Elsevier Editorial System(tm) for Marine Micropaleontology
Manuscript Draft

Manuscript Number: MARMIC-D-14-00020R3

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

Article Type: Research Paper

Keywords: Benthic foraminifera
Anthropogenic impact
Natural variability
Atlantic Water inflow
Heavy metals
SW Barents Sea

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Abstract: While today the SW Barents Sea is a relatively un-impacted and uncontaminated area, industrial activities related to the petroleum industry are projected to increase in the coming decades. This makes the area a valuable natural laboratory to establish pre-impacted baselines as a precursor for future seabed monitoring programs. Here we present benthic foraminiferal assemblages and metal concentrations in four sediment cores from the Ingøydjupet trough, SW Barents Sea, covering approximately the last 150 years. This information supports the application of foraminiferal assemblages as a bio-monitoring tool applicable in high latitudes.
At all stations, metal concentrations in the sediment correspond to no effect concentrations. The down-core metal concentrations are mainly attributed to natural variability of the clay fraction and total organic content of the sediments. Agglutinated foraminifera are poorly preserved down-core. Patterns in the calcareous foraminiferal assemblages suggest an enhanced food supply as a result of increased Atlantic Water inflow through the region during the last 150 years. At near-shore stations, the Norwegian Coastal Current additionally influences assemblages. Decadal scale climatic oscillations are indicated by increased calcareous fluxes and are attributed to variability in the food-rich Atlantic Water. This study serves as an important baseline data set prior to increasing industrial activities in the SW Barents Sea, and thereby contributes to a better understanding of natural environmental variability.

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*Research Highlights

Highlights

- Sediment heavy metal levels in the SW Barents Sea are of background value
- Benthic foraminifera reflect increased inflow of Atlantic Water towards present day
- Benthic foraminifera reflect changes in bottom current strength
- The data set is considered to reflect the natural variability of the region
- The data set serves as a pre-impacted baseline

Tromsø, 19-08-2015

Response to review - Ms. Ref. No.: MARMIC-D-14-00020R2

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

Dear Professor Frans Jorissen,

Please find attached our updated manuscript. We have changed our manuscript according the suggestions raised by you in your second review. This means that we have applied your suggested language corrections and have removed unnecessary repetition when applicable. The latter especially by reorganizing paragraph 6.2.3 and 6.3.

Our American co-author, JoLynn Carroll, did a thorough language check. Our manuscript should therefore now qualify as Standard English.

Yours sincerely,

Noortje Dijkstra

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

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1. Introduction

In polar regions, benthic foraminifera have been proven to be accurate indicators of paleoenvironmental and paleoceanographic changes both on glacial-interglacial and shorter time scales. Benthic foraminifera have specific environmental preferences and they preserve well in the sedimentary record. In pristine environments, the distribution of benthic foraminifera is mainly affected by water temperature and salinity, food availability, substrate type and the amount of dissolved oxygen (Murray, 2006). Benthic foraminifera are used to monitor changes in environmental conditions because they have specific environmental preferences (Boltovskoy et al., 1991; Schafer, 2000; Scott et al., 2001; Murray, 2006) and fast turnover rates (Kramer and Botterweg, 1991).

Studies in European waters, e.g. the French Atlantic coast, the Mediterranean and southern Norway, have demonstrated the potential of both living and fossilized benthic foraminiferal assemblages to serve as environmental quality indicators (e.g. Armynot du Châtelet et al., 2004; Alve et al., 2009; Frontalini and Coccioni, 2011; Bouchet et al., 2012; Dolven et al., 2013). The application of benthic foraminifera as environmental quality indicators is less well established in polar regions (e.g. Elberling et al., 2003). The use of benthic foraminifera as a bio-monitoring tool is complicated due to variability in both the ecosystem and the physical environment. Therefore, detailed site-specific studies are needed to a) understand the relation between benthic foraminifera and the physical environment; b) gain insight into the natural variability of the region; and c) establish the pre-impacted baseline conditions.

In this paper we discuss data from the Ingøydjupet trough in the southwestern Barents Sea (Fig. 1). This sub-polar environment is known to be relatively uncontaminated (Boitsov et al., 2009; Dijkstra et al., 2013), although petroleum industry activities are increasing in the area.

This makes the region a valuable natural laboratory to establish pre-impacted baseline conditions for this region.

To optimize the use of benthic foraminifera as a bio-monitoring tool for petroleum industry discharges, it is important to separate between assemblage changes as a result of natural changes in the environment and those resulting from anthropogenic activities. This requires acquiring information on the present spatial natural variability within the area (Dijkstra et al., 2013), the temporal variability of both benthic foraminiferal assemblages and sediment properties, and the natural range and variability of metal concentrations. These three parameters respond to changing oceanographic conditions and sedimentary regimes.

The overall objective of the present study is to gain insight into the natural range and temporal variability of benthic foraminiferal assemblages and metal concentrations in Ingøydjupet. This is accomplished by characterizing the down-core distribution of benthic foraminiferal assemblages and the ranges and fluctuations of metal concentrations on a high-resolution time scale in four sediment cores covering the last 150 years. These parameters are correlated with down-core changes in sediment properties and total organic carbon (TOC) concentrations studied in Junttila et al. (2014) which reflect changes in bottom current strength, water mass dominance, food availability and the sediment regime. The outcome of the study establishes the pre-impacted baseline conditions for future reference.

2. Regional settings

Ingøydjupet was formed by an eroding ice sheet. Water depths of over 400 meters are found in this glacial trough. To the west is a shallow bank area, known as Tromsøflaket (Fig.1) (Andreassen et al., 2008). The sedimentary environment in the SW Barents Sea is characterized by strong bottom currents on the shallow banks, e.g. Tromsøflaket, and low energy currents in the deeper areas, e.g. Ingøydjupet. This results in relatively coarse-grained sediments at shallow water depths as a result of winnowing, while finer sediments are deposited in the deeper areas. Ingøydjupet is therefore known as a local depo-center for sediments transported by the prevailing water masses in this region (e.g. Bellec et al., 2008; Dijkstra et al., 2013; Junttila et al., 2014).

The Norwegian continental margin and SW Barents Sea comprise two water masses: Atlantic Water and Coastal Water. Ingøydjupet is influenced by the North Cape Current (NCaC; 3 °C; > 35 psu) which transports Atlantic Water and the Norwegian Coastal Current (NCC; 3-13 °C; 30-35 psu) which transports Coastal Water (Hopkins, 1991; Ingvaldsen et al., 2004) (Fig. 1). The average current velocity of the NCC (30 cm/s) is generally higher than the average velocity of the NCaC (< 5 cm/s) (Ingvaldsen et al., 2004).

The pathway of Atlantic Water is topographically steered by the continental margin entering the Barents Sea trough the Bjørnøyrenna trough. The relatively deeper glacial troughs, e.g. Ingøydjupet and Bjørnøyrenna, enable the inflow and outflow of Atlantic Water across the shelf (Moseidjord et al., 1999).

The NCC originates mainly from the Baltic, with contributions from the North Sea and runoff from the the Norwegian mainland, hence the lower salinities (Ikeda et al., 1989). The NCC is a density driven current system. Due to mixing with Atlantic Water from the NCaC, the salinity of the NCC increases towards the north, while stratification is reduced (Blindheim, 1987).

The boundary between the NCC and NCaC is a well-defined front where cold, low salinity Coastal Water meets warmer and more saline Atlantic Water (Hopkins, 1991). In general, Coastal Water is found in the upper 50-100 m of the water column during summer and < 200 m during winter (Sætre, 2007). The Coastal Water forms a wedge that thins toward the north (Ikeda et al., 1989), with increased mixing of the water masses offshore (Blindheim, 1987). The depth of the NCC is strongly influenced by freshwater input, tidal currents, wind conditions, bottom topography and Atlantic Water (Sætre, 2007). Hence, there is strong spatial and temporal variability in the location and depth of the front between these two water masses. The influence of lower salinity Coastal Water is observed at the bottom of the Ingøydjupet trough during periods of extensive mixing.

CTD measurements performed during sediment core retrieval showed surface water temperatures between 9.2 to 10.3°C and salinities between 34.5 to 34.9 psu. Bottom temperatures fluctuated between 4.1 and 4.6°C and bottom salinities of 35.1 psu were measured (Table 1; Fig. 2). The temperature-depth and salinity-depth profiles of cores 151 and 152 indicate the presence of a stratified water column in the NCC in the upper 20-50 m of the water column. The NCaC predominates at deeper water depths. The CTD profile of cores 150 and 154 showed a less pronounced stratification, with smaller salinity difference between the top and bottom sections of the water column. This indicates mixing of the water column occurred during the period of our sampling expedition.

The SW Barents Sea remains ice-free year-round due to the presence of warm Atlantic Water (Skagseth et al., 2008) as well as during the historical past (Divine and Dick, 2006; Smedsrud et al., 2013).

The inflow of warm Atlantic Water is an important heat source for the Arctic, and has a direct influence on the climate and sea ice formation in the Barents Sea. The variable inflow of warm and saline Atlantic Water towards the north is poorly understood. It is often linked to atmospheric forcing mechanisms on millennial to sub-decadal time scales, for example, the

North Atlantic Oscillation and shifts in the Atlantic Meridional Overturning Circulation (AMOC) (Dickson et al., 2000; Goosse and Holland, 2005; Trouet et al., 2011). On millennial or centennial time scales, climatic fluctuations include, for example, the Little Ice Age (LIA) and the Modern Period (MP) (e.g. Lamb, 1977; Grove, 1988; Bradley, 2000; Bengtsson et al., 2004; Eiríksson et al., 2006; Overland et al., 2008; Berner et al., 2011). The climatic conditions of the LIA (1500-1900 CE) are thought to be the result of a weak AMOC and negative North Atlantic Oscillation state, while the MP (1900 CE to present) is a result of an intensification of the AMOC, i.e. enhanced heat transport towards the region (Trouet et al., 2011). The timing of these responses might differ among regions (Trouet et al., 2011; Cunningham et al., 2013).

On decadal time scales, local wind forcing has been suggested as the main driver for decadal scale temperature oscillations and increased Atlantic Water inflow into the Barents Sea (Bengtsson et al., 2004; Risebrobakken et al., 2010). Records of sea surface temperatures (Rayner et al., 2003) and atmospheric temperatures (Ikeda, 1990) show: a cool early 1920s, warming from the mid-20s until the1950s, a cooling during the 1960s and 1970s, and a warming after the 1980s. Two temperature transects in the Barents Sea, i.e. the Fugløy-Bear Island transect west of Ingøydjupet (Ingvaldsen et al., 2002) and the Kola section in the south eastern Barents Sea (PINRO, 2013; Smedsrud et al., 2013), registered similar oscillations in the entire water column. Additionally, proxy records from the Arctic reconstructed enhanced inflow of Atlantic Water since 1980 CE (Spielhagen et al., 2011).

