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Benthic foraminifera as indicators of natural variability and anthropogenic impact

Environmental change in the SW Barents Sea and Hammerfest Harbor

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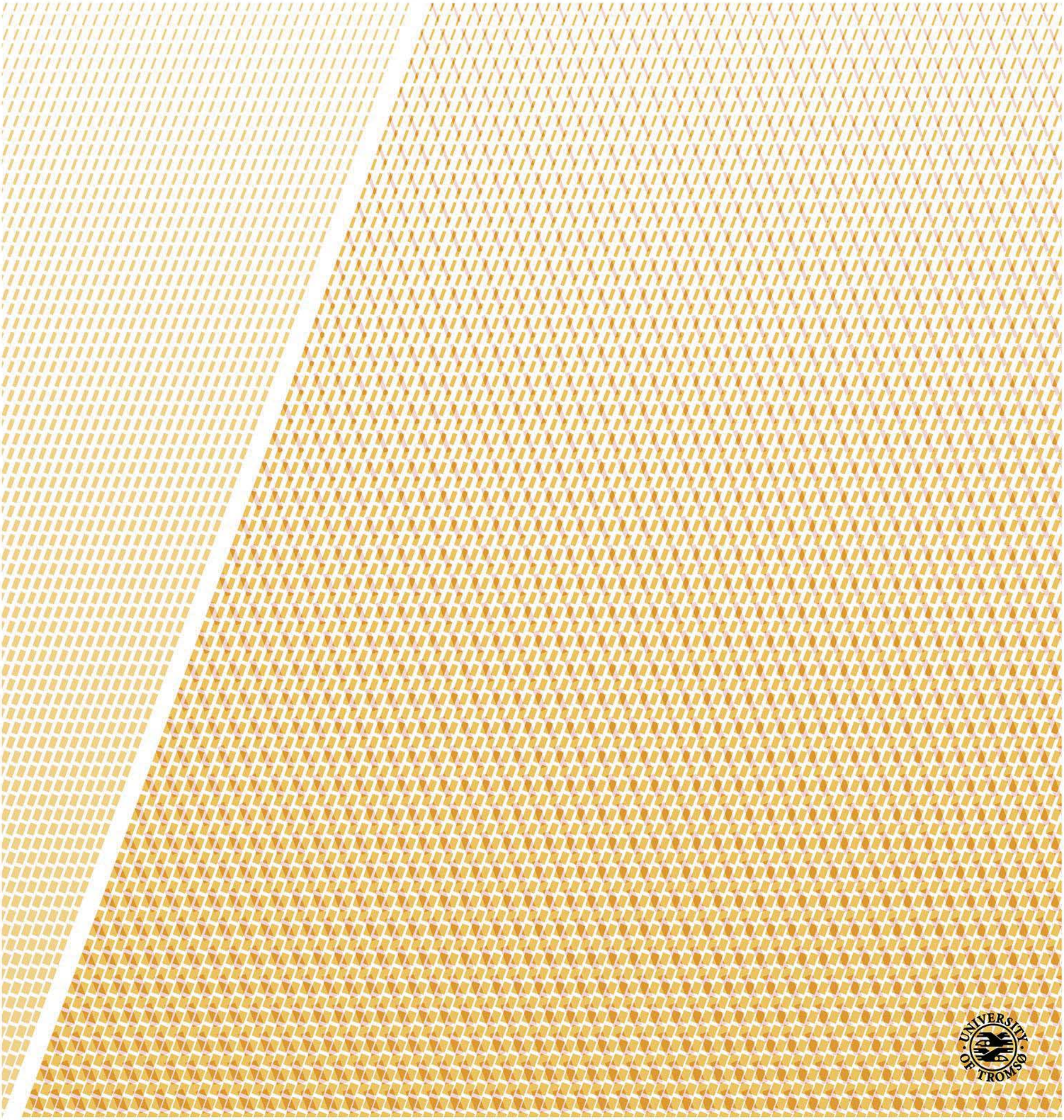
Noortje Dijkstra

A dissertation for the degree of Philosophiae Doctor – October 2013



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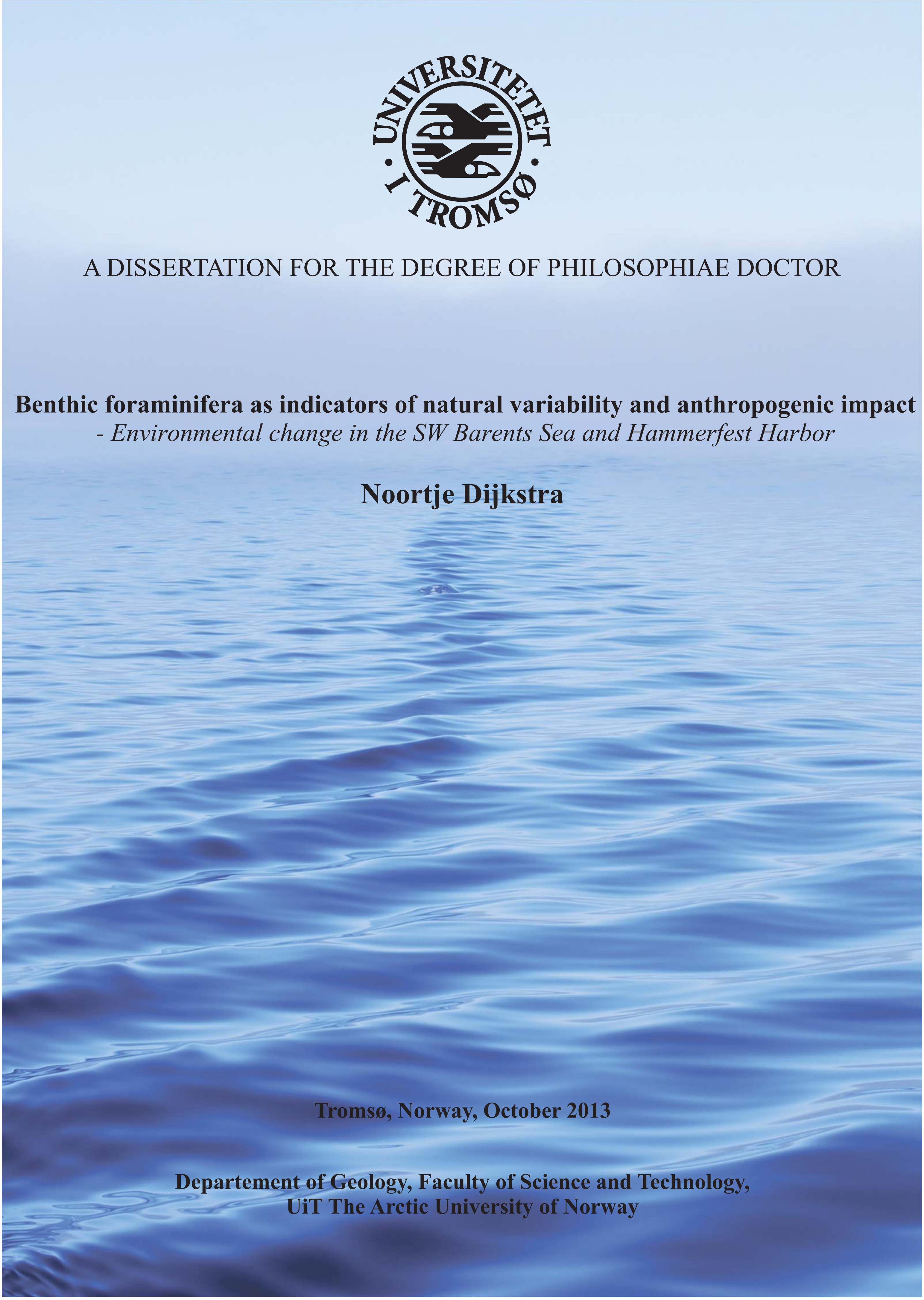

A DISSERTATION FOR THE DEGREE OF PHILOSOPHIAE DOCTOR

Benthic foraminifera as indicators of natural variability and anthropogenic impact

- Environmental change in the SW Barents Sea and Hammerfest Harbor

Noortje Dijkstra

Tromsø, Norway, October 2013

Departement of Geology, Faculty of Science and Technology,
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“The Arctic expresses the sum of all wisdom: Silence”

- Walter Bauer

“Borders I have never seen one. But I have heard they exist in the minds of some people”

- Thor Heyerdahl

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1. Preface

This doctoral thesis is the results of a 3 years PhD study within the *Northern Environmental Waste Management (EWMA)* program financed through *Forskningsløft i Nord* (NORDSATSING) of the Norwegian Research Council (grant number: 195160) and EniNorge AS. The overall goal of the EWMA project is to develop a distinct Northern Norwegian competence cluster in waste handling of Arctic oil industry and shipping activities. The PhD-project was carried out at the Department of Geology, University of Tromsø -The Arctic University of Norway (UiT), Tromsø, Norway.

Analyzed sediment samples were provided by EWMA-project collaborators at the Department of Chemistry of UiT, Tore Lejon and Kristine Bondo Pederesen (paper I); the Mareano project through the Norwegian Polar Institute (paper II); Statoil AS through UniLab AS (paper II); or collected by the authors (paper II, III and IV).

During the span of the PhD study, the candidate participated and assisted on marine-geological and geophysical cruises with the *R/V Helmer Hanssen* arranged by the Department of Geology at UiT. As part of the PhD education, the candidate participated in national and international courses, both in topics related to the PhD study, and general topics within the field of (marine) geology. Beyond the obligatory 30 credit point, the candidate attended three short courses on statistical topics and one course in scientific writing.

The candidate is a member of the FOraminiferal BIo-Monitoring expert workgroup (FOBIMO) and participated in a number of workshops intended to strengthen the position of benthic foraminifera as bio-monitoring tool.

Results of this doctoral thesis were presented as first author in four oral and five poster presentations during national and international workshops and conferences. The thesis resulted in five scientific papers that contribute towards a better understanding of the utility of benthic foraminifera as indicators of both anthropogenic and natural environmental changes in the (sub-)Arctic region.

The scientific papers are:

Paper 1:

Dijkstra, N., Junttila, J., Carroll, J., Husum, K., and Hald, M., **The impact of contaminants and grain size on benthic foraminiferal assemblages in the harbor of Hammerfest, northern Norway,** *submitted to Norwegian Journal of Geology*

Paper 2:

Dijkstra, N., Junttila, J., Carroll, J., Husum, K., Elvebakk, G., Godtliebsen, F., and Hald, M., **Baseline benthic foraminiferal assemblages and habitat conditions in a sub-Arctic region of increasing petroleum development,** *in press at Marine Environmental Research*, 2013, doi:10.1016/j.marenvres.2013.09.014

Paper 3:

Dijkstra, N., Junttila, J., Husum, K., Carroll, J., and Hald, M., **Natural variability of benthic foraminiferal assemblages and metal concentrations during the last 150 yrs. in the Ingøydjupet trough, SW Barents Sea,** *manuscript intended for submission to Marine Micropaleontology*

Paper 4:

Junttila, J., Carroll, J., Husum, K., and Dijkstra, N., **Sediment transport and deposition in the Ingøydjupet trough, SW Barents Sea**, *submitted to Continental Shelf Research*

Paper 5:

Schönfeld, J., Alve, E., Geslin, E., Jorissen, F., Korsun, S., Spezzaferri, S., and Members of the FOBIMO group*[1], 2012, **The FOBIMO (Foraminiferal Bio-Monitoring) initiative – Towards a standardized protocol for soft-bottom benthic foraminiferal monitoring studies**. *Marine Micropaleontology*, vol. 94-95, p. 1-13

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[1] * Abramovich, S., Almogi-Labin, A., Armynot du Chatelet, E., Barras, C., Bergamin, L., Bicchi, E., Bouchet,V., Cearreta, A., Di Bella, L., **Dijkstra, N.**, Disaro, S.T., Ferraro, L., Frontalini, F., Gennari, G., Golikova, E., Haynert, K., Hess, S., Husum, K., Martins, V., McGann, M., Oron, S., Romano, E., Sousa, S.M., and Tsujimoto, A..

2. Acknowledgements

This PhD thesis would not have been here today without the support and guidance of many people.

First of all, I would like to acknowledge my team of supervisors including Prof. Morten Hald, Prof. JoLynn Carroll, Dr. Juho Junttila and Dr. Katrine Husum. I am very grateful that I got the opportunity to start this PhD project. Thank you for supporting me throughout the years, for giving me constructive feedback on my work and for believing in me. Special thanks should go to Juho, my main supervisor during my studies. You provided me not only with guidance, but also with many cups of coffee and some 'fantastic' word jokes. Being a good supervisor, *"you has it"*! Katrine also deserves a big thank you. Even though you were on paper not officially my supervisor, you were always there for organizational help and giving me scientific directions. Morten and JoLynn always managed to make time in their busy schedule to provide me with feedback and help when it was most needed.

Takk, Thank You, Kiitos, Tak!

There are many people at the university whose technical and organizational help contributed to the realization of this thesis. The EWMA-project leaders Stian Røberg and Morten Brattvoll; the 'lab-ladies' Trine Dahl, Ingvild Hald and Edel Ellingsen; the captain and crew of *R/V Helmer Hanssen*; the technical staff members Steinar Iversen, Bjørn Runar Olsen, Rolf Andersen, Jan P. Holm and; the administrational staff members Magrethe Lindquist and Annbjørg Johansen. Also all the EWMA-project partners, in particular Tore Lejon and Kristine Bondo Pedersen should be mentioned here. Tusen Takk til dere!

Maarten Prins and Simon Troelstra are thanked for awakening my interest in (Arctic) marine geology and introducing me to the world of science. Dorthe Klitgaard Kristensen gave me the opportunity to move to Tromsø. So far the best decision of my life. Thank you!

Many friends and colleagues at the Department of Geology are thanked for inspiring me, and maybe most importantly for spending everyday life at the institute and all the social activities outside of work. Also, I would like to acknowledge all the fascinating people I met throughout the years on numerous workshops, conferences and courses, in particular my AG-326 UNIS-friends. Naming all of you would double the length of this thesis.

A special thanks goes to the Bene(lux) group: Diane, Sarah and Nicole, for giving me a piece of home away from home and real friendship. Lindsay is thanked for moral support, good

advice and making Tromsø feel as my new home immediately. Also Pati&Matze are thanked for their kindness and huge hospitality. And thank you Wesley, for being the friend back at home for more than 15 years now. It means a lot!

The biggest “Thank You” goes to my family: Johan, Mariët and Anneloes & Matt. For always encouraging me to do just that little bit more than I think I am able to do, for supporting me, and for all the phone calls, messages and post cards making me forget we are living so far apart. My parents always ‘forced’ me to look at rocks, flora, fauna and glacial moraines during the summer vacations, of which many were spent in Scandinavia. I guess it gave me the curiosity needed to write this PhD thesis. Thank you for always telling me: *“Het komt wel goed schatje”*. Misschien hebben jullie inderdaad gelijk…

Tromsø, October 2013

3. Introduction and objectives

Urbanization of the coastal areas and industrial activities in the open sea have increased since the 19th century and resulted in extensive alternation of estuarine, coastal and open marine environments. Enhanced contaminations of these environments may result in changes to the structure and function of the ecosystem. World-wide regulatory statuses were enacted to prevent further deterioration and to restore the ecological quality of these ecosystems. In Europe this included adoption of the Water Framework Directive (WFD; EuropeanCommission, 2003) and the Marine Strategy Framework Directive (MSFD; EuropeanParliament, 2008). These directives are designed to achieve and maintain good environmental status of estuarine, coastal and open marine environments by 2020 (EuropeanCommission, 2010). Good environmental status applies to both the concentrations of pollutants in the marine environment and the structure and function of the ecosystem. The MSFD underlines the necessity to select and define bio-indicators: species or groups of species that can reflect the state of the environment or ecosystem. The impact of contaminants on organisms has traditionally been tested by the use of macrofaunal organisms. Amongst these organisms, easily applicable and objective descriptors were selected. Based upon the diversity and relative abundance of macrofaunal bio-indicators (Pearson and Rosenberg, 1976), biotic indices were developed, enabling a quantitative estimation of the state of the environment (e.g. Borja et al., 2000; Borja et al., 2007; Borja et al., 2009; Diaz et al., 2004).

The use of benthic foraminifera as bio-indicators is less established; however previous studies have proven the ability of benthic foraminifera to monitor the environmental quality (e.g. Alve, 1995; Alve et al., 2009; Armynot du Châtelet et al., 2009; Armynot du Châtelet et al., 2004; Bouchet et al., 2012; Bouchet et al., 2007; Coccioni et al., 2009; Dolven et al., 2013; Ferraro et al., 2006; Frontalini et al., 2009; Hess et al., 2013). An adequate bio-indicator is characterized by fast turnover rates and specific habitats. Benthic foraminifera meet these criteria: they have a short reproductive cycle, typically one month to one year (Kramer and Botterweg, 1991) and have specific environmental preferences (Boltovskoy et al., 1991; Murray, 2006; Schafer, 2000; Scott et al., 2001).

The preservation of foraminiferal tests in the sediment after death is one of the main advantages of benthic foraminifera in bio-monitoring studies in comparison to macrofauna. Preservation of foraminiferal tests in sediment archives enables the reconstruction of pristine pre-impacted faunal conditions. This is especially useful in areas were no pre-impacted baseline studies have been carried out, since comparison of the fauna between impacted sites and pristine reference sites is complicated by the high spatial variability of foraminifera. Reference conditions from pristine sites, with similar ecological characteristics as impacted sites, are thus challenging to establish (Alve et al., 2009).

To further strengthen the position of benthic foraminifera as a bio-monitoring tool, standardization of methodology is needed. Whereas the macrofaunal scientific community has largely standardized their methodology and developed biotic indices (ANSI, 2007; Borja et al., 2000; Rees et al., 2009; Rosenberg et al., 2005; Rumohr, 2004), a consensus on methodology to be used in benthic foraminiferal bio-monitoring studies was not established until recently. Full implementation of this standardized methodology will occur in the years to come. Additionally, Bouchet et al. (2012) recently formulated classes defining ecological quality status (EcoQS) based on living benthic foraminifera applicable to fossil assemblages as well (Dolven et al., 2013).

Benthic foraminifera are amongst the most abundant and diverse group of shelled microorganisms in the marine environment (Sen Gupta, 1999). In pristine environments, the distribution of benthic foraminifera is mainly affected by variables including water mass temperature and salinity, the availability of nutrients, the type of substrate and the amount of dissolved oxygen (Murray, 2006). Anthropogenic stressors may lead to alternations in the community structure of benthic foraminifera. This include changes in density and diversity (Schafer, 1973; Yanko et al., 1994), high abundance of opportunistic species (e.g. Ellison et al., 1986; Murray, 2006; Pearson and Rosenberg, 1976), barren areas (Elberling et al., 2003; Ferraro et al., 2006; Samir, 2000), test deformations (e.g. Geslin et al., 1998; Yanko et al., 1998) and changes of the test chemistry (Nigam et al., 2006).

Identifying the state of the environment with the use of benthic foraminifera is often complicated by the natural variability of both the ecosystem and the physical environment. Furthermore, the impact of anthropogenic stressors on benthic foraminiferal communities depends on the type of stressors, the supply rate, the bio-availability of the contaminants and the geographical location. Therefore, site specific impact studies are needed to develop an accurate bio-monitoring tool, linking responses of foraminiferal assemblages to observed environmental conditions.

While several studies focus on the use or development of foraminifera as a bio-indicator in areas of the Mediterranean, the Atlantic Coast and southern Norway fjords, few studies focus on high latitude areas. High latitude areas are however valuable areas to monitor environmental changes and to test the applicability of benthic foraminifera to monitor environmental change. The areas are still relatively pristine, yet industrial activities are projected to increase in the near future.

The overall objectives of this thesis is to contribute to the understanding of the imprint of both natural and anthropogenic induced environmental changes on benthic foraminifera in an (sub) Arctic region subjected to increased anthropogenic activities. Sub-objectives were established to answer to the overall objective and are:

a) Establish pre-impact baseline conditions of the present state of the environment, both in terms of the variations in benthic foraminiferal faunal distributions and sediment properties, i.e. grain size and contaminant levels. Such pre-impact baseline conditions can be used for future references to monitor potential environmental change.

b) Understand the relationship between benthic foraminifera, ocean currents and sediment properties on a high resolution time scale over the last 150 years.

c) Test the utility of benthic foraminifera as indicators of anthropogenic impacts in the (sub-) Arctic region.

The objectives were accomplished by:

a) Characterization of the benthic foraminiferal assemblages, i.e. both modern living assemblages and past assemblages covering the last 150 years.

b) Characterization of sediment properties, i.e. grain size distributions, sediment accumulation rates, sortable silt mean grain size, smectite clay mineral assemblages and total organic carbon content.

c) Characterization of contaminant concentrations, i.e. concentrations of (heavy) metals and persistent organic pollutants.

d) Defining the relation between foraminiferal distribution, sediment properties and contaminant concentrations by a set of statistical methods, i.e. Q- and R- mode clustering, Pearson correlations, principal component analysis and multiple regression linear modeling.

The area of focus of this thesis is the relatively pristine southwestern Barents Sea and its adjacent coastal area, where petroleum related activities are expected to expand. With these prospects for the coming years, the region is a valuable natural laboratory to monitor and assess the impact of increasing industrial activities on the environment (Paper II-IV).

Additionally, a highly impacted harbor environment in the Barents Sea coastal region was studied (Paper I) to test the behavior of benthic foraminifera in a sub-arctic area subjected to anthropogenic impact.

During the research period of this PhD thesis, consensus was reached by topical experts (FOBIMO network) on a standardized methodology for living benthic foraminiferal studies with a focus on bio-monitoring (Paper V).

This study contributes to the establishment of pre-impacted reference conditions of the area of study, increased understanding of the natural variability within the studied area, and the development of a bio-monitoring tool using benthic foraminifera applicable in high latitudes. With the expected increase of industrial activities in the polar regions, and consequently the potential for increased industrial discharges into the marine environment such a bio-monitoring tool is expected to be of great relevance for the region.

4. Study areas and oceanographic setting

In this study sediment samples from the harbor of Hammerfest (paper I), Northern Norway, and the SW Barents Sea (paper II-IV) were analyzed (figure 1). Methodology paper V is not confined to a specific area. The study area in the SW Barents Sea is characterized as open marine and influenced mainly by two ocean currents, while the harbor of Hammerfest is mainly influenced by local hydrological features.

4.1 Hammerfest Harbor

The inner harbor of the town of Hammerfest (70°39′45″N 23°41′00″E) is focus of paper I (figure 1). The inner harbor is a 600 meter wide embayment with water depths ranging from 2 to 40 m. Salinity in the water column of the harbor embayment varies between 31 to 34 psu (Akvaplan-niva, 1995). September temperatures are of approximately 8^{o}C (Akvaplan-niva, 1995), while November temperatures are around 6.5^{o}C. Bottom current speeds of < 5 cm/s, are measured for the inner part of the harbor (Akvaplan-niva, 2013), and occasionally exceeding 10 cm/s. In the NE corner of the harbor, fresh water enters the embayment by the river Storelva draining from the lake Storvatn.

Activities in the harbor include ship traffic associated with the petroleum, fishing and tourism industry. Other activities in and around the harbor include small scale industry, shipyards, mechanical workshops, and depots of oil, salt and coal (Skjegstad et al., 2003). Contaminants also enter the harbor embayment via leakage of polluted soils, illegal discharges from sewers and the disposal of garbage. Additionally, contaminants are discharged into the harbor via inflow of the River Storelva which drains from the highly polluted Lake Storvatn (Skjegstad et al., 2003). Pollutants mainly include heavy metals and persistent organic pollutants (POPs).

