Highlights

- Assessment of environmental effect from marine drill cutting release in 2006/07
- Fossil benthic foraminiferal faunas depict smothering effects
- Live and fossil benthic foraminiferal faunas show post drilling faunal recovery
- Fossil faunas allow establishment of in-situ reference conditions

Identifying past petroleum exploration related drill cutting releases and influences on the marine environment and benthic foraminiferal communities, Goliat Field, SW Barents Sea, Norway

Steffen Aagaard-Sørensen[1*], Juho Junttila[1], and Noortje Dijkstra[1]

[1]Department of Geosciences, UiT The Arctic University of Norway in Tromsø, Postboks 6050 Langnes, N-9037 Tromsø, Norway

[*]Corresponding author; e-mail: steffen.sorensen@uit.no

Abstract.

The present multiproxy investigation of marine sediment cores aims at: 1) Identifying dispersion of petroleum exploration related drill cutting releases within the Goliat Field, Barents Sea in 2006/07 and 2) Assessing past and present influence of drill cuttings on the marine environment. The cores were recovered 5, 30, 60, 125 and 250 meters from the drill site in the eastward downstream direction.

Downstream dispersion of drill cuttings is evaluated by examining sediment grain size distribution and barium (Ba), heavy metal, total organic carbon and sulfur concentrations. Dispersion of drill cuttings was limited to <125 meters east from the drill site. Influence of drill cutting releases on the marine environment is assessed via microfaunal analysis of primarily calcareous benthic foraminifera. The findings suggest contemporaneous physical smothering at ≤ 30 meters from the drill site, with a natural fauna reestablishing after drilling cessation indicating no long-term effect of drill cutting releases.

Keywords.

Oil/Gas exploration drilling

Drill cuttings

Foraminifera

Sediments

Heavy metals

SW Barents Sea

1. Introduction

Oil and gas explorations and test drillings have been conducted in the Norwegian part of the Barents Sea since 1980, with 129 exploration wells drilled per January 2016 (Norwegian Petroleum Directorate Factpages, 2016). Since the 1970`s evidence of adverse effects on the marine environment due to operational discharge of drill cuttings and fluids has emerged (e.g. Davies et al., 1984; Kingston, 1992; Olsgard and Gray, 1995; Breuer et al., 1999; Mojtahid et al., 2006; Bakke et al., 2013; Falk et al., 2013). These adverse effects include stress to and eradication of benthic communities due to physical smothering by real-time sedimentation of released particles and/or subsequent reactivation/resuspension of previously settled particles (e.g. Olsgard and Gray, 1995; Hess et al., 2013; Reynier et al., 2015; Figueiredo et al., 2015; Järnegren et al., 2016). Discharge related pollutants [THC(Total Hydrocarbons), heavy metals, etc.) can also have acute toxicological effects and long-term effects via post sedimentary migration of pollutants within the sediment or leakage into the bottom waters (e.g. Richardson, 1984; Olsgard and Gray, 1995; Grant and Briggs, 2002; Breuer et al., 2008; Denoyelle et al., 2012; Allers et al., 2013).

In order to protect the marine environment in Norwegian sectors legislation was introduced by the Norwegian government with the aim of achieving zero harmful discharges to the sea (Knol, 2011). Offshore environmental monitoring in the Barents Sea was initiated in 1998 and geochemical sediment analyses have shown background levels of heavy metals and THCs in most parts of the region with elevated heavy metals (most notably barium) and THC primarily observed in localized areas associated with oil and gas exploration (Falk et al., 2013 and references therein).

Exploration drilling in the Goliat field, SW Barents Sea started in 2000 and 18 development wells were drilled between 2013-2015 (Norwegian Petroleum Directorate Factpages, 2016) while production started March 2016 (Petro.no, 2016).

The purpose of the present research is to examine the potential past and present-day environmental impact of water-based drilling mud (weighing, lubricating, stabilizing material) and drill cuttings (collectively referred to as drill cuttings) released to the marine environment. The impacts of drill cuttings are examined in five push cores obtained by ROV (Remotely Operated Vehicle) in an eastward transect downstream from and within 250 m of exploration well 7122/7-5(A), drilled within the Goliat oil field in 2006 (28. Nov)-2007 (13. Jan) (Falk et al., 2013).