3. Material and methods

3.1 Sample retrieval and treatment

Sampling locations were selected in the deepest water depths of Ingøydjupet (Fig. 1, Table 1) where sediment accumulation rates are expected to be highest. Sediment cores were retrieved with a multi-corer in late July 2011 on the *R/V Helmer Hansen* of UiT The Arctic University of Norway (Fig. 1, Table 1). Conductivity, temperature and depth (CTD) were measured before retrieval of the cores. Six sediment cores were retrieved simultaneously with one multi-corer cast, of which two sediment cores were used in this study. The two cores were subsampled directly after retrieval at 1 cm intervals down to 20 cm. Core 154 was sampled down to 18 cm due to its short length. One core per station was used for analyses of grain size parameters and the foraminiferal assemblage study; the other core set was used for ^{210}Pb dating, heavy metal analyses and TOC analyses. Samples were stored cool (<5°C) and were freeze-dried before further analyses. Samples were wet sieved at mesh widths of 63 µm, 100 µm and 1 mm. The silt and clay fraction (<63 mm) was analyzed on a Micrometics SediGraph 5100 according to the method described in Coakley and Syvitski (1991). Weight percentages of sand (>63 µm), silt (4-63 µm) and clay (<4 µm) were calculated from the resulting grain size distributions. The 100 µm – 1 mm fraction was dried for foraminiferal analyses.

Grain size analyses, sortable silt mean grain size analyses and TOC analyses were performed at the Department of Geology, UiT. The sediments were ^{210}Pb dated at GEL Laboratories in Charleston, USA. Methodology and results of these parameters have been described previously by Junttila et al. (2014).

3.2 Metal concentrations

Metal concentrations were analyzed at UniLab AS, Fram Centre in Tromsø, Norway. Samples intended for metal analyses, were homogenized and sieved through a 2 mm mesh size before being decomposed with nitric acid. Concentrations of barium (Ba), cadmium (Cd), copper (Cu), chromium (Cr), lead (Pb), titanium (Ti) and zinc (Zn) were analyzed using inductively coupled plasma atomic emission spectroscopy (ICP-AES) or inductively coupled plasma sector field spectroscopy (ICP-SFMS), depending on the concentrations of the metals in the samples. Standard procedures of the Norwegian Standard 4770 were followed (Mannvik and Wasbotten, 2008; Mannvik et al., 2011; NorwegianStandard, 1994). Concentrations of Mercury (Hg) were measured with atom fluorescence (AFS) following the procedures of Norwegian Standard 4768 (NorwegianStandard, 1989; Mannvik and Wasbotten, 2008; Mannvik et al., 2011;).

3.3 Benthic foraminiferal assemblages

In polar regions, benthic foraminifera generally have small test sizes (Knudsen and Austin, 1996), and therefore assemblages from these regions have mainly been analyzed using the >100 µm size fraction. Hence in this study dead faunas were studied in the 100 µm to 1 mm fraction, to enable comparison to previous studies from the area (e.g. Hald and Steinsund, 1992; Saher et al., 2009; Saher et al., 2012; Steinsund, 1994). Samples were picked dry. A minimum of 300 individuals was identified per sample from a known split. Flux was calculated following the method of Ehrmann and Thiede (1985):

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

where SAR is the sediment accumulation rate. Bulk density was calculated from the sediment water content and porosity, with the assumption of an average mineral density of 2.45 g/cm^3. Sediment accumulation rates calculated by the Constant Rate of Supply (Appleby and Oldfield, 1992) model were used (see Chapter 4). Due to the high resolution dating of the cores (1 cm interval), sediment accumulation rates vary from sample to sample (Fig. 3).

3.4 Taxonomical notes

Benthic foraminifera were identified to species level following the generic classification of Loeblich and Tappan (1987) and the holotype descriptions in the Ellis and Messina catalogues. Nomenclature followed the accepted species names published in the WoRMS database (Hayward et al., 2014). Some species were grouped (Supplementary data A). The following groups were retained:

Cribrostomoides spp. Small specimens of *Cribrostomoides* impeding accurate identification. Includes among others *C. nitidum*, *C. kosterensis* and *C. subglobosum*.

Reophax spp. Unidentifiable specimens of *Reophax* species. Additionally contains fragments of larger *Reophax* spp.

Trochammina spp. Small specimens of *Trochammina*, includes among others T. *nana, T. nitida* and *T. rotaliformis*.

Cassidulina spp. Small specimens or specimens with damaged aperture or unclear umbilicus, impeding distinguishing between *C. laevigata* and *C. neoteretis*.

Elphidium spp. Small specimens of several *Elphidium* species, for which exact species identification was impeded and hence grouping was considered more appropriate. Might include specimens of *E. albiumbilicatum*, *E. excavatum*, *E. subarcticum* and *E. bartletti*.

Islandiella spp. Lumped species of *I. norcrossi* and *I. helenae.* Tests were often small impeding accurate identification, hence lumping was considered more appropriate.

In addition, it should be noted that *Epistominella nipponica* is morphologically identical to the deep-water species *Alabaminella weddellensis* from North Atlantic studies (e.g. Jennings et al., 2011; Knudsen et al., 2004; Rasmussen and Thomsen, 2004). Corresponding to results from other Barents Sea studies, we refer to this species as *E. nipponica*. Limited knowledge is available on the environmental preferences of *E. nipponica* (Hald and Steinsund, 1992; Steinsund, 1994; Saher et al., 2009). Therefore, this species has been interpreted, when appropriate, in line with the environmental preference of *A. weddellensis*, i.e. as an opportunistic species associated with pulsed phytodetritus (Gooday and Lambshead, 1989; Gooday et al., 1993; Smart and Gooday, 1997; Sun et al., 2006).

3.5 Data processing

Statistical analyses were performed to identify relationships among abiotic variables, i.e. clay abundance, TOC and metal concentrations. The analyses were performed to test whether changes in metal concentrations are associated with natural variability in clay and TOC, given the affinity of metals to these parameters (e.g. Contu et al., 1984; Horowitz, 1991; Degetto et al., 1997; Kennedy et al., 2002). The relationships among abiotic variables is expressed using a Pearson correlation calculated with Past 3.06 (Hammer et al., 2001). Before statistical analyses, values of all parameters were log transformed (log(1+X)) to remove the effects of different orders of magnitudes between variables and increase the importance of less abundant parameters (Manly, 1997). Correlation coefficients (r) (table 3) are considered to be of intermediate statistical relevance when the two-tailed probability (p) is between 0.01 and 0.05 and of high relevance when $p<0.01$ (Hammer et al., 2001).

4. Age model

Sediment cores were dated using the ^{210}Pb method. Three different models were used to calculate the age of deposition and to test the reliability of the determined ages, as described by Appleby and Oldfield (1992). The performance of these three models have been previously described and discussed in Junttila et al. (2014). In this study, sedimentation rates and age-depth relationships were calculated using the Constant Rate of Supply (CRS) model. This model assumes a constant flux of excess ^{210}Pb over time, but does not require a constant mass accumulation rate, allowing estimation of the variation in sedimentation rate over time

(Appleby and Oldfield, 1992). The ^{210}Pb fluxes derived by the CRS model ranged from 0.85 to 1.11 pCi/cm^2 yr (Fig. 3).

The ^{210}Pb inventory of cores 150 and 154 fell to zero at 18.5 cm and 15.5 cm core depth respectively. The ages below these intervals were extrapolated down to 20 cm using the sediment accumulation rates of the last dateable sediment interval. The estimated ages of the bottom of the cores 150 to 154 correspond to 1878, 1921, 1878 and 1864 CE (Common Era) respectively (Fig. 3).

In core 150, an interval of rapid sedimentation was observed (8-12 cm core depth). This interval was interpreted as disturbed and therefore samples from this interval were removed from the results presented below.

The CRS model does not consider effects of bioturbation on the ^{210}Pb fluxes down-core. Bioturbation, typically observed in the top of cores, can be recognized in the ^{210}Pb profile as a constant ^{210}Pb flux activity in the upper sediment intervals. This pattern was not observed in cores 150 and 154 (Fig. 3) and bioturbation was therefore assumed to be negligible in these cores. In core 151 however, an almost constant ^{210}Pb flux was observed for the top of the core, down to 4.5 cm core depth, corresponding to 2003 CE. Additionally, in core 152, the ^{210}Pb flux of the top 2.5 cm, corresponding to 2002 CE, showed indication of disturbance. Care should therefore be taken when interpreting the ages and sedimentation rates of these intervals in cores 151 and 152.

The ^{137}Cs activity in these sediment cores was below the detection limit and therefore this time marker could not verify the derived ^{210}Pb sediment ages. The absence of the ^{137}Cs time marker was attributed to the relatively low sediment accumulation rates and variable sediment sources in this region (Junttila et al., 2014).

5. Results

5.1 Metal concentrations

Concentrations of Ba, Cd, Cr, Cu, Hg, Pb, Zn and Ti were measured throughout the cores (Fig. 4; supplementary data B). Metal concentration ranges are summarized in Table 2. The Pearson correlation reveals that most metal concentrations correlate with either clay or TOC contents (r- and p-values are given in table 3). The following correlations were found on either an intermediate ($0.01<p<0.05$) or high significance level ($p<0.01$). In core 150, Cr, Cu and Zn show positive correlations with clay, while Hg and Pb show positive correlations with TOC (table 3). In core 151, Ba, Cd, Cr, Cu, Zn and Ti positively correlate with clay, while Pb correlates with TOC. In core 152, Cr, Cu and Zn correlate with clay, while Ba, Hg, Pb and Ti correlate with TOC. In core 154, a positive correlation with TOC is observed for Ba, Cr, Hg, Pb, Zn and Ti. Cd concentrations in core 154 are negatively correlated with both TOC and clay. Additionally, negative correlations include Cr (TOC) and Hg and Pb (clay) in core 150; Cr (TOC) in core 151; and Ba, Hg and Pb (clay) and Cr, Cu and Zn (TOC) in core 152. The following did not show a statistically significant affinity to TOC or clay: Ba, Cd and Ti in core 150; Hg in core 151; Cd in core 152; and Cu in core 154.

5.2 Benthic foraminiferal assemblages

Benthic foraminifera were present throughout all sediment intervals in the four cores. In total, 93 different taxa were identified; 59 calcareous and 34 agglutinated taxa (Supplementary data A). The total number of taxa ranges from 49 (core 152) to 58 (core 151) (Table 4).

5.2.1 Agglutinated assemblages

The flux of agglutinated foraminifera decreases rapidly down-core, with fluxes of <1 #/cm^2/year after 3,5 to 7,5 cm down-core (Fig. 5). Consequently, the relative abundance of agglutinated specimens decreases from between 28% (core 151) to 57% (core 152) of the total assemblage at the core top to < 5% at 3.5 cm (core 154) to 7.5 cm (core 151) core depth. The taphonomical loss of agglutinants indicates a poor preservation of agglutinants. *Cribristomoides, Reophax* and *Trochaminna* spp. and *Ammoglobigerina globigiriniformis* are abundant among the agglutinated taxa (Supplementary data A).

Down-core reduction of agglutinated foraminifera is a well-known phenomenon (Murray, 2006 and references therein). This poor down-core preservation of agglutinated taxa requires calculations of flux and relative abundance excluding all agglutinated taxa (Mackensen et al., 1990; Harloff and Mackensen, 1997), to avoid erroneous low relative abundances of calcareous taxa and increasing total fluxes towards the core top. Hence, relative abundances and fluxes presented below are based on the calcareous taxa only.

