjorden was seen during this study caused by an inflow of AW in late winter (AW marked in red; Fig. 2 A) (Cottier et al., 2007). This limited the mixing in the water column, and thereby disturbed the initiation of spring bloom (Hegseth et al., 2009) which in turn resulted in limited food supply to the benthos. Following the atypical spring conditions later in summer the absolute fauna abundance and the food-sensitive *N. labradorica* were found to be reduced (paper I) probably related to the changed food conditions deviating from the normal development in Kongsfjorden. Due to the lack of sampling in spring and early summer it is unclear how

strongly the benthic foraminiferal fauna was affected by this earlier in the year. Moreover, the effect of later and smaller blooms during that year on the benthic foraminiferal fauna is also not analysed.

In a typical summer (Fig. 2 C) the nutrient reservoir in the pelagic zone is normally depleted after the spring bloom. Stratification develops due to the large gradient in water masses properties, mainly temperature and salinity (salinity not indicated in Fig. 2) and the prolonged stratification inhibits nutrients renewal. These factors limit the food flux and are expected to reduce absolute abundance of benthic foraminifera and in particular the food-sensitive species like *N. labradorica*. But a typical hydrological feature in summer is that AW (Fig 2 C) is advected into Kongsfjorden and thereby provides an additional source of nutrients to the already developed pelagic production. In this situation the supply fresh phytodetritus may still persist (Fig. 2 C) in sufficient amounts in order to maintain the abundance of benthic foraminifera and in particular *N. labradorica*. The low oxygen conditions at the sea bed occur as a result of enhanced degradation of organic matter through biological and chemical processes consuming oxygen (Fig. 2 C). Stratification of the water column also decreases oxygen concentration due to poorer ventilation of the bottom water. The temperature increase (in water and atmosphere) driven mostly by insolation, also promotes glacial and riverine input of suspended matter into the fjord and during summer higher sediment accumulation rates from the summer glacial meltout occur (Fig. 2 C). Larger amounts of suspended matter reduce the pelagic production whereas the high sediment accumulation at the fjord bottom results in dilution of organic matter that reduces the labile organic matter storage in the surface sediment habitat. This seems to be better tolerated by the calcareous fauna than the agglutinated.

In autumn (Fig. 2 D) the pelagic production is terminated due to the reduced insolation. The low amount and quality of the remaining food (refractory organic matter) (Fig. 2 D) reduce the abundance of the food-sensitive species, such as *N. labradorica*, and is partly replaced by species able to cope with poorer food conditions, e.g., *Globobulimina auriculata*. Similar to the summer season the overall warm hydrological conditions and related higher sediment accumulation is reflected in the lower relative abundance of agglutinated fauna.

Lastly, paper IV provides evidence on the microhabitat conditions in the upper centimeters of the sea bed, hence more detailed information than presented in Figure 2. It shows that bio-structures in the sediments created by macro-fauna builds a bio-irrigation system that can provide oxygen and food for deeper dwelling foraminifera in the sediments. This enables these species to survive below the anoxic boundary found in the sediment otherwise. Knowledge on the existence of biostructures and the bio-irrigation system therefore adds further to the understanding and complexity of the benthic foraminiferal habitat in the sediments in addition to the conditions described in Figure 2. The infaunal behavior in relation to bio-irrigation also bears implications on geochemical proxies, i.e. stable carbon isotopes in this case. As the stable isotopes of the benthic foraminifera trace the bio-irrigation system which is closer to surface waters they are considered valid as good geochemical tracers.

The second aim of this study was to reconstruct paleoceanographic changes during the last two millennia in cores from northwestern Svalbard shelf, and apply the knowledge from the studies of living benthic foraminifera, in addition to existing knowledge. The records point toward the inflow of Atlantic Water as a primary driver of long term as well as centennial environmental variability on the NW Svalbard shelf. The most distinct faunal signal is recorded from AD 1200-1500 and is attributed to the development of highly productive oceanographic fronts between the Arctic and Atlantic water masses. This is followed by a significant shift towards more severe conditions from AD 1500-1900 corresponding to the Little Ice Age. Overall, the centennial time scale variability found in the two Svalbard records is similar in timing to the well-known climate anomalies found in Europe. Despite of the large centennial environmental variability, the long term trends can be observed as an overall gradual reduction in glacial influence and possible oceanographic warming of the NW Svalbard shelf over the last two millennia.