The impact of drill cutting release on the marine environment is assessed via study of micro fauna compositions of shell bearing calcareous benthic foraminifera (total, species specific and relative abundance), in addition to total abundance of planktic and agglutinated benthic foraminiferal forms, observed within the retrieved sediment. Planktic foraminifera live and record the environmental conditions in the upper part of the water column at ~ 0-200 m water depth (Carstens and Wefer, 1992) and posthumously descend to the seabed where they fossilize. Benthic calcareous foraminiferal shells are commonly made of secreted calcium carbonate ($CaCO_3$) while agglutinated forms construct their shell by cementing together sedimentary grains. Agglutinated shells can be more or less firmly cemented and therefore the fossilization potential of individual species may vary greatly while also depending on the environmental setting and rate of sediment accumulation (Schröder, 1988; Murray, 2006 and references therein). Benthic foraminifera live on or within the seabed sediment and provide information about the ocean floor environment. Most benthic foraminifera have an average living depth within topmost 5 cm of the sediment (e.g. Schönfeld, 2001; Motajid et al., 2010) although some have been observed living at sediment depth down to 15 cm (e.g. Corliss, 1985, 1991; Kaminski et al.,1988). Benthic calcareous foraminifera have fast reproduction rates (Kramer and Botterweg, 1991) and respond rapidly to changes in the natural marine environment while displaying a high degree of specialisation (Polyak et al., 2002; Sejrup et al., 2004; Saher et al., 2009; 2012). Studies show a significant foraminiferal response to physical and chemical stressors (e.g. Alve et al., 1991, 1995; Mojtahid et al., 2008; Popadić et al., 2013; Vidović et al., 2014; Martins et al., 2015; Schintu et al., 2016; Dijkstra et al., 2016) including drill cuttings (Mojtahid et al., 2006; Jorissen et al., 2009; Denoyelle et al., 2010; Hess et al., 2013). In addition, calcareous foraminifera have a relatively high resistance to post-mortem destruction making fossil calcareous benthic faunas well suited to reconstruct environments before and assess impacts in the aftermath of drill cutting release/sedimentation (e.g. Jorissen et al., 2009; Hess et al., 2013).

In the present examination, analyses of fossil and live foraminiferal faunas allow assessment of 1) effect from drill cutting release in 2006/07 and subsequent micro faunal recovery, 2) potential long term impacts on the local micro faunal community/marine environment and 3) in-situ faunal reference conditions.

2. Regional settings and background

2.1. Study area

The Barents Sea is a 1.3 million km^2 shelf area with numerous bathymetric features including troughs and banks sculptured by the glaciations and deglaciations of the area (Winsborrow et al., 2010). The banks are high current erosion areas with sandy sediment and the troughs are lower energy sedimentation basins with fine-grained sediments (i.e. clay, silt) (Hald and Steinsund, 1996 and refs therein). Surface sediments in the southern Barents Sea today mainly originate from erosion of Quaternary coastal and shallow bank deposits and discharge from rivers in addition to land-derived terrigenous and *in-situ* produced marine organic matter (Knies et al., 2006 and refs therein; Knies and Martinez, 2009).

The main troughs in the SW Barents Sea are the north-south trending Ingøydjupet reaching depths of 450m which is bordered to the north by the deeper Bjørnøyrenna (Fig. 1A, B). The Ingøydjupet is bordered to the west and east by shallower (100-300m) bank areas called the Tromsøflaket and Nordkappbanken, respectively (Fig. 1B). The Goliat exploration area is situated in the western part of the Ingøydjupet on the border between the Ingøydjupet and the Tromsøflaket and has water depths ranging from 340-390m (Fig. 1B).

2.2 Water masses in the SW Barents Sea

The water masses in the SW Barents Sea are dominated by Atlantic Water and Norwegian Coastal Water (Fig. 1A). Atlantic Water (Temperature (T) > 3°C; Salinity (S) > 35) enters the Barents Sea between Bjørnøya and the Norwegian coast and is transported eastward by the North Cape Current (NCaC) (Fig. 1A). Norwegian Coastal Water (T=3-9°C; S < 34.5), transported by the Norwegian Coastal Current (NCC), flows eastward along the Norwegian coast forming a northwards thinning wedge above the Atlantic Water (Loeng et al., 1997; Aure and Strand, 2001; Ingvaldsen et al., 2004). CTD (conductivity, temperature, and depth) measurement of the water column to 343 meters below sea surface was made prior to push coring in November, 2014 at the site of exploration well 7122/7-5. The CTD shows that the water column was dominated by Atlantic Water with temperatures ranging from 5.2-6.7°C and salinities of ~35 above and ~35.3 below 145 meters water depth (Fig. 1E).

2.3. Drill cutting and drilling mud release

The present study is conducted in the eastern direction downstream from abandoned well 7122/7-5, which includes a sidetrack well (7122/7-5A) (71.27° N; 22.28° E) situated within the Goliat exploration area (Falk et al., 2013) (Fig. 1C). The exploration well was drilled at a water depth of 370 meters during late 2006 and early 2007. From 2000 to the present multiple other exploration and development wells were drilled within a radius of ~3km to the north, east and south of well 7122/7-5 (Fig. 1C) (Norwegian petroleum Directorate factmaps, 2016). During drilling procedures 412 tons of drill cuttings, consisting of crushed bedrock, in addition to 711 tons of low risk water based drilling mud, including commonly used drill mud weight materials were released to the sea (Falk et al., 2013).

3. Material and methods

Sediment cores were collected in the Goliat Field in November 2014 using the support vessel R/V Njord Viking (Fig. 1, Table 1). The Goliat Field is an active exploration/development area with restricted access. Preparations for production were ongoing and a network of sea bed installations/pipelines were already installed (ENI Norge, 2016). In order to eliminate risk of damage to seabed installations, coring in the restricted area is only allowed when performed by professional ROV (remotely operated vehicle) operators aided by real-time video.