5.2.2 Calcareous assemblages

Most calcareous foraminifera are well preserved with little indication of dissolution. The calcareous flux (Fig.6 A) reaches maximum values between 25 (core 152) and 441 #/cm^2/year (core 151); minimum fluxes vary between <1 (core 150) and 2 #/cm^2/year (core 151) (Table 4). The average calcareous flux is highest in core 151 (mean = 52 #/cm^2/year) and lowest in core 152 (mean = 9 #/cm^2/year).

In cores 150, the calcareous flux increases towards present day. A pronounced increase in calcareous flux after 1907 CE is observed. Calcareous species fluxes in 151 also generally increase toward the present day, albeit that highest fluxes are observed in the middle part of the core. In core 152 fluxes generally increase towards the present day, while the calcareous flux in 154 shows an overall decline.

The distribution of the most common calcareous species, i.e. species with average relative abundances of >5 % in at least one sample of each core, are shown in Fig. 6 B. All cores are dominated by *Epistominella nipponica* (mean relative abundance = 38%) and *Melonis* *barleeanus* (23%). Other common species are *Lobatula lobatula* (7%), *Cassidulina laevigata* (7%) and *Cassidulina neoteretis* (5%) (Supplementary data A).

The relative abundance of *E. nipponica* increases towards the top of cores 150, 151 and 152; whereas the relative abundance of this species in core 154 increases from the base of the core until 1968 CE. Thereafter the abundance of this species is low (1968 – 2011 CE) in comparison to the preceding interval (1864 -1968 CE). A pronounced increase in relative abundance of *E. nipponica* is observed around 1907 CE in core 150. This corresponds to the rapid increase in total calcareous species flux and results in a shift of dominance from *M. barleeanus* to *E. nipponica.* The 1878 – 1907 CE interval in core 150 and the 1968-1997 CE interval in core 154, are the only intervals where *E. nipponica* does not dominate the assemblage. In these intervals, the assemblage is dominated by *M. barleeanus.* The relative abundance of *M. barleeanus* declines in core 150, while an overall increase is observed in the other cores. In all cores the relative abundances of *C. laevigata* and *C. neoteretis* decrease towards present day. In cores 150 and 151 the relative abundance of *L. lobatula* declines towards the top of the core. In cores 152 and 154, the relative abundance of *L. lobatula* declines from the base of the core until 2002 CE and 2003 CE respectively. Thereafter, relative abundances increase towards the core top (Fig. 6).

6. Discussion

6.1 Natural variability of metal concentrations and anthropogenic influences

The Pearson correlation displayed that most of the metal concentrations show a positive correlation on a high ($p<0.01$) or intermediate ($0.01<p<0.05$) significance level with either the clay or TOC content of the cores (Fig. 4; Table 3). However, some exceptions occur and are discussed further below. The affinity of metals to finer particles and TOC is well known and is attributed to the absorptive properties of organic matter and clay minerals as well as the larger specific surfaces of fine grained sediment particles (e.g. Contu et al., 1984; Horowitz, 1991; Degetto et al., 1997; Kennedy et al., 2002). It may therefore be concluded that the temporal trends of most of the analyzed metals in the cores are largely determined by changes in sediment properties, rather than changes in the input of metals, i.e. enrichment or depletion by a source.

In Ingøydjupet, the natural temporal variability of the bottom current strength has a large impact on grain size distributions (Junttila et al., 2014); high bottom current velocities result in winnowing of fine grained particles, while the coarser particles remain in place. This results in relatively coarser grain size distributions and a high sortable silt mean grain size during periods of enhanced bottom current velocities. Additionally, inflowing Atlantic Water of the NCaC transports organic matter (Knies and Martinez, 2009) towards the region. Changes in bottom current velocities and inflow of Atlantic Water thus have an indirect effect on the accumulation of metals. Additionally, changes in the prevailing current direction may also result in the transport of more metals and/or contaminants from different source areas towards the region. The development of a bio-monitoring tool therefore requires both baseline information on the interaction between sediment properties and benthic foraminifera and baseline information on the natural range and variability of contaminant concentrations, contaminant interactions with sediments and changes in oceanographic conditions.

For some metals, the Pearson correlation does not show a statistically significant correlation with TOC or clay on high to intermediate significance levels (Table 3). In core 150, Ba and Ti show a similar pattern as TOC and clay respectively, albeit not statistically significant according to the Pearson correlation matrix. Similarly, in core 154, Cu shows a similar pattern as TOC, and in core 151, Hg shows a similar pattern as clay, but again, the Pearson correlation coefficients are not statistically significant. The absence of a statistically significant correlation may be due to the fact that the metal concentrations are the result of multiple variables, e.g. both clay and TOC contents, rather than clay or TOC alone. The Pearson correlation is a bivariate method, hence the influence of multiple variables on the metal distribution will in many cases not lead to significant correlations with the individual parameters.

In core 152, Cd is strongly elevated between 1915 and 1964 CE. In core 150 a similar Cd peak is observed between 1893 and 1926 CE. Previous studies have documented relatively high Cd concentrations that were not attributable to grain size properties or enhanced deposition of contaminants (AMAP, 1998). These high Cd concentrations were thought to result from Cd fixation by precipitation of sulphides in the sub-surface. This may also be a possible explanation for the higher Cd concentrations in the mentioned intervals of cores 150 and 152 although sulphides were not analysed in our study. A pollution source of Cd is unlikely considering the age of the depth intervals with elevated concentrations. In core 154, Cd concentrations decrease down-core and show a statistically significant negative correlation with both TOC and clay content (Table 3) in spite of the known affinity of Cd to organic compounds (Kjeldsen and Christensen, 1996). Kjeldsen and Christensen (1996) ascribed similar patterns to diagenetic processes leading to vertical mobilization and migration of Cd in the sediment. Hence the absence of a positive correlation between clay or TOC and Cd in core 154, might be the result of post-depositional processes. Jensen et al. (2009) observed similar Cd profiles and attributed them to diagenetic processes. As a result of diagenesis, Cd profiles are not considered reliable for assessing the temporal variability of the element (AMAP, 1998).

In core 152, many of the analyzed metals show a positive correlation with clay together with a negative correlation with TOC, or vice versa (Fig.4; table 3). This is attributed to the typical opposite down-core trend of TOC and clay as shown in this core.

The Norwegian Pollution Control Authorities have developed guidelines for the environmental quality of contaminated sediments (Bakke, 2010) following the principles of the risk assessment guidelines of the European Water Framework Directive (WFD: WFD, 2000). The Norwegian environmental regulations define reference (background) concentrations of metals in sediments and four additional classes based on the ecotoxicity of the contaminants (Bakke, 2010). The five classes are defined accordingly; I: background levels of metal concentrations; II: low concentrations with no toxic effects; III: medium concentrations with toxic effects after chronic exposure; IV: high concentrations with toxic effects after short-time exposure; V: very high concentrations with acute toxic effects. These environmental classes exist for all studied metals in this study, apart for Ba and Ti (see Supplementary data B for the concentration ranges of the classes for each of the metals). The transition between classes II and III is most important since it separates no effect concentrations from chronic toxicity concentrations (Bakke, 2010). The following intervals showed metal concentrations corresponding with class II (no toxic effects): Hg in core 150 (1982-2009 CE) and core 154 (1990-2008 CE); Cr in core 151 (1921-1933 CE) and; Cd in core 154 (1864-1889 CE, 1902 CE and 1935 CE). All other metals in core intervals have metal concentrations corresponding to background/reference conditions, i.e. class I (Fig.4, Table 2 and Supplementary data B). Since all metal concentrations fall within classes I or II it should be emphasized that metal concentrations are of levels considered to have no impact on the environment (Bakke, 2010). Similar no effect concentrations for metals were observed in surface sediment samples from Ingøydjupet and the adjacent Tromsøflaket (Dijkstra et al., 2013).

Sediment cores from nearby locations in Ingøydjupet (Jensen et al., 2009), showed increased concentrations of Hg and Pb after ~1960 CE, with values still in classes I and II. Similar patterns are observed in cores off Greenland (AMAP, 2005). This coincides with the timing of the onset of releases of leaded gasoline into the atmosphere (AMAP, 2005). Hg and Pb are known to be transported towards the Arctic region by long range atmospheric transport from more industrialized parts of the Northern Hemisphere (Asmund and Nielsen, 2000; AMAP, 2005). In our study, concentrations of Hg and Pb in core 152 are, relative to other parts of the core, low and stable until ~1960 CE; thereafter their concentrations rapidly increase. Although Hg and Pb contents are correlated with increased TOC content, it could very well indicate an anthropogenic signal as well. In cores 150 and 154, Hg and Pb also increase towards the present, as does the TOC content, albeit with no clear shift observed around 1960 CE. Pollution records often register decreased Pb and Hg concentrations after the 1970s/1980s as a result of the reduction and subsequent ban of leaded gasoline and better technologies for coal combustion (AMAP, 2005). In core 152, Hg concentrations indeed decrease after 1985 CE, whereas Pb concentrations decrease in the very top of the core. This decrease is not observed in cores 150 and 154.

We therefore argue that the patterns of Hg and Pb concentrations are the only potential signs of anthropogenic induced input of metals to the environment. With metal concentrations considered to be non-critical (class I or II) according to the Norwegian Pollution Control Authorities guidelines (Bakke, 2010) and metal variability correlated with TOC or clay content, we suggest that the Ingøydjupet environment may be characterized as relatively un-impacted during the last 150 years. The relatively high amount of fine grained sediments and TOC in the sediment cores (Fig. 4), and the strong correlations observed between metals and fine grained sediments and TOC, indicates that Ingøydjupet sediments serve as a natural trap for contaminants. This is illustrated by the overall highest metal concentrations in core 154 corresponding to the highest amount of fine grained sediments (clay + silt) and TOC (Fig. 4), further indicating that clay and TOC efficiently absorb metals for reasons explained above (e.g. Contu et al., 1984; Horowitz, 1991; Degetto et al., 1997; Kennedy et al., 2002).

6.2 Benthic foraminiferal assemblages

6.2.1 Living versus dead assemblages

Faunal assemblages are dominated by *E. nipponica, M. barleeanus, L. lobatula* and *C. laevigata.* Similar species were abundant within the living assemblages from surface samples from Ingøydjupet and the nearby Tromsøflaket (Dijkstra et al., 2013). Note that these living assemblages (Dijkstra et al., 2013) represent the total relative abundances including agglutinated foraminifera, while dead assemblages (this study) represent relative abundances of only the calcareous faunal fraction.

The living benthic foraminiferal assemblage in Tromsøflaket is dominated by epifaunal suspension feeders, e.g. *L. lobatula* and *Trifarina angulosa* (e.g. Mackensen et al., 1985; Hald and Steinsund, 1992) as expected for this high-energy environment with a predominance of coarse-grained sediments on the seafloor. Dijkstra et al. (2013) also observed the highest abundances of living *C. laevigata* on the Tromsøflaket plateau in association with coarse-grained sediments. In Ingøydjupet, the living benthic foraminiferal assemblage is dominated by infaunal species, e.g. *M. barleeanus* and *Nonionella auricula* which thrive on buried organic material (e.g. Linke and Lutze, 1993; Steinsund, 1994; Fontanier et al., 2002) and prefer fine-grained sediments and calm environments (Dijkstra et al., 2013). Nevertheless, living specimens of *L. lobatula* and *C. laevigata* were also present in substantial numbers in Ingøydjupet.