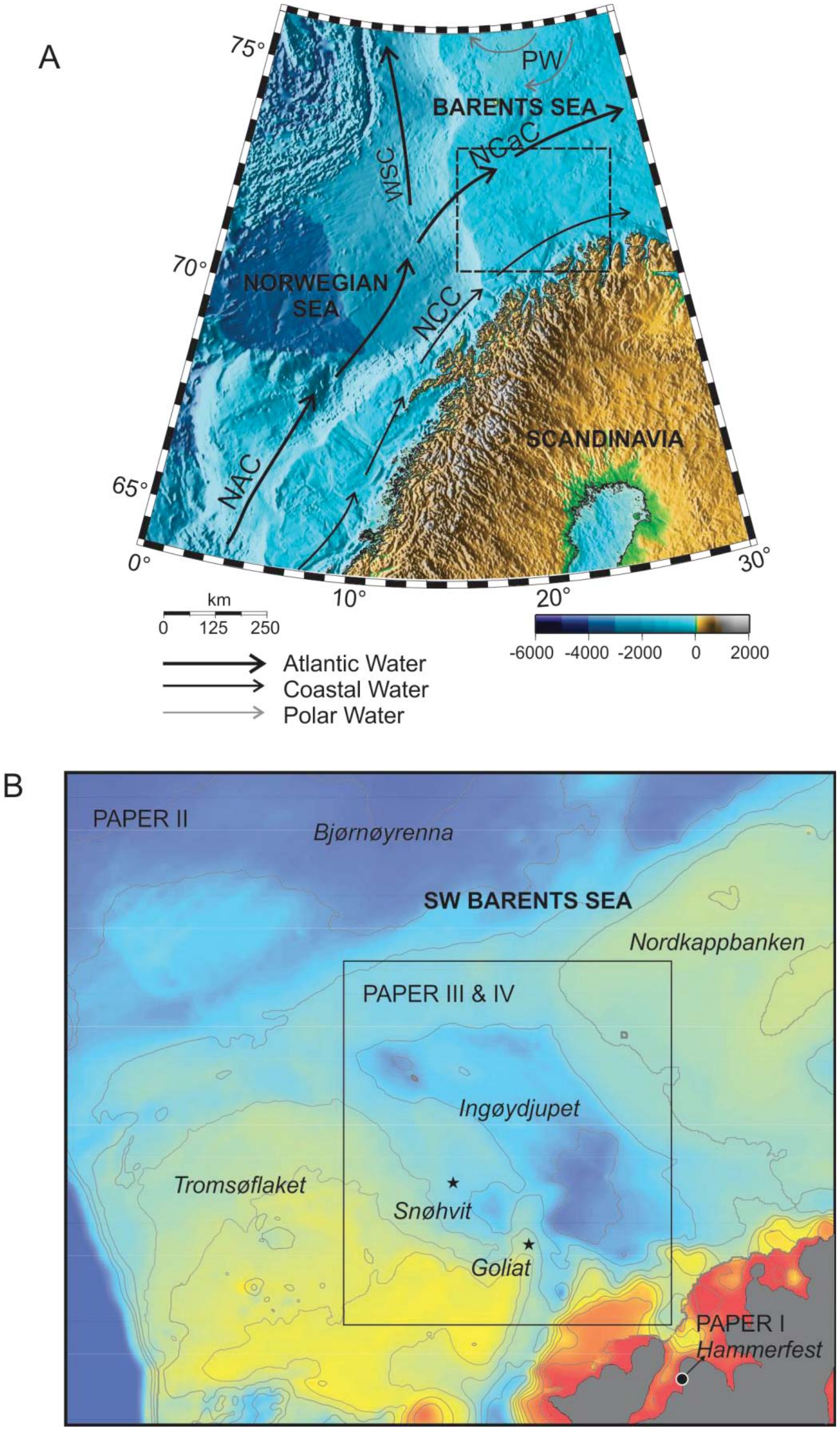

Figure 1. Overview maps. (a) Map of the northern North Atlantic and western Barents Sea showing the major ocean currents. NAC = North Atlantic Current, WSC = West Spitsbergen Current, NCaC= North Cape Current, NCC = Norwegian Coastal Current, PW = Polar Waters. Area of map (b) is indicated. Map modified after bathymetric and topographic maps provided by Jan Sverre Laberg and Tom Arne Rydningen; (b) Detailed bathymetric map of the SW Barents Sea. The studied areas of paper I-IV are indicated, as are the most important location names and the Snøhvit and Goliat fields. Map was modified after bathymetric map provided by Monica Winsborrow.

Especially pollutants associated to shipyards, i.e. cupper and tributyltin (TBT), used to be of exceptional high concentrations (Danielsberg et al., 2005). These were major components of ship painting until their use was banned in 2003.

Environmental studies with focus on contaminant concentrations in the water column, surface sediments and biota have been conducted in the harbor since 1985 (e.g. Bakke et al., 2001; Dahl-Hansen, 2005; Evenset et al., 2006; Jahren and Hellands, 2009; Johnsen and Jørgesen, 2006; Skjegstad et al., 2003). This chemical analysis showed that sediments from the inner harbor all correspond to levels considered as unacceptable according to the guidelines of the WFD (Skjegstad et al., 2003). Additionally, analysis of contaminants concentrations in mussels and bivalves were unacceptably high, while contaminant concentrations in the water column were in general lower, however still of significant level (Jahren and Hellands, 2009).

Due to the high environmental risk the municipality of Hammerfest formulated measures to diminish the contaminant rates of the sediments. These included: a) mapping of pollution sources; b) preventing and limiting the input of contaminants into the marine environment; c) cleaning the harbor from garbage and; d) stabilizing the polluted sediments by changing shipping routes. In addition, a start was made to cap, remove or remediate the contaminated sediments of the harbor basin (Jahren and Hellands, 2009).

4.2 SW Barents Sea

Paper II to IV focus the Tromsøflaket-Ingøydjupet area located in the SW Barents Sea (figure 1). The Barents Sea is a relatively shallow epicontinental sea covering a wide continental shelf. It is bounded to the north and west by continental slopes, to the east by Novaja Zemlja and to the south by the Fennoscandian coast. The Barents Sea is characterized by bank areas, e.g. Tromsøflaket, and transverse glacial troughs, e.g. Ingøydjupet. The shallow bank area of Tromsøflaket lies at 150 to 300 meters of water depth. To the west, the bank is bounded by the steep slopes of the Egga shelf edge, and to the south by Sørøydjupet. The NE-SW trending glacial trough Ingøydjupet is bordering Tromsøflaket to the east with water depths of over 400 m. Both Ingøydjupet and Tromsøflaket are bordered by the cross shelf trough Bjørnøyrenna, with water depths between 300 – 500 m (Andreassen et al., 2008).

During the Late Weichselian, the Barents Sea ice sheet advanced until the edge of Tromsøflaket. The southern Barents Sea deglaciated after 15 000 ^{14}C (e.g. Andreassen et al., 2008; Hald et al., 1990; Ottesen et al., 2005; Vorren and Kristoffersen, 1986). Holocene sediments are deposited above the Late Weichselian glacigenic diamicton. The sediment regime of the region is influenced by strong currents on the shallow bank areas, for example

Tromsøflaket and calm conditions in the deeper trough of Ingøydjupet (Bellec et al., 2008; Bellec et al., 2009; Jensen et al., 2009), resulting in a thin cover (< 1 m) of coarse grained material in the bank areas, and a thicker cover (1-15 m) of fine grained sediments in the deeper troughs (Hald and Steinsund, 1992; Hald et al., 1990; Vorren et al., 1989). The Holocene sediment cover is mainly derived from re-depositing of glacigenic sediments as well as from the modern environment (Hald and Vorren, 1984; Vorren et al., 1978).

Warm and saline Atlantic Water (AW) enters the Barents Sea with the North Atlantic Current (NAC; T > 2°C; S > 35 psu) (Swift, 1986). The direction of the NAC is topographically steered along the Norwegian shelf (figure 1). The NAC splits into a zonal and a meridional component north of Norway. The meridional component, the West Spitsbergen Current (WSC; 3 °C < T > 7 °C; 34.9 < S > 35.2 psu), flows northward along the continental shelf and west of Spitsbergen towards the Arctic Ocean (Schauer et al., 2004). The zonal component, the North Cape Current (NCaC; T > 3 °C; S > 34.9) flows eastward into the SW Barents Sea (Hopkins, 1991; Schauer et al., 2002; Ådlandsvik and Loeng, 1991). The coastal zone of Norway is influenced by the Norwegian Coastal Current (NCC; 3 < T > 13 °C; 30 < S > 35 psu), which overlies both the NAC and the NCaC, in a thinning wedge towards the west and north respectively, with maximum thicknesses of 150 meters water depth (Aure and Strand, 2001; Sætre and Ljøen, 1971). The polar front in the northwestern part of the Barents Sea separates the WSC from the East Spitsbergen Current (ESC; < 0 °C, 34.3 - 34.8 psu). The ESC brings relatively fresh and cool water into the Barents Sea (Loeng, 1991).

The investigated area (paper II-IV) is influenced by the NCaC and NCC only. The NCC dominates the southern part by Tromsøflaket, while the NAC dominates the rest of the bank (Bellec et al., 2008; Vikebø and Ådlandsvik, 2005). The core sites in Ingøydjupet are situated under the axes of the inflowing NCaC and the NCC. The water column in the present day Ingøydjupet is characterized by a stable stratification with NCaC at the bottom and the NCC in the first 30-50 m of the water column (Chistyakova et al., 2010; Ingvaldsen et al., 2004; Loeng, 1991). Bottom current velocities of < 5 cm/s were reconstructed for Ingøydjupet, while bottom current velocities are between 5 to 50 cm/s on Tromsøflaket (Bellec et al., 2008).

The SW Barents Sea area is considered to be relatively pristine currently; input of contaminants to the area mainly occurs through the atmosphere by long-range transport. However, large hydrocarbon reserves were identified in the region. Extensive petroleum exploration and production in the near future is therefore expected. Other industrial activities in the Barents Sea are confined to fishing activities and ship traffic.

The first exploration drilling started after opening of the region during the 1980s. In 2007, the Snøhvit field was the first field to start producing. Production at the nearby Goliat field will start in late 2014 (NPD, 2012).

Sources of contaminant and disturbances associated with drilling operations are caused by drilling muds, drill cuttings and produced water. Drill cuttings mainly contain crushed rock material. Drilling muds are used to lubricate the drill hole and might contain small quantities of heavy metals and polycyclic aromatic hydrocarbons (PAHs). Currently only discharge of water based drill cuttings and drilling muds from the top-hole is allowed in the Barents Sea to extents not harmful to the environment (Øfjord et al., 2012). Produced water consists of a mixture of sea water and formation water. This formation water is the natural layer of water found below the hydrocarbons in the reservoir field. To achieve maximum oil recovery, sea water is injected into the field to force the hydrocarbons out. Discharges of these produced waters might result in the release of oil components and other chemicals into the environment (Ekins et al., 2006). At present, a zero-harmful discharge policy applies to the Barents Sea region, implying that only discharges of amounts considered to be non-harmful to the environment are allowed (Knol, 2011).

5. Material and Methods

Papers I to III presented in this thesis are based upon analyses of benthic foraminiferal fauna analyses complemented with sedimentological, geochemical and oceanographic data, from surface samples and sediment cores from the SW Barents Sea and harbor of Hammerfest, Northern Norway. Paper IV focuses on sediment properties and sediment accumulation rates in the Ingøydjupet trough. The description and evaluation of the methodology used in these papers is presented below. Paper V discusses the appropriate methodology in bio-monitoring studies using living benthic foraminifera. This FOraminiferal Bio-Monitoring (FOBIMO) protocol was established (2011) and published (2012) after most of the sediment samples intended for living benthic foraminifera analyses (paper I-II) were collected (2006-2011) and analyzed (2010-2011). The used methodology in the living benthic foraminiferal studies in papers I and II therefore deviate on some points from the FOBIMO-protocol. Rationale for the used methodology, the differences between the used methodology and the FOBIMO-protocol and the possible effects this might have on the outcome of the analyses is discussed in chapter 5.7.

5.1. Sample retrieval and treatment

Surface sediment samples collected in Hammerfest harbor (paper I), were retrieved with a van Veen grab corer in October 2010. Sample locations were chosen close to sites used in previous environmental studies (Skjegstad et al., 2003). Surface sediment samples collected in the SW Barents Sea (paper II), were retrieved with a multi corer, box corer, van Veen grab or a combi corer, depending on the substrate type and sampling campaign. Surface sediment samples were retrieved during several sampling campaigns in June 2006, April 2007, June 2010 and July 2011 (Andreassen, 2011; Jensen et al., 2007, 2008; Mannvik et al., 2011). Samples locations include sites close to petroleum industry related activity and more regional sites. The sediment cores from Ingøydjupet (paper III-IV) were retrieved with a multicorer by the *R/V Helmer Hanssen* in July 2011. Sample locations were selected at the deepest water depths in Ingøydjupet.

All collected samples and cores were carefully studied for disturbances; only visible undisturbed surfaces and cores were used for further analyses. Replicate samples were not collected. In addition to sediment samples, at some sample localities CTD (conductivity, temperature, density) measurements were taken with a *Seabird SBE 911 plus* to obtain information about the physical oceanographic properties of the water column.

Living benthic foraminiferal assemblages (paper I and II) were studied in the uppermost centimeters of the sediment; the 0-2 cm interval of the samples from Hammerfest harbor and the 0-1 cm interval of the samples from the SW Barents Sea. A rose Bengal enthanol mixture (1g/L ethanol 95%) was added to preserve and stain the living foraminifera (Walton, 1952) immediately after sub-sampling. The added mixture was equal to the sample volume to ensure dilution of the mixture by poor water did not result in concentrations below 70 %; the minimum concentrations for preservation of specimens (Murray, 2006). Samples were stored cool until further laboratory processing for a minimum period of 2 weeks (Lutze and Altenbach, 1991).

The analyzed multi-corers from Ingøydjupet (paper III and IV) were sub-sampled at a one centimeter interval directly after retrieval down to 20 cm core depth. Samples were stored cool until further analyses.

5.2. Granulometric analyses

Samples were wet sieved at 63 µm, 100 µm and 1 mm meshes. The multi-corer samples of paper III and IV were freeze dried before sieving. Bulk samples and sieved size fractions were weighted to enable calculations of grain size distributions. The 100 µm – 1 mm fractions were kept for foraminiferal analyses; samples intended for living foraminiferal counts were kept in rose Bengal until further analyses, samples intended for dead foraminiferal counts were dried.

The < 63 µm fraction was analyzed on the Micrometics SediGraph 5100 according to the method described by Coakly and Syvitski (Coakley and Syvitski, 1991) to determine weight percentages of silt (4 – 63 µm) and clay (< 4 µm). The > 63 µm fraction corresponds to the sand content of the samples.

Sortable silt mean grain-size ($\overline{SS}$) was analyzed for the sediment samples presented in paper II-IV. The $\overline{SS}$ was calculated from the 10 – 63 µm fraction and is based on the principle of the ability of particles < 10 µm to flocculate (Bianchi and McCave, 1999; Hass, 2002; McCave et al., 1995). In paleo-records the $\overline{SS}$ enables the reconstruction of mean current velocity. Such reconstructions are difficult for modern sediments as a result of the high variability of current strength due to the presence of eddies (McCave et al., 1995). Therefore, patterns observed in $\overline{SS}$ will be considered only as indicators of changes in bottom current strength.

Clay mineral composition of the < 2 µm fraction was analyzed (paper II and IV) by X-ray diffraction (XRD) according to the procedures described by Jensen et al. (2007) for the analyses preformed at Norwegian Geological Survey (NGU) and according to the method of Moore and Reynolds (1997) described by Rüther et al. (2012) for the analyses at the Iceland GeoSurvey. The data was processed using the MacDiff software version 4.2.5 (Petschick, 2010). Quantification of the abundance of the minerals is expressed as weight percentage, and occurred by by peak fitting of the four clay minerals: illite, smecite, chlorite and kaolinite.

5.3. Geochemical analyses

The total organic carbon (TOC) content of the samples from Hammerfest harbor (paper I) was analyzed using infrared spectrometry (IR-S) according to the Norwegian Standard EN 13137-A (NorwegianStandard, 2011). The TOC of most of the samples from the SW Barents Sea (paper II-IV) was analyzed using a Leco CS-2000 induction furnace. Prior to analyses, the inorganic matter ($CaCO_3$) was removed from the bulk sediments using HCl (10 %). Samples were place in an oven and headed to 1350 °C to burn all components other than organic carbon. Furthermore, the Total Organic Matter (TOM) concentration of a selection of surface samples (paper II) was measured according to the methods described by Mannvik et al. (2011). Analyses are based on a similar principle as the TOC analyses; however samples are headed up to 480 °C. This lower temperature results in quantification of not only organic carbon, but also organic matter, oxygen, nitrogen and sulfur. Therefore TOC and TOM values are not directly comparable; however they are expected to reflect similar patterns.

Metal concentrations and persistent organic pollutant of the surface samples from Hammerfest (paper I) were analyzed by *Eurofins Environmnetal Testing Norway AS*. Arsenic, lead, cupper, chromium, nickel and zinc concentrations were analyzed using inductively coupled plasma atomic emission spectroscopy (ICP-AES) according to Norwegian Standard (NS) method EN ISO 11885 (NorwegianStandard, 2009). Cadmium was analyzed using inductively coupled plasma mass spectroscopy (ICP-MS) according to NS method EN ISO 17294-2 (NorwegianStandard, 2004). Mercury was analyzed using atomic absorption spectroscopy (AAS) according to NS method NS 4768 (NorwegianStandard, 1989). The concentrations of the different polycyclic aromatic hydrocarbon (PAHs) and total hydrocarbons (THC) were measured with gas chromatography (GC) following NS method ISO DIS 16703-Mod (NorwegianStandard, 2011). Tributyltin (TBT) concentrations were analyzed using GC following an intern certified method of Eurofins.

Metal concentrations of the sediment samples from the SW Barents Sea (paper II-III) were analyzed by *Unilab AS* or NGU. Before analyzes, sediments were dried at 40 °C, homogenized, sieved and decomposed with nitric acid (HNO_3). Concentrations of barium, cadmium, cupper, chromium, zinc and lead were analyzed using ICP-AES or inductively coupled plasma sector field mass spectrometry (ICP-SFMS) depending on the metal concentration following NS 4470 (NorwegianStandard, 1994). Hg concentrations were analyzed with atom fluorescence (AFD) according to method NS 4768 (NorwegianStandard, 1989).

5.4. Benthic foraminiferal analyses

Living benthic foraminifera (paper I and II) were quantified and identified in the 100 µm to 1 mm size fraction. A modified Elmgren wet splitter (Elmgren, 1973) was used to split the samples into a practical size. The species were wet picked, to better distinguish between stained and non-stained specimens. The staining of rose Bengal differs between the different species. In general, a bright stain inside more than half of the test was the criterion for a specimen to be considered as alive during sample taking (de Stigter et al., 1998; de Stigter et al., 1999). Additionally, for agglutinated foraminifera the presence of stain in the aperture was an extra criterion to be considered as living.

Counting and identification of the dead fauna (paper III) was performed in the 100 to 1 µm size fraction. Species were dry picked and a dry splitter was used for partitioning of the sample when needed.

In the studies of both the living and the dead fauna calcareous and agglutinated species were considered; organic walled species were not. A minimum of 300 specimens from a known split of the sediment was counted and identified, to precisely determine the abundances of the species in the assemblages (Patterson and Fishbein, 1989). When less than 300 living specimens were observed in a sample, the whole sample volume was counted and identified. Specimens were identified down to species level following the generic classification of Loeblich and Tappan (1987) and the holotype descriptions of Ellis and Messina (1940–1978). The accepted nomenclature as referred to in the WoRMS database (Appeltans et al., 2012) is used in this thesis.

The foraminiferal results are presented in different terms as defined below:

- *Relative abundance*

The relative abundance of a species in a sample is the percentage of the species in relation to all the other counted specimens in the sample.

- *Absolute abundance*

The absolute abundance of a species is the number of specimens of the species with standardization for a sediment volume of 50 ml (living specimens; paper I and II) or 1 gram of bulk sediment (dead specimens; paper III).

- *Foraminiferal and species flux*

Fluxes were calculated (paper III) as described by Ehrmann and Thiede (1985) with:

flux (#/cm^2/yr) = absolute abundance (#/g) x bulk density (g/cm^3) x SAR (cm/yr)

with # is the number of specimens and SAR abbreviating sediment accumulation rates. The bulk density was reconstructed from the moisture content and porosity of the sediments assuming an average mineral density of 2.45 g/cm^3.

- *Diversity*

The taxonomic diversity is expressed as the Shannon index (H'; Shannon, 1948) or the bias corrected Shannon-Wiener index (expH'$_{bc}$; Chao and Shen, 2003) and was calculated using respectively the PAST software (Hammer et al., 2001) and the Entropy library (version 1.2.0; Hausser and Strimmer, 2009) of the statistical language R (version 2.14.2; RDCTeam, 2012).

5.5. Chronology

Chronologies of the investigated sediment cores presented in paper III and IV were constructed based on ages obtained by ^{210}Pb dating. Analyses were performed at *GEL Laboratories* in Charleston, South Carolina, USA. The cores were dated on a 1 cm interval. All ages were calculated for mid-layer depths. Three models are generally used to determine

^{210}Pb ages and will be briefly summarized here. A detailed overview of these models can be found in Appleby and Oldfield (1992).

Ages are calculated according to the general decay equation:

$$A_i(t) = A_0 \times e^{-\lambda t} \tag{1}$$

from which t can be solved:

$$t = \frac{1}{\lambda} \times \left(\frac{A_0}{A_i(t)} \right) \tag{2}$$

where $A_i(t)$ is the measured ^{210}Pb activity at interval 'i', corresponding to time 't'; λ is the ^{210}Pb decay constant (0.03114 yr^{-1}); A_0 is the initial ^{210}Pb activity of which the definition depends on the used model.

In the simplest model, the Constant Flux, Constant Sedimentation (CF-CS) model, a constant ^{210}Pb flux and a constant sediment accumulation rate is assumed. In the CF-CS model, A_0 corresponds to the ^{210}Pb activity at the sediment-water interface.

In the Constant Rate of Supply (CRS) model the ^{210}Pb flux is assumed to be constant. The sediment flux varies with time. A_0 (or $A_{inventory}$) is expressed as the total ^{210}Pb inventory and is calculated according to:

$$A_{inventory} = \sum_{i \to \infty} \left({}^{210}Pb \right)_i \times d_i \times \rho_i \tag{3}$$

where $(^{210}Pb)_i$ is the excess ^{210}Pb activity in layer 'i', d_i is the thickness of layer 'i', and ρ_i is the bulk density of layer 'i'. Bulk densities and porosities were calculated from sediment moisture contents assuming an average mineral density of 2.45 g/cm^3.

The Constant Initial Concentration (CIC) model assumes that the initial sedimentation activity of ^{210}Pb is constant and that the ^{210}Pb flux is proportional to the sediment flux. The sediment flux is allowed to vary with time. A_0 is the extrapolated ^{210}Pb activity at the sediment-water interface.

Ages of the cores presented in paper III and IV are based upon the CRS model; linear sedimentation accumulation rates presented in paper IV were based on the Constant Initial Concentration (CIC) model.

5.6. Statistical methods

A number of statistical methods were performed (paper I and II). The similarity of sample stations based on their abiotic variables was defined with Q-mode hierarchical clustering, using Ward's method and Euclidean distance (Ward, 1963). The main modes of variations within the abiotic variables were defined using a principal component analysis (PCA) (Davis, 2002; Harper, 1999). Analyzed abiotic parameters were only included when measured in every sample station of the study. Before analysis the parameters were normalized to remove the effect of different orders of magnitude (Manly, 1997).