The following considerations were made when selecting the coring transect for examination: 1) Select an older exploration well allowing assessment of potential long-term effect and microfaunal recovery after cessation of drill cutting release; 2) Optimize the possibility of detecting the targeted 2006/07 drill cutting release by selecting the study coring transect downstream from the examined well; 3) Minimize secondary pollution/influence from nearby drilling activities by selecting an upstream (according to the prevailing west to east current direction) well for examination.

Five coring sites were selected at distances of 5, 30, 60, 125 and 250 m from well 7122/7-5 (Fig. 1C, D). All cores were taken at ~370 m water depth. Two cores were taken at each station within ca. one meter from each other (Table 1) by pressing transparent tubes (60 cm in length; 8 cm inner diameter) into the sediment using the ROV mounted robotic arms. The twin cores at each station are in the following collectively be referred to as core 5, 30, 60, 125 and 250, respectively. At every station one core was frozen as a whole and one was subsampled immediately at 1 cm resolution down to 20-21cm core depth and subsequently frozen (ca. -20^{o}C) (Table 1) (e.g. Dijkstra et al., 2013). The frozen cores were x-rayed using a Geotek x-ray core imaging system at the Arctic University of Norway in Tromsø (UiT) geological laboratory **(**Fig. 1D; Table 1). The frozen cores were subsequently defrosted and subsampled at 1 cm resolution at UiT for further analysis. Sediment TOC and sulfur (S) weight percentages (wt.%), were measured on freeze dried sediments that were pre-treated with HCl (10%) prior to combustion using a Leco CS 744 furnace at UiT. The heavy metal analyses were performed following EPA methods 200.7 and 200.8 by Unilab As, Tromsø. The sediment was analyzed for content of Barium (Ba), Mercury (Hg), Cadmium (Cd), Chromium (Cr), Copper (Cu), Lead (Pb), Zinc (Zn) and Titanium (Ti). The results are presented as mg/kg (Fig. 3).

Subsamples frozen after subsampling onboard the retrieval vessel were weighed before and after freeze drying at UiT and the sediment water content calculated. Grain size distribution of sediment samples was measured using a Beckman Coulter LS 13320 laser particle size analyser at UiT according to the method described by Xu (2000). Prior to analysis ~2 gram freeze dried sediment sample per depth interval was treated with HCl and H_2O_2 in order to remove carbonates and organic matter, respectively. Detailed description can be found in Dijkstra et al. (2016). Each sample was analyzed three times and the average grain-size values of the results were calculated and grouped (<2μm, 2-63μm, 63-125μm, 125-250μm and 250-2000μm) (Fig. 4).

The top five (0-5cm) frozen subsamples at each core station were stained with rose bengal to allow distinction between live and fossil foraminifera. Rose bengal adsorbs to protein in live and not yet decomposed cytoplasm thereby staining living (or recently dead) specimens making them appear red/pink under the microscope whereas fossil foraminifera retaining no cytoplasm are not stained and will remain white/grey (Walton, 1952; Bernhard 1988). The Rose Bengal solution was added to the samples shortly after they arrived at UiT and subsequently the samples were allowed to slowly defrost at 4°C. At each core station rose bengal stained (0-5 cm core depth) and freeze dried samples (5-20 cm core depth) used for microfaunal analysis were washed over 1mm, 100μm and 63μm meshes, dried and weighed by fraction. Benthic calcareous and planktic foraminifera were picked and identified to species level, while agglutinated benthic forms were identified to genus level. Foraminifera were picked in sediment splits of the 100 μm-1 mm size fraction to enable comparison to studies from the region (Hald and Steinsund, 1992; Knudsen, 1998; Polyak et al., 2002; Sejrup et al., 2004, Saher et al, 2009; 2012; Dijkstra et al., 2013; 2015). From most samples a specimen number of ca. 300 (~260-310 specimens) fossil benthic calcareous forms was picked. However, in some samples/intervals abundance of fossil calcareous benthic foraminifera was low and only ≥100 specimens were picked. The live calcareous benthic foraminifera were less abundant and a minimum of ~60 individuals were picked which still allows a statistically reliable determination of faunal community distribution (e.g. Forcino, 2012; Forcino et al., 2015). On the basis of the live and fossil benthic foraminiferal counts, calculation of relative abundance of species (%) in addition to total and species specific abundance (specimens(#)/gram dry sediment), was performed. Planktic foraminifera in addition to live and fossil agglutinated foraminifera were picked and are presented as total abundance. However, it must be emphasized that in case of agglutinated forms, only whole or minutely broken individuals were counted which likely underestimates their total abundance as counting of fragments of multi-chambered or tubular specimens was not conducted (e.g. Enge et al., 2011).

Flux (specimens(#)/cm^2/yr) of total planktic, benthic agglutinated and calcareous foraminifera was calculated following the method of Ehrmann and Thiede (1985):

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

where SAR is the sediment accumulation rate constructed at 1 cm resolution via ^{210}Pb dating. Bulk density was calculated from the sediment water content and porosity, with assumption of an average mineral density of 2.45 g/cm^3. Benthic calcareous faunal diversity indexes (Shannon index (H) and Simpson`s index of Diversity (1-D)) were calculated on relative species abundance data using Past version 3.14 (Hammer et al., 2001).