Living specimens of *E. nipponica* were most frequently observed at sites with low species diversity (Dijkstra et al., 2013). Similar observations were made for dead assemblage observed in surface samples on the flanks of Ingøydjupet where few other foraminifera were present (Hald and Steinsund, 1992). Statistical analyses suggested that factors other than temperature, sediment composition and TOC controlled the distribution pattern of this species. The high abundance of *E. nipponica* was attributed to sediment reworking by high bottom current speeds and transportation of this species from the Tromsøflaket bank area to the flanks of Ingøydjupet (Hald and Steinsund, 1992). The small size and round form of this species enables tests to be easily picked up when bottom current speeds are high (Scott and Medioli, 1980; Murray et al., 1982).

Cassidulina neoteretis was observed infrequently in the living assemblage. Living specimens of *C. neoteretis*, associated to high food availability and chilled Atlantic Water (Mackensen and Hald, 1988), were slightly more abundant in the samples from Ingøydjupet. Although *Nonionella auricula* was frequently observed in the living assemblages, it represented <5% of the dead assemblage. The low abundance of this species may also be the result of the fragility of this species resulting in poorly preserved specimens in the sedimentary archive (Saher et al., 2012).

6.2.2 Correlations between benthic foraminifera and metal concentrations

As described above, all metal concentrations are associated with 'no effect' levels (classes I and II) according to the Norwegian system for classification of environmental quality (Bakke, 2010). Hence an impact of the metals on the benthic foraminiferal assemblages is not expected. Non-impacted, pre-pollution, faunas have previously been reported from a Norwegian fjord where metal concentrations also correspond to classes I and II (Polovodova Asteman et al., 2015).

Nevertheless, similarities are detected when comparing down-core patterns of metal concentrations (Fig.4) to patterns of the relative abundance of some species (Fig. 6). This is illustrated below by two examples and visualized in Supplementary figure I.

In core 150, the Pearson correlation found a positive correlation for Cr with clay and a negative correlation for Hg with clay, both with a high significance level ($p<0.01$; Table 3). Similarly, *E. nipponica* exhibits a negative trend with both clay and Cr content (Fig. 6) as well as with Hg (Supplementary figure I). However, since these metal concentrations are below effects levels (classes I and II), their influence on foraminiferal distribution may rather be attributed to the influence of changes in clay and TOC content both on foraminiferal assemblages and metal distributions.

Another example is seen in core 154 where a positive correlation at high significance level is observed for Pb and Hg with TOC content. In this core *C. neoteretis* exhibits a negative trend while *M. barleeanus* exhibits a positive trend with TOC. While both *C. neoteretis* and *M. barleeanus* distributions are influenced by sediment properties, they both appear to be influenced by changes in metal concentrations (Supplementary figure I).

The importance of sediment structure on benthic foraminiferal assemblages is well documented in pollution and bio-monitoring related studies (e.g. Armynot du Châtelet et al., 2009; Celia Magno et al., 2012; Dijkstra et al., 2013). To avoid erroneous conclusions when interpreting foraminiferal patterns and contaminant levels, grain size and organic matter distributions should also be investigated.

6.2.3 Foraminiferal distribution patterns of the last 150 years

Atlantic Water is the main conveyor of heat towards northern latitudes in addition to a transporter of nutrients. Previous studies attributed climatic changes during the Late Holocene to variability of the influx of Atlantic Water to the northern North Atlantic region (Dickson et al., 2000; Goosse and Holland, 2005). Knies and Martinez (2009) showed that TOC in the SW Barents Sea is mainly composed of marine organic material originating from the nutrient rich Atlantic Water, indicating a high vertical export of organic matter. High biological productivity results in increased organic detritus fluxes providing an important primary and secondary food source for benthic foraminifera (Loubere and Fariduddin, 1999). The variability in inflow of the nutrient rich Atlantic Water therefore influences the benthic foraminiferal assemblages (Table 5).

The benthic foraminiferal assemblage observed in sediment cores from Ingøydjupet (Supplementary data A) are dominated by species, e.g. *E. nipponica, C. laevigata, M. barleeanus* and *C. neoteretis,* reflecting the relatively warm and/or food rich Atlantic Water influenced environment. It is therefore, that the observed overall increase in total calcareous flux (Fig. 6A) towards present day in cores 150, 151 and 152 likely reflects higher food availability and warmer conditions in response to an increase in the influence of Atlantic Water at the core localities. The increased inflow of Atlantic Water towards Ingøydjupet, corresponds to proxy-based records from the northern North Atlantic and Barents Sea covering the last 2000 years (e.g. Hald et al., 2011, Spielhagen et al., 2011, Wilson et al., 2011). Spielhagen et. al. (2011) observed a further intensification and warming of Atlantic Water inflow towards the Arctic after 1980 CE. Our records from Ingøydjupet showed overall increased species fluxes after approximately 1980 CE, suggesting intensification of Atlantic Water inflow. It should be noted that for cores 151 and 154, this increase does not result in fluxes that are higher than in earlier parts of the record. This may be the consequence of decreased fluxes in preceding intervals. Nevertheless, an enhanced influence of Atlantic Water after 1980 CE is supported by increased TOC values (Fig. 6) and increased abundances of the smectite clay mineral of the cores (Junttila et al., 2014). Smectite has no local source in the SW Barents Sea and is known to be transported by the NCaC from the mid-Atlantic ridge, Vøring plateau and Faroe Islands to the SW Barents Sea (Junttila et al., 2010; Vogt and Knies, 2009).

On top of the overall increase in flux, there is a pronounced shift from relatively low to relatively high total calcareous species fluxes in core 150 at 1907 CE, emphasizing low food availability before and a sudden large increase in food input after 1907 CE. This enhanced food availability is related to enhanced inflow of nutrient rich Atlantic Water to the core site after 1907 CE for reasons explained above. The timing of the pronounced increased calcareous species fluxes in core 150 corresponds to the transition of the LIA to the MP around 1900 CE (Lamb, 1977). Previous studies reconstructed a weak AMOC, and hence transport of Atlantic Water towards the north, during the LIA (Dickson et al., 2000; Goosse and Holland, 2005). Also from the base at core 151, a large increase in calcareous flux is observed, implying increasing food availability in the first half of the twentieth century. The age of the LIA/MP transition is however not covered by core 151, which core bottom was dated at 1921 CE. No clear flux increases at the LIA/MP transition were observed in cores 152 and 154. This suggests that sites 152 and 154, located further offshore, have been in contact with Atlantic Water before 1900 CE, whereas site 150, and potentially 151, located closest to shore, was in contact with Atlantic Water later, i.e. the NCaC penetrated into Ingøydjupet towards core sites 150 and 151 only after the LIA/MP transition. Junttila et al. (2014) reconstructed the highest influence of NCaC at the locality of core 154 based on the TOC and smectite content of the core. The continuous presence of Atlantic Water at site 154 is also reflected by the low variability in calcareous species fluxes and a minor decline in flux towards the sediment-water interface. We attribute the two peaks in flux in core 154 around 1900 and 1930 CE to high sedimentation rates reconstructed by the ^{210}Pb age model.

The high abundances and dominance of *E. nipponica* reflects a high phytodetritus flux to the seafloor (e.g. Gooday and Lambshead 1989, Gooday et al., 1993) and relatively warm conditions (e.g. Steinsund, 1994; Knudsen et al., 2004; Jennings et al., 2011; Saher et al., 2012), i.e. presence of Atlantic Water. The increase of the relative abundance of *E. nipponica* towards the top of cores 150, 151 and 152 suggests an increased influence of Atlantic Water, which is corroborated by the increased calcareous flux. The shift to fauna dominated by *E. nipponica* (Fig. 6B) after 1907 CE supports increased food availability and hence the presence of Atlantic Water at the core site after the LIA/MP transition. Wilson et al. (2011) observed increased abundances of *E. nipponica*, and total fluxes, since 1900 CE in a core north of our study area. These increases are accompanied by higher δ^{18}O-reconstructed bottom water temperatures. *E. nipponica* is a species thriving in warmer bottom waters (Steinsund, 1994; Knudsen et al., 2004; Jennings et al., 2011; Saher et al., 2012). The faunal change at 1907 CE in core 150 might therefore not only indicate enhanced food supply but additionally a warming of the bottom waters due to occurrence of Atlantic Water at the site. This is in line with temperature increases at the LIA/MW transition observed in proxy records from the northern North Atlantic (e.g. Spielhagen et al., 2011).

The continuous presence of *M. barleeanus* corresponds to a high and steady food supply of degraded organic matter and high sedimentation rates (e.g. Mackensen et al., 1985; Hald and Steinsund, 1992; Linke and Lutze, 1993) as reflected in the fine-grained and organic-rich environment of Ingøydjupet (Dijkstra et al., 2013; Junttila et al., 2014) (Fig. 4). The dominance and high relative abundance of *M. barleeanus* in core 150 before 1907 CE and in core 154 after 1968 CE, is attributable to changes in the abundances of *E. nipponica* rather than changing environmental conditions.

The distribution pattern of *L. lobatula*, associated with coarse sediments and high bottom current velocities (Nyholm, 1961; Mackensen et al., 1985) reflects changes in the physical environment. This species declines toward present-day time in cores 150 and 151. Additionally *L. lobatula* declines until 2002 CE and 2003 CE in cores 152 and 154 respectively. This corresponds to an increase in the fine silt fraction, reflecting the epifaunal behavior and the preference of this species for coarse sediments. The increase of *L. lobatula* in the top of cores 152 and 154 corresponds to an increase in sand content.

A decline of *C. laevigata* and *C. neoteretis* towards present time is observed in all cores. Both species are associated with Atlantic Water, the latter with cold Atlantic Water. The patterns in relative abundance of the other dominant species and the increase in calcareous species fluxes, suggest an increase in food input and warm conditions associated with increasing Atlantic Water inflow. We therefore argue that the decline in *C. laevigata* is a result of changes in the physical environment. *Cassidulina laevigata* and *C. neoteretis* are limited by fine sediments (Mackensen et al., 1985; Mackendsen and Hald, 1988, Qvale, 1985; Jennings et al., 2004). In all cores, the fine silt fraction increases toward the present day, creating progressively unfavorable conditions for these species and hence a decline in relative abundances. The decrease of *C. neoteretis*, associated with cold Atlantic Water (Mackensen and Hald, 1988) may also be attributed to warming of the bottom water.

In addition to Atlantic Water, the Coastal Water of the NCC is known to be a seasonal source of nutrients that provides nutrients during summer (Peinert, 1986) that triggers phytoplankton primary production, leading to an additional source of organic flux for benthic fauna. Calcareous species fluxes are in general higher in cores 150 and 151 in comparison to the other core locations, especially in the 1907-1960 CE (core 150) and 1940-1978 CE (core 151) intervals. Hence we argue that in addition to nutrients from Atlantic Water, nutrient input from Coastal Water also contributed to the food supply for benthic faunas through mechanisms explained above. High abundances of *E. nipponica* between approximately 1920-

1960 CE and 1940-1980 CE in cores 150 and 151 respectively support this hypothesis, because the morphological identical species *A. weddellensis* (see taxonomical notes) is associated with pulsed or seasonal phytodetritus (e.g. Gooday and Lambshead, 1989).