6. Implications - Benthic foraminifera as indicators of past marine environments

Reconstructing paleoenvironments using benthic foraminifera as a proxy have been widely used by geologists since the late 1950's (e.g., Jorissen et al., 2007). Since the inferences on past environmental changes depend on the knowledge between modern benthic foraminifera to concurrent environmental factors this has been the main objective of many studies relating modern benthic foraminifera and the environment. Over the years ideas and findings on this subject have developed from relating benthic foraminifera to water depths, sea bed grain size composition and water masses (Jorissen et al., 2007). According to van der Zwaan et al. (1999) foraminifera should be regarded as generalist which is advantageous in order to avoid rapid extinction, and from this the authors infer that parameters like temperature and salinity are not very important in benthic foraminiferal distribution. In more recent decennia flux of organic carbon and available oxygen are therefore by many researchers regarded as the main factors controlling the distribution of benthic foraminifera. This knowledge was compiled into a concept known as the TROX-model (Jorissen et al., 1995). Based on investigations in the Adriatic Sea Jorissen et al. (1995) established the TROX-model that describes the benthic foraminiferal occurrences being controlled exclusively by available oxygen and food. Later the TROX model has been refined, and it was suggested that organic carbon flux was the main parameter controlling the foraminiferal habitat based on a study along a depth transect in the Bay of Biscay (Fontainer et al., 2002). Oxygen has also been suggested not to be a limiting factor for deep infaunal species, and finally biological interactions such as competition for labile organic matter may also be of relevance in controlling where foraminifera live in the sediments (Jorissen et al., 1998; Jorissen, 1999; van der Zwaan et al., 1999; Fontanier et al., 2002). Lastly, Fontainer et al. (2002) acknowledge that the TROX-model is oversimplified. One reason is that some benthic ecosystems are known to show variability on seasonal or inter-annual time scales.

In comparison to the TROX-model the results presented in this thesis also find food availability to be of importance to the benthic foraminifera. However, the present study also shows that the organic carbon flux is strongly controlled by the oceanographic conditions in the Arctic fjord environment (papers I and III). An implication from this study is that benthic

foraminifera thereby indirectly can reflect changes in oceanography, and as such can be used to decipher on paleoceanographic changes. The link between the primary productivity in surface or near subsurface waters and any changes in the ocean circulation is, however, generally not discussed in papers dealing with the TROX-model. This does not necessarily mean that there is a disagreement between the TROX-model and the results in this thesis but simply that at the moment the TROX-model does not take into account the mechanisms responsible for changes in primary productivity which is considered to be the primary forcing on the benthic foraminifera (Fontainer et al., 2006).

In the current study the hydrological parameters are also identified to play a major role in controlling the foraminiferal distribution and abundance mainly via the influence on sediment input and direct relation to primarily salinity (papers I and III). Hence, in the Arctic fjord environmental setting the proximity of glaciers and hydrography play an apparent role in controlling the benthic foraminiferal composition. This is perhaps not surprising since the environmental settings used in establishing the TROX-model are generally in temperate slope environments often with water depths from relatively shallow to deep water. Settings such as submarine canyons experiencing high sediment deposition have, however, been shown to concur with the TROX-model in terms of infauna benthic foraminifera (Koho, 2008).

In this study Loubere et al. (2011) (paper IV) show that due to the burrowing by macro- and meiofauna a bio-irrigation system is created in which benthic foraminifera can seek particular micro-environmental conditions that provide sufficient available oxygen and organic carbon below the oxic-anoxic boundary found in the sediments otherwise. In comparison to the TROX-model occurrences of deep infauna below the oxic layer are explained by their capability to feed on bacteria. Alternatively, the deep infauna could be explained in a similar manner as presented in Loubere et al. (2011). It cannot, however, be excluded that infaunas exist that may develop adaptations to environments controlled by other processes in order to survive in anoxic environments by foreexample denitrification (e.g., Risgaard-Petersen et al., 2006) and also capabilities to withstand longer periods of no food input by feeding on other sources such as bacteria or stored carbon in the sediments (e.g., Jorissen et al., 1998; Alve, 2010).

In conclusion, the findings in this study concur in many aspects with the current concept of the TROX-model but there are also disagreements. The main reason behind the disagreements may be attributed to the very different types of environmental settings and that the TROX-model is designed to provide an overall conceptual model without a high degree of details. From the results of this study it can be concluded that combined effect of changes in hydrography and its influence on flux of organic carbon, salinity and temperature changes and sediment supply from glaciers in the inner fjord are the main factors controlling the distribution of the benthic foraminifera. The link between the oceanography and the organic carbon flux also imply that benthic foraminifera can be used as a proxy of past variations in water masses, in addition to primary productivity.

7. Future work

The papers presented in this thesis (papers I, III and IV) attempt to relate Arctic benthic foraminifera to environmental changes in a more open marine settings, an Arctic fjord. Although this study has provided new understandings on the annual and seasonal dynamics of benthic foraminifera faunas in an Arctic fjord setting under strong influence from Atlantic Water inflow the newly obtained knowledge also generated new questions or issues that deserve further attention in the future. Most of these are related to the studies of living foraminifera that raise the need for further development in terms of sampling, methodology and measurements on environmental variables.

The seasonal sampling was collected with time interruptions of up to more than half a year and due to the logistic difficulties material from the winter season is entirely missing. As the transition from winter to spring and summer may occur within weeks, sampling in shorter time intervals (for example every second week) should be carried out in order to study the behaviour of the fauna and the geochemical composition of the foraminifera tests in relation to the environmental changes. When sampling on such short time scales, i.e., less than a few weeks, better and more accurate staining methods than Rose Bengal are required as Rose Bengal is known to have some weaknesses (Bernhard, 2000; Walker et al., 1974; Martin and Steinker, 1973). An alternative applicable staining method would be the CellTrackerGreen (CTG) method used in paper IV. This staining method requires an active metabolism of the specimens ensuring that only the living cells are stained. This method has been applied in multiple studies (e.g., Bernhard et al., 2006) and was tested in a subproject during this thesis. The results from the latter study support earlier studies focusing on the comparison of Rose Bengal and CTG staining (e.g., Bernhard et al., 2006), and shows that Rose Bengal stains more individuals than the CTG method (Fig. 3).