4. ^{210}Pb dating and sediment age determination

^{210}Pb dating used for sediment age determination was performed on selected sediment samples (Table 2) at GEL Laboratories in Charleston, USA. Determinations of ^{210}Pb were performed by analysis of ^{210}Po via alpha spectrometry. ^{226}Ra and ^{137}Cs were determined via gamma spectrometry using the 662 keV photopeak for ^{137}Cs and radon daughter peaks for ^{226}Ra (295, 352, and 609 keV; Kim and Burnett, 1986). “Excess ^{210}Pb” (not supported by decay of ^{226}Ra in the sediment) is determined by subtracting the measured ^{226}Ra activity in each sample from the total ^{210}Pb assuming that the supported ^{210}Pb is in secular equilibrium with radium. The excess ^{210}Pb activities were corrected for radioactive decay between sampling and analysis. All ^{137}Cs activities were below minimum detectable activity, and therefore Cs could not be used to corroborate the sediment age determination. 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). The Constant Rate of Supply (CRS) model (Appleby and Oldfield, 1992) was used to calculate ages for mid-layer depths, assuming constant a ^{210}Pb flux within the timeframe under consideration (Table 2). Cores 5 and 60 either had insufficient data or showed no discernible trend to allow extrapolation or interpolation of excess ^{210}Pb in the missing layers, while excess ^{210}Pb did not reach zero in core 125 (Table 2). Thus, no sediment age was established in these cores. In cores 30 and 250, the excess ^{210}Pb reached background levels (Table 2). For the purpose of the ^{210}Pb age determination of core 30 we assigned an assumed age of 2006 (due to anthropogenic impact; see discussion) to the upper layers (2-11 cm core depth) and calculated ages from 11-20 cm sediment depth. In core 250 zero age (2014) at the sediment surface was assumed and ages were calculated to 9 cm sediment depth. ^{210}Pb dates based on CRS were obtained in two ways: (1) by use of a commercial program (Shukla, 1996); and (2) manual (spreadsheet) calculation of CRS ages. The manually calculate CRS ages, agreed well with those estimated by the software and are the ones presented (table 2; Fig. 2). The main difference between the manual and computer program approaches is that the software extrapolates any excess ^{210}Pb that may be remaining at the bottom of the core based on trends in the activities and porosities to estimate the total excess ^{210}Pb inventories, albeit only little extrapolation was necessary for both cores. ^{210}Pb dating in core 30 and 250 showed sediment ages dating back to 1954 and 1918, respectively (Table 2; Fig. 2). Apparent sedimentation rates calculated at 11-20 cm core depth in core 30 and at 0-6 cm core depth in core 250 are 0.91-5mm/yr (av~1.7mm/yr) and 0.3-1.6mm/yr (av~0.6mm/yr), respectively (Table 2; Fig. 2).

5. Results

5.1. Lithology, X-ray imaging, grain size, water content, total organic carbon, sulphur and heavy metal concentration

Visual and x-ray photograph inspection of the cores reveal sediments that consist of homogenous dark brownish grey hemipelagic clayey/sandy mud, occupying the entirety of cores 125 and 250 in addition to the very top and lower sections of cores 30 (below ~11cm) and 60 (below ~6cm). Sediments consisting of light grey/brown clayey/sandy mud, represented as brighter light grey sections in the x-ray images, are intermittently observed throughout core 5 as bands and scattered chunks in a darker brownish matrix (dark grey color in X-rays images), while expressed as a distinct band at ca. 2-11 cm core depth in core 30 and as a somewhat indistinct band at ca. 3-6 cm core depth in core 60 (Fig. 1D).

The grain size composition throughout core 5 shows fluctuating contents of sediments <63µm (clay+silt) (range(r)~16-70%; average(av)~47%), fine sand (63-125µm) (r~21-59%; av~39%) and medium sand (125-250µm) (r~1-28%; av~13%), with clay (<2µm) values exceeding 10% at 9-11 and 3-7cm core depth and almost no sediment >250µm (Fig. 4). The water content of core 5 decreases from 54% at 20cm to an average of ~35% for the above sediments (Fig. 4).

In core 30 the lower section (12-20cm) predominantly consists of sediments <63µm (r~37-69%; av~57%) with stable water content (r~32-36%; av~33%) (Fig. 4). The upper part of core 30 (0-12cm) shows more sediments <63µm (r~56-85%; av~71%) with clay values exceeding 10% at 3-6cm core depth (Fig. 4) and elevated water content (r~34-70%; av~48%) (Fig. 4). In core 60 highest values of material <63µm is found at 2-4cm core depth (r~79.8-79.9%; av~80%) with lower values found below (r~55-74%; av~62%) and above (r~67-72%; av~70%) and this interval (Fig. 4). The lower part (5-20cm) of core 60 holds lowered water contents (r~24-37%; av~31%) compared to the upper part (0-5cm) (r~42-61%; a~51%) (Fig. 4). Cores 125 and 250 hold somewhat similar grain size distributions exemplified by sediments <63µm averaging of 61 and 63%, respectively. However, the sediment in core 250 becomes coarser towards the top whereas no such trend is observed in core 125. Moreover core 125 is the only core in this study that intermittently contains >10% coarse sand (>250µm) (Fig. 4). Cores 125 and 250 have similar water content profiles with slightly elevated values in the top sediment and average values of 26 and 27%, respectively (Fig. 4).