The NCC is known to have higher bottom current velocities than the NCaC (Ingvaldsen et al., 2004), and the fluctuations of the relative abundances of *E. nipponica*, *M. barleeanus* and *L. lobatula* indicate enhanced bottom current speeds during the 1920-1960 CE (core 150) and 1940-1980 CE (core 151) intervals for reasons explained below. Hald and Steinsund (1992) attributed high abundances of *E. nipponica* to high velocities of the NCC, as a result of reworking of this species by strong bottom currents on the shallower Tromsøflaket bank area and transportation to the flanks of Ingøydjupet. Later studies by Hayward et al. (2002) and Saher et al. (2012) linked *E. nipponica* to increased reworking and bottom current strength. The high abundances of *E. nipponica* in core 150 (1920-1960 CE) correspond to coarser sediments and high sortable silt mean grain size (Fig. 6C) (Junttila et al., 2014) and might, therefore, also be the result of higher NCC current velocities (e.g. McCave et al., 1995, Bianchi and McCave, 1999; Hass, 2002). A strong bottom current is also suggested by the decreased abundance of *M. barleeanus*, a species associated to fine grained sediments and calm conditions (e.g. Mackensen et al., 1985, Hald and Steinsund, 1992). *L. lobatula*, thrives on coarse sediments and thereby indicates strong hydrodynamic activity (Mackensen et al., 1985). The apparent contradiction of lower abundances in a high energy environment may be due to the preference of *L. lobatula* for lower salinities (S<32 psu; Murray, 1991). This indicates the presence of the less saline NCC during these time intervals. Hence, we argue that the foraminiferal assemblages of the cores nearest to shore, cores 150 and 151, are additionally influenced by fluctuations in the depth and strength of the Norwegian Coastal Current.

6.3 Variability of Atlantic Water inflow

As Atlantic Water transports both heat and nutrients, resulting in enhanced food supply for benthic foraminifera for reasons explained above, temperature records and foraminiferal flux records might show similar patterns. It should be noted that, as a result of uncertainties in our age model, it is not feasible to construct detailed temperature fluctuations based on these records. Nevertheless, common long term trends are observed when comparing the calcareous species fluxes to temperature measurements from the Kola section (PINRO, 2013) and the Fugløy-Bear Island transect (Ingvaldsen et al., 2002) (Fig. 7). The total calcareous species flux of core 150 shows some similarity to decadal scale climatic oscillations. The warm period between the mid- 1920s and 1950s, measured in both transects, is additionally observed in sea surface temperature records (Rayner et al., 2003) and atmospheric temperature measurements (Ikeda, 1990) from the Northern Hemisphere. The warm anomaly, as a result of enhanced heat influx by Atlantic Water, corresponds to increased foraminiferal fluxes in core 150 as a result of enhanced food supply. During the cool 1960s and 1970s (Ikeda, 1990; Rayner et al., 2003), foraminiferal fluxes decrease in core 150, indicating cooler conditions and reduced Atlantic Water inflow (Knies and Martinez, 2009). An increase in foraminiferal fluxes occurs during the warm 1980s implying enhanced inflow of Atlantic Water in core 150. The correspondence between temperature records and flux records is less pronounced in core 151 and absent in core 152 and 154. The absence or less pronounced signal of core 152 and 154 in comparison to core 150 might be the result of differences in the dominant water masses at these core sites. As previously mentioned cores 152 and 154 are influenced by NCaC during the entire covered time span, while core 150 and 151 also experience periods of weak or even absent Atlantic Water inflow. A change in influence of NCaC at the latter two coring locations therefore has had a larger effect on the foraminiferal assemblages.

The natural variability of food availability due to variable Atlantic Water inflow has been shown to be important factors influencing benthic foraminiferal assemblages. It is therefore important that both Atlantic Water variability and changes in the physical environment are considered when using benthic foraminifera to monitor changes in environmental conditions. Additionally, sediment TOC content has been linked with variable inflow of Atlantic Water (Knies and Martinez, 2009, Junttila et al., 2014), while clay content responds to changing bottom current strength. A strong positive correlation was observed between TOC and clay content with metal content in the cores. It is therefore essential to consider the role of natural variability in oceanographic conditions when using benthic foraminiferal assemblages to monitor for potential anthropogenic impacts on the environment.

7. Conclusions

Metal concentrations and benthic foraminiferal assemblages have been investigated in four sediment cores from Ingøydjupet, SW Barents Sea, to gain insight into the temporal variability of these two parameters during the last 150 years. The data set serves as a reference database for monitoring future potential environmental impacts associated with petroleum industry activities. Metal concentrations and benthic foraminiferal assemblages were compared to sediment properties: grain size distribution, sortable silt mean grain size and total organic carbon as presented previously in Junttila et al. (2014).

Metal concentrations in the sediment correspond to predicted no effect levels (classes I and II; Bakke, 2010) and therefore are not expected to result in adverse effects on foraminiferal assemblages. Down-core changes in metal concentrations are mainly attributed to changes in clay and TOC content and thus reflect natural variability in this region. Only the distribution of Pb and Hg in the upper part of core 152 might represent an anthropogenic signal. The strong correlation of the metal concentrations with sediment properties, and the strong influence of water masses on sediment distribution (Junttila et al., 2014), indicates that changes in oceanographic conditions might influence the future deposition of contaminants in the region. It is therefore of great relevance to take into account natural variability when monitoring changes in contaminant levels. In the present study, the observed similarities in down-core patterns of benthic foraminifera species and metal concentrations more likely reflect an effect of the affinity of both foraminifera to either clay or TOC, than an impact of metals on the foraminiferal assemblages.

Agglutinated species were poorly preserved in the sedimentary record and were omitted from flux and relative abundance calculations. The species *E. nipponica*, *M. barleeanus*, *L. lobatula*, *C. laevigata* and *C. neoteretis* dominated the assemblages, reflecting the relatively warm conditions and, hence, high food flux attributable to Atlantic Water inflow in Ingøydjupet.

Three cores showed increased calcareous species fluxes towards present day, indicating favorable food conditions as a result of enhanced inflow of nutrient rich Atlantic Water during the past 150 years. Furthermore, near shore assemblages in cores 150 and 151 were influenced by the NCC during some intervals of time. The benthic foraminiferal assemblage of cores 152 and 154, located furthest off shore, is mainly influenced by changes in the inflow of Atlantic Water.

The foraminiferal assemblages of some of the cores reflect climatic signals on a longer time span, such as the transition between the Little Ice Age and Modern Period (core 150). Decadal scale climatic oscillations might be visible in the near shore cores 150 and 151 in their total foraminiferal flux, with higher total fluxes during periods of increased Atlantic Water inflow.

The results of this study provide baseline information for the development of a foraminiferal bio-monitoring tool applicable in high latitude waters. With the expected increase in industrial activities an adequate bio-monitoring tool will be of great value.

Acknowledgement

This study was conducted as a part of the Environmental Waste Management (EWMA) - project funded by the Research Council of Norway (project nr.195160), Eni Norway and UiT The Arctic University of Norway, as well as the Barents Sea Drill Cuttings Research Initiative (BARCUT) – a project funded by Eni Norway and RDA Troms county. We acknowledge the Captain and crew of *R/V Helmer Hansen* for help during core recovery. Jan P. Holm helped prepare figure 1 A and B. We acknowledge Elena Golikova and Monika Weiβschnur for the analyses and assistance in the laboratory. We are grateful to two anonymous reviewers and the Editor Frans Jorissen for constructive feedback on the manuscript.

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Figure captions

Fig. 1. Regional settings and study area. (A) Major ocean currents of the Norwegian Sea and western Barents Sea. Abbreviations: NAC = North Atlantic Current; NCaC = North Cape Current; NCC = Norwegian Coastal Current; PW = Polar Water; (B) Close up of the western Barents Sea showing surface currents. Oil- and gas fields and exploration wells are indicated (stars); (C) Bathymetric map of the study area. Core locations are indicated. Color scale reflects water depth; the contour interval is 50m. Coordinates of the coring locations are given in Table 1.

Fig. 2. Temperature and salinity profiles at the coring locations. Continuous lines reflect the temperature profile (°C); dashed lines reflect the salinity profile (psu).

Fig. 3. Age models of the cores (dots) based on the Constant Rate of Supply (CRS) model (Appleby and Oldfield, 1992) and excess ^{210}Pb profiles (open squares). The cores were dated on a 1 cm interval (vertical axis). The interval of rapid sedimentation in core 150, interpreted as a disturbance, is indicated between the dashed lines. Ages of the base of the cores are mentioned; top of the cores correspond to 2011 (modified after Junttila et al., 2014).

Fig. 4. Grain size, TOC and metal concentrations plotted against calendar years: (A) sand (black), silt (dark grey), clay (light grey) and TOC (red line) content of the cores expressed in weight percentages. Modified after Junttila et al. (2014); (B) metal concentrations throughout the cores expressed in mg/kg. Boundary between environmental class I (background) and class II (good) (table 2) is indicated when it falls within plotted concentration range. Lower boundary of class III and higher does not fall within plotted concentrations range.

Fig. 5. Down core distribution of agglutinated (black) and calcareous foraminifera (grey) relative abundances and total agglutinated flux (black line).

Fig. 6. Foraminiferal abundances and grain size properties of the sediment cores. (A) Total calcareous species fluxes; (B) relative abundance (black line; lower x-axis) and species' flux (grey shading; upper x-axis); (C) grain size parameters (grey scale; lower x-axis), TOC (black; upper X-axis) and sortable silt mean grain size (red; upper x-axis). Modified after Junttila et al. (2014). All data are plotted against calendar years CE based on ages determined by ^{210}Pb dating.

Fig. 7. (A) Measurement of annual mean ocean temperatures between 0-200 m of the Kola section (PINRO, 2013; Smedsrud et al., 2007) and the Fugløya-Bear Island (FBI) transect (Ingvaldsen et al., 2002). Fifteen-year moving average filter (thick lines) of the annual mean temperatures (thin dashed lines) is shown. (B) Total calcareous species flux of core 150, 151, 152 and 154.