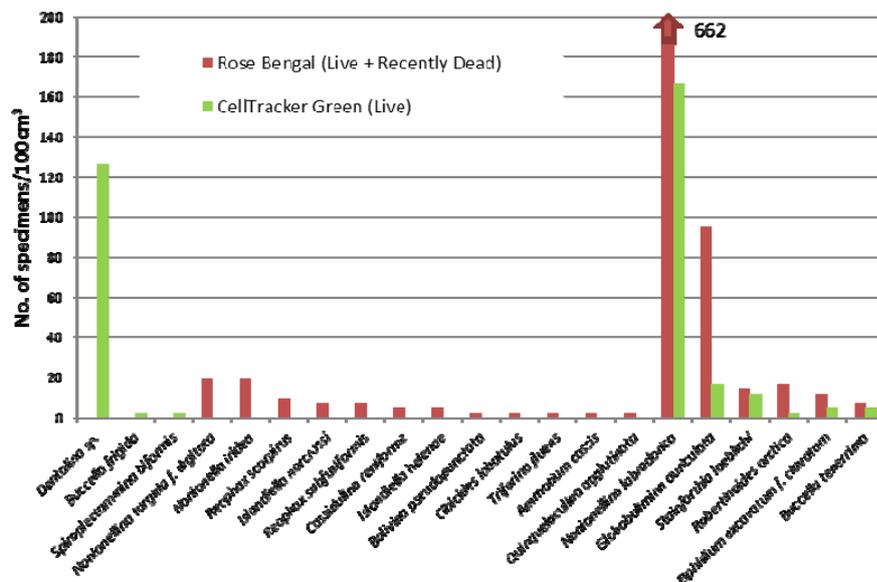


Fig. 3. Comparison of benthic-foraminifera densities in the surface sediment sample from the outer Kongsfjorden stained with: CellTracker Green (CTG), (i.e. live specimens, green bars); and in the same sample stained with Rose Bengal (RB) after performing the CTG counts (CTG stained specimens were not removed before adding RB, red bars).

This probably indicates that the Rose Bengal stains specimens that died shortly prior to sampling. The high number of species stained exclusively by Rose Bengal (Fig. 3) may, however, also indicate that some species are particularly sensitive to the stress caused by sampling. This is of relevance when using the CTG as these species may require more for the active reagents used for the CTG to be metabolized by the foraminifera. The foraminifera take up of the CTG is time dependent and this is not fully examined in the Arctic environmental setting yet. In this study the samples were left for 8-10 hours. Still, these issues should be investigated more and taken into account when using CTG in the Arctic.

Moreover, foraminifera show patchiness. In future studies, although time consuming, at least two replicates from a station should be analysed in order to evaluate the possible influence of patchiness of benthic foraminifera, and how it relates to the irregular lateral distribution of phyto-detritus and biostructures as indicated in paper IV.

Due to the main goal of increasing the value of benthic foraminifera as a proxy in the Arctic the analyses focused exclusively on the mature/adult specimens ($>106\ \mu\text{m}$). However, the analyses of smaller/juvenile species (e.g., $>63\ \mu\text{m}$; e.g. Korsun & Hald, 2000) would provide useful information about the reproduction of the foraminifera in space and time, and give more insight in the seasonal responses of foraminifera to the environmental changes.

More exact estimates of the organic carbon flux to the fjord floor are highly essential to evaluate the response of foraminiferal production and species composition. Such studies could be performed through the integration of surface sampling, as well as the deployment of sediment traps and/or moorings over the sampling sites, the latter measuring the chlorophyll-a concentration within the entire water column. In this context it would be beneficiary to collaborate with biologists focusing on primary productivity and other marine biota. In paper I it is pointed out that not only the quantity of the food supply influences the benthic fauna, but also the quality. Therefore, more detailed investigation on the food selection by benthic foraminifera would improve the understanding on different aspects related to food. A potential tool for studying the ingestion of potential food items by the benthic foraminifera is to analyse lipid (fatty acid and sterol) biomarkers (e.g. Ward et al., 2003; Suhr et al., 2008). Lipids can be used to identify the diet composition and carbon sources utilized by a wide variety of marine organisms, since all groups of organisms have specific lipid compositions (Harwood and Russell, 1984; Falk-Petersen et al., 2000b; Pond et al., 2000). Ward et al. (2003) successfully used the lipid biomarkers to indicate that foraminifera fed preferable on diatoms from sewage outfalls.

Lastly, the use of benthic foraminifera as a proxy also requires a good understanding of how the modern fauna analogues are translated into fossil assemblages. Therefore future investigations should also focus on how the living communities are represented in the fossil record. One of the main issues is to investigate how well tests are preserved in the sediments, which may differ among species.

8. References

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