Total organic carbon (TOC) levels are <0.7 wt.% in all samples and fluctuation within individual cores never exceeds 0.4 wt.% while difference in average TOC levels between separate cores site are less than 0.25 wt.% (Fig. 3). Sulphur (S) levels are high (>0.5 wt.%) and fluctuating throughout core 5 and elevated at 2-11 and 2-5 cm core depth in core 30 and core 60, respectively. In cores 125 and 250 S levels are consistently low (<0.09 wt.%) and display minute fluctuation (Fig. 3).

The heavy metal analysis shows that the most metal contents (Hg, Cd, Cr, Cu, Pb, Zn, Ti) in all of the sediment are comparable to background values (Bakke et al., 2007; 2010) (Fig. 3). Heavy metal values exceed background levels at a few depth intervals, including; Cu > 0.35 mg/kg at 15-17 cm in core 5, Hg > 0.15 mg/kg at 3-4 cm in core 60 and Cd > 0.25 mg/kg at 6-10 in core 250. Barium (Ba) shows the largest fluctuations within and between cores but is not included in the official pollution classification system (Bakke et al., 2007; 2010) (Fig. 3). In core 5 Ba values are highly fluctuating (r~550-5000 mg/kg; av~2600 mg/kg). The values exceed ~1000 mg/kg from 0-17cm and remain high exceeding 550 mg/kg at 17-20cm. In core 30 high Ba values are found from 0-11 cm with especially elevated values from 2-11 cm (r~1200-4800 mg/kg; av~2900 mg/kg). From 11-20 cm values remain stable and below 90 mg/kg (r~50-90 mg/kg; av~70 mg/kg). In core 60 Ba values are highest just below the surface at 1-6 cm (r~570-3200 mg/kg; av~2000 mg/kg). Below 6 cm values remain low and stable (r~60-149 mg/kg; av~92 mg/kg) (Fig. 3). In cores 125 and 250 Ba values are generally stable and low with average values of 60 and 80 mg/kg, respectively. Slightly elevated Ba values > 100 mg/kg are observed at 1-3 cm in core 125 and at 0-2 and 6-7 cm core depth in core 250 (Fig. 3).

5.2 Foraminifera

The analysis of the living (Rose Bengal stained) and dead (non-stained) benthic foraminiferal fauna revealed 71 fossil benthic calcareous species (live (rose bengal stained) =40) (Figs. 5, 6, 7; table 3; Supplementary data). In addition, 7 planktic species and 14 different benthic agglutinated genera were identified but only total abundances were calculated (Fig. 6). Most dead calcareous specimens have well preserved tests although minor signs of visual test abrasion and damage were observed in cores 5 and 30. The down core total abundance fossil benthic calcareous and agglutinated forms vary between 10-2580 and 0-96 #/g dry sediment, respectively and planktic foraminifera between 0-1174 #/g dry sediment (Fig. 6). Relatively most abundant fossil calcareous benthic foraminiferal species are: *Elphidium excavatum* forma *clavata* (0-40.5%), *Cassidulina laevigata* (0.8-32.9%), *Cassidulina reniforme* (0.3-32.2%), *Cibicides lobatulus* (3.9-29.7%) *Epistominella nipponica* (0.3-27.7%), *Trifarina angulosa* (0-15%), *Nonionellina labradorica* (0-10.4%) and *Melonis barleeanus* (0-8.2%) (Fig. 5). *E. e.* f. *clavata* and *C. reniforme* show highest relative abundance (≥20%) in lower parts of core 5 (>10cm) and core 250 (>14cm) in addition to at 5-8 cm core depth in core 30, while highest relative abundance (≥20%) of *C. laevigata*, *C. lobatulus* and *E. nipponica* largely can be observed in the remaining core sections (Fig. 5). Largest fossil calcareous benthic faunal evenness and diversity as calculated using the Simpson (1-D) and Shannon (H) indexes, respectively, is observed in the upper part (>10cm) of core 5, at 5-11 cm in core 30 and the lower parts of cores 60, 125 and 250 (Fig. 5). Elevated total abundances of fossil benthic calcareous and agglutinated forms are observed in the top 0-5 cm sediment in all cores where most abundant species >50 #/gram dry sediment (#/g) are *C. laevigata*, *C. lobatulus* and *E. nipponica* with the addition of *E. e.* f. *clavata* only in core 5 (Fig. 6). The highest total abundances of both fossil benthic and planktic forms are observed just below 12 and 4 cm core depth in core 30 and core 60, respectively, where most abundant benthic species >400 #/g are *C. laevigata*, *C. lobatulus* and *E. nipponica* in addition to *T. angulosa* observed at >150 #/g. Total planktic abundance reach >500 #/g (Fig. 6).