Figure 1

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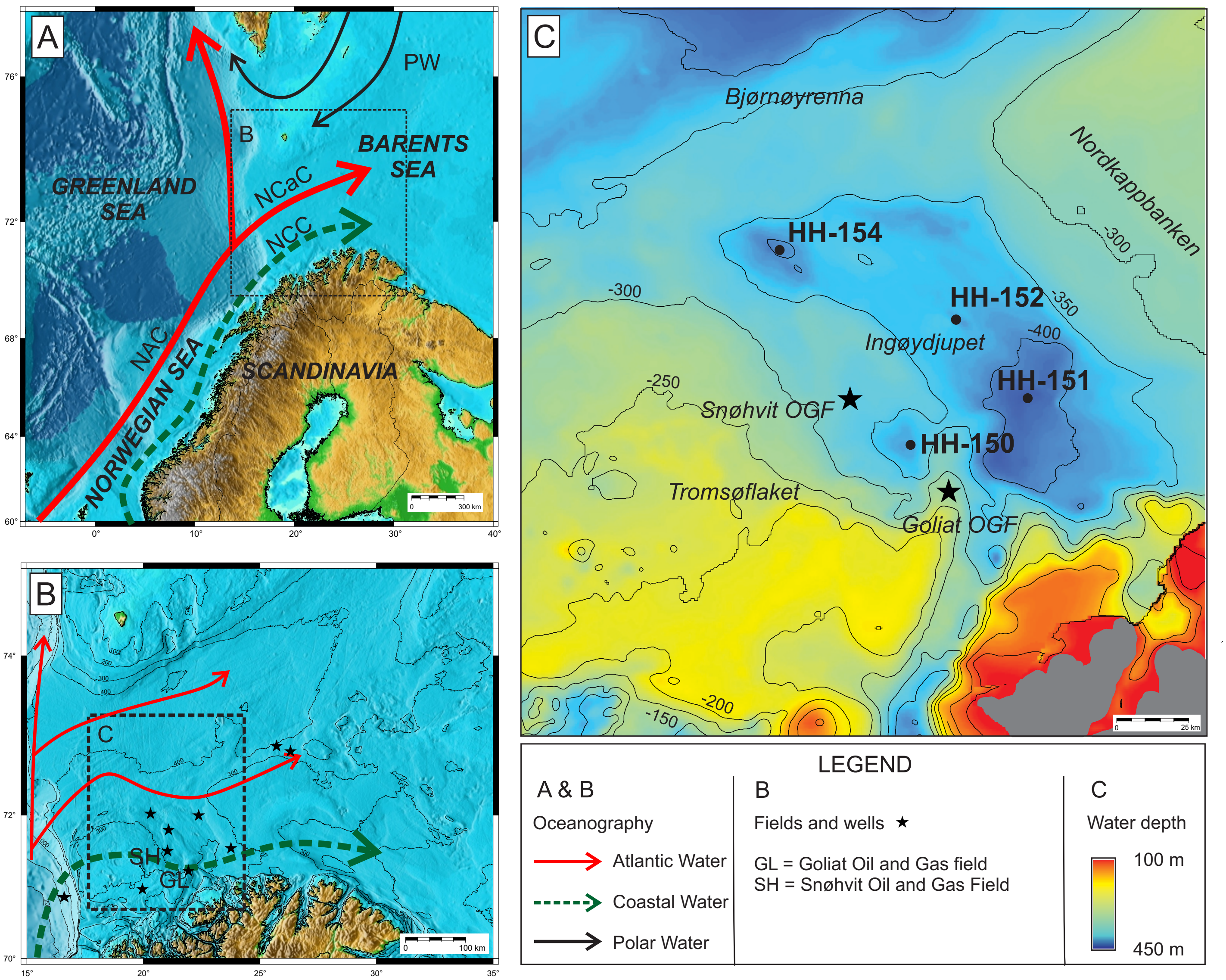

Figure 2
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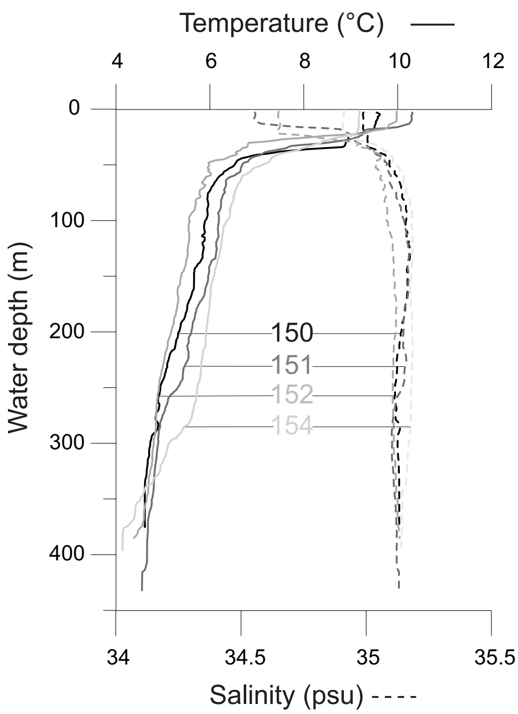

Figure 3

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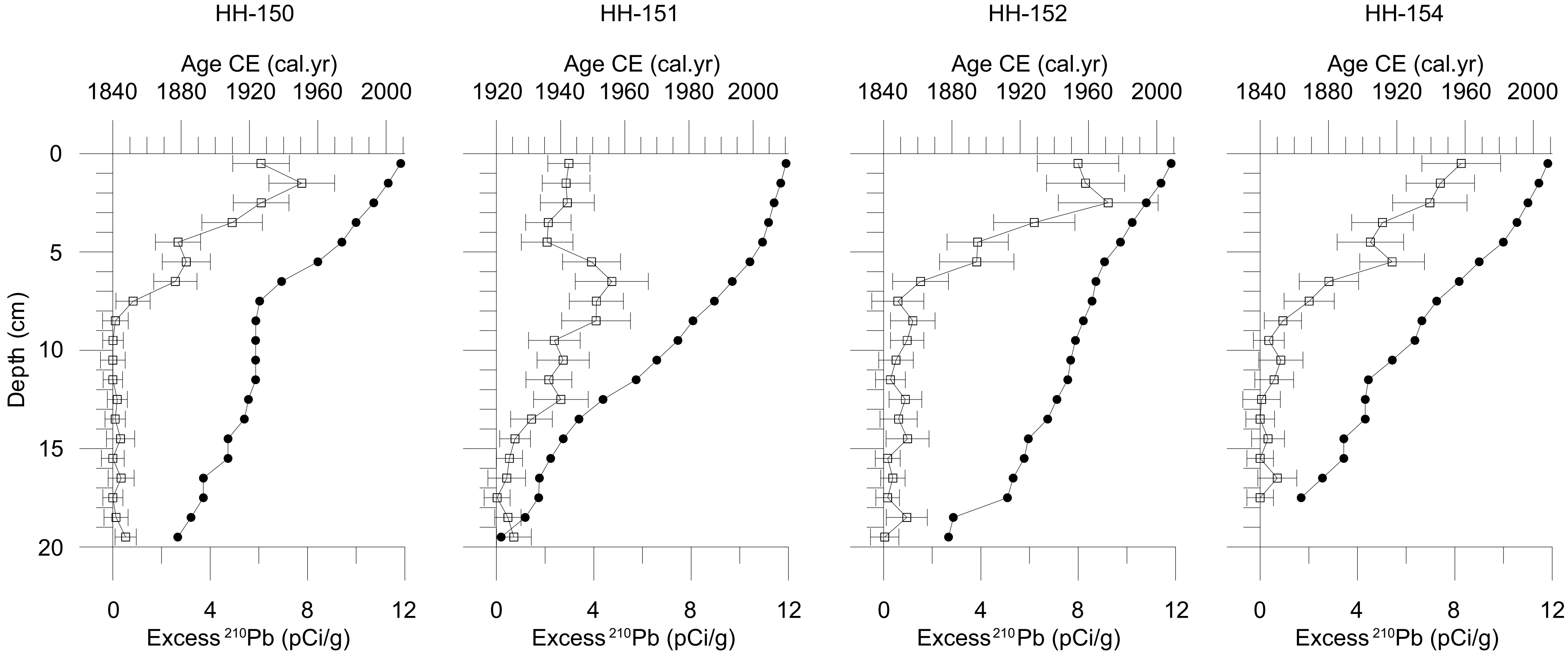

Figure 4

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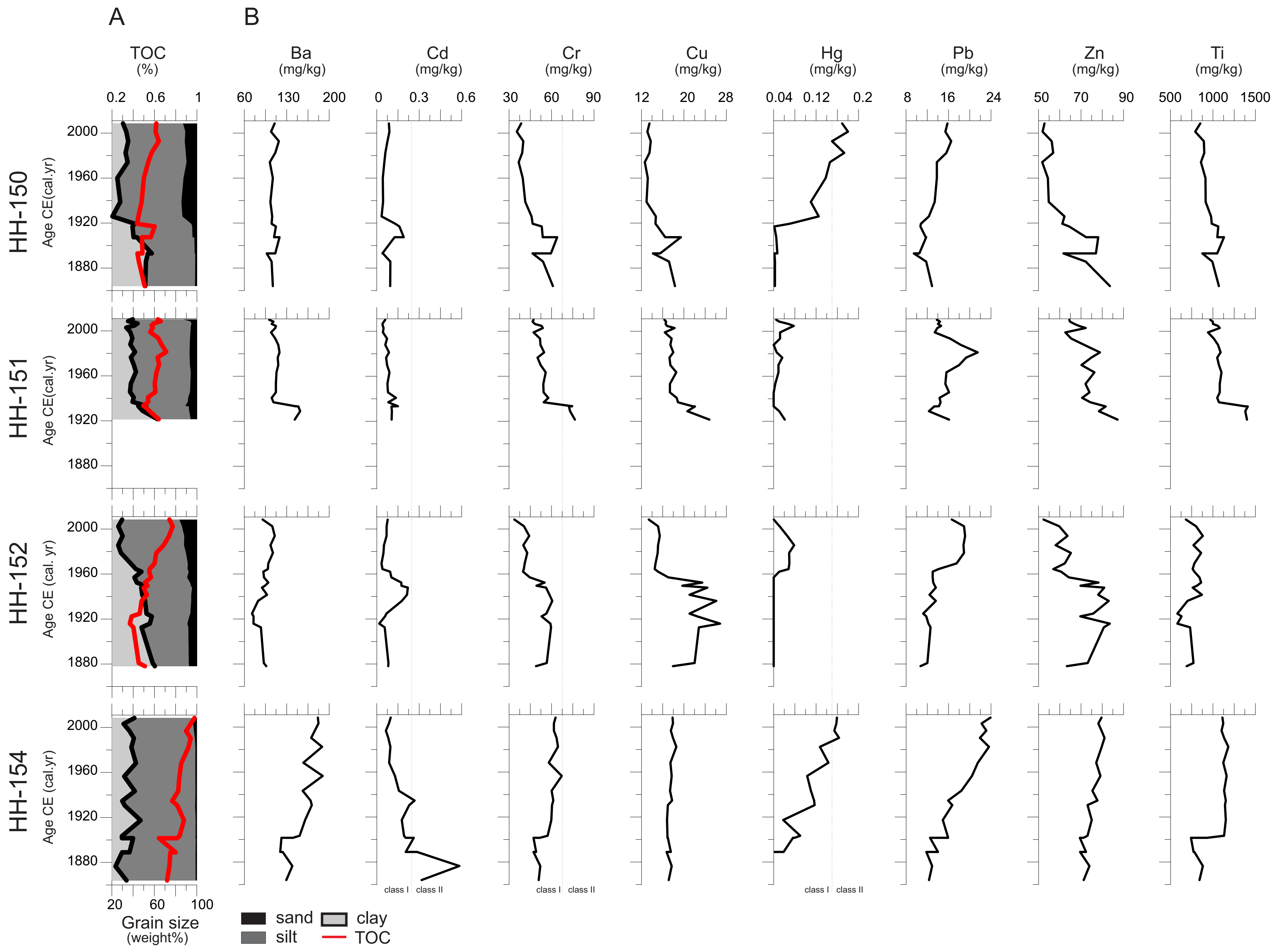