Sub-assemblages or associations within the total living foraminiferal assemblage were defined with R-mode hierarchical clustering, using Ward's method and Euclidean distance (Ward, 1963) based on the absolute abundance of the species. Absolute abundance were standardized and normalized before clustering was applied to increase the importance of the less abundant species (Manly, 1997). Only species with a relative abundance of > 5 % in at least one sample were considered to avoid bias of the data set (Fishbein and Patterson, 1993).

The relation between abiotic variables and the benthic foraminiferal assemblage was found with a Pearson correlation matrix (paper I) or multiple regression linear models (paper II). The multiple regression linear models used a stepwise regression with bidirectional elimination, using the Akaike information criterion (AIC). The model defined which of the abiotic variables are needed to explain the distribution of the benthic foraminiferal assemblage in the best possible way.

Q- and R-mode hierarchical clustering, PCA and the Pearson correlation matrix were performed using the statistical program PAST (version 2.17c; Hammer et al., 2001) Multiple regression linear modelling was performed using the statistical program R (version 2.14.2c; RDCTeam, 2012).

5.7. Rationale methodology

The methodology used for preparation and handling of samples intended for living benthic foraminiferal analyses presented in paper I and II, deviate from the FOBIMO-protocol (paper V) for reasons discussed above. The main points from which the methodology in paper I and II deviate from the methodology presented in paper V and the potential this might have on the outcome and interpretation of the results presented in those papers, are the following:

a) Sampling device

Sediment surfaces can be easily disturbed during sample taking. Disturbance of the sediment layer is smallest when interface corers are used, e.g. a Barnett multiple corer type sampler (Barnett et al., 1984). Such interface corers can successfully operate in fine sediments, however are not always successful in sandy sediments. In sandy sediments box corers facilitate a good and undisturbed recovery (Bouma and Marshall, 1964). Grab corers can create a strong bow wave during employment, disturbing the structure of the sediment (Riddle, 1989; Wigley, 1967). During recovery through the water column, part of the sample might be washed out, resulting in a potential loss of foraminiferal species (Schönfeld, 2012). The use of an interface corer or a box corer, depending on the sampling substrate, is therefore a mandatory requirement for bio-monitoring studies using living benthic foraminifera according to the FOBIMO-protocol (Schönfeld et al., 2012). The use of grab samplers should be avoided on soft substrates; on sandy substrates grab samplers might occasionally be the only possible device for sample collecting.

Most of the surface sediment samples in paper II of this thesis were collected using either a multi corer or box corer. However, some of the samples, i.e. those close to exploration and drilling sites, were collected with a grab corer. Additionally, surface sediments from the harbor of Hammerfest (paper I) were collected using a grab corer. This was the only possibility to collected samples from these locations. All collected surface sediment samples were carefully studied for potential disturbances of the sediment surface. However, disturbances might not always be visually recognizable. Disturbances might results in loss of diversity and foraminiferal density, and therefore care should be taken when interpreting the results from surface samples collected by a grab sampler.

b) Replicates

The distribution of benthic foraminifera is known to be patchy (Barras et al., 2010; Bernstein et al., 1978; Fontanier et al., 2003; Griveaud et al., 2010). Studies of living benthic foraminifera are often based on non-replicate analyses, which might result in a variability which is not representative for the actual assemblage of the sample location (Schönfeld, 2012). Heterogeneity might be obtained by collecting replicate samples from each sample location. A statistical study by Bouchet et al. (2012) concluded that three replicates are sufficient for determining a reliable representation of the diversity at the sample locations. To accurately describe the variability of the ecosystem, the FOBIMO-protocol made it a mandatory recommendation to obtain and analyze three replicates at each sample site (Schönfeld et al., 2012).

In the in this thesis presented studies of living foraminifera (paper I and II), non-replicate samples were analyzed. This might result in an over representation of variability of the studied area. This should be taken into account when interpreting the foraminiferal counts of the areas. Care should be taken when comparing the here presented results with samples taken from the same sites in the future to detect changes in distribution patterns. Changes in regional, rather than local or site specific foraminiferal distribution patterns might therefore be more accurate for describing environmental changes.

c) Size fraction

Paper I and II investigated the living foraminiferal assemblages in the 100 µm – 1 mm fraction. Which size fraction is most appropriate for analyses of living benthic foraminifera has been under debate for a long time. An inventory by Schönfeld (2012) concluded that the > 125 µm fraction is currently the most common size fraction used in living foraminiferal studies. Several studies have however shown a considerable loss in diversity and foraminiferal density when a larger fraction, i.e. > 125 µm or 150 µm, is used rather than a smaller fraction, i.e. > 63 µm (Fontanier et al., 2006; Fontanier et al., 2008; Mojtahid et al., 2008). Therefore, considering only the larger fraction might result in an underrepresentation of the small species and juveniles (Duchemin et al., 2007; Schröder et al., 1987). A study by Bouchet et al. (2012) concluded however that important environmental parameters are adequately reflected by both fine and coarse fractions. The FOBIMO-protocol concluded to make analyses of the > 125 µm a mandatory recommendation for bio-monitoring studies (Schönfeld et al., 2012).

In the polar regions foraminiferal tests do often not exceed test diameters of over 125 µm (Knudsen and Austin, 1996). Therefore the > 100 µm is often analyzed in these regions. Additionally, this size fraction was chosen in the studies of this thesis to enable comparison of the results with results from previous studies from the same region (e.g. Hald and Steinsund, 1992, 1996; Saher et al., 2009; Saher et al., 2012; Steinsund, 1994). Analyses of the living benthic foraminifera in the > 100 µm fraction of the surface sediment samples presented in paper II, also enables comparison to the dead assemblages presented in paper III. The > 100 µm fraction in paper III was chosen to enable comparison to other paleo-studies (e.g. Chistyakova et al., 2010; Hald et al., 2011; Husum and Hald, 2004; Jernas et al., 2013; Wilson et al., 2011).

Given the conclusions of Bouchet et al. (2012) it is expected that the studied size fraction of 100 µm – 1 mm can adequately reflect important environmental changes. However, it must be taken into account that the smaller species might not have been registered, and consequently the true diversity of the samples might be higher. Additionally, comparison of the established baselines and assemblages in these papers can in the future only be compared to studies using a similar size fraction.

6. Summary of papers

Paper 1:

Dijkstra, N., Junttila, J., Carroll, J., Husum, K., and Hald, M., **The impact of contaminants and grain size on benthic foraminiferal assemblages in the harbor of Hammerfest, northern Norway,** *submitted to Norwegian Journal of Geology*

The harbor of Hammerfest, northern Norway is highly contaminated by persistent organic pollutants (POPs) and heavy metals, due to discharges from local industrial activities and ship traffic. The main objective of this study was to evaluate the utility of benthic foraminiferal assemblages from the harbor as indicators of anthropogenic stressors. Sediment grain size properties, contaminants levels and foraminiferal assemblages of the harbor environment were characterized. The relationship between the abiotic variables and benthic foraminiferal species was established using principal component analyses (PCA), Q-mode clustering and a Pearson correlation matrix. Due to recent measures taken in the harbor to diminish the input of contaminants, sediment contaminant concentrations have decreased since 1998 (Skjegstad et al., 2003). However, contaminant levels still correspond to an environmental quality considered being harmful to the environment (level III-V). These high contaminant levels are reflected in the foraminiferal community, showing a low density and diversity. Diversity values correspond to environmental status levels II to IV. Sample stations can be divided into three groups based on abiotic variables, reflecting the high variability of habitat characteristics and anthropogenic stressors in the harbor. Group I is associated with stations highly affected by ship traffic. Grain sizes are coarse due to reworking of the sediment by ship propellers and levels of tributyltin (TBT) are high due to shipyard activities. The foraminiferal assemblage in these locations is dominated by the species: *L. lobatula*, *B. marginata*, *C. albiumbilicatum* and *B. frigida*. Group II covers the least impacted, however still heavily contaminated sites. Sediments are in general fine grained and contain high levels of heavy metals. The foraminiferal assemblage in these locations is dominated by stress tolerant species: *S. fusiformis, S. biformis, B. spathulata* and *E. excavatum*. Group III consists of one station, located in front of a river outlet and is characterized by high levels for heavy metal concentrations and total organic carbon (TOC). The sample was barren of living benthic foraminifera. The absence of living foraminifera can be attributed to a combination of fresh water inflow from the river, high contaminant concentrations and a high TOC content. The patterns identified through this investigation provide a valuable baseline for future investigations of the ecological impacts of industrialization in northern coastal communities.

Paper 2:

Dijkstra, N., Junttila, J., Carroll, J., Husum, K., Elvebakk, G., Godtliebsen, F., and Hald, M., 2013, **Baseline benthic foraminiferal assemblages and habitat conditions in a sub-Arctic region of increasing petroleum development,** *in press at Marine Environmental Research,* doi:10.1016/j.marenvres.2013.09.014

Petroleum production will expand significantly in the Barents Sea in the coming years, raising the chance for increased industrial releases into the marine environment. The purpose of this study was to establish the present day pre-impact baseline conditions for the SW Barents Sea. The study is based on a set of surface samples retrieved from the Tromsøflaket-Ingøydjupet region where petroleum related activities will increase in the coming years. Surface sediment samples were investigated on their living benthic foraminiferal assemblages, their sediment properties and their concentrations of a selection of metals. Relationships between habitat characteristics and foraminiferal assemblages were established using statistical methods including principal component analysis, Q- and R-mode clustering and multiple regression linear modeling. Metal concentrations never exceeded threshold levels considered to be harmful to the environment, indicating that the area reflects pre-impacted baseline conditions. A slight elevation of metal concentrations can be observed in the fine grained sediments of the deeper area, due to the ability of clay minerals and organic matter to trap contaminants. This might indicate that the deep areas serve as trapping zones of contaminants related to discharges from petroleum drilling sites nearby. Three associations were distinguished in the foraminiferal assemblage of the region reflecting the different habitat characteristics found in the study area. The first association is mainly dominated by epifaunal species, i.e. *L. lobatula*, *T. angulosa* and *C. laevigata*. This *Lobatula-Trifarina* (LT) association is more frequently, though not exclusively, observed in samples from the shallow Tromsøflaket. The species of the LT-association reflect the habitat characteristics predominating on the relatively shallow Tromsøflaket, i.e. high bottom current activity and coarse grained sediments. The second association is mainly dominated by infaunal species, e.g. *M. barleeanus*, *P. bulloides* and *N. auricula*. This *Melonis-Nonionella* (MN) association is more abundant in samples from the relatively deep Ingøydupet. The species of the MN-association reflect the habitat characteristics of the Ingøydjupet trough, i.e. fine grained sediment, relatively high availability of organic matter and calm bottom current conditions. The third association consists of *Reophax* spp., *Trochammina* spp., and *E. nipponica*. No clear habitat preference was observed for this association within the study area. The outcome of this study might contribute to the development of a bio-monitoring tool applicable to the study area using benthic foraminifera. Both the LT-association and MN-association were considered as potential bio-indicators for this region due to their specific habitat characteristics and feeding strategy; the R-association was not considered to be useful for bio-monitoring due to the absence of a habitat pattern.

Paper 3:

Dijkstra, N., Junttila, J., Husum, K., Carroll, J., and Hald, M., **Natural variability of benthic foraminiferal assemblages and metal concentrations during the last 150 yrs. in the Ingøydjupet trough, SW Barents Sea,** *manuscript intended for submission to Marine Micropaleontology*

The use of benthic foraminifera as bio-monitoring tool is often complicated by the natural variability of both the ecosystem and the physical environment. Therefore site specific studies are needed to understand the interaction between benthic foraminifera and the physical environment and to gain insight into the range of natural variability. Four 20 cm long sediment cores from the Ingøydjupet trough were investigated on their benthic foraminiferal assemblage and metal concentrations. The objective of this paper was to characterize the temporal variability of these parameters over a 150 year time span. These variables were correlated to changes in sediment properties and TOC as presented in Junttila et al. (submitted) (Paper IV). The results were interpreted in terms of changes in strength and dominance of the water masses prevailing in the trough, i.e. the North Cape Current (NCaC) and Norwegian Coastal Current (NCC). Species associated to temperate water masses dominated the assemblage, i.e. *E. nipponica*, *M. barleeanus*, *L. lobatula* and *C. laevigata*. Additionally *C. neoteretis* associated with colder water masses was frequently observed. Foraminiferal distributions in the near shore cores 150 and 151, were affected by a strong influence of fluctuating strength of the NCC. A strong and relatively stable bottom current was active at these locations between 1926-1978 CE and 1940-1988 CE respectively. The foraminiferal assemblages of core 152, located in the middle of trough, experienced influence of both the NCC and NCaC throughout the studied time interval. Changes in foraminiferal assemblages of core 154, located furthest off shore, can be attributed to changes in inflow of the NCaC. Superimposed on the local trends, all cores showed an increased influence of the NCaC towards present times. The reconstructed patterns of variability in bottom current strength and water mass dominance correspond to those reconstructed by Junttila et al. (submitted) (Paper IV) based on sediment properties. Additionally, the foraminiferal assemblages of some cores might reflect the climatic transition between the Little Ice Age and the Modern Warming. Decadal scale climatic oscillations between warm and cool temperatures can also be observed in some of the cores. Metal concentrations in the sediments correspond to background levels. Down core changes are attributable to clay and TOC content, and therefore reflect the natural variability of the region. Only the down core distribution of Pb and Hg in core 152 might reflect an anthropogenic signal related to combustion of leaded gasoline. The strong correlation between contaminants and sediment properties, and the strong influence of water masses on the sediment distributions, indicates that changes in oceanography might have an influence on the deposition of contaminants in the region.

Paper 4:

Junttila, J., Carroll, J., Husum, K., and Dijkstra, N., **Sediment transport and deposition in the Ingøydjupet trough, SW Barents Sea**, *submitted to Continental Shelf Research*

Increased petroleum activities in the SW Barents Sea might result in an increase of releases of drill cuttings into the ocean. This requires site specific knowledge on potential pathways and accumulation areas of released drill cuttings and contaminants. The objectives of this paper were to determine the sediment accumulation rates, to characterize the natural variability of sediment assemblages and to determine the effect of bottom currents on the transportation of sediment in the Ingøydjupet trough. Baseline characterization of four sediment cores from known accumulation areas in the Ingøydjupet trough were investigate in terms of grain size, smectite clay mineral content, sortable silt mean grain size and total organic carbon (TOC). Results were interpreted in relation to the role of bottom currents as transport agents of sediments. Variations in smectite content and TOC revealed information on sediment sources. Average sediment accumulation rates of the investigated cores decreases with distance offshore, and vary between 1 to 2.4 mm/yr. Additionally, the analyzed variables reflect the distribution of the two main water masses in this area; the Norwegian Atlantic Current (NAC) and Norwegian Coastal Current (NCC). The down core distribution of sortable silt mean grain size and fine sediment fractions revealed a more variable and stronger bottom current allied to the NCC active at two coring localities near shore. The increasing sand content towards the top of these cores, indicates an intensification of the strength of the current towards present day. More stable and calm bottom current conditions are active in the station farthest offshore. The higher TOC concentrations measured here indicate the influence of the NAC at this locality. The deepest station, situated in the middle of Ingøydjupet showed influence of both the NAC and NCC, with both stronger bottom currents and higher TOC contents.

Contribution to paper 4:

The thesis author participated in retrieving, sampling and evaluating the quality of the investigated cores. Additionally, contribution to paper 4 was given by evaluating the data of the sediment properties and the age model, and by discussing the implications this data had for reconstruction of the variability and influence of the NAC and NCC.

Paper 5:

Schönfeld, J., Alve, E., Geslin, E., Jorissen, F., Korsun, S., Spezzaferri, S., and Members of the FOBIMO group*[2], 2012, **The FOBIMO (Foraminiferal Bio-Monitoring) initiative – Towards a standardized protocol for soft-bottom benthic foraminiferal monitoring studies**. *Marine Micropaleontology*, vol. 94-95, p. 1-13

The ecological quality of the marine ecosystem is traditionally monitored by surveys of the composition of the macrofaunal community. During the last decades, benthic foraminifera have also proved to be helpful indicators of ecological quality, given their high reproduction rates, specialized environmental preferences and preservation potential in the fossil record. The latter enables reconstruction of past levels of ecological quality. Whereas macrafaunal bio-monitoring studies are performed according to a standardized methodology, this did not exist for benthic foraminifera until publication of this paper. The main goal of the FOraminiferal Bio-Monitoring (FOBIMO) expert workshop was to develop a set of recommendations of standardized methods. This paper presents a list of mandatory and advisory recommendations regarding methodology to be used in bio-monitoring studies using living benthic foraminifera. The mandatory recommendations should be followed in order for such studies to qualify as comprehensive and according to the norms. Scientific rigor and practical limitations were taking into account when defining the recommendations. The list of recommendations is intended to strengthen the use of benthic foraminifera in bio-monitoring studies and not to limit the pure scientific studies.

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[2]* Abramovich, S., Almogi-Labin, A., Armynot du Chatelet, E., Barras, C., Bergamin, L., Bicchi, E., Bouchet, V., Cearreta, A., Di Bella, L., **Dijkstra, N.**, Disaro, S.T., Ferraro, L., Frontalini, F., Gennari, G., Golikova, E., Haynert, K., Hess, S., Husum, K., Martins, V., McGann, M., Oron, S., Romano, E., Sousa, S.M., and Tsujimoto, A..

Mandatory recommendations include:

- Usage of an interface or box corer in soft sediments to prevent sediment disturbances. A grab samples can only be used on hard grounds.
- Sampling of the 0 to 1 cm interval of the sediment surface.
- Collection and analyzes of three replicate samples from at each monitoring site.
- Washing of samples over a 63 µm screen, however counting should occur in the > 125 µm fraction.
- Counting of whole splits. Either wet or dry splitters are to be used.
- Soft shelled foraminifera are not to be included in bio-monitoring studies.
- Counted foraminifera of one replicate per station are to be archived for future references. Also census and laboratory data are to be archived.

Advisory recommendations include:

- Samples should be 50 cm^2, corresponding to a coring tube with an 8 cm inner diameter.
- Ethanol with a concentration of > 70 % is recommended as a preservative.
- A Rose Bengal ethanol mixture with a concentration of 2 g per liter and a staining time of at least 14 days is advised.
- Separation by means of heavy liquids should be avoided.
- Analyzing of the > 63 µm fraction might be desirable in some environments.
- Both wet and dry picking is considered to be appropriate.
- Dead assemblages can contain important information on pre-impacted conditions; living fauna in deeper sediment levels may also yield extra information
- Untreated samples might be preserved and stored for future references when possible.

Application of this protocol is a first step towards strengthening and acceptance of benthic foraminifera as reliable bio-monitoring tool.

Contribution to paper 5:

The thesis author is part of the FOBIMO expert group and actively participated in the discussions and decisions that lead to this paper, in addition to helping preparing it.

7. Synthesis

The overall objective of this thesis was to elucidate the imprint of both natural and anthropogenic induced environmental changes on benthic foraminifera in the SW Barents Sea and the Hammerfest harbor, Northern Norway. In Hammerfest harbor, the environment is highly contaminated due to industrial activities. The SW Barents Sea is considered to be relatively pristine, however industrial activities are projected to expand in the years to come. In order to improve the understanding of foraminiferal responses to contaminants in these regions, it is not only necessary to understand the impact of contaminants (paper I), the natural response to changes in the physical environment are also of importance (paper II-IV). Establishing baseline conditions are of great value for development of a bio-monitoring tool based on using benthic foraminifera. Detailed benthic foraminiferal assemblage studies were performed in this thesis in combination with characterizations of the physical environment, i.e. sediment properties and contaminant concentrations in both contaminated and un-impacted areas. To strengthen the position of benthic foraminifera as indicators it is also crucial that a standardized methodology protocol is developed, to enable comparison of environments (paper V).

The following main conclusions were reached based upon the results presented in the thesis:

- In the contaminated Hammerfest harbor, stress tolerant species dominate the assemblages (paper I), reflecting the different anthropogenic stressors active in the harbor. In the pristine SW Barents Sea (paper II and III), both living and dead assemblages reflect the natural variability of the physical environment of the region.
- Stressors having direct or indirect influence on the living assemblage of Hammerfest harbor (paper I) are: (a) disturbance of the sediments by ship propellers; (b) high persistent organic pollutant and heavy metal concentrations and; (c) the inflow of fresh, highly contaminated river water.
- The living foraminiferal assemblage in the SW Barents Sea (paper II) can be divided into three groups: (a) Epifaunal species tolerating higher bottom current speeds dominate the surface sediments from the shallow Tromsøflaket, which are characterized by coarse grain sizes due to the prevailing high bottom current speeds; (b) Infaunal species associated to fine grain sizes and high food availability dominate the assemblages in the relatively deep Ingøydjupet with reduced bottom current speed, and; (c) Species with no clear habitat preference or spatial distribution pattern. The first two associations are considered to have

potential to be included in a bio-monitoring tool applicable to the studied area, as they have a specific habitat preference and feeding strategy.

- The dead assemblages from Ingøydjupet covering the last 150 years (paper III) were mainly influenced by the variability in strength or dominance of the two prevailing water masses in the Ingøydjupet trough; i.e. the Norwegian Coastal Current (NCC) and North Cape Current (NCaC).
- Changes in sediment properties of the cores from Ingøydjupet reconstructed similar patterns of variability in the NCC and NCaC (paper IV) as suggested by the dead foraminiferal assemblages (paper III). The variability in strength and dominance of the NCaC and NCC has a strong influence on the deposition regime in the trough. A strong correlation between sediment properties and metal concentrations was observed, indicating that changes in the oceanography might have an influence on the deposition of contaminants in the region as well (paper III).
- Standardization of methodology is crucial to strengthen further development of benthic foraminifera as a bio-monitoring tool. The guidelines and recommendations formulated by the FOBIMO expert workgroup are a large step forward (paper V). Bio-monitoring studies based on living benthic foraminifera, should follow the recommended methodology to qualify as accurate.

Overall, this study elucidated the response of benthic foraminifera to both natural and anthropogenic induced environmental changes in the sub- Arctic region. Benthic foraminifera show a strong and specific response to different types of anthropogenic stressors (paper I). In the investigated pristine SW Barents Sea, benthic foraminifera mainly react to, and reflect the high natural variability of the region (paper II-IV). Petroleum production is projected to expand significantly in the SW Barents Sea in the coming years raising the potential of increased industrial discharges. The outcome of this study contributes to the development of a bio-monitoring tool applicable to the (sub-) Arctic region using benthic foraminifera (see next chapter). Such a bio-monitoring tool is expected to be of great relevance to monitor potential deterioration of the environment. Additionally, a bio-monitoring tool can be applied to monitor potential recovery of the environmental quality in the contaminated Hammerfest harbor, were measures are implemented to diminish contaminant levels.

8. Outlook and future work – Towards a benthic foraminiferal bio-monitoring tool for the Arctic region

The marine environment is affected by environmental challenges, including global warming, ocean acidification and input of pollutants. This also applies to the Arctic region. Governmental programs, e.g. the WFD and MSFD, were initiated to maintain or achieve an acceptable environmental status. These measures require accurate information on the status of the environment. Evaluating the status of the environment can for example be done with the use of bio-monitoring tool. Such tools are based upon the abundance and physical condition of organisms able to indicate pollution or human impact. Development of an accurate bio-monitoring tool requires adequate indicator species, definition of biotic indices and well established reference conditions, for reasons explained below.