Fluxes of total planktic, calcareous and agglutinated foraminifera at 0-6 cm core depth in core 250 are between 4-24, 11-100 and 0.4-5 #/cm^2/yr, while significantly higher values are observed in core 30 below 12 cm core depth reaching 31-356, 109-1115 and 4-55 #/cm^2/yr, respectively (Fig. 6).

At all distances from the drill hole the abundance of live (rose bengal stained) specimens rapidly decline down core (Fig. 6). If not otherwise stated, reference to live fauna in the further description and discussion, will represent the combined signal of stained foraminifera found at 0-5 cm core depth within each core as all stained specimens are presumed alive (or recently dead) and thus in combination approximate the standing stock at the time of coring (Figs. 5, 6, 7).

Across the five cores the relatively most abundant live calcareous benthic species are: *T. angulosa* (11.5-27.8%), *C. lobatulus* (10.1-25.4%), *E. nipponica* (8.5-23.8%) and *C. laevigata* (4.6-15.6%), which together comprise 50-70% of the total live fauna in the individual cores. Other abundant species are *Q. seminula* (1.8-15.5%), *S. bulloides* (0-9.1%) and *C. reniforme* (2.5-6.5%) (Fig. 7). Live *E. e.* f. *clavata* is observed only in cores 5 and 30 at 4.0% and 1.1%, respectively (Fig. 7). Live calcareous benthic faunal evenness (1-D) and diversity (H) indexes are highest in core 5 and gradually decline with distance from the drill hole resulting in lowest values observed in core 250 (Figs. 5, 7). Live benthic specimens in the top 0-5cm of the sediment occur in abundance ranging between 0-7.8 #/g for calcareous forms and 0-5.6 #/g for agglutinated forms (Fig. 6). In all cores highest abundance of live specimens were found in the top sediment (0-1 cm; r~2.4-7.8 #/g).

6. Discussion

6.1. Identifying past petroleum exploration related drill cutting releases.

Release of drilling cuttings from abandoned well 7122/7-5(A) occurred in 2006/07. The drill cuttings consist of water based drill mud and grinded top hole sediment and bedrock (Falk et al., 2013) with chemistry and mineralogy thus reflecting the drill mud and the strata being drilled (Neff, 2005). The drill cuttings were released to the seabed and supposedly mainly accumulated close to the drill hole, while part of the material was carried downstream from the release site by the, predominantly eastward, ocean current (e.g. Ingvaldsen et al., 2004) (Fig. 1) during the time of release and in the aftermath due to post depositional sediment reactivation. First indication of drill cuttings within the retrieved sediments came during onboard subsampling where light grey/brown sediments were observed throughout core 5 and in top sections of cores 30 and 60, in comparison to darker brown sediments observed below and throughout cores 125 and 250 furthest away from the drill hole. These observations were suspected, and later confirmed (see below), to represent presence of barite which is a generally white/colorless mineral commonly used as weighing material in drilling mud (Neff, 2005). X-ray photography also revealed brighter sections and bands within the same sediment intervals (Fig. 1D) further supporting the presence of drill cuttings as barite produces a brighter signal in x-ray photos due to high density and X-ray absorption ability (e.g. Nin et al., 2013).

Elevated heavy metal values, linked to drilling operations and oil production, have been observed at and in the vicinity of drill cutting piles and platforms in the North Sea (Breuer et al., 2004 and ref therein). However, in the present study most heavy metal concentrations (Hg, Cd, Cr, Cu, Pb, Zn, Ti), at all distances from the drill hole, are comparable to background levels as classified by the Norwegian Pollution Control Authority (Bakke et al., 2007; 2010) and documented in local non-impacted areas (Dijkstra et al., 2013, 2015) (Fig. 3). Elevated sediment Ba levels are common at and near drill cutting piles and are linked to Barite often used and release during drilling procedures (Breuer et al., 2004 and ref therein; Neff, 2005). Barite/barium sulphate ($BaSO_4$) is a naturally occurring mineral that generally is considered nontoxic to humans and marine organisms (Neff and Sauer, 1995; Moffett et al., 2007). The natural Ba levels observed in local sediments are below 200 mg/kg (Dijkstra et al., 2015) which we use in the present study as a threshold to distinguish non-impacted sediments from sediments impacted by drill cuttings that hold elevated Ba values (Fig. 3). Drill cutting impacted sediments with elevated Ba concentration (>550 mg/kg) continuously above background levels (Dijkstra et al., 2013; 2015) are found throughout core 5 (Fig. 3). The sediment in core 5 generally is coarser than further from the drill hole, and contains relatively high levels of sediments >63µm likely due to settling of coarser sediment fractions of drill cuttings close to the drill hole (Fig. 4). However, at 4-6 and 8-13 cm core depth notably high Ba values (>2900 mg/kg) are found alongside somewhat elevated levels of finer sediment (clay+silt, <63µm), which may indicate an association between Ba and fine grained components of the drill cuttings (Fig. 4). In cores 30 and 60 elevated Ba levels and water contents were observed at ~2-11 and ~2-5 cm core depth, respectively (Fig. 3). In both cores the abrupt transition from low to high Ba values (Fig. 3) indicates the commencement of drill cutting sedimentation which is accompanied by fining of the sediment with an increase of the silt+clay fraction (<63µm) (Fig. 4), indicating settling of finer drill cutting related sediments downstream from the drill hole.