Figure 5

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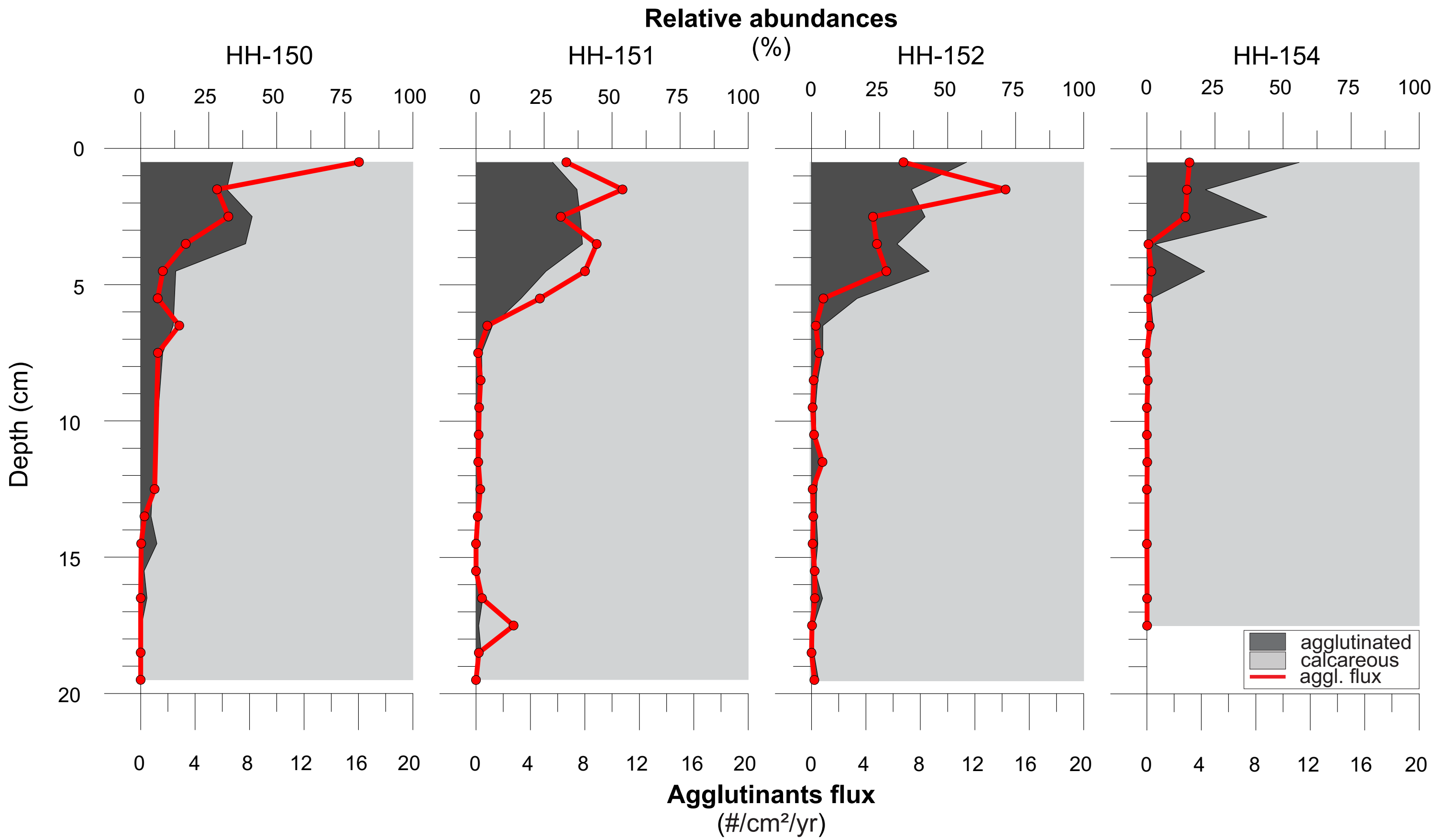

Figure 6

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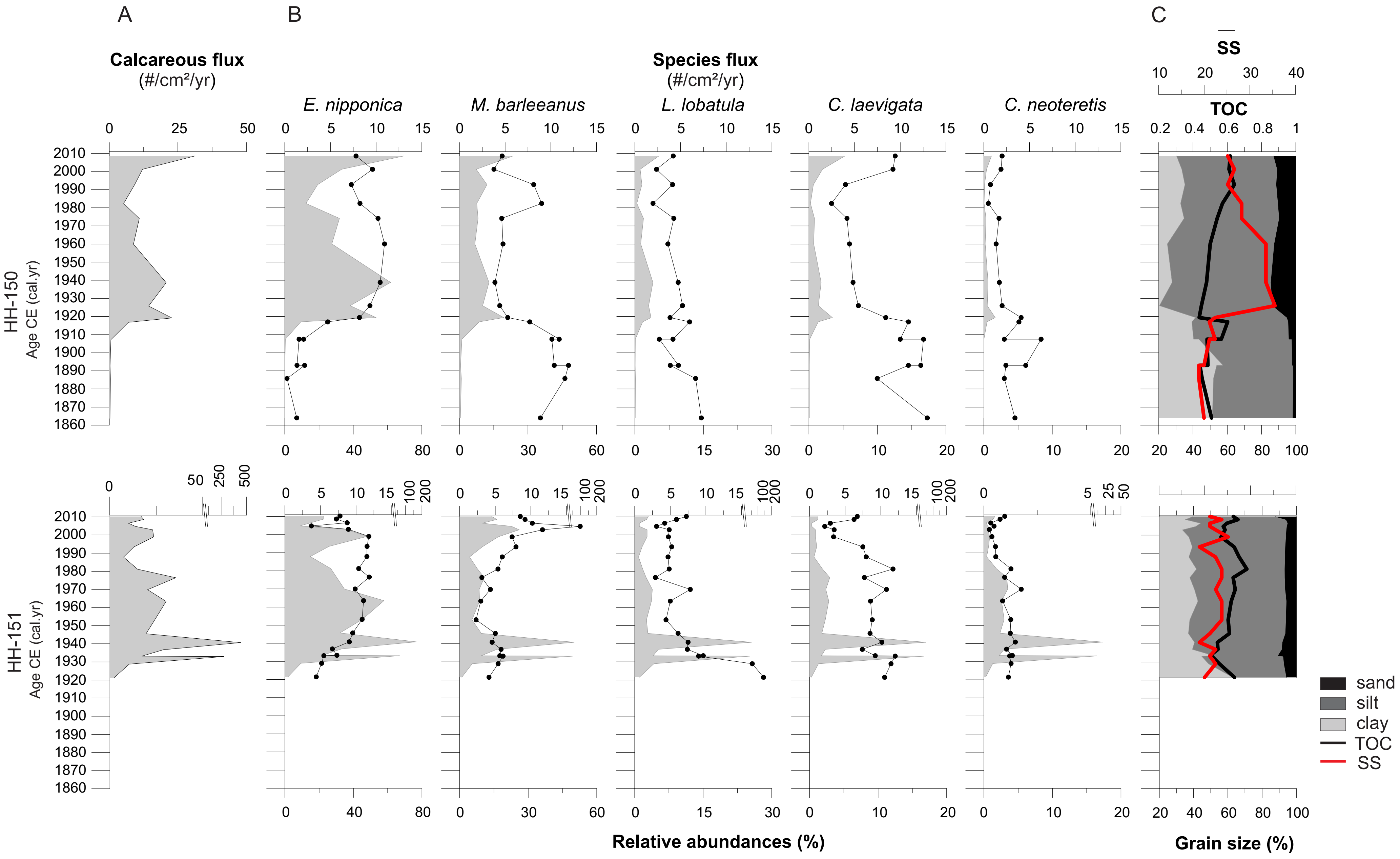

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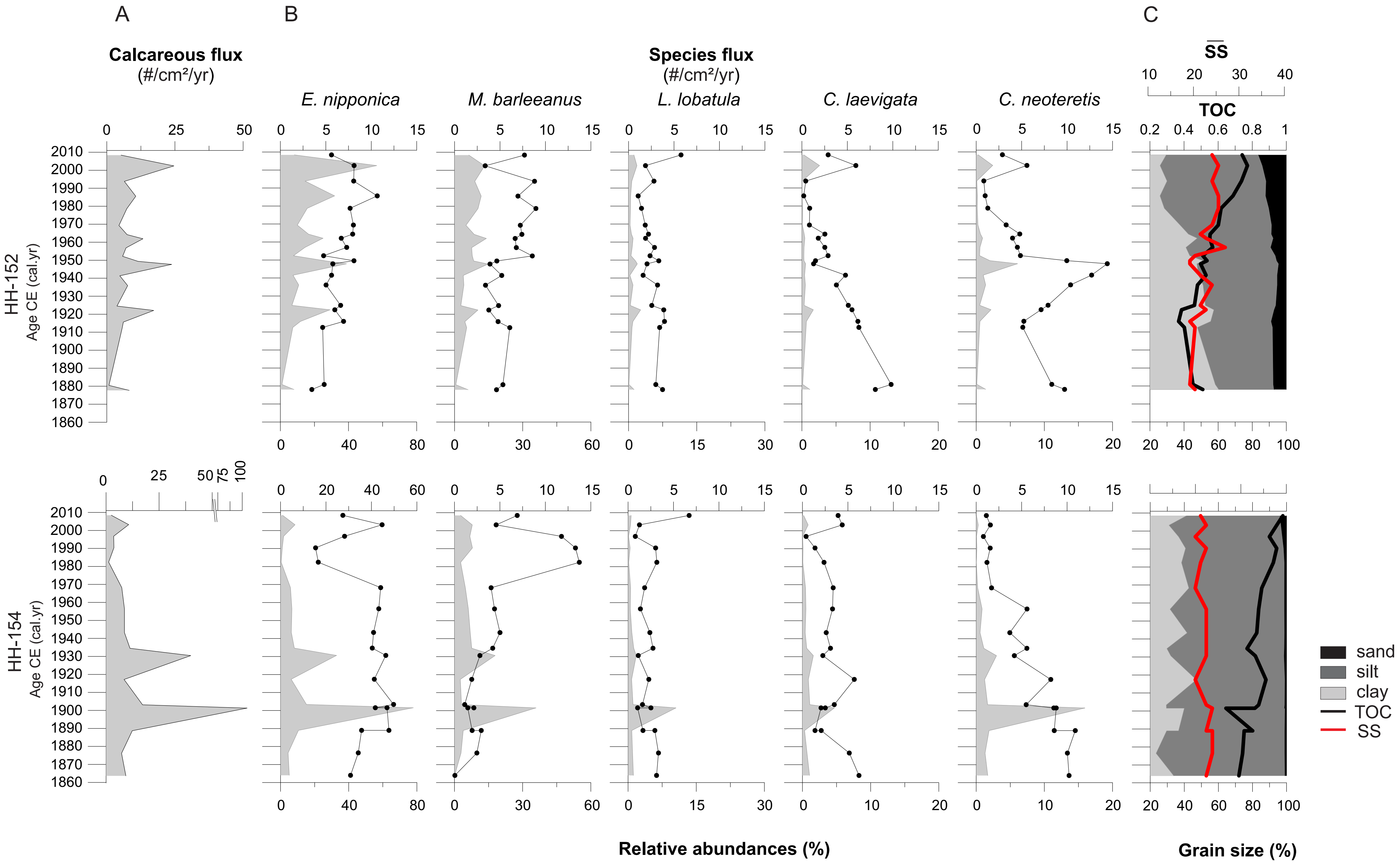

A
B
C
Calcareous flux
(#/cm²/yr)
Species flux
(#/cm²/yr)
E. nipponica
M. barleeanus
L. lobatula
C. laevigata
C. neoteretis
SS
TOC
HH-152
Age CE (cal.yr)
HH-154
Age CE (cal.yr)
sand
silt
clay
TOC
SS
Relative abundances (%)
Grain size (%)