Bio-monitoring of the marine environment is conventionally based on functional groups or indicator species belonging to macrofauna (e.g. Borja and Dauer, 2008; Josefson et al., 2009). A growing number of studies demonstrate however the suitability of benthic foraminiferal species as indicators of the environmental quality in impacted areas with different disturbance sources, e.g. contamination by aquaculture, oil spills, heavy metal pollution, urban sewage and deposition of drill cuttings (e.g. Alve, 1995; Alve et al., 2009; Armynot du Châtelet et al., 2009; Armynot du Châtelet et al., 2004; Bouchet et al., 2012; Bouchet et al., 2007; Burone et al., 2006; Coccioni et al., 2009; Dolven et al., 2013; Ferraro et al., 2006; Frontalini et al., 2009; Hess et al., 2013; Martínez-Colón et al., 2009; Morvan et al., 2004; Nigam et al., 2006; Scott et al., 2001).

8.1 Indicator species

Benthic foraminifera are suitable as indicator species of disturbances because of their high degree of adaptation and fast turnover rates. Changes in assemblage composition or the presences of high numbers of stress tolerant species can be considered as adequate recorders of the impact of environmental changes. However chemical analyses will still be required additionally to determine the type of stressors responsible for the deterioration (Martínez-Colón et al., 2009).

Hily (1984) proposed a model to divide soft-bottom macrofauna into five groups based upon their response to anthropogenic stressors or other disturbance sources (figure 2). With some adaptations this model can be applied to benthic foraminifera as well (Schönfeld, pers. comm. 2012).

The groups (figure 2) have been defined by (Borja et al., 2000; Grall and Glemarec, 1997):

(a) Group I: *Sensitive species*. Dominant at the reference site, disappear or decrease towards sites of maximum disturbances.

(b) Group II: *Indifferent species* No clear trend in abundance, decrease towards highest disturbed sites.

(c) Group III: *3rd order opportunists*. Abundant at the reference sites, clearly increase towards the pollution source. Their density maximum is further away from the disturbance source than those of group IV and V.

(d) Group IV: *2nd order opportunists*. Absent at reference sites, increase towards disturbance source, with a density maximum between those of group III and V.

(e) Group V: *1st order opportunists*. Absent at the reference sites, strongly increase abundance towards disturbance source, with a density maximum close to the disturbance source.

After assignment of the species of an assemblage of to a group, the summed relative abundance of each of the groups can be calculated. These relative abundances can then be used as input to calculate a biotic coefficient (BC), according to model proposed by Borja et al. (2000). These BCs give an objective number to estimate the state of the environment. Such biotic coefficients are not developed yet for benthic foraminifera.

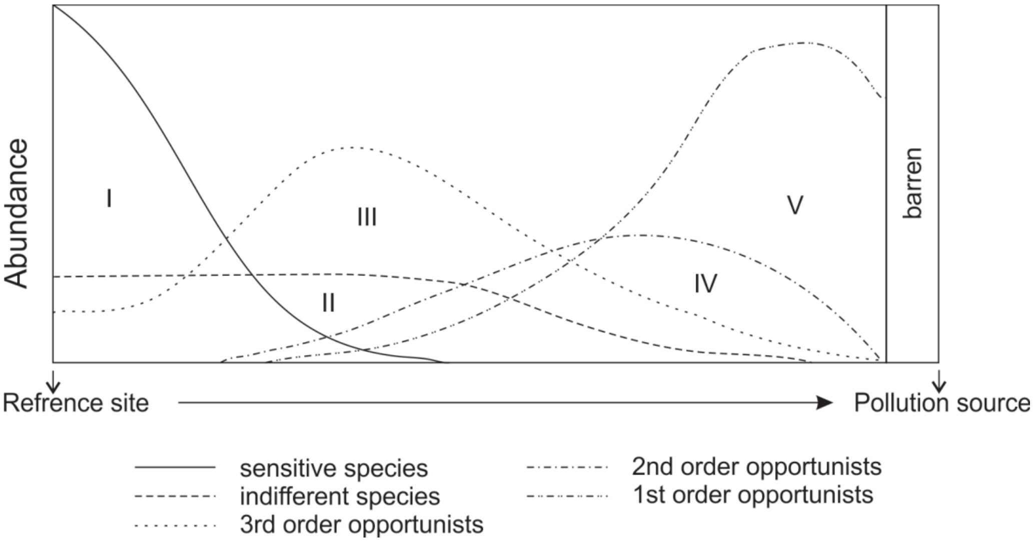

Figure 2. Theoretical model. *Schematic scheme showing the theoretical distribution of five ecological groups (y-axis) along a transect of increasing disturbance or pollution (x-axis). Modified after the model by Hily (1984) with adaptations by J. Schönfeld (personal communication, 2012).*

From the results presented in this thesis, it is not possible to study stepwise changes in the benthic foraminiferal assemblage along a pollution gradient yet, due to the relative pristine conditions of the Ingøydjupet trough with no local contaminant source (paper II-III) and the absence of non-impacted reference sites in the highly contaminated Hammerfest Harbor.

However clear habitat preferences and distinct feeding strategies of the defined associations from the SW Barents Sea were documented (paper II), which possibly might be a first step to define indicator species for the region. The toxicity of a pollutant is highly depended on its bioavailability, i.e. if organisms are able to take up the pollutant. Mesothropic conditions can increase bioavailability of contaminants. This explains why infaunal taxa, as those dominating in the Ingøydjupet trough, are most likely to encounter bio-available contaminants in mesothropic to eutrophic environments (Martínez-Colón et al., 2009). Additionally, indication was found that the Ingøydjupet trough might serve as a trap for contaminants (paper II-III). This makes the epifaunal species of Ingøydjupet, potential early indicators of changes in the environmental quality.

Future work should include transects away from production or exploration wells in Ingøydjupet to identify possible impacts of drill cutting discharges or produced water and their associated contaminants on indicator species. However contaminant levels along these transects are most likely low due to strong regulations from the Norwegian Government. Alternatively a laboratory study with similar physical conditions and assemblages as the investigated areas could contribute to identification and definition of indicator species. It is however important that such experiments are performed under similar physical conditions as these parameters have influence on the bio-availability of toxins (Martínez-Colón et al., 2009). Furthermore, definition of indicator species using results from other locations is also possible. However, it must be taken into account that applicability to our investigated areas might only be possible when similar physical environment apply. Finally, focus in future studies should not only be on the dominating species, as in the papers included in this thesis, but also on the rare, less abundant species. These are known to contribute most to the diversity of the benthic foraminiferal community (Murray, 2013). As diversity often decreases in impacted areas (Schafer, 1973; Yanko et al., 1994), rare species are crucial to detect changes in the quality of the marine ecosystems (Cao et al., 1998).

8.2 Biotic indices

Besides identification of indicator species, definition of biotic indices is an important step in the development of a bio-monitoring tool for the polar region. Diversity is often used as input for bio-indices enabling a quantitative definition of the environmental quality. It might however also be relevant to include BCs into such indices.

Currently environmental quality is mainly described with the use of biotic indices based on macrofauna, e.g. AMBI and M-AMBI (Borja and Tunberg, 2011; Muxika et al., 2007). Benthic foraminifera might be suitable for such a biotic index as well. Bouchet et al. (2012) were the first to define a quantitative classification based on benthic foraminifera. This EcoQS index is based upon the diversity of the samples from the investigated region. Diversity was expressed as the bias corrected Shannon-Wiener Index (Chao and Shen, 2003), ranging from 0, corresponding to an azoic sample, to the highest expected diversity of the investigated region (Bouchet et al., 2012). The range in diversity was then equally divided into five EcoQS classes. These classes correspond to those of the WFD classification, i.e. unacceptable statuses, bad and poor, and acceptable statuses, moderate, good and high (WFD, 2000). Correlation between the defined diversity classes to the WFD classes of oxygen conditions gave a strong linear response, indicating that the EcoQS classes based on foraminiferal diversity accurately reflect the state of the environment (Bouchet et al., 2012). It must however be noted that reference conditions are often type and site specific (WFD, 2000). It might therefore be more appropriate to develop site-specific boundaries between EcoQS classes for application to other regions.

Adjustment of the criteria established by Bouchet et al. (2012) might be necessary before they are applied in this study’s investigated areas, due to the specific physical environment and unique assemblage structures. Not only a biotic index based on diversity of the samples might be of importance for the region, additionally, a biotic index using the indicator species defined along the steps explained in chapter 8.1 might be relevant for the region.

Future studies, might also include a joint comparison of differences between the performances of both macrofauna and benthic foraminifera as indicators of environmental changes caused by both natural and anthropogenic processes. This can be based upon assemblage characteristics, indicator species or biotic indices. A study by Włodarska-Kowalczuk et al. (2013) is the only published study comparing macrofauna and benthic foraminiferal assemblages in high latitudes. Such comparison would be a natural extension of the present PhD thesis work in the investigated areas.

8.3 Reference conditions

The assessment of environmental quality is based upon the extent of deviation from reference conditions (WFD, 2000). These reference conditions are often defined by comparison of impacted sites to non-impacted environments (e.g. Bigot et al., 2008; Borja et al., 2012; Borja and Tunberg, 2011; Bouchet and Sauriau, 2008; Muxika et al., 2007). Definition of true reference conditions in present-day ecosystems is often difficult as these conditions are site-specific and are rarely found due to high rates of degradation of ecosystems as a result of long term input of contaminants to the environment (Alve et al., 2009). The preservation of foraminiferal tests in the fossil record enables both the objective reconstruction of historical environmental disturbances and the reconstruction of *in situ* reference or pre-impact conditions, provided that possible impacts of taphonomic processes are considered (Alve et al., 2009). Comparison of the pre-impacted baseline assemblages in sediment cores to the modern living foraminiferal assemblage at the same location, enables the determination of the impact of anthropogenic stressors (Alve et al., 2009). This recognition of anthropogenic disturbances might however be obscured by background natural variability (Elliott and Quintino, 2007). Therefore, long term data on natural variability is necessary to distinguish if a low diversity is due to a natural stressed environment or due to anthropogenic stress. The results presented in this thesis, reconstructed the pre-impacted baselines and natural variability of the investigated areas (paper II-IV). The SW Barents Sea is still considered to be a pristine area (paper II and III). With the prospects of increased industrial activities and possible enhanced input of associated contaminants to the environment, the area is a valuable natural laboratory to monitor and assess the impact of these activities on the environment, by comparison to the baselines defined through this PhD thesis.

It was not possible to study reference sites or define pre-impacted baselines in Hammerfest Harbor. Future studies in the harbor embayment could include investigation of sediment cores from the deepest part of the embayment. This could reveal the pollution history of the embayment, and might enable the reconstruction of reference conditions. Current measures to diminish the contaminant levels in the harbor could benefit largely from definitions of references conditions. These reference conditions help determine if a poor environmental quality is solely attributable to high contaminant levels, or if natural stressors, as for example fresh water inflow or oxygen depletion, are also critical stress factors the harbor. Hammerfest harbor is one of the many high latitude harbors affected by pollution. Investigations of benthic foraminifera in other high latitude harbor environments might therefore be of interest in the future, to either investigate the impact of these high pollution levels on the environmental quality, or to monitor restoration of environmental quality after capping and remediation of the impacted areas.

To summarize, this thesis provided baselines of pre-impacted conditions of an area under increased industrial development (Paper II), insight into the natural variability of this system (Paper III and IV), and knowledge on the behavior of benthic foraminifera under high environmental stress (Paper I) in a high latitude environment. Results presented in this work can serve as a valuable input for a bio-monitoring tool applicable in these regions. Additionally it can serve as a baseline for future comparison to monitor changes in the environmental quality of the marine ecosystem. Furthermore, standardization of the methodology of living benthic foraminiferal studies for bio-monitoring purposes (paper V) has contributed to the scientific rigor of benthic foraminifera as an accurate and reliable bio-monitoring tool.

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Paper I

The impact of contaminants and grain size on benthic foraminiferal assemblages in the harbor of Hammerfest, northern Norway

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Paper II

Baseline benthic foraminiferal assemblages and habitat conditions in a sub-Arctic region of increasing petroleum development

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Baseline benthic foraminiferal assemblages and habitat conditions in a sub-Arctic region of increasing petroleum development

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Abstract

The aim of this study is to establish pre-impact baseline conditions for an Arctic region where petroleum activities are projected to increase in the coming decades. We characterize the spatial distribution of living benthic foraminifera in the Tromsøflaket-Ingøydjupet region of the Barents Sea and relate this to sediment properties and their associated metal concentrations. Metal concentrations of the sediments did not exceed threshold levels of harmful environmental effects, indicating that the area exhibits pre-impact baseline conditions. Foraminiferal assemblages reflect the pristine environment. Epifaunal species dominate in Tromsøflaket, a high energy environment characterized by coarse grained sediments. Infaunal species dominate in Ingøydjupet, a low energy environment characterized by fine grained sediments. Metal concentrations were slightly elevated in the fine grained sediments from Ingøydjupet which suggest that these areas may in the future serve as trapping zones for contaminants associated with discharges from nearby petroleum sites.

1. Introduction

The southwestern (SW) Barents Sea contains significant oil and gas resources. Exploration activities were initiated in this region during the 1980s (NPD, 2012). Gas production started at the Snøhvit Field in 2007 while oil production will begin at the Goliat Field in 2014 (Fig. 1b). Petroleum production in the region is projected to expand significantly in the coming years, increasing the potential for releases of industrial waste into the marine environment. Chemical releases associated with petroleum production, resource shipments and accidents may include a variety of metals, petroleum hydrocarbons, and other organic compounds. With these prospects for the coming years, the region is a valuable natural laboratory to monitor and assess the impact of increasing industrial activities on the environment.

The model of macro-benthic community response to chemical discharges (Pearson and Rosenberg, 1976) is today the standard methodology used to demonstrate the impact of petroleum industry related activities on the Norwegian continental shelf. However, benthic foraminifera are also sensitive indicators of environmental conditions. In pristine environments the foraminiferal distribution is mainly affected by abiotic parameters, including temperature, salinity, nutrient availability, bottom substrate and dissolved oxygen (Murray, 2006). Changes have been documented in environments exposed to stressors including low foraminiferal density and diversity (Schafer, 1973; Yanko et al., 1994), high numbers of opportunistic species (e.g. Ellison et al., 1986; Murray, 2006; Pearson and Rosenberg, 1976), alterations of test chemistry (Nigam et al., 2006) and deformation of the test (e.g. Geslin et al., 1998; Yanko et al., 1998).

Environmental monitoring studies using benthic foraminiferal assemblages have several advantages. Benthic foraminifera are widely distributed and have specific environmental preferences (Boltovskoy et al., 1991; Murray, 2006; Schafer, 2000; Scott et al., 2001). They are often present in high numbers in marine sediments, therefore allowing for small sediment samples to be used in order to achieve statistically reliable assessments (Murray, 2006). Foraminiferal reproductive cycles are short, and therefore their response to environmental change is fast (Kramer and Botterweg, 1991). Finally, benthic foraminiferal tests remain in the fossil record, enabling the reconstruction of past environments and therefore pre-impact conditions (Alve, 1991a, b; Dolven et al., 2013). Recently, a list of recommendations to standardize the methodology in bio-monitoring studies using benthic foraminifera was formulated (Schönfeld et al., 2012).

The use of fauna as a monitoring tool is often complicated due to natural variability in both the ecosystem and the physical environment. As a result, site specific impact studies are needed in a variety of habitat types in order to develop an accurate bio-monitoring tool using benthic foraminifera. Such studies link responses of foraminiferal assemblages to observed environmental conditions.

With few studies performed in high latitude areas, the aim of the present investigation is to establish a pre-impact reference point for a relatively pristine area where industrial activities are projected to increase over time. This baseline study establishes a data set of the spatial distribution of living benthic foraminifera in the Ingøydjupet-Tromsøflaket region of the SW Barents Sea (Fig. 1). Previous studies in this region on modern distributions of benthic foraminifera focused mainly on the relationship between foraminiferal assemblages, oceanography, grain size and climate change (Hald and Steinsund, 1992; Saher et al., 2009; Saher et al., 2012; Steinsund, 1994).

The living benthic foraminiferal assemblage in the Ingøydjupet-Tromsøflaket region, SW Barents Sea (Fig.1) was investigated together with sediment properties, i.e. grain size, organic matter content and concentrations of a selection of metals. Relationships between sediment properties and assemblage distributions were determined using principal component analysis and a multiple regression linear model. The study supports the development of a bio-monitoring tool using foraminifera.

2. Regional setting

The southwestern part of the Barents Sea (Fig. 1) is characterized by bank areas incised by transverse glacial troughs. Our study area comprises two banks: Tromsøflaket in the west and Nordkappbanken to the east (Fig. 1b). Water depths range between 150 and 200 m on the Tromsøflaket bank area. Tromsøflaket is bounded by slopes towards three glacial troughs: Ingøydjupet (>400 m) in the east; Bjørnøyrenna (>400 m) to the north and Sørøysundet (280-300 m) to the south. In the west, Tromsøflaket is bounded by the steep Egga shelf edge (Fig. 1b).

The sedimentary characteristics of the open marine environment have previously been investigated in this region. Studies included grain-size distributions (Vogt and Knies, 2008), total organic carbon (TOC) concentrations (Knies and Martinez, 2009), metals and polycyclic aromatic hydrocarbons (PAHs) (Bakke et al., 2001; Boitsov et al., 2009a, b; Boitsov et al., 2011; Dahle et al., 2009; Jensen et al., 2009; Mannvik and Wasbotten, 2008; Mannvik et al., 2011; Nøland et al., 1999; Trannum et al., 2004).

In the Barents Sea, water masses are comprised of Arctic, Atlantic, Coastal and local waters (Carmack, 1990; Hopkins, 1991; Loeng, 1991; Mosby, 1968; Treshnikov, 1985). In the study area, Atlantic and Coastal water are the dominating water masses (Fig. 1a). Atlantic water is transported northwards by the Norwegian Atlantic Current (NAC). Temperatures are in general >2 ° C, but can vary seasonally by about 2 ° C; salinity of the NAC is around 35 psu (Hopkins, 1991; Ådlandsvik and Loeng, 1991). The NAC turns eastward into the Barents Sea at the northern tip of Tromsøflaket (Ingvaldsen et al., 2004). The Norwegian Coastal Current (NCC; 3 to 13 ° C) is a surface current following the Norwegian coast from the south into the Barents Sea and is relatively fresh (30 to 35 psu) due to the local input by river runoff (Aure and Strand, 2001; Sætre and Ljøen, 1971).

A model by Vikebø and Ådlandsvik (2005) implies that the NCC dominates the southern part of Tromsøflaket, while the NAC dominates the rest of the bank. Based on sediment patterns in iceberg plough marks, Bellec et al. (2008) reconstructed a similar pattern with Atlantic water entering Tromsøflaket both from the northwest across the slope, and from Bjørnøyrenna in the north. In Ingøydjupet, a stratified water column with Atlantic Water at the bottom and Coastal Water in the upper 30-50 meters of the water column was observed (Chistyakova et al., 2010; Ingvaldsen et al., 2004; Loeng, 1991).

3. Material and methods

3.1 Sampling procedures

Sediment samples were collected (2006-2011) and analyzed (2010-2011), before establishment (2011) and publication (2012) of the FOBIMO-protocol (Schönfeld et al., 2012). The here used sampling and analysis techniques might therefore deviate from the recommendations made in the FOBIMO-protocol.

In total 37 surface samples, covering the top centimeter (0-1 cm) of the sediment surface, were collected during four different sampling campaigns in June 2006, April 2007, June 2010, and July 2011 (Fig. 1b; Table 1). Surface samples from 2006 and 2007 were provided by the Mareano project (www.mareano.no), hereafter referred to as the 'Mareano-set', and cover Tromsøflaket and the slopes towards Ingøydjupet. Surface samples from 2010, provided by Statoil AS and hereafter referred to as the 'Statoil-set', were taken in the proximity of the producing Snøhvit Field, the Goliat Field and other exploration wells. Samples from 2011 were collected on board of *R/V Helmer Hanssen* of the University of Tromsø (UiT) in the deepest parts of Ingøydjupet, and are hereafter referred to as the 'UiT-set'. At some of the sample localities, physical oceanographic properties were measured with a CTD (Seabird SBE 9111 plus), providing information on temperature (T) and salinity (S) throughout the water column (Table 1).

Sediment samples were retrieved with a multi corer, box corer, van Veen grab or a combi grab, depending on substrate type and sampling campaign (Table 1). After retrieval the surface of the samples were carefully studied for disturbances (Andreassen, 2011; Jensen et al., 2007, 2008; Mannvik et al., 2011). Especially grab corers are known to easily disturb the sediment surface, which might results in the loss of some specimens (Riddle, 1989; Wigley, 1967). Only undisturbed surfaces were used for further analyses. Sub samples were taken for analyses of metal concentrations, total organic carbon (TOC), grain size, clay mineral analyses and foraminiferal assemblages. None of the sampling expeditions included the collection of replicate samples. Analyses of the sample sets were performed at the University of Tromsø, Iceland GeoSurvey, Norwegian Geological Survey and UniLab AS (Table 1).

All samples of the Mareano-set were kept frozen (-18 ° C) until further analyses, apart from those intended for foraminiferal analyses which were stored cool (4 ° C). All of the Statoil samples were frozen (-20 ° C) directly after retrieval. All sediment samples from the UiT-set were stored cool (4 ° C).

3.2 Grain size parameters and total organic carbon

Sediments were wet sieved at size fractions 63 µm, 100 µm and 1 mm. Silt and clay fractions (<63 µm) were analyzed on the Micrometics SediGraph 5100 according to the technique described by Coakley and Syvitski (1991). Weight percentages of sand (>63 µm), silt (4-63 µm) and clay (<4 µm) fractions were calculated from the resulting grain size distributions.

Sortable silt mean grain-size (SS) was calculated from the sedigraph analyses using the 10-63µm fraction (Bianchi and McCave, 1999; Hass, 2002; McCave et al., 1995). Whereas in paleo-records the mean current velocity can be calculated from SS, this is not possible for modern sediments (McCave et al., 1995). Hence we are concentrating only on patterns seen in SS, and interpret these as changes in strength of the bottom current.

X-ray diffraction (XRD) was applied to the < 2 µm fraction to differentiate between the different clay minerals: kaolinite, chlorite, illite and smectite. Mareano samples were analyzed at the Geological Survey of Norway (NGU) according to the procedures described by Jensen et al. (2007) and Vogt and Knies (2008); Statoil and UiT were analyzed at the Iceland GeoSurvey (ISOR) are according to the method of Moore and Reynolds (1997) as described by Rüther et al. (2012). MacDiff software version 4.2.5 (Petschick, 2010) was used to process the XRD measurements and quantify the four different clay minerals. Since smectite might be an indicator of inflow of Atlantic waters (Junttila et al., 2010; Vogt and Knies, 2008), only smectite was considered in the studies.

The TOC concentrations of the samples of the Mareano and UiT-set were analyzed using a Leco CS-200 induction furnace. Inorganic matter was removed from the bulk sediment with HCl (10%) prior to measurement. During measurement, samples are placed in an oven (1350 ° C), burning all components except organic carbon. For the Statoil-set, instead of TOC, total organic matter (TOM) concentrations were measured according to the method described by Mannvik et al. (2011). Due to lower heating temperatures during the analyses of TOM (480 ° C), this method quantifies sediment organic carbon, organic matter, oxygen, nitrogen and sulfur concentrations.

3.3 Chemical analyses

The sediment samples for chemical analyses were dried at 40 °C, homogenized and sieved at a <2mm mesh before decomposing with nitric acid (HNO_3). Barium (Ba), cadmium (Cd), copper (Cu), chromium (Cr), zinc (Zn) and lead (Pb) concentrations were analyzed with inductively coupled plasma atomic emission spectroscopy (ICP-AES) or inductively coupled plasma sector field spectroscopy (ICP-SFMS), depending on the concentrations of the metals, following the procedures of Norwegian Standard (NS) 4770. Concentrations of mercury (Hg) were analyzed with atom fluorescence (AFS) following the procedures of NS 4768. Chemical analyses of the samples of the Mareano-set were prepared according to the methods described in Jensen et al. (2007, 2008); preparation of the Statoil-set and UiT-set were according to the methods described in Mannvik et al. (2011).