The top sediment at 0-2 cm core depth in core 30 and 60 has low but still slightly elevated Ba levels compared to background values as observed in other cores/core sections (Fig. 3) and non-impacted local cores (Dijkstra et al., 2015). This slight Ba enrichment likely represent sediments settling after cessation of drilling activity influenced by a combination of bioturbation of the more Ba enriched sediment below in conjunction with reworking of unconsolidated Ba enriched top sediments upstream (e.g. Neff et al., 1989).

Cores 125 and 250 situated furthest away from the drill site are roughly comparable in regards to sediment properties (Figs. 3, 4) with Ba and other heavy metal values measured at or slightly above (e.g. Cd) background levels (Bakke et al., 2010; Dijkstra et al., 2013, 2015). One higher Ba value (325 mg/kg) observed in core 250 at 6-7 cm core depth (Fig. 3) has an age of >100 years according to the ^{210}Pb derived age reconstruction (Fig. 2; Table 2) and is thus not associated to the 2006/07 drill cutting release.

Ba, S and Hg concentration variability largely follows the same trends in the five cores (Fig. 3), indicating affiliation of the elements to the sediments released to the sea as part of the drill cuttings. Ba and S, none of which are part official pollution classification system (Bakke et al., 2007; 2010), both largely originate from Barite, used during the drilling process (Breuer et al., 2004 and ref therein; Neff, 2005). Hg introduced to the marine environment is of greater concern, as it is toxic to marine organisms (Calabrese et al., 1977) and humans (Bernhoft, 2012). However, the Hg concentrations never surpass accepted non-toxic levels and fall into the “Good” category as defined by official Norwegian pollution classification system (Bakke et al., 2007; 2010).

Titanium concentrations in the five cores show different trends than other elements with low levels mainly observed throughout core 5 and at ~3-9 cm in core 60 (Fig.3). This distribution likely also reflects the composition of the strongly drill cutting influenced sediments close to the drill hole which apparently are less Ti enriched than sediments in other cores/core sections (Fig. 3) or in non-impacted local cores (Dijkstra et al., 2015).

6.2. Pre and post drilling sedimentation rates

Sedimentation rates established by ^{210}Pb dating in non-impacted core 250 and below the drill cutting influenced section in core 30 are comparable in ranges observed in non-impacted local areas (Junttila et al., 2014). This finding suggests that natural sedimentation occurred at 30 m from the release site prior to drill cutting release and continuously at 250 m from the release site (Table 2, Fig 2). In the uppermost parts of cores 30 and 60, approximately 2 cm of sediment with slightly elevated Ba values overlay strongly Ba enriched drill cutting influenced sediment sections (Fig. 3). By assuming that the approximately 2 cm of sediment was deposited after cessation of drilling activity in January 2007 until core retrieval in November 2014, the apparent post impact sedimentation rate is ~2.5 mm/yr at both sites (Table 2). This value likewise is within the range of sedimentation rates estimated in local non-impacted cores (Junttila et al., 2014) and thus tentatively support the interpretation that the surface ~2 cm of cores 30 and 60 represent post-drilling sedimentation.

6.3. Fossil foraminiferal faunal assessment

Drill cutting influenced sediments are constrained to 0-5 and 0-11 cm in cores 60 and 30, respectively and throughout core 5 (See above) (Fig. 3). No drill cutting influenced sediments are observed in cores 250 and 125 and the foraminiferal fauna in the two cores therefore is expected to express natural un-impacted conditions (Fig. 5). Most of core 250 and upper part of core 125 (0-8cm core depth) in addition to below drill cutting influenced sediments in core 30 and core 60 hold similar benthic foraminiferal fossil fauna compositions (Fig. 5). This fauna composition resembles a natural modern Holocene fauna as observed in the SW Barents Sea with dominance of *E. nipponica*, *C. laevigata* and large abundance of the high energy environment species *T. angulosa* and *C. lobatulus* (Fig. 7) (Sejrup et al., 2004; Saher et al., 2009; Dijkstra et al., 2013). In these core sections the faunal diversity (Shannon H) and evenness (Simpson 1-d) is ~2-2.4 and ~0.8-0.85, respectively, which in case of diversity is comparable to the range observed in modern natural foraminiferal fauna in the area (Dijkstra et al., 2013).

In cores 30 and 60 elevated foraminiferal total abundances, including calcareous, agglutinated and planktic forms are observed below the drill cutting influenced sediment (Fig. 6). These abundances are higher than observed within the surface ~2 cm of sediments across all cores suggesting that foraminiferal production was larger in the years preceding drilling cutting release in 2006/07 than at present (Fig. 6). This assertion is corroborated by the foraminiferal fluxes of total benthic and planktic forms calculated below the drill cutting impacted section in core 30 which show values significantly higher than in the surface ~2 cm of 250 (Fig. 6) and, regarding benthic forms, higher than observed in non-impacted local areas (Dijkstra et al., 2015).