Figure 7

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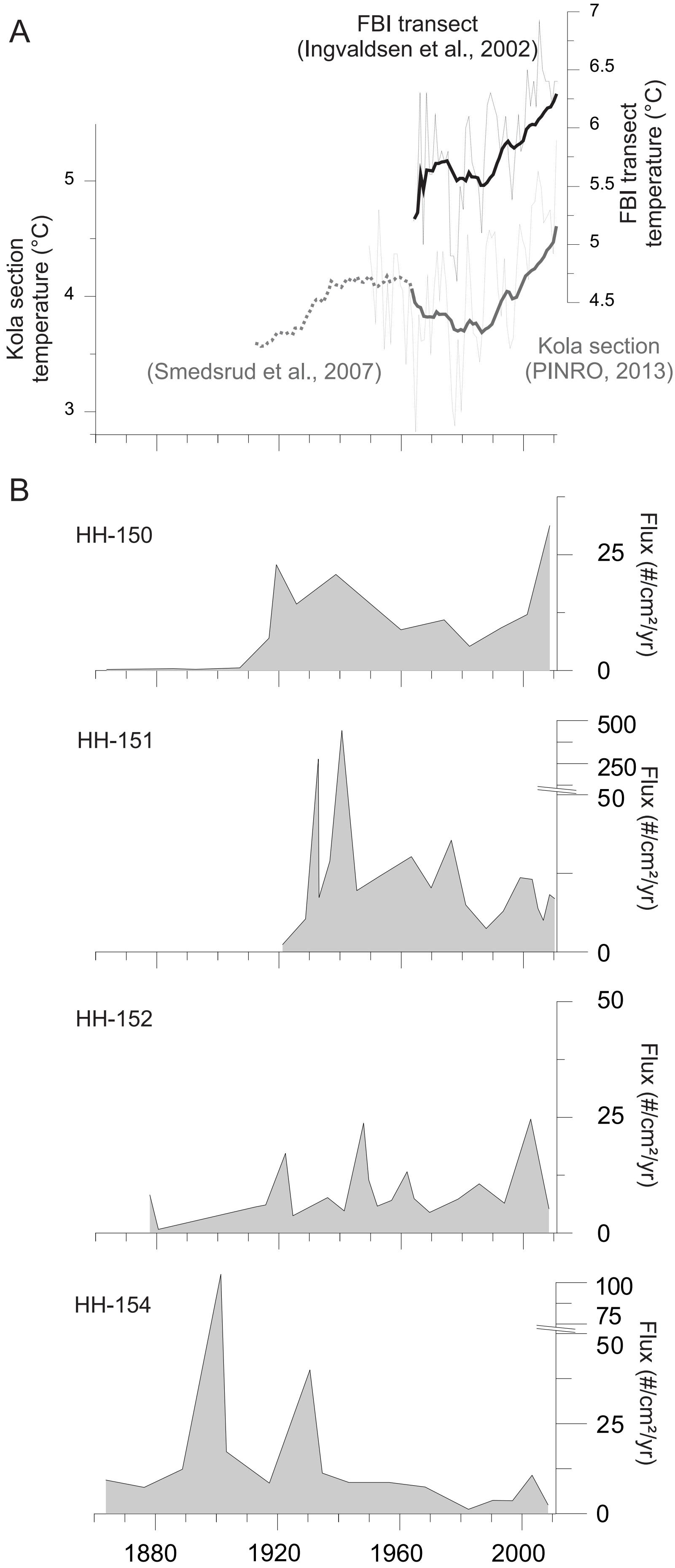

Tables

Table 1. Water depth, locations and bottom/surface temperatures and salinities for the coring sites.

Station	Water depth (m)	Latitude (N)	Longitude (E)	Temperature (°C)		Salinity (PSU)	
				surface	bottom	surface	bottom
150	383	71 24.36328	21 38.57391	9.5	4.6	34.9	35.1
151	434	71 30.24011	22 46.08809	10.3	4.5	34.5	35.1
152	394	71 44.30040	22 19.19057	9.9	4.4	34.6	35.1
154	400	72 01.18311	20 36.01878	9.2	4.1	34.9	35.1

Table 2. Ranges of values of grain size parameters and TOC after Junttila et al. (2014) and ranges of metal concentrations per core. Metal concentrations per sample can be found in Supplementary data II. The boundaries of between class I and II, which are predicted no effect concentrations are indicated for the relevant contaminants and are after Bakke 2010, following WFD, 2000. Bold font indicates values are within class II.

Core	TOC %	Clay %	Silt %	Sand %	Ba mg/kg	Cd mg/kg	Cr mg/kg	Cu mg/kg	Hg mg/kg	Pb mg/kg	Zn mg/kg	Ti mg/kg
150	0.4-0.6	20-58	41-67	2-14	97-118	0.03-0.19	36-64	11-19	0.04-**0.18**	9-17	52-84	791-1130
151	0.5-0.7	35-64	31-61	6-12	101-152	0.04-0.15	47-**77**	15-26	0.04-0.08	12-22	63-87	941-1410
152	0.4-0.8	26-60	32-62	4-16	73-110	0.02-0.22	34-61	12-29	0.04-0.08	11-19	12-84	580-880
154	0.6-0.98	30-47	52-70	1-4	119-189	0.06-**1**	47-67	16-18	0.04-**0.16**	12-24	69-81	740-1180
Class (Bakke, 2010)					Ba mg/kg	Cd mg/kg	Cr mg/kg	Cu mg/kg	Hg mg/kg	Pb mg/kg	Zn mg/kg	Ti mg/kg
	I				-	<0.25	<70	<35	<0.15	<30	<150	-
	II				-	0.25-2.6	70-560	35-51	0.15-0.63	30-83	150-360	-

Table 3. Pearson correlation between grain size properties and metal concentrations. Correlation coefficient (r) and two tailed probability (p) are given. Black bold corresponds to correlation significant at p=0.01 level; Grey bold corresponds to correlation significant at p=0.05 level.

		Core 150		Core 151		Core 152		Core 154	
		clay	TOC	clay	TOC	clay	TOC	clay	TOC
Ba	r=	0,006	0,37	**0,739**	-0,37	**-0,67**	**0,761**	0,182	**0,731**
	p=	0,981	0,159	2E-04	0,112	0,001	1E-04	0,469	6E-04
Cd	r=	0,331	0,238	**0,541**	-0,38	0,244	-0,06	**-0,65**	**-0,76**
	p=	0,21	0,375	0,014	0,094	0,299	0,792	0,003	3E-04
Cr	r=	**0,644**	**-0,5**	**0,799**	**-0,49**	**0,722**	**-0,8**	0,276	**0,739**
	p=	0,007	0,048	2E-05	0,029	3E-04	3E-05	0,268	5E-04
Cu	r=	**0,568**	-0,4	**0,809**	-0,41	**0,721**	**-0,81**	0,071	0,438
	p=	0,022	0,128	2E-05	0,073	3E-04	2E-05	0,779	0,069
Hg	r=	**-0,73**	**0,586**	0,262	-0,02	**-0,58**	**0,457**	0,319	**0,718**
	p=	0,001	0,017	0,264	0,943	0,007	0,043	0,197	8E-04
Pb	r=	**-0,55**	**0,732**	-0,13	**0,728**	**-0,94**	**0,848**	0,382	**0,877**
	p=	0,028	0,001	0,582	3E-04	4E-10	2E-06	0,118	2E-06
Zn	r=	**0,658**	-0,44	**0,694**	-0,18	**0,628**	**-0,75**	0,316	**0,813**
	p=	0,006	0,09	7E-04	0,442	0,003	2E-04	0,201	4E-05
Ti	r=	0,414	-0,42	**0,786**	-0,43	-0,44	**0,518**	0,246	**0,703**
	p=	0,111	0,107	4E-05	0,058	0,052	0,019	0,325	0,001

Table 4. Number of observed species and ranges of total calcareous and agglutinated flux flux, relative calcareous abundance and species flux per core.

core	# species	Agglutinated flux (#/cm2/year)			Calcareous flux (#/cm2/year)			*E.nipponica* relative abundance (%)			*M.barleeanus* relative abundance (%)			*L. lobatula* relative abundance (%)			*C. laevigata* relative abundance (%)			*C. neoteretis* relative abundance (%)		
		mean	min	max	mean	min	max	mean	min	max	mean	min	max	mean	min	max	mean	min	max	mean	min	max
150	56	3	0	16	10	0.3	31	32	1	58	30	15	48	9	4	15	11	3	17	3	1	8
151	58	3	0	11	52	2	441	36	15	49	21	7	53	11	5	28	8	2	13	3	1	5
152	49	2	0	14	9	1	25	35	18	57	24	13	36	5	2	12	5	0	13	8	1	19
154	49	1	0	3	16	1	105	50	21	66	19	0.2	55	5	2	13	4	1	8	7	1	15

Table 5. Summary of the environmental preferences of the most common benthic foraminifera from the studied cores. Abbreviations: T = temperature, S = salinity, AW = Atlantic Water, NCC = Norwegian Coastal Current

Species	Physical environment and water mass preferences	Feeding strategy and microhabitat preferences	References
E. nipponica	High T (>4 °C) and S, associated with AW Associated with reworking and high bottom current velocities		(e.g. Hald and Steinsund, 1992; Steinsund, 1994; Saher et al., 2009;)
*A.weddellensis**	Associated with AW, T > (3.5°C) Strong bottom currents	Phytodetritus feeder Associated to seasonal phytodetritus flux	(e.g. Gooday and Lambshead, 1989; Gooday et al., 1993; Smart and Gooday, 1997; Hayward et al., 2002; Rasmussen and Thomsen, 2004; Sun et al., 2006)
M. barleeanus	Normal S and no T preferences Fine grained sediments and high sedimentation rates Secondary related to AW	Infaunal species Degraded organic matter, probably feeding on associated bacteria, steady food supply Feeding strategy depending on type of available food	(e.g. Mackensen et al., 1985; Hald and Steinsund, 1992, 1996; Linke and Lutze, 1993; Steinsund, 1994; Fontanier et al., 2002)
L. lobatula	Wide T range, S >32 psu Negative correlated to NCC Coarse sediments or attached to polychaete tubes in fine sediments High bottom current velocities	Epifaunal Suspension feeders Tolerate limited food supply Associated to low organic content sediments	(e.g. Nyholm, 1961; Mackensen et al., 1985; Hald and Steinsund, 1992; Steinsund, 1994)
C. laevigata	Saline and warm AW Coarse sediments Limited by fine sediments	Infaunal Moderate to high organic flux. Associated to low organic content sediments (possibly due to poor preservation organic matter in coarse sediments)	(e.g. Mackensen et al., 1985; Qvale, 1985; Mackensen and Hald, 1988; Altenbach et al., 1999; Jennings et al., 2004)
C. neoteretis	Chilled AW (<5 °C), however in warm areas nutrient availability is main controlling factor Fine grained	Infaunal Degraded organic matter or bacteria associated to phytodetritus	(e.g. Mackensen and Hald, 1988; Gooday and Lambshead, 1989; Jennings et al., 2004)

* see remarks in 3.4 Taxonomical notes

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