3.4 Foraminiferal assemblages

A rose Bengal ethanol mixture (1g/1L ethanol 95%) was added to the sediment samples intended for foraminiferal analyses to stain the cytoplasm and distinguish between living (stained) and dead fauna (Walton, 1952). Samples of the Mareano and UiT-set were stained directly after retrieval. Samples of the Statoil set, frozen directly after retrieval, were stained during the thawing process before analyses. Samples were gently shaken to enable staining of living foraminifera within sediment clumps. Staining of the samples was allowed for a minimum of two weeks (Lutze and Altenbach, 1991).

In polar regions benthic foraminifera have mainly be analyzed using the > 100 µm size fraction due to the generally small size of the foraminifera from these environments (Knudsen and Austin, 1996). Hence, living benthic foraminiferal assemblages were studied in the 100 µm to 1 mm size fraction. This additionally allows a direct comparison to previous studies of living foraminifera from the Barents Sea (e.g. Hald and Steinsund, 1992, 1996; Saher et al., 2009; Saher et al., 2012; Steinsund, 1994). Both calcareous and agglutinated species were considered. The samples were split using a modified Elmgren wet splitter (Elmgren, 1973). The samples were examined wet to better distinguish between stained and non-stained specimens. The coloration of rose Bengal stained living specimens differs among species. However, in general only specimens with a bright stain inside more than half of the chambers were considered to be living at the time of sampling (de Stigter et al., 1998; 1999). For agglutinated foraminifera, the presence of stain in the aperture was an additional requirement to be considered as living. A minimum of 300 specimens from a known split of the sediment was identified to precisely determine the relative abundance of species of the assemblage (Patterson and Fishbein, 1989). When less than 300 living specimens were present in the sample, the whole sample volume was counted. The living foraminifera were identified down to species level following Loeblich and Tappan (1987) and Ellis and Messina (1940–1978), except for the *Reophax* and *Trochammina* species. Those were grouped as *Reophax* spp. and *Trochammina* spp.

Absolute abundance of species was normalized to a sample volume of 50 ml (specimens/50 ml of sediment). The taxonomic diversity of the foraminiferal assemblages was investigated using the Shannon index (H'; Shannon, 1948), and was calculated with the PAST software (version 2.17c; Hammer et al., 2001) using the absolute abundances of all observed species, with grouping of the *Reophax* and *Trochammina* species.

3.5 Data analysis

Similarity between the stations based on the measured abiotic variables was determined with Q-mode hierarchical clustering, using Ward's method and Euclidean distance (Ward, 1963). Additionally, a principal component analysis (PCA) was performed on the abiotic variables to find the main modes of variation (Davis, 2002; Harper, 1999).

Depth, SS, fine fraction (<63 µm), smectite and the concentrations of Pb, Ba, Hg, Cd, Cr, Cu and Zn were included. Sand, silt and clay are expressed as percentages. To avoid bias in the statistical analyses by variables influencing each other, silt and clay were summed to reflect the fine fraction (<63 µm), while the coarse fraction represented by sand (>63 µm) was left out of the analyses. The assumption was made that a positive correlation to the fine fraction implies a negative correlation to the coarse fraction and vice versa. Ti, TOM and TOC were also removed from the calculations, since they were not measured in every station and might bias the results. R68-3a and R68-3b were left out of the clustering and PCA due to a lack of metal concentrations data (Table 1).

Abiotic variables were standardized before analyses to remove the effect of different orders of magnitudes by subtracting the mean (μ) of the variable from the analyzed value (X) and dividing by the standard deviation (σ): i.e. standardized value = (X-μ)/σ.

To identify different associations within the living foraminiferal assemblage, foraminiferal species were grouped with R-mode hierarchical clustering, using Ward's method and Euclidean distance (Ward, 1963). Absolute abundance, standardized to 50 ml of sediment was used as input for R-mode clustering. Only species that had a relative abundance of >5 % in at least one sample were considered (Fishbein and Patterson, 1993).

Relations between abiotic variables and benthic foraminifera were found by multiple regression linear modeling using a stepwise regression with bidirectional elimination, using the Akaike information criterion (AIC). The same abiotic variables and foraminiferal species as for the Q-mode and R-mode clustering were used as input for the linear model. The linear model defines which of these abiotic variables are necessary to explain, in the best possible way, the variability observed in the benthic foraminiferal assemblages. The model was run for both the summed abundances of the species of the associations found by the R-mode clustering and for each of the species separately. To test the significance and performance of the model the two way probability (p) and multiple regression coefficient (mR^2) was calculated. A correlation is considered to be of intermediate to high significance when $p<0.01$ (see Table 2 for a more detailed classification).

Q- and R-mode hierarchical clustering and principal component analysis (PCA) were performed using the statistical program PAST (version 2.17c; Hammer et al., 2001). Stepwise regression was performed using the statistical program R (version 2.14.2; RDCTeam, 2012).

4. Results

4.1 Grain size parameters and total organic carbon

Generally, the silt and clay content increases at water depths deeper than ~317m, with coarser grain sizes observed at Tromsøflaket (sand to sandy silt; average sand content: 58 %) and finer sediments (clayey silt to silt; average sand content: 12%) prevailing in Ingøydjupet (Fig. 2a and b). Particles >1 mm consist mainly of gravel, shell (fragments) and sponge spicules. Sediment samples from Tromsøflaket are rich in sponge spicules. Some >1 mm fractions of the sediment samples contained larger dead foraminifera, mainly *Ammolagena clavata*, *Lobatula lobatula*, *Paromalina coronata* and *Psammosphaera fusca*. Some of these foraminifera were found attached to the substrate; however none of the foraminifera were stained and are therefore not considered in this study.

The organic content of the samples is reflected by TOC (Mareano-set and UiT-set) and TOM (Statoil-set) (Fig. 2b). Since TOM reflects organic carbon content as well as the oxygen, nitrogen and sulfur concentrations, TOM concentrations are consequently higher than TOC concentrations. TOC varies between 0.24 % and 0.98%; TOM varies between 1.90 and 7.60%. However, both parameters indicated a similar pattern. In general, TOC and TOM concentrations are slightly higher in the finer grained sediments deposited in the deeper areas compared to coarser grained sediments deposited in shallower areas (Fig. 2b).

Clay mineral assemblages (smectite, illite, kaolinite and chlorite) were analyzed. Only smectite is considered here as a tracer of Atlantic water inflow (Junttila et al., 2010; Vogt and Knies, 2008). Smectite concentrations fluctuate between 0 and 18 %, with an average abundance of 5.8 % (Fig. 2c). Smectite concentrations are highest in the samples from Ingøydjupet.

Sortable silt mean grain size (SS) fluctuates between ~19 µm and ~30 µm (average value ≈ 23 µm). This indicator of bottom current strength (Bianchi and McCave, 1999; Hass, 2002; McCave et al., 1995), has comparable average values in both Tromsøflaket and Ingøydjupet. Values are slightly enhanced in the samples from Nordkappbanken and are particularly low in the samples taken around the Snøhvit Field (Fig. 2c).

4.2 Metal concentrations

Concentrations of the analyzed metals are presented in Fig. 3 (values are tabulated in Appendix A).

In general, Cr (average concentrations ≈ 27 mg/kg), Cu (average ≈ 10 mg/kg), Pb (average ≈ 14 mg/kg), Ti (average ≈ 562 mg/kg) and Zn (average ≈ 43 mg/kg) show elevated concentrations toward the deeper water depths of Ingøydjupet, which coincides with the higher silt and clay contents of the sediments from this region. Ba (average ≈ 105 mg/kg) and to less extent Pb, have elevated concentrations around the Snøhvit Field. Cd (average ≈ 0.10 mg/kg) has no clear spatial trend and has two peaks of elevated concentrations at station R81 and R87 on Tromsøflaket. Also Hg (average ≈ 0.05 mg/kg) has no clear spatial pattern, but has elevated concentrations in stations HH150, HH154 and NVA-05.

Almost all metal concentrations measured in the surface sediments correspond to background levels (level I) according to the guidelines of the Water Framework Directive (WFD; EuropeanCommission, 2003). Only the Cd concentration of station R87 and Hg concentrations of stations HH150, HH154 and NVA-05 correspond to a good environmental status; WFD level II. Metal concentrations were never at harmful environmental levels, i.e., WFD level III to V.

4.3 Benthic foraminiferal assemblages

A total of 134 living benthic foraminiferal species, 103 calcareous and 31 agglutinated, were identified in the samples. Only 19 species of these have a relative abundance of >5 % in at least one sample and together describe between 73 and 96 % of the total living assemblage. Diversity (H') varies between 1.9 (sample HH150) and 3.0 (sample R22) of the Shannon Index (Fig. 4). Although a spatial trend for H' is not pronounced, diversity seems to be slightly lower in the samples from Ingøydjupet. H' was calculated using the grouped abundance of *Trochammina* and *Reophax* species. Therefore, the true H', i.e. when the different *Trochammina* and *Reophax* species would have been counted separately, would have been slightly higher. However, the spatial pattern of H' is expected to be similar.

The number of living specimens varies from 84 (station SF-11) to 6874 specimens (station R81) per 50 ml of sediment (Fig. 4). Despite the low foraminiferal abundance of station reg09-04 and R17 located on Tromsøflaket, foraminiferal abundance is in general decreased in the samples from the Snøhvit field and the deeper areas of Ingøydjupet (R5, R4, R3). Sediment samples collected at the Snøhvit Field have a relatively low foraminiferal abundance.

The relative and absolute abundance of the most frequent taxa is plotted in Fig. 5. The assemblage of living foraminifera is dominated mainly by *Reophax* spp., *Lobatula lobatula*, *Trifarina angulosa* and *Epistominella nipponica*. In addition, *Trochammina* spp., *Cassidulina laevigata*, *Nonionella auricula*, *Cassidulina reniforme* and *Melonis barleeanus* are commonly observed.

In general, patterns of these species show that *L. lobatula*, *T. angulosa, C. reniforme* and *C. laevigata* are more common in the Tromsøflaket samples (Fig. 5a-d). *C. reniforme* was only observed in the samples from Tromsøflaket, and is absent in the samples from Ingøydjupet and Nordkappbanken (Fig. 5d). *M. barleeanus, N. auricula* and *Trochammina* spp., are more frequently observed in Ingøydjupet (Fig. 5e-g). *Reophax* spp. does not show a clear spatial trend (Fig. 5h), whereas the relative abundance of *E. nipponica* is remarkably higher in the stations from the Snøhvit Field (Fig. 5i). The high relative abundance of *E. nipponica* in the Snøhvit samples is not visible in the absolute abundance of the species. In fact, the absolute abundance of *E. nipponica*, and other species, is lower in the Snøhvit samples in comparison to the other stations.

4.4 Habitat characteristics – Q-mode clustering and PCA

Q-mode clustering delineates two sedimentary groups based on water depth, fine sediment fraction (<63 µm), SS, smectite content and metal concentrations (Fig. 6a). In general, samples from the shallower Tromsøflaket were grouped in cluster I (average water depth = 268 m), hereafter referred to as the TF-cluster (filled symbols in Fig. 1). Cluster II mainly comprises samples from the deeper Ingøydjupet (average water depth = 388 m), hereafter referred to as the ID-cluster (open symbols in Fig. 1). Exceptions are stations R7 from Ingøydjupet grouped in the TF-cluster and R87 from Tromsøflaket grouped in the ID-cluster.

Similar clusters of samples were found by the PCA (Fig. 6b). The first component of the PCA, PCA1, explains 43.9% of the variance; the second component, PCA 2, explains 14.8% of the variance. PCA1 is positively correlated to Cu, Cr, Zn, Pb, Ba and the fine (<63 µm) sediment fraction, and negatively correlated to SS. PCA2 positively correlates to depth, smectite, Zn and SS, and negatively correlates to Cd, Pb and Ba.

Samples of the TF-cluster have negative values on the PCA1-axis, and plot thus in opposite direction as the metals and fine fraction, suggesting that samples of the TF-cluster negatively relate to these abiotic variables (Fig. 6b). SS plots in similar directions as samples from the TF-clusters, implying a positive relationship between these samples and SS.

Most of the samples of the ID-cluster show a positive relationship to PCA1 and concomitantly a strong positive response to fine (<63 µm) sediments as well as many of the metal concentrations (Fig. 6b).

4.5 Foraminiferal associations – R-mode clustering

R-mode clustering grouped the most abundant living benthic foraminiferal into three sub-assemblages or associations (Fig. 7a). The first association, the *Lobatula-Trifarina* association (LT-association; Fig. 7a) is dominated by *L. lobatula* and *T. angulosa*. In addition, *C. laevigata* and *C. reniforme* are important attribute species in this association. In general, the abundance of species from the LT-association decreases towards Ingøydjupet (Fig. 5 a-d). Also the summed abundances of the species of the LT-association are highest on Tromsøflaket and decreases towards Ingøydjupet (Fig. 7b).

The second association, the *Reophax* association (R-association; Fig. 7a), is dominated by *Reophax* spp. In addition, *Trochammina* spp. and *E. nipponica* are part of this association.

There is no unilateral regional pattern observed for the three species of the R-association (Fig. 5 g-i); the summed abundance possibly shows a small increase towards Ingøydjupet (Fig. 7b).
The third association, the *Melonis-Nonionella* association (MN-association; Fig. 7a) consists of the frequently abundant *M. barleeanus*, *N. auricula* and *Pullenia bulloides*. In addition, the less abundant *Fissurina marginata, Elphidium excavatum, Cribroelphidium incertum, Miliolinella* sp., *Islandiella norcrossi, Quinqueloculina seminulum, Elphidium* sp., *Islandiella helenae* and *Rosalina* sp. are grouped in this association. The overall pattern observed for the dominant species of the MN-association (Fig. 5e-f) is an increase from Tromsøflaket towards Ingøydjupet. This increase is less pronounced for the summed abundance of the MN-association (Fig. 7b), most likely due to the less frequent species which have no clear spatial pattern.

4.6 Foraminifera - habitat relationships - multiple regression linear modeling

Multiple regression linear models were fitted to find relationships between abiotic variables and the benthic foraminiferal species and associations (Table 2 and Appendix B).
The best fitting model for the LT-association found a negative response of the species of the group to fine fraction (p= 0.16) and Ba (p=0.08), while a positive response to Cd (p=0.02) and Zn (p=0.004) was found. In addition, a strong negative response to Cr (p=0.005) is observed. The mR^2 of the linear model for the LT-association is 0.42. In general, similar relations were observed when the linear model was run for the species of the LT-association separately. Exceptions are *T. angulosa*, which positively relates to SS (p=0.06) and *C. laevigata* which negatively relates to Cu (p=0.0007).
The chosen model for the R-association calculated negative responses to water depth (p=0.23), fine fraction (p=0.07), smectite (p=0.19), Pb (p=0.004) and Hg (p=0.06). The R-association positively correlates to SS (p=0.08), Cd (p=0.0002), Cr (p=0.11) and Zn (p=0.04). The mR^2 of the model for the R-association is 0.56. The low mR^2 value (0.06) of *Trochammina* spp. indicates that the abiotic variables used as input to the model, do not explain the distribution of this species group.
The best fit linear model for the MN-association found a positive response of the species to SS (p=0.18), Cd (p=0.0001) and Zn (p=0.04) and negative responses to the fine fraction (p=0.01), Ba (p=0.12) and Hg (p=0.16). The mR^2 of the linear model for the MN-association is 0.53. Some deviations to the linear model of the MN-association were found when the model was run for the individual species. The most pronounced differences are: the negative response of *F. marginata* (p=0.006) and *E. excavatum* (p=5.87e-05) to Pb; the strong positive

response of *Miliolinella sp.* (p=0.0009) and strong negative response of *M. barleeanus* (p=0.0001) and *P. bulloides* (p=0.004) to Cu and; the negative response of *Miliolinella sp.* (p=8.78e-05) and *Q. seminulum* (p=0.01097) to Zn. *Rosalina sp.* was the only species for which no significant relation was found to any of the explanatory variables included in the model.

5. Discussion

The projected increase in petroleum industry related activities in the SW Barents Sea might result in increased releases of contaminants into the marine environment. To assess the impact of these activities on the environment, site specific and accurate bio-monitoring tools are needed. The aim of the present investigation is to establish a baseline data set of the spatial distribution of living benthic foraminifera in the relatively pristine Ingøydjupet-Tromsøflaket region. The present day habitat of benthic foraminifera was characterized (grain size, organic matter content, metal concentrations) and the relationship between foraminiferal associations and habitat characteristics was identified.

5.1 Habitat characteristics and foraminiferal assemblages

In the Ingøydjupet-Tromsøflaket region, three foraminiferal associations were identified by R-mode clustering: the LT-association, the R-association and the MN-association (Fig. 7a). Q-mode clustering divided the sediment samples into two clusters based on their abiotic variables: the TF-cluster consisting of samples from Tromsøflaket and the ID-cluster consisting of samples from Ingøydjupet (Fig. 6). The response of these associations to abiotic variables was modeled using a multiple regression linear model.

The LT-association is dominated primarily by *L. lobatula* and *T. angulosa*, but also *C. laevigata* and *C. reniforme* are grouped in this association. The abundance of the LT-association is in general highest in samples clustered in the TF-cluster, characterized by coarse grain sizes (Fig. 7 and 2). The multiple regression linear model (Table 2; Appendix B) found a negative relation for fine grained (<63 μm) sediments and the LT-association. Consequently this implies a positive response of the LT-species to the coarse fraction (see explanation in 3.5: Data analysis). Previous studies documented similar preferences for coarse grained sediments for *C. laevigata, L. lobatula* and *T. angulosa* (Hald and Steinsund, 1992; Harloff and Mackensen, 1997; Mackensen et al., 1993; Mackensen and Hald, 1988; Mackensen et al., 1985; Nyholm, 1961). It must be noted however, that the negative response of species of the LT-association to fine grain sizes is not highly statistically significant ($p>0.01$). This might be a result of the occurrence of the LT-species in both the fine grained samples, i.e. samples from the ID-cluster, and coarser grained samples, i.e. samples from the TF-cluster (Fig. 5a-d). In finer grained habitats, *L. lobatula* occurs attached to, for example, polychaete tubes (Steinsund, 1994).

Both *L. lobatula* and *T. angulosa* tolerate high hydrodynamic activity (Hald and Steinsund, 1992). The linear model found a positive response between *T. angulosa* and the bottom current indicator SS. The high abundance of these current indicating species, together with the positive response of the TF-cluster to coarse grained sediments, implies high bottom current velocities at Tromsøflaket. The positive relation between SS and the TF-cluster found by the PCA (Fig. 6) also indicates enhanced bottom current velocities here. The relationship between mean grain size and current speed is well studied with higher bottom current velocities associated with erosion and transport of coarser grained particles (e.g.Gao and Collins, 1992; Hjulström, 1935; Li and Amos, 2001; Nichols, 1999; Yang, 2006). At Tromsøflaket, bottom current velocities are strong enough to erode and transport fine grained sediments away exhibiting a predominance of coarser grained sediments on the seafloor. Bellec et al. (2008) calculated bottom current velocities on Tromsøflaket based upon sediment maps inferred from backscatter data of video transects. Near-seafloor velocities fluctuated between 5 to 50 cm/s, with the highest current speeds at the shallowest parts of Tromsøflaket and in Sørøysundet (Bellec et al., 2008).

Thus, the foraminiferal species of the LT-association dominating at Tromsøflaket reflect the prevailing habitat conditions at Tromsøflaket, i.e., coarse grained sediments and high bottom current velocity.

The R-association, dominated by *Reophax* spp. and with *E. nipponica* and *Trochammina* spp. as important attribute species, shows in general a negative response to the fine fraction and on a lower significance level a positive response to SS (Table 2). *Trochammina* spp. poorly relates to any of the abiotic parameters included in the linear model and has a low mR^2 (0.06). This might indicate the indifference of the species to any of the explanatory variables included in the model or be an effect of the poor preservation potential of the fragile tests of the species (Hald and Steinsund, 1992).

There is no unilateral regional pattern observed for the three species of the R-association (Fig. 5g-i). Despite the weak positive relation found by the linear model for sand and SS, the summed abundance shows a small increase towards Ingøydjupet (Fig. 7b). This is mainly the effect of the increase of *Trochammina* spp. (Fig. 5g) towards Ingøydjupet; *Reophax* spp. (Fig. 5h) has no regional trend, *E. nipponica* (Fig. 5i) has maximum relative abundances around the Snøhvit Field. The increase of *Trochammina* spp. towards Ingøydjupet might be the effect of the calmer bottom water conditions in this area and relatively higher sedimentation rates (see discussion below), enabling the preservation of the species. *Reophax* spp. is known to thrive in both muddy and coarse environments (Murray, 2006), explaining the absence of a regional pattern.

The relative abundance of *E. nipponica* is highest around the Snøhvit Field. It must be noted however, that the absolute abundances of *E. nipponica* is low in these samples, as is the absolute abundance of the other living species (Fig. 5) and overall foraminiferal abundance (Fig. 4). In previous studies, highest abundances of *E. nipponica* were observed on the flanks of Ingøydjupet where few other foraminifera were present (Hald and Steinsund, 1992). This was attributed to reworking facilitated by the small size and round feature of the species (Murray et al., 1982; Scott and Medioli, 1980). The specimens of *E. nipponica* identified in this study were all clearly stained, and were therefore considered to be living during sampling. No clear signs of reworking, i.e., damaged tests, were observed. The presence of *E. nipponica*, while other species are absent, might also suggest an opportunistic behavior. Other *Epistominella* species, i.e. *Epistominella vitrea* and *Epistominella exigua,* and the morphologically identical deep water species *Alabaminella weddellensis* are interpreted as opportunistic species tolerant to high food availability (Jorissen et al., 1992), varying organic flux (Altenbach et al., 1999) and pulsed phytodetritus (Gooday et al., 1993; Gooday and Lambshead, 1989; Smart and Gooday, 1997; Sun et al., 2006) respectively. However, organic matter concentrations around the Snøhvit Field are not of values considered to limit foraminiferal distribution (Fig. 2). It is therefore suggested that the peak in relative abundance of *E. nipponica* is the effect of high sediment accumulation rates around the field. Hald and Steinsund (1992) observed the highest concentrations of *E. nipponica* when Holocene sediments were thickest. The increase of the fine fraction in the Snøhvit Field compared to Tromsøflaket, indicates calm bottom conditions. These calm conditions enable the settling of fine sediments and might result in high sediment inputs compared to the surrounding area. This enhanced sediment input might dilute the foraminiferal signal, explaining the low absolute abundances observed around the Snøhvit Field (Fig. 4). Similar low foraminiferal abundances and fine grain size were also observed in the deepest stations of Ingøydjupet, (R5, R4, R3), suggesting that similar calm conditions and high sedimentation rates might dilute the foraminiferal signal (Fig. 3 and 4).

To summarize, although the linear model indicates a slight preference of the R-association to coarser grained habitats with higher current speeds, there is no strong habitat-species relationship identified for this assemblage.

The third association, the MN-association is dominated by *M. barleeanus*, *N. auricula* and *P. bulloides*. In addition, nine less frequent species are clustered in this association (Fig. 7a). The main species of the MN-association are in general more abundant in the samples from the ID-cluster (Fig. 5e-f), characterized by fine grained sediments and relatively higher percentages of organic matter (Fig. 2). The linear model found a positive response of the MN-species to SS and a negative response of these species to the fine sediment fraction (<63 µm; Table 2). Especially for *M. barleeanus* and *P. bulloides*, this negative response to fine sediments is surprising, because both species are known to thrive in fine grained sediments (Hald and Steinsund, 1992; Mackensen et al., 1985). However, many of the species of the MN association can exist both as infaunal and epifaunal depending on food supply and grain size (Alve and Murray, 1999; Linke and Lutze, 1993; Matera and Lee, 1972). Most of these species are indeed observed in both the coarse sediments of Tromsøflaket and in the fine sediments of Ingøydjupet (Fig. 5). This might explain the negative response to fine grained sediments.

The relatively low mR^2 values calculated by the linear model for *M. barleeanus, P. bulloides* and *N. auricula* might be the result of the fact that organic matter was not included as an explanatory variable in the model. Organic matter is known to have a strong influence on the distribution of *M. barleeanus*, *P. bulloides* and *N. auricula*, which feed on buried decayed organic detritus (Fontanier et al., 2002; Korsun and Polyak, 1989; Steinsund, 1994).

The fine grained sediments of the ID-cluster and foraminiferal species preferring calm bottom conditions indicate low bottom current velocities in Ingøydjupet. Bellec et al (2008), indeed calculated lower bottom velocities for Ingøydjupet (<5 cm/s) compared to Tromsøflaket (5-50 cm/s).

Although not fully supported by the linear model, the foraminiferal species of the MN-association reflect the prevailing conditions at Ingøydjupet, i.e., fine grained sediments, calm bottom water conditions and relatively higher concentrations of organic matter.

The mR^2 of the linear models varied between 0.06 and 0.75 with an average mR^2 of 0.42 (Table 2, Appendix B). The often relatively low mR^2 of the linear models, might be the result of the high variability within the study area, the indifference of certain foraminiferal species to environmental parameters used as input variables and/or, the low metal concentrations (see discussion below). The low mR^2 values might also indicate the presence of explanatory variables that were not incorporated into the model. Besides grain size and metal concentrations, differences in bottom water conditions (T and S), competition between species and nutrient availability might influence the distribution of foraminifera within the study area. Bottom water conditions and organic matter content were not included in the linear model, since they were not measured consistently at every station. Despite the presence of two prevailing water masses in the studied area, NCC and NAC, CTD measurements taken during sampling do not show large variations in bottom T and S for the study area ($\Delta T= 1.81$ ° C; $\Delta S=0.01$ psu; Table 1). Bottom T and S are therefore not expected to have a direct influence on the distribution patterns of the three assemblages identified for this study area. Differences in concentrations of TOC and TOM, reflecting nutrient availability, are however expected to explain partly the difference of the foraminiferal distribution between the two regions (see discussion below).

Some considerations regarding the methodology of this study should be taken into account when interpreting the foraminiferal results and when comparing these to past and future studies to monitor environmental change. Foraminiferal assemblages in the 100 µm – 1 mm fraction were studied. Previous studies have shown a considerable loss in both diversity and foraminiferal abundance when larger fractions (> 125 µm or 150 µm) rather than smaller fractions (> 63 µm) were analyzed (Fontanier et al., 2006; Fontanier et al., 2008; Mojtahid et al., 2009). Analyses of the larger fractions only, may therefore result in underrepresentation or absence of small species and juveniles (Duchemin et al., 2007; Schröder et al., 1987). A recent study by Bouchet et al. (2012) concluded however that foraminiferal assemblages of both fine and coarse fractions adequately reflect important environmental parameters. The FOBIMO-group made it a therefore a mandatory recommendation to study the > 125 µm fraction (Schönfeld et al., 2012). However, in the polar regions foraminiferal tests do often not attain test diameters of over 125 µm (Knudsen and Austin, 1996), hence the > 100 µm is often analyzed in these regions. The living 100 µm – 1 mm fraction is expected to adequately reflect potential future impacts of contaminants. It must however be noted, that our baselines only represent the studied size fraction.

Only one replicate at each sample location was analyzed. The distribution of living benthic foraminifera is known to show patchiness, and the use of non-replicate samples might therefore reflect an unrepresentative variability (Barras et al., 2010; Bernstein et al., 1978;

Fontanier et al., 2003; Griveaud et al., 2010). Variability between sample localities was indeed observed in this study. However most of this variability could be explained by the variability in habitat characteristics of that sample locality (see discussion below). The three foraminiferal associations are therefore expected to reflect the general faunal distribution patterns of the region. Nevertheless, variability due to patchiness should be taken into account in future comparison of foraminiferal assemblages at the same sample locations.

Sediment samples for foraminiferal analyses were collected over a time span of 5 years in different months (April, June and July). This might affect the interpretation of the results due to interannual and seasonal variability. Temporal variability in, for example, food availability might result in reproductive responses and high abundances of opportunistic taxa (e.g. Duchemin et al., 2008; Fontanier et al., 2006; Fontanier et al., 2008; Fontanier et al., 2002; Gooday and Hughes, 2002). Overall the reconstructed spatial pattern of benthic foraminifera and habitat characteristics (Fig.2 and Fig.5) does not show any variability between the four different sample sets that can be attributed to seasonal or interannual variability, e.g. large differences in organic matter between the sample sets or high numbers of opportunistic species. The presence of interannual and seasonal variability should however be taken into account when these foraminiferal associations are compared with future studies.

The distribution of the three foraminiferal associations reflect the natural variability in the studied area, i.e. differences in water depth, grain size, bottom current velocity and the availability of organic matter. In general, weak responses were observed of foraminiferal species to metal concentrations. These weak response, both negative and positive, are likely due to the low concentration levels of metals, with all concentrations characterized as background levels (WFD level I; EuropeanCommission, 2003). Exceptions are Cd and Zn, showing a strong positive response to the standardized absolute abundance of most of the foraminiferal species. This might be explained by the fact that these elements have oceanic distribution patterns related to nutrients; i.e., dissolved Cd has a distribution similar to the nutrient phosphate (Boyle, 1988; Boyle et al., 1976; Elderfield and Rickaby, 2000), while Zn displays a refractory nutrient-type distribution and is well correlated with silica (Bruland and Franks, 1983; Bruland et al., 1978; Martin et al., 1993). The positive responses therefore might be a secondary effect and reflect the affinity of the foraminifera to organic matter, rather than an affinity to the elements.

5.2 Sediment characteristics and metal concentrations

The increase of metal concentrations and organic matter from Tromsøflaket towards Ingøydjupet (Fig. 3) is an effect of the increase in fine grained particles, rather than an effect of enhanced supplies to this region. Previous studies have documented a positive correlation between finer particles (clay and silt) and metal concentrations, due to the absorptive properties of clay minerals and the large specific surface area of finer particles (e.g. Contu et al., 1984; Degetto et al., 1997; Horowitz, 1991; Kennedy et al., 2002). This is supported by the positive correlation between the <63 μm fraction and most of the metals found by PCA (Fig. 6b) and the similar trends of <63 μm fraction and metal concentrations along the depth transect (Fig. 3). Additionally, organic matter is known to have an affinity to finer grain sizes (Kennedy et al., 2002). Organic matter was not included in the PCA. However, we observe a slight increase of organic matter concentrations towards the deeper Ingøydjupet (Fig. 2). Studies by Contu et al. (1984) and Degetto et al. (1997) suggest also a positive correlation between organic matter and Hg, Pb, Cu and Zn. It is therefore suggested that higher organic matter concentrations in the deeper stations also contribute to the observed higher metal concentrations detected in samples from these localities.

Some exceptions are observed to this general pattern of finer grained sediments with higher metal concentrations in Ingøydjupet, and coarser grained sediments with lower metal concentrations on Tromsøflaket (Fig. 2 and 3). These deviations might be the effect of local topography, i.e., local depressions or topographic highs. Bellec et al. (2008) showed that the morphology of Tromsøflaket has a large influence on sediment deposition with relatively coarse sediments on ridges and shallow banks, and relatively fine sediments in depressions and on the slopes of Tromsøflaket (Bellec et al., 2008). The effect of high local variability is seen both in the metal concentrations and distribution of the foraminiferal associations. For example, the relatively fine grained sediment samples R87 and R17 (Fig. 2) have relatively high concentrations of some of the metals (Fig. 3) and a relatively high abundance of species of the MN association (Fig. 7b). These conditions indicate calm bottom conditions yet Tromsøflaket is characterized as a high energy environment. Another example is R11, a station rich in SS and therefore indicating high current velocities, which shows relatively high abundances of the current tolerant species of the LT association (Fig. 2 and 7b). This local variability might also be reflected in the linear model, by the sometimes relatively low mR^2-values.

Ba concentrations around Snøhvit are elevated compared to other surrounding stations (Fig. 3), although concentrations still correspond to background levels (WFD level I)

(EuropeanCommission, 2003). Ba is one of the constituents of barite ($BaSO_4$) used as a weighting agent during the drilling process (Carroll et al., 2000). Low values of SS and relatively high clay percentages (Fig. 2) were observed in the Snøhvit samples. The bathymetric map of the study area (Fig. 1) shows that the Snøhvit samples are located in a small basin sheltered by relatively shallow areas. This most likely implies calm conditions, i.e., low bottom current velocities, at the Snøhvit Field, enabling the settling of fine grained sediments. Chemical discharges from the Snøhvit Field may therefore not be transported over long distances but rather be deposited locally in this basin. However, when contaminant-laden fine grained sediments are transported away from the Snøhvit Field, they are likely to settle in Ingøydjupet. The drop in current speed, prevailing fine grained sediments and relatively higher TOC concentrations indicate that the sediments of Ingøydjupet might serve as a trap for contaminants.

5.3 Implications for bio-monitoring

Responses of the ecosystem to different anthropogenic stressors have been extensively studied in temperate regions, but few data exist for the (sub-) Arctic region. A study of macro benthic communities by Olsen et al. (2007), suggests that (sub-) Arctic benthic communities are more vulnerable to petroleum related stressors than those in temperate regions. Therefore, indicators of environmental impact need to be further developed for the (sub-) Arctic region specifically. Currently, macro-benthos community structure is often the standard methodology to test the impact of anthropogenic activities on marine sedimentary environments. However, benthic foraminifera are also sensitive indicators of environmental condition, and have proven to be early indicators of the impact of stressors on the ecosystem (e.g. Alve, 1991a; Alve, 1995; Alve et al., 2009; Armynot du Châtelet et al., 2009; Armynot du Châtelet et al., 2004; Bouchet et al., 2007; Coccioni et al., 2009; Ferraro et al., 2006; Foster et al., 2012; Frontalini et al., 2009; Hess et al., 2013; Jorissen et al., 2009; Mojtahid et al., 2006; Nigam et al., 2006; Yanko et al., 1998; Yanko et al., 1994). Additionally, their large abundances (Murray, 2006), in comparison to macro fauna, enables statistically robust observations of faunal communities. The use of bio-indicators can be complicated by the strong natural and regional variability of benthic organisms. Hence when applying bio-indicators, it is essential to first obtain a solid understanding of the factors controlling natural variability, the range of this variability, and documentation of local baseline and pre-impact conditions.

For example, Carroll et al. (2000) reported that 92% of the variability in benthic macro fauna communities close to petroleum fields on the Norwegian continental shelf are mainly attributed to local natural factors, such as water depth, grain size and inter-annual variations. Only 8% of the variation in community composition was attributable to the effects of contaminants. As previously noted, the present study indicates that the observed benthic foraminiferal assemblages in this study are predominantly affected by natural factors, e.g. grain size, food availability and current speed.

The range of metal concentrations detected in this study is comparable to those found in the surrounding region (table 3; Renaud et al., 2008). The range of the measured metal concentrations is considered to be of background to good environmental quality according to the WFD levels of environmental status (EuropeanCommission, 2003; Molvær et al., 1997). Therefore, our study area is characterized as pristine; the measured metal concentrations and foraminiferal assemblages reflect pre-impact conditions.

The only sign that might indicate an anthropogenic disturbance is the elevated Ba levels (and to a lesser extent Pb) around the Snøhvit Field. Drill cuttings are rich in non-degradable and non-toxic Ba, making Ba a useful tracer of drilling related discharges. Other toxic heavy metals (Cd, Pb and Zn), commonly found in water-based drilling muds, do not generally affect benthic macro fauna (Carroll et al., 2000). However, the deposition of drill cuttings on the natural sediment surface can have a smothering effect on both the sessile benthic macro fauna and foraminifera. Whereas macro fauna are able to migrate through this layer (Carroll et al., 2000; Schaanning et al., 2008; Trannum et al., 2011; Trannum et al., 2010), benthic foraminifera only need a coverage of 2 cm to decline severely in abundance (Hess et al., 2013). Although indications of high sedimentation rates at the Snøhvit Field were observed, these are not expected to be associated with drill cutting discharges from petroleum operations.

Two of the three foraminiferal associations reflect the physical conditions of the investigated sub-regions. The LT-association, frequently abundant in the coarse grained high energy environment of Tromsøflaket, is dominated by epifaunal suspension feeders preferring these types of environments. The MN-association, frequently abundant in the fine grained calm environment of Ingøydjupet, is dominated by infaunal species thriving on buried organic material and preferring these calm environments. Similar patterns were observed in macro fauna assemblages from this region (Carroll et al., 2000; Renaud et al., 2008). In areas with coarse sands, suspension feeding bivalves and carnivorous worms dominated, while in fine deposits burrowing bivalve mollusks and tube dwelling polychaete worms thrived (Carroll et al., 2000).

The species of the R-association do not show a regional pattern, nor do they exhibit a clear response to the physical environment. Due to this lack of regional pattern, species of the R-association are not likely to prove useful as bio-indicators in this region. The mainly epifaunal species of the LT-association and mainly infaunal species of the MN-association have a clear habitat preference, and are therefore considered as potential bio-indicators for this region. In addition, their differences in feeding strategies provide relevant information on the impact of human activities on ecosystems (Jørgensen et al., 2011). The epifaunal species of the LT-association feed on high quality food sinking through the water column or the most recently deposited organic matter on the sediment surface. These suspension feeders might therefore be more sensitive and rapid indicators of environmental contaminations than infaunal species, since contaminants follow the same pathways as the organic matter these species feed on (Jørgensen et al., 2011). In addition, species of the LT-association are less mobile due to their sessile nature, compared to the relatively mobile species of the MN-association. In the case of drill cutting releases, the infaunal species of the MN-association are likely to migrate through this layer, whereas the sessile LT-associated species are likely to get smothered (Hess et al., 2013). Due to their feeding strategy and sessile nature, species of the LT-association might be more vulnerable to anthropogenic impact and might thus be better bio-indicators than MN-associated species. The MN-associated species on the other hand, are more abundant in fine grained sediments, where due to the fine grain sizes and calm water conditions, contaminants are more likely to accumulate. Toxicity threshold levels may therefore be exceeded more quickly and consequently an anthropogenic impact will be detected more rapidly.

Four considerations should be made when developing a bio-monitoring tool for the SW Barents Sea, using the baseline conditions established in this study. Firstly, the differences in distribution of the foraminiferal associations are mainly the effect of grain size and organic matter availability and reflect the high natural variability of the studied region. This suggests that site specific conditions have a larger impact than regional scale differences (Renaud et al., 2008). When a tool is developed using the here described associations as input, it can only be applied to locations with physical properties within the range covered by this study.

Secondly, benthic species exhibit a threshold effect rather than a gradual response to, for example, increased metal concentrations (Carroll et al., 2000). The responses observed in the present study between foraminiferal assemblages and metal concentrations might therefore be different when such threshold levels are exceeded. Additionally, potential toxicity of metals also depends on factors such as acidity, oxygen conditions and the presence of inorganic elements such as sulfides (Somerfield et al., 1994). Metals as Cu and Cr can be bio-available under aerobic conditions, while they occur as metal-sulfide complexes and are thus non-bioavailable in anaerobic environments (Hare et al., 1994). The modeled relationships are therefore only valid within the range (Table 3) of the explanatory variables used as input to the model and under similar acidity and oxygen conditions.

Thirdly, the linear model only included the dominant species (i.e. species with a relative abundance of > 5% in at least one sample). Rare species are known to contribute most to the diversity of the benthic foraminiferal community (Murray, 2013). Since diversity is often reduced in impacted areas (Schafer, 1973; Yanko et al., 1994), rare species are crucial to detect ecological changes and are therefore critical in bio-monitoring studies (Cao et al., 1998). Therefore, not only changes in the distribution pattern of the three defined associations might provide information on environmental change in the study area. Changes in the diversity of the samples (H') might also be of importance.

Additionally, changes in the Barents Sea may include other factors than discussed here, such as climate change, ocean acidification and the activity of natural seeps. These factors might influence benthic foraminiferal assemblages and should therefore additionally be considered when developing a bio-indicator for monitoring the environment in the future.

6. Conclusions

This study has documented the present day, pre-impacted state of the marine environment in the SW Barents Sea. The range of measured metal concentrations in the study area indicates background to good environmental quality according to the Water Framework Directive levels of environmental status. The environmental properties and benthic foraminiferal assemblages are therefore considered to reflect pre-impact conditions for this region.

Three benthic foraminiferal associations were defined within the Tromsøflaket-Ingøydjupet region. Their distribution patterns are driven by the natural variations in the physical environment of the region. On the shallow Tromsøflaket, the physical environment is characterized by coarse sediments and high bottom current velocities. In this region, the *Lobatula-Trifarina* (LT) association has been identified with the sessile epifaunal species, *L. lobatula, T. angulosa* and *C. laevigata* predominating and reflecting the higher energy physical environment of Tromsøflaket. In Ingøydjupet, the physical environment is characterized by deeper water depths and calmer current conditions, with sediments of finer grain size and higher organic matter concentrations. Here, a *Melonis-Nonionella* (MN) association prevails, with *M. barleeanus, P. bulloides* and *N. auricula* as dominant species.

These infaunal species thrive on fine grained sediments and degraded organic matter. A third association, the *Reophax* (R) association, consisting of *Reophax* spp., *Trochammina* spp. and *E. nipponica* did not show a clear habitat preference.

Species of the LT-association and MN-association are considered to be good bio-indicators, due to their specific habitat preferences and feeding strategies; those of the R-association are not considered as an adequate bio-indicator due to the absence of a clear regional and habitat pattern. The sessile nature and feeding strategy of species of the LT-association might make them more vulnerable to environmental disturbances. Species of the MN-association however dominate in fine grained sediments, where contaminants are more likely to settle and effects of increased contamination might be detected more rapidly.

Overall, this study establishes the pre-impact conditions of the SW Barents Sea which contributes to the development of a bio-monitoring tool using benthic foraminifera for the region. Petroleum production is projected to expand significantly in the Barents Sea in the coming years, raising the potential for increased industrial discharges into the marine environment. Hence, such a bio-monitoring tool is expected to be of great relevance for this region.

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Appendix A. Sediment properties

sample	SS	Clay	Silt	Sand	Smectite	Pb	Ba	Hg	Cd	Cr	Cu	Zn	Ti	TOC	TOM	cluster
PL529-01	22.40	6.78	16.87	76.35	11.57	14.55	150.45	0.04	0.07	38.55	17.05	60.70	1091.50	N/A	4.00	ID
R81	25.13	19.68	50.17	30.14	2.87	10.80	93.00	0.01	0.21	26.00	7.23	41.00	569.00	0.61	N/A	TF
reg9-04	23.72	7.50	17.54	74.95	4.14	11.07	39.20	0.06	0.08	14.80	5.71	24.83	378.67	N/A	2.30	TF
reg9-06	25.13	11.10	30.59	58.30	2.43	15.10	62.40	0.02	0.08	30.20	7.89	34.30	555.33	N/A	3.70	TF
R92	22.40	7.18	30.44	62.38	9.77	10.40	31.50	0.04	0.11	11.30	4.61	47.40	N/A	N/A	N/A	TF
R14	25.13	12.44	32.09	55.47	4.14	9.80	55.60	0.02	0.10	13.70	6.49	27.90	408.00	0.60	N/A	TF
R87	22.40	17.68	54.12	28.20	3.75	26.20	102.00	0.04	0.30	26.80	11.40	5.23	661.00	0.86	N/A	ID
R22	23.72	15.95	34.58	49.47	10.95	10.50	77.60	0.02	0.10	15.30	7.08	30.00	488.00	0.57	N/A	TF
R17	23.72	14.55	47.14	38.32	7.41	13.80	83.20	0.03	0.10	18.90	8.81	37.10	444.00	0.74	N/A	TF
R45	23.72	3.68	13.10	83.22	1.78	6.12	30.10	0.04	0.07	11.40	3.02	36.20	N/A	N/A	N/A	TF
R11	29.87	18.48	34.59	46.92	3.50	6.60	62.30	0.01	0.10	11.40	3.42	19.20	322.00	0.30	N/A	TF
R10	23.72	19.52	33.85	46.63	5.63	11.10	61.00	0.02	0.10	15.10	5.90	28.20	365.00	0.48	N/A	TF
reg9-05	29.87	8.50	11.35	80.15	2.80	5.22	29.77	0.01	0.01	11.57	3.49	14.00	311.33	N/A	1.90	TF
R8	23.72	9.02	14.33	76.65	10.27	12.40	79.20	0.03	0.10	25.30	8.30	43.60	312.00	0.24	N/A	TF
SF-11	22.40	23.21	65.76	11.03	2.57	22.40	196.33	0.05	0.15	32.70	14.50	63.97	500.67	N/A	7.60	ID
SN-11	19.96	36.62	41.79	21.59	0.74	17.87	341.00	0.05	0.13	24.47	11.07	49.03	339.67	N/A	5.30	ID
SN-03	18.84	36.43	45.86	17.71	1.83	17.83	164.33	0.08	0.10	35.17	13.77	58.77	584.00	N/A	5.20	ID
SD-11	18.84	37.05	47.18	15.76	3.22	19.50	137.00	0.02	0.08	35.80	13.70	59.03	556.00	N/A	5.90	ID
SE-11	18.84	20.89	44.04	35.06	0.74	13.27	364.00	0.02	0.08	23.57	12.53	41.93	364.33	N/A	4.00	ID
R7	22.40	25.82	58.78	15.39	11.20	5.30	34.00	0.01	0.10	11.30	3.22	19.90	528.00	0.53	N/A	TF
HH150	25.13	30.38	56.75	12.87	7.94	15.80	110.00	0.17	0.09	38.60	11.90	52.80	851.00	0.62	N/A	ID
R5	25.13	25.10	61.85	13.05	3.35	12.90	76.10	0.02	0.10	28.70	9.44	47.00	603.00	0.69	N/A	ID
R4	22.40	30.02	67.15	2.83	14.00	15.90	103.00	0.03	0.10	34.60	11.50	57.50	707.00	0.87	N/A	ID
R3	22.40	20.53	75.30	4.18	7.89	13.50	93.60	0.03	0.10	34.70	10.80	56.00	708.00	0.70	N/A	ID
R68-3a	22.40	14.10	79.76	6.14	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	ID
R68-3b	22.40	27.90	67.22	4.89	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	ID
R67-2b	23.72	30.11	64.59	5.30	17.10	14.60	98.40	0.03	0.10	34.70	11.40	56.10	693.00	0.77	N/A	ID
R68-2a	22.40	25.97	66.81	7.22	18.16	15.70	101.00	0.03	0.10	36.10	11.80	57.40	723.00	0.93	N/A	ID
R68-1a	22.40	26.51	69.70	3.78	11.13	14.50	95.40	0.03	0.10	32.60	10.80	53.40	665.00	0.85	N/A	ID
HH151	21.14	39.55	48.32	12.14	0.51	13.80	101.00	0.04	0.06	47.30	15.40	64.50	969.00	0.63	N/A	ID
HH152	23.72	29.54	54.18	16.28	0.90	16.60	89.90	0.04	0.08	33.70	11.70	52.30	680.00	0.74	N/A	ID
HH154	21.14	41.22	54.95	3.83	5.14	23.90	181.00	0.16	0.10	62.80	17.30	79.60	1110.00	0.98	N/A	ID
HEL01-6	26.62	8.69	24.59	66.72	3.04	7.28	42.07	0.04	0.05	12.17	5.91	24.40	269.00	N/A	2.40	TF
reg10-01	26.62	18.95	54.64	26.41	0.55	15.57	102.83	0.04	0.04	36.07	13.23	55.80	425.00	N/A	4.40	ID
NVA-05	23.72	6.24	33.46	60.30	0.00	10.83	80.50	0.20	0.10	26.47	9.70	42.03	239.00	N/A	3.10	ID
	%	%	%	%	%	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	%	%	

Appendix A: Sortable silt mean grain size (SS), grain size distribution (weight%), smectite (%), metal concentrations (mg/kg), total organic content (TOC) and total organic matter (TOM). 'Cluster' indicates to which cluster found with the Q-mode clustering the sample was associated (figure 6): i.e. Tromsøflaket-cluster (TF) or Ingøydjupet-cluster (ID). Samples are sorted following the depth transect used in the figures.

Appendix B. Multiple regression linear model

Lobatulus-Trifarina association

	LT-association		*C. reniforme*		*C. laevigata*		*T. angulosa*		*L. lobatula*	
	estimate	p=	estimate	p=	estimate	p=	estimate	p=	estimate	p=
intercept	435.6	0.00302	36.74	0.039548	99.46	0.004154	130.36	0.00266	169.06	0.00421
depth	-	-	-	-	-	-	-	-	-	-
SS	-	-	-	-	-	-	97.53	0.06263	-	-
< 63 µm	-263.4	0.16472	-	-	-113.13	0.012970	-	-	-	-
smectite	-	-	-	-	-	-	-	-	-	-
Pb	-	-	-	-	-	-	-	-	-	-
Ba	-281.3	0.07606	-38.06	0.059371	-	-	-	-	-98.94	0.12038
Hg	-	-	-	-	-	-	-	-	-	-
Cd	411.2	0.01568	57.36	0.005687	130.69	0.001956	111.12	0.02536	83.51	0.18233
Cr	-789.3	0.00530	-122.55	0.000669	-	-	-258.60	0.00185	-294.62	0.00746
Cu	-	-	-	-	-213.50	0.000709	-	-	-	-
Zn	852.8	0.00420	121.36	0.001335	237.65	0.000562	230.48	0.01158	238.95	0.03619
mR^2	0.419		0.4194		0.4736		0.3679		0.3004	

Appendix B : Outcome of the best fitting multiple regression linear model. Values given below ‘intercept’ and ‘estimate’ reflect the linear model that describes the correlation between the abiotic parameters and foraminiferal species in the most optimum way. The two way probability is given by p, while mR^2 represents the multiple R^2. Interpretation of the linear model can be found in table 3.

(continues below)

Reophax association

	R-association		*Trochammina* spp.		*E. nipponica*		*Reophax* spp.	
	estimate	p=	estimate	p=	estimate	p=	estimate	p=
intercept	395.41	8.54e-06	104.69	9.89e-05	119.92	6.23e-05	170.82	3.43e-06
depth	-111.84	0.232828	-	-	-40.74	0.185680	-	-
SS	173.62	0.078092	-	-	82.49	0.016138	64.41	0.106889
< 63 µm	-213.14	0.065492	-	-	-51.42	0.168211	-114.34	0.009866
smectite	-106.23	0.193461	-	-	-46.82	0.109033	-64.78	0.045901
Pb	-477.50	0.003886	-	-	-110.60	0.015921	-263.59	0.000194
Ba	-	-	-33.18	0.167	-	-	-	-
Hg	-163.36	0.058984	-	-	-50.17	0.083287	-70.59	0.043278
Cd	449.72	0.000278	-	-	155.08	0.000318	250.33	5.28e-06
Cr	323.46	0.110242	-	-	-	-	174.14	0.025928
Cu	-	-	-	-	-	-	-	-
Zn	337.50	0.040293	-	-	163.32	0.002025	148.36	0.028155
mR^2	0.5575		0.06068		0.5593		0.6625	

(continues below)

Melonis-Nonionella association

	MN-association		*N. auricula*		*Miliolinella sp.*		*M. barleeanus*		*P. bulloides*		*F. marginata*	
	estimate	p=	estimate	p=	estimate	p=	estimate	p=	estimate	p=	estimate	p=
intercept	140.11	1.57e-08	35.089	8.76e-05	18.267	7.16e-05	17.678	8.49e-05	19.280	3.77e-05	13.084	0.00154
depth	-	-	22.282	0.0133	-	-	-	-	-	-	-	-
SS	33.85	0.181018	-	-	-	-	-	-	-	-	-	-
< 63 µm	-62.48	0.013168	-	-	-	-	-11.244	0.03761	-9.047	0.09749	-8.167	0.12111
smectite	-	-	-	-	-	-	-	-	-	-	-7.225	0.09678
Pb	-	-	-	-	-	-	-	-	-	-	-19.023	0.00636
Ba	-35.97	0.118306	-	-	-10.857	0.03636	-	-	-	-	-6.832	0.15282
Hg	-27.34	0.156946	-	-	-	-	-	-	-	-	-6.041	0.15602
Cd	95.23	0.000127	-12.452	0.1269	22.939	1.42e-05	12.202	0.01340	13.248	0.00920	34.666	1.05e-06
Cr	-	-	-	-	-	-	-	-	-	-	-	-
Cu	-	-	-	-	28.129	0.00094	-29.710	0.00015	-21.739	0.00407	-	-
Zn	61.00	0.037805	-15.377	0.0804	-32.139	8.78e-05	34.439	6.89e-05	25.810	0.00197	21.571	0.00226
mR^2	0.5264		0.2701		0.7507		0.4856		0.3518		0.6504	

	E. excavatum		*Q. seminulum*		*Elphidium sp*		*I. helenae*		*C. incertum*		*Rosalina sp.*		*I. norcrossi*	
	estimate	p=	estimate	p=	estimate	p=	estimate	p=	estimate	p=	estimate	p=	estimate	p=
intercept	7.590	0.0764	10.180	3.91e-05	5.198	0.00705	3.057	0.03573	2.533	0.0836	1.0677	0.0153	7.067	0.0597
depth	-	-	-3.872	0.12548	-	-	-	-	-	-	-	-	-	-
SS	-	-	-	-	-	-	-	-	-	-	-	-	8.501	0.0628
< 63 µm	-	-	-	-	-	-	-6.524	0.00212	2.125	0.1437	-	-	-	-
smectite	-11.794	0.0127	-	-	-	-	-	-	-	-	-	-	-	-
Pb	-39.302	5.87e-05	-	-	-	-	-	-	-	-	-	-	-	-
Ba	-	-	-5.177	0.06174	-	-	-	-	-	-	-	-	-	-
Hg	-8.099	0.0950	-	-	-	-	-3.875	0.02142	-	-	-	-	-	-
Cd	38.409	8.18e-07	-	-	-2.916	0.11555	2.506	0.09834	-	-	-	-	-	-
Cr	20.416	0.0461	-	-	-2.574	0.16213	12.292	0.00244	-	-	-	-	-	-
Cu	-	-	11.271	0.01097	-	-	-6.962	0.03973	-	-	-	-	6.772	0.1340
Zn	13.258	0.1133	-9.762	0.00756	-	-	-	-	-	-	-	-	-	-
mR^2	0.6383		0.3189		0.1383		0.3969		0.06768		-		0.1181	

Table 1. Sample locations and conducted analyses.

Stations and corresponding coordinates (in decimal degrees), location, water depth, water temperature (T) and salinity (S) for the different sample sets. In addition, the coring equipment used to collect surface sediments for each analyses and the institute where those analyses were performed are given. For samples taken close to exploration wells the field name is indicated. Abbreviations: GS= grain size, SS=sortable silt mean grain size, ID= Ingøydjupet, TF= Tromsøflaket, NB= Nordkappbanken, BR=Bjørnøyrenna, BC= box corer, GC=grab corer, MC=multi corer, UiT=University of Tromsø, ISOR= Iceland GeoSurvey, NGU= Norwegian Geological Survey, UL= UniLab AS, N/A= not analyzed.

Sample	**location**			**analyses**					**depth**	**CTD**	
Mareano 2006	*lat*	*long*	*region*	*GS/SS*	*Forams*	*Clay*	*metals*	*TOC/ TOM*	*(m)*	*T (C)*	*S (psu)*
R3	71.33833333	22.42611111	ID	BC(UiT)	BC(UiT)	MC(NGU)	MC(NGU)	MC(NGU)	435	5.01	35.13
R4	71.33638889	22.48972222	ID	BC(UiT)	BC(UiT)	MC(NGU)	MC(NGU)	MC(NGU)	433	4.89	35.13
R5	71.30388889	22.53444444	ID	BC(UiT)	BC(UiT)	MC(NGU)	MC(NGU)	MC(NGU)	422	5.06	35.13
R7	71.32638889	22.21083333	TF	BC(UiT)	BC(UiT)	MC(NGU)	MC(NGU)	MC(NGU)	355	5.18	35.13
R8	71.28027778	22.14277778	TF	BC(UiT)	BC(UiT)	MC(NGU)	MC(NGU)	MC(NGU)	313	5.38	35.14
R10	71.21722222	21.45583333	TF	BC(UiT)	BC(UiT)	MC(NGU)	MC(NGU)	MC(NGU)	321	5.45	35.14
R11	71.22277778	21.72805556	TF	BC(UiT)	BC(UiT)	MC(NGU)	MC(NGU)	MC(NGU)	301	5.31	35.14
R14	71.13361111	21.44055556	TF	BC(UiT)	BC(UiT)	MC(NGU)	MC(NGU)	MC(NGU)	221	5.75	35.14
R17	71.270989	21.17611111	TF	BC(UiT)	BC(UiT)	MC(NGU)	MC(NGU)	MC(NGU)	280	5.71	35.14
R22	71.04333333	21.85777778	TF	BC(UiT)	BC(UiT)	MC(NGU)	MC(NGU)	MC(NGU)	249	5.82	35.14
R45	70.88555556	21.80138889	TF	GC(UiT)	GC(UiT)	MC(ISOR)	MC(NGU)	N/A	300	5.95	35.13
R68-1	71.321072	22.48853	ID	BC(UiT)	BC(UiT)	MC(NGU)	MC(NGU)	MC(NGU)	440	N/A	N/A
R68-2a	71.319952	22.49888889	ID	BC(UiT)	BC(UiT)	MC(NGU)	MC(NGU)	MC(NGU)	440	N/A	N/A
R68-2b	71.31722222	22.50138889	ID	BC(UiT)	BC(UiT)	MC(NGU)	MC(NGU)	MC(NGU)	435	N/A	N/A
R68-3a	71.31666667	22.49527778	ID	BC(UiT)	BC(UiT)	N/A	N/A	N/A	438	5.22	35.13
R68-3b	71.32083333	22.50333333	ID	BC(UiT)	BC(UiT)	N/A	N/A	N/A	435	N/A	N/A
Mareano 2007											
R81	71.16388889	18.65222222	TF	BC(UiT)	BC(UiT)	BC(ISOR)	MC(NGU)	MC(NGU)	349	N/A	N/A
R87	71.301743	20.33888889	TF	BC(UiT)	BC(UiT)	BC(ISOR)	MC(NGU)	MC(NGU)	239	N/A	N/A
R92	71.07472222	19.57166667	TF	BC(UiT)	BC(UiT)	BC(ISOR)	MC(NGU)	N/A	202	N/A	N/A
Statoil 2010											
HEL 01	71.588432	24.099612	NB/Heilo	GC(UiT)	GC(UiT)	GC(ISOR)	GC(UL)	GC(UL)	302	N/A	N/A
NVA-05	72.916358	25.88912	BR/Norvarg	GC(UiT)	GC(UiT)	GC(ISOR)	GC(UL)	GC(UL)	381	N/A	N/A
PL529	70.84835363	16.55828915	shelf/Bøna	BC(UiT)	BC(UiT)	BC(ISOR)	BC(UL)	BC(UL)	1389	N/A	N/A
reg 09-04	71.00189157	18.99970658	TF	GC(UiT)	GC(UiT)	GC(ISOR)	GC(UL)	GC(UL)	187	N/A	N/A
reg 09-05	71.275564	22.11647404	TF	GC(UiT)	GC(UiT)	GC(ISOR)	GC(UL)	GC(UL)	307	N/A	N/A
reg 09-06	71.02907465	19.65660024	TF/Lunde	GC(UiT)	GC(UiT)	GC(ISOR)	GC(UL)	GC(UL)	194	N/A	N/A
reg 10-01	72.62878933	22.78128686	BR	GC(UiT)	GC(UiT)	GC(ISOR)	GC(UL)	GC(UL)	382	N/A	N/A
SD-11	71.59191651	21.27961423	ID/Snøhvit	GC(UiT)	GC(UiT)	GC(ISOR)	GC(UL)	GC(UL)	336	N/A	N/A
SE-11	71.59527269	21.18950676	ID/Snøhvit	GC(UiT)	GC(UiT)	GC(ISOR)	GC(UL)	GC(UL)	337	N/A	N/A
SF-11	71.61089457	21.06035211	ID/Snøhvit	GC(UiT)	GC(UiT)	GC(ISOR)	GC(UL)	GC(UL)	317	N/A	N/A
SN-03	71.4919087	21.08882364	ID/Snøhvit	GC(UiT)	GC(UiT)	GC(ISOR)	GC(UL)	GC(UL)	326	N/A	N/A
SN-11	71.48824219	21.08779078	ID/Snøhvit	GC(UiT)	GC(UiT)	GC(ISOR)	GC(UL)	GC(UL)	326	N/A	N/A
UiT 2011											
HH-150	71.405744	21.643258	ID	UiT(MC)	UiT(MC)	MC(ISOR)	MC(UL)	MC(UiT)	383	4.61	35.13
HH-151	71.504059	22.766747	ID	UiT(MC)	UiT(MC)	MC(ISOR)	MC(UL)	MC(UiT)	434	4.55	35.13
HH-152	71.738064	22.319259	ID	UiT(MC)	UiT(MC)	MC(ISOR)	MC(UL)	MC(UiT)	394	4.40	35.13
HH-154	72.019437	20.599746	ID	UiT(MC)	UiT(MC)	MC(ISOR)	MC(UL)	MC(UiT)	400	4.14	35.14

Table 2. Multiple regression linear model.

Interpretations of the outcome of the best fitting multiple regression model. Positive responses between abiotic variables and benthic foraminiferal species/associations are indicated by the green shading, while negative responses are indicated by the red shading. The two-way probability of the found relations (p) is given by the shading and symbols as indicated in the legend. The multiple R^2 (mR^2) is given. Values describing the linear model can be found in Appendix B. Abbreviations: SS = sortable silt mean grain size, <63 µm = fine sediment fraction, Pb = lead, Ba = barium, Hg = mercury, Cd = cadmium, Cr = chromium, Cu= copper, Zn = zinc.

	water depth	SS	<63 µm	smectite	Pb	Ba	Hg	Cd	Cr	Cu	Zn	mR^2
***I: Lobatulus-Trifarina* association**			🟥			🟥 .		🟩 *	🟥 **		🟩 **	0,419
- *C. reniforme*						🟥 .		🟩 **	🟥 ***		🟩 **	0,4194
- *C. laevigata*			🟥 *					🟩 **		🟥 ***	🟩 ***	0,4736
- *T. angulosa*		🟩 .						🟩 *	🟥 **		🟩 *	0,3679
- *L. lobatula*						🟥		🟩	🟥 **		🟩 *	0,3004
***II: Reophax* association**	🟥	🟩 .	🟥 .	🟥	🟥 **		🟥 .	🟩 ***	🟩		🟩 *	0,5575
- *Trochammina* spp.						🟥						0,06068
- *E. nipponica*	🟥	🟩 *	🟥	🟥	🟥 *		🟥 .	🟩 ***			🟩 **	0,5593
- *Reophax* spp.		🟩	🟥 **	🟥 *	🟥 ***		🟥 *	🟩 ***	🟩 *		🟩 *	0,6625
***III:Melonis-Nonionella* association**		🟩	🟥 *			🟥	🟥	🟩 ***			🟩 *	0,5264
- *N. auricula*	🟩 *							🟥			🟥 .	0,2701
- *Miliolinella* sp.						🟥 *		🟩 ***		🟩 ***	🟥 ***	0,7507
- *M. barleeanus*			🟥 *					🟩 *		🟥 ***	🟩 ***	0,4856
- *P. bulloides*			🟥 .					🟩 **		🟥 **	🟩 **	0,3518
- *F. marginata*			🟥	🟥 .	🟥 **	🟥	🟥	🟩 ***			🟩 **	0,6504
- *E. excavatum*				🟥 *	🟥 ***		🟥 .	🟩 ***	🟩 *		🟩	0,6383
- *Q. seminulum*	🟥					🟥 .				🟩 *	🟥 **	0,3189
- *Elphidium* sp.								🟥	🟥			0,1383
- *I. helenae*			🟥 **				🟥 *	🟩 .	🟩 **	🟥 *		0,3969
- *C. incertum*			🟩									0,06768
- *Rosalina* sp.												-
- *I. norcrossi*		🟩 .								🟩		0,1181

		p=	significance
🟥	🟩	>0.1	low
🟥 .	🟩 .	0.05-0.1	poor
🟥 *	🟩 *	0.01-0.05	intermediate
🟥 **	🟩 **	0.001-0.01	good
🟥 ***	🟩 ***	0-0.001	high

Table 3. Ranges of variables and threshold levels.

Ranges of values for water depth, grain size and organic matter, as well as a selection of metal concentrations for the study area and offshore region IX (Renaud et al., 2008). Threshold levels correspond to concentrations at the lower limit of WFD level III (EuropeanCommission, 2003), reflecting lower boundary of concentrations levels considered to be harmful to the ecosystem (Molvær et al., 1997).

	Tromsøflaket-Ingøydjupet (this study)	**region IX** (Renaud et al., 2008)	**threshold levels** (Molvær et al., 1998)
depth (m)	187-1389	160-365	
<63 µm/pellite (%)	16.8-97.2	5.9-96.6	
TOM (%)	1.9-7.6	1.3-11.3	
Ba (mg/kg)	29.8-364	19-945	
Cd (mg/kg)	0.01-0.3	0.025-0.339	2.6
Cu (mg/kg)	3.02-17.3	1.9-19.1	51
Hg (mg/kg)	0.01-0.2	0.020-0.08	0.63
Pb (mg/kg)	5.22-26.2	22.8-45.3	83
Zn (mg/kg)	5.23-79.6	0.7-60	360

Figure 1. Regional setting.

Maps of the regional setting and study area showing: (a) Northern Norway and the western Barents Sea region with the regional oceanography and polar front. (b) Bathymetric map of the study area. (c) Detail of area indicated on b. Sample locations are indicated; see legend for symbol explanation. Filled symbols correspond to the samples clustered in the Ingøydjupet cluster (ID), open symbols correspond to samples clustered in the Tromsøflaket cluster (TF) as given in Fig. 6. Oil/gas fields (OGF) and exploration wells (EW) are indicated by black stars. Approximate location of the sample transect is depicted (dashed line). Bathymetric contours are in meters at a 50 m interval. Coordinates of the sample locations are given in Table 1.

Figure 1

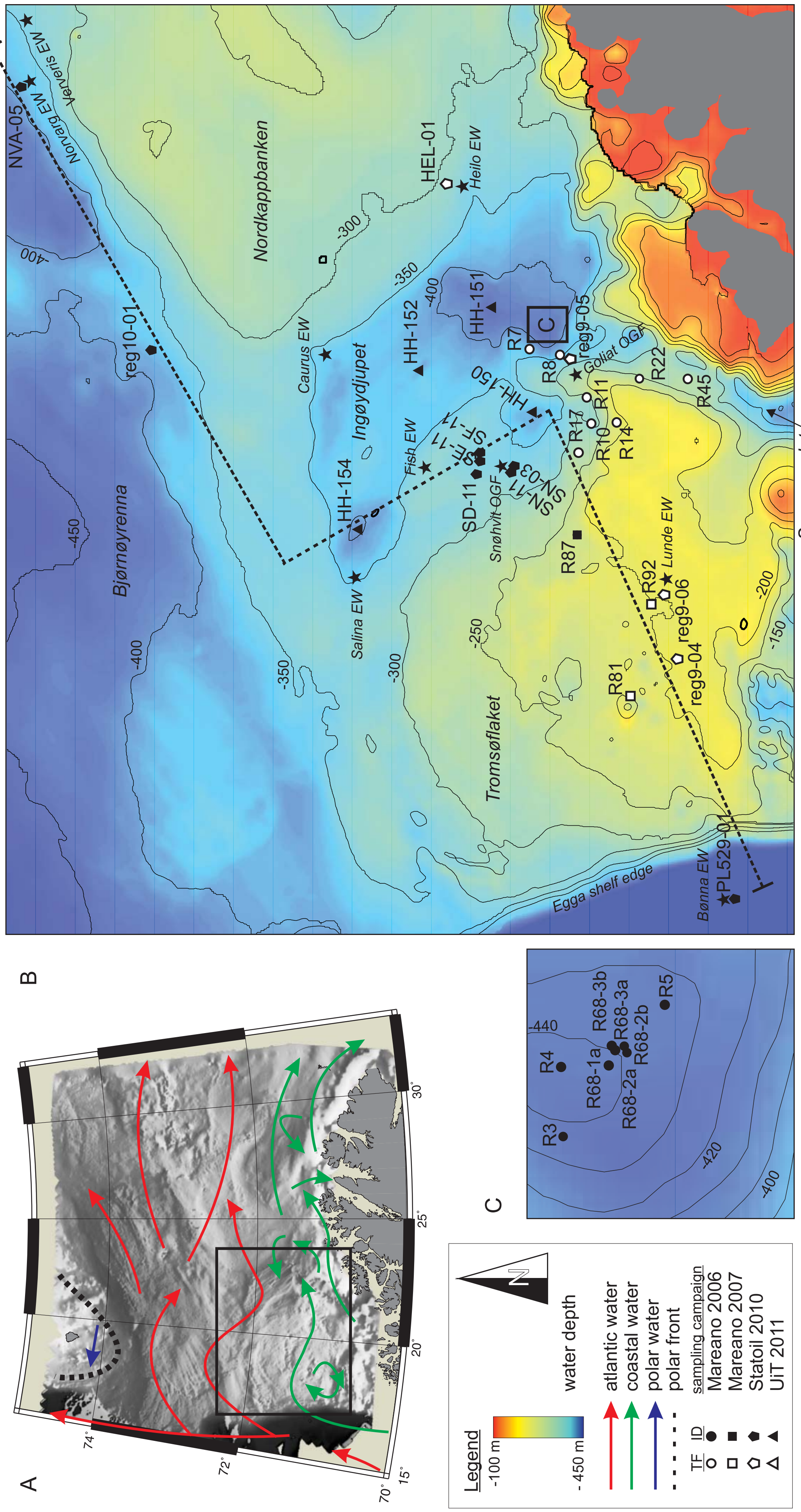

A
B
C
70°
72°
74°
15°
20°
25°
30°
NVA-05
Norvarg EW
Ververis EW
Nordkappbanken
HEL-01
Heilo EW
-300
-400
-350
reg10-01
Caurus EW
Ingøydjupet
HH-152
HH-151
HH-150
HH-154
Fish EW
SF-11
SD-11
SN-11
SN-03
Snøhvit OGF
Salina EW
Bjørnøyrenna
-450
-250
Tromsøflaket
R7
R8
reg9-05
Goliat OGF
R22
R45
R11
R17
R10
R14
R87
R92
Lunde EW
reg9-06
reg9-04
R81
-200
-150
Sørøysundet
Egga shelf edge
Bønna EW
PL529-01
R3
R4
R68-1a
R68-2a
R68-3b
R68-3a
R68-2b
R5
-440
-420
-400
Legend
-100 m
- 450 m
water depth
atlantic water
coastal water
polar water
polar front
TF
ID
sampling campaign
Mareano 2006
Mareano 2007
Statoil 2010
UiT 2011
N

Figure 2

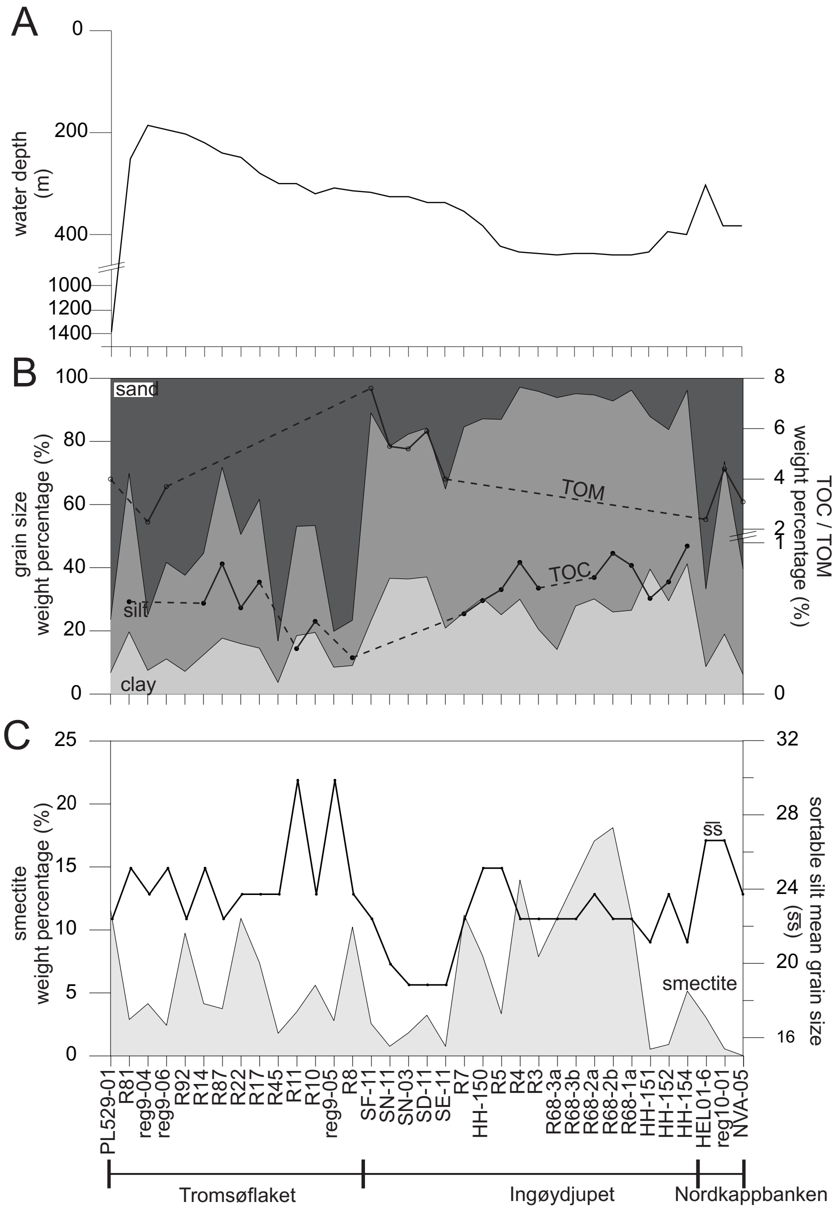


Figure 2. Sediment properties.

Water depth, sediment properties and organic matter content along the depth transect indicated in Fig. 1b: (a) water depth in meters (m). Note the axis break. (b) Grain size distributions (left y-axis) expressed as weight percentages of clay (< 4µm), silt (4-63 µm) and sand (> 63 µm). Total organic carbonate (TOC; black dots) and total organic matter (TOM; open dots) is given by the line plots (right y-axis). The dashed line indicates the absence of data at stations given at the x-axis. Note the axis break in the right y-axis. (c) Abundance of the clay mineral smectite (left y-axis) and the sortable silt mean grain size (right y-axis). Regions are indicated below the x-axis.

Figure 3

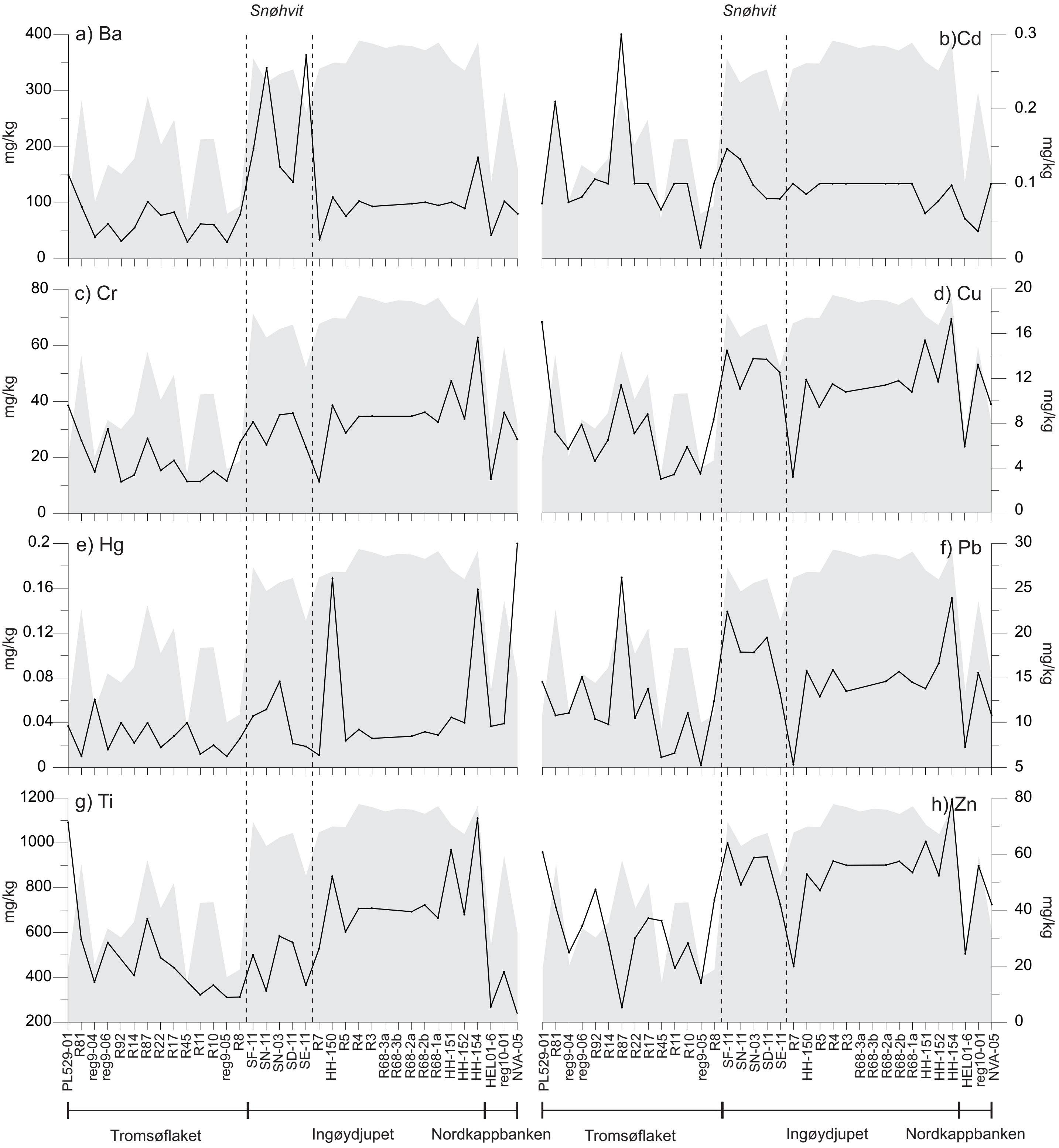


Figure 3. Metal concentrations.

Metal concentrations (mg/kg) for the analyzed metals (black line): (a) barium; (b) cadmium; (c) chromium; (d) copper; (e) mercury; (f) lead; (g) titanium; (h) zinc. Concentrations are plotted along the depth transect indicated in Fig. 1b. Grey shading behind the plots reflect the fine fraction (<63 μm). Samples from the Snøhvit Field are indicated between the dashed lines. Regions are indicated below the x-axis.

Figure 4

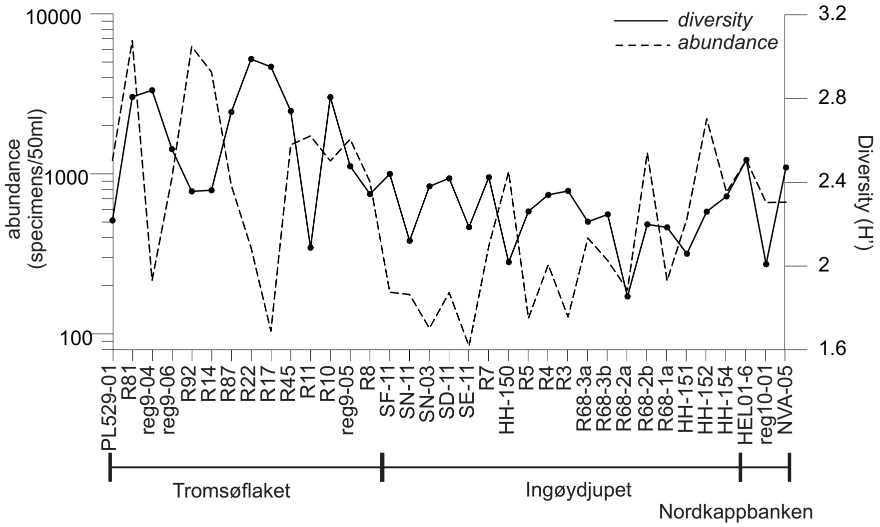


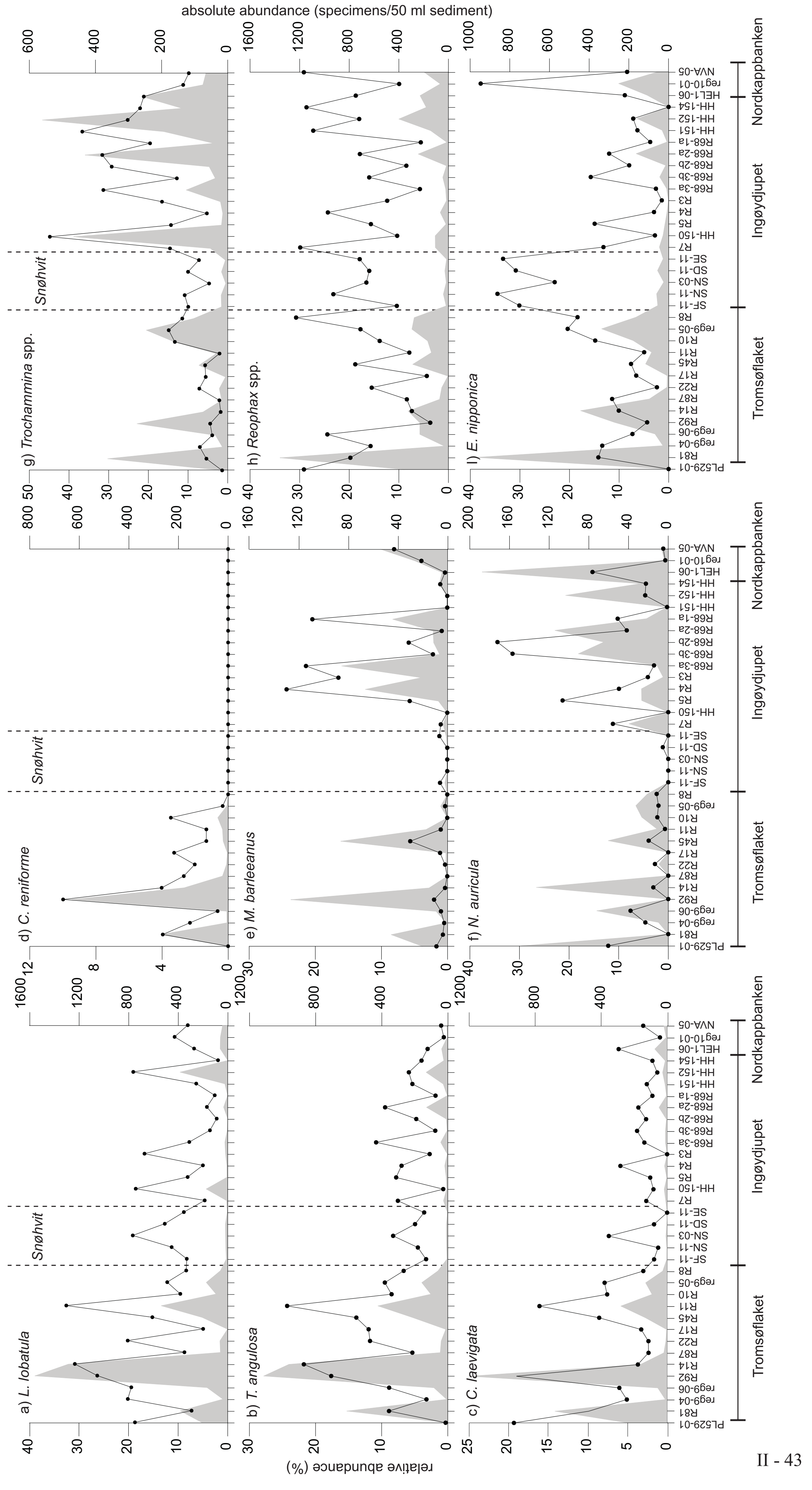
Figure 4. Foraminiferal abundance and diversity.

Foraminiferal abundance (number of specimens/50 ml of sediment; left y-axis; dashed line) and diversity (H'; right y-axis; black line) along the depth transect indicated in Fig. 1b. Note the log scale on the left y-axis. Regions are indicated below the x-axis.

Figure 5. Foraminiferal species abundance.

Absolute abundance standardized for 50 ml of sediment (grey filled area; right y-axis) and relative abundance (black line; left y-axis) of the dominant species in the studied surface samples along the depth transect indicated in Fig. 1b: (a) *Lobatula lobatula*; (b) *Trifarina angulosa*; (c) *Cassidulina laevigata*; (d) *Cassidulina reniforme*; (e) *Melonis barleeanus*; (f) *Nonionella auricula*; (g) *Trochammina* spp.; (h) *Reophax* spp.; (i) *Epistominella nipponica.* Regions are indicated below the x-axis.

Figure 5



absolute abundance (specimens/50 ml sediment)
relative abundance (%)
a) L. lobatula
b) T. angulosa
c) C. laevigata
d) C. reniforme
e) M. barleeanus
f) N. auricula
g) Trochammina spp.
h) Reophax spp.
i) E. nipponica
Snøhvit
Tromsøflaket
Ingøydjupet
Nordkappbanken
0
10
20
30
40
0
400
800
1200
1600
0
5
10
15
20
25
0
4
8
12
0
200
400
600
800
0
40
80
120
160
0
40
80
120
160
200
0
50
0
200
400
600
0
200
400
600
800
1000
PL529-01
R81
reg9-04
reg9-06
R92
R14
R87
R22
R17
R45
R11
R10
reg9-05
R8
SF-11
SN-11
SN-03
SD-11
SE-11
R7
HH-150
R5
R4
R3
R68-3a
R68-3b
R68-2b
R68-2a
R68-1a
HH-151
HH-152
HH-154
HEL1-06
reg10-01
NVA-05

Figure 6

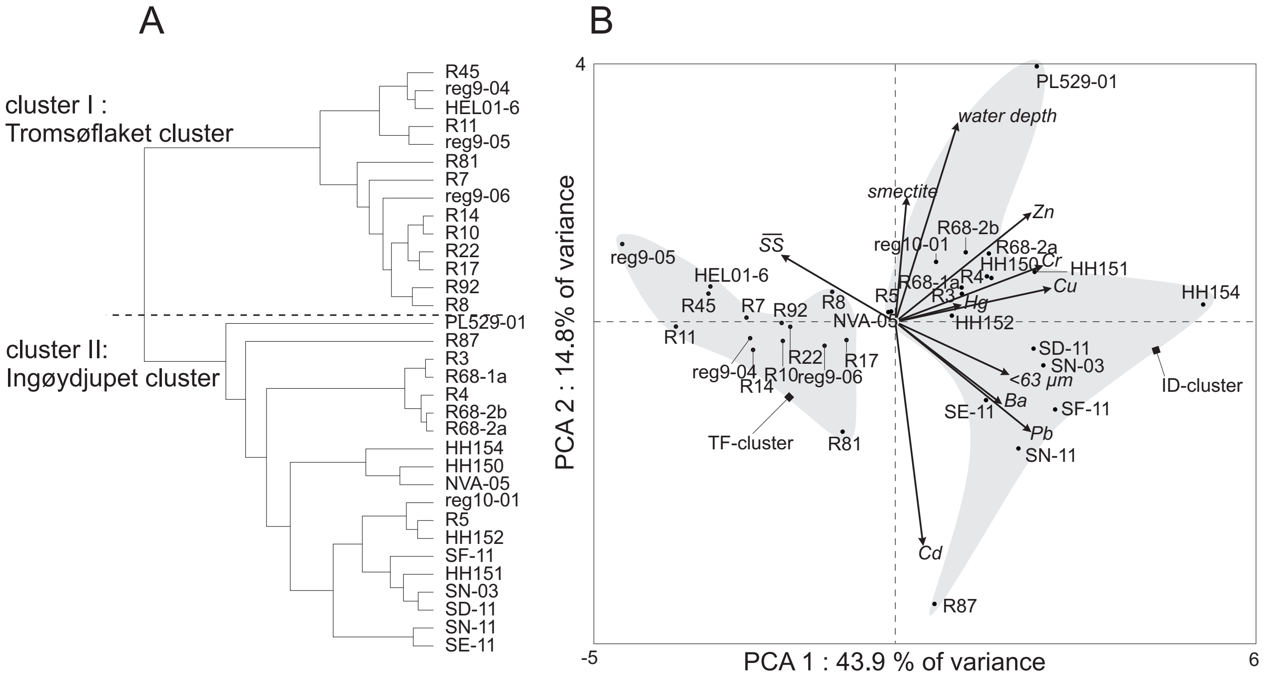


Figure 6. Habitat characterization.

Statistical analyses: (a) Q-mode clustering of sample sites based on standardized metal concentrations and sediment properties using Ward’s method (Euclidean distance); (b) principal component analysis with same parameters as used in Q-mode clustering. Grey areas represent cluster I and II found with the Q-mode clustering.

Figure 7

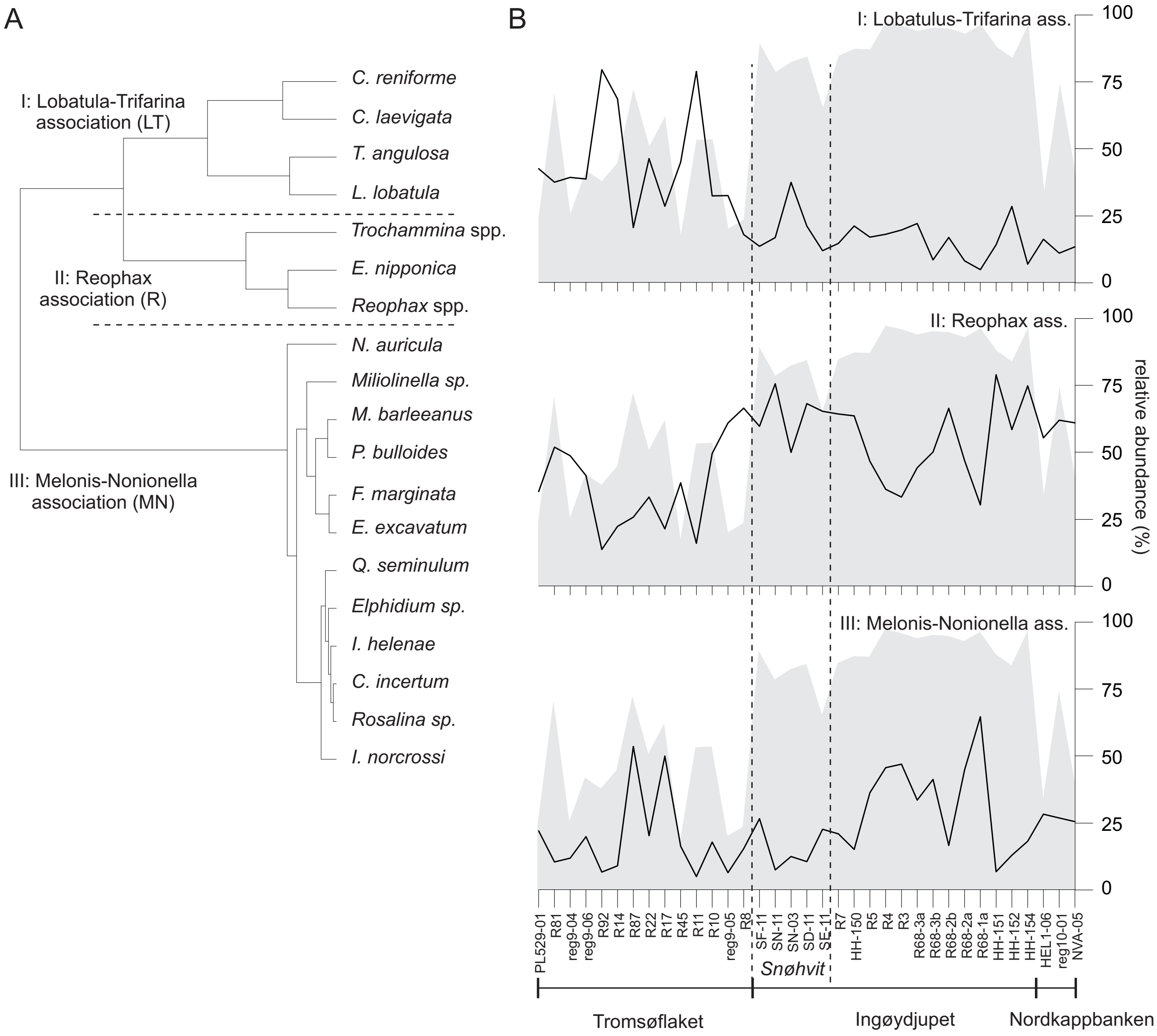


Figure 7. Fauna-habitat responses.

Statistical analysis: (a) R-mode clustering of the common foraminiferal species; (b) Summed relative abundance of the species of the three associations found with the R-mode clustering along the depth transect indicated in Fig. 1b. The grey shading represents the fine fraction (< 63 µm). Regions are indicated below the x-axis.

Paper III

Natural variability of benthic foraminiferal assemblages and metal concentrations during the last 150 yrs. in the Ingøydjupet trough, SW Barents Sea

Noortje Dijkstra, Juho Junttila, Katrine Husum, JoLynn Carroll and Morten Hald

Manuscript intended for submission to Marine Micropaleontology

Paper IV

Sediment transport and deposition in the Ingøydjupet trough, SW Barents Sea

Juho Junttila, JoLynn Carroll, Katrine Husum and **Noortje Dijkstra**

Submitted to Continental Shelf Research

Paper V

The FOBIMO (FOraminiferal BIo-MOnitoring) initiative—Towards a standardised protocol for soft-bottom benthic foraminiferal monitoring studies

Joachim Schönfeld, Elisabeth Alve, Emmanuelle Geslin, Frans Jorissen, Sergei Korsun, Silvia Spezzaferri and **Members of the FOBIMO group**[i]:

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