The composition and elevated total abundances of benthic and planktic foraminiferal fauna in addition to elevated abundance of the epibenthic species *C. lobatulus* and *T. angulosa* (Polyak et al., 2002; Murray, 2006), observed below the drill cutting influenced sediment sections in cores 30 and 60 (Fig. 6) suggest that the 2006/07 faunal composition potentially was preserved with minimal alteration by processes otherwise present during slow natural burial.

Especially the high total abundance of agglutinated forms, which have larger susceptibility to post-mortem destruction (Schröder, 1988; Murray, 2006 and references therein), seem to support this assertion. In local non-impacted sediments agglutinated forms largely disappear below 6 cm sediment depth (e.g. Dijkstra et al., 2015) while no similar peaks in agglutinated foraminiferal abundance is observed at depth in other cores within the present transect (Fig. 6). The abrupt large changes in foraminiferal concentrations and Ba levels at ~11 cm core depth in core 30 further suggests that upon delivery of the ~8 cm thick layer drill cutting related material, the ambient fauna was smothered and bioturbation was halted (Figs. 3, 6). This observation is contrasted in core 60 where the transition from low to high Ba is more gradual, which indicates that fauna partially survived the impact of the more moderate layer of ~2-3cm drill cutting related material (as opposed to ~8 cm in core 30) (Fig. 3) and some bioturbation persisted. This assertion is in line with mesocosm experiments by Hess et al. (2013) showing survival of ambient foraminiferal fauna, when only a thin layer of drill cuttings is being deposited.

At the lowermost part of both cores 250 and 125 (> 8 cm core depth), in addition to the lowermost part of core 60, a benthic fauna composition with dominance of *E. e.* f. *clavata* and *C. reniforme* and elevated relative abundances of *N. labradorica* is observed (Fig. 5). Simultaneously the total abundance of calcareous and agglutinated benthic in addition to planktic foraminifera are low (Fig. 6) while somewhat elevated faunal evenness and diversity is observed (Fig. 5). This faunal composition typically signifies colder and possibly harsher environmental conditions (e.g. Sejrup et al., 2004; Saher et al 2009). These intervals contain no evidence of drill cuttings and hence the faunal compositions and abundances are solely related natural climatic fluctuations. However, a benthic fauna comparable to the abovementioned natural low abundance fauna with dominance of *E. e.* f. *clavata* and *C. reniforme* (Figs. 5, 6) is also found in the drill cutting influenced sediment sections of core 5 (below 5 cm core depth) and at 5-8 cm core depth in core 30. The co-dominant species *E. e.* f. *clavata* (Fig. 5) is part of the opportunistic and tolerant *Elphidium excavatum* group which has been found to dominate/thrive in polluted and/or naturally stressed environments (e.g. Alve, 1995 and ref therein; Hald and Korsun, 1997). The presence of *E. e.* f. *clavata* therefore could be related to the stressed conditions associated with the introduction of drill cuttings to the area. However, assuming that this species and the general foraminiferal fauna, populated and reproduced in-situ during the potential 47 days of drill cutting release, an approximate flux of total indigenous benthic calcareous foraminifera larger than 10000 (core 5) and 2000 (core

30) #/cm^2/yr, would be implied. These foraminiferal flux values are significantly higher than observed in local un-impacted areas (Dijkstra et al., 2015) and calculated elsewhere within the present material (Fig. 6), therefore suggesting that the fauna may be ancient and instead largely have been introduced as part of the released drill cuttings. A tentative support of this assertion comes from the observation of some visually slightly abraded specimens within these sediment sections, which may relate to abrasion received during drilling and subsequent release. In core 60 the drill cutting influenced section at ~2-6 cm core depth (Fig. 3) holds no concurrent change in foraminiferal composition, diversity and evenness as observed in cores 5 and 30 (Fig. 5). This lack of faunal change tentatively confirms that *E. e.* f. *clavata* and *C. reniforme* are unlikely to be indigenous/living during the period of drill cutting release in cores 5 and 30. Instead we assert that foraminiferal specimens as constituents of the drill cuttings seemingly settled together with coarser sediment fractions closer to the release site while finer Ba and S enriched drill cuttings containing low amounts of foraminifera, settled at 60 m from the drill hole (Figs 3, 4, 5).

In the surface ~2 cm sediments in all examined cores the fossil fauna is dominated by *E. nipponica*, *C. laevigata*, *T. angulosa* and *C. lobatulus* (Fig. 5) with elevated total abundances of both calcareous and agglutinated forms (Fig. 6) resembling natural modern faunas in the SW Barents Sea (Sejrup et al., 2004; Saher et al., 2009; Dijkstra et al., 2013). This observation suggests reestablishment of a natural fauna after cessation of drill cutting release in 2007. The faunal diversity and evenness values are also similar across the transect, with slightly elevated values of both parameters in core 5 mainly due to presence of *E. e.* f. *clavata* and *C. reniforme* (Fig. 5). Incidentally, core 5 is the only studied core strongly influenced by drill cutting within the topmost sediment as exemplified by relatively high average Ba (and S) values (Fig. 3). This observation suggests bioturbation of in-situ Ba-enriched sediments below and/or sustained influence from reactivatable local Ba-enriched sediments. The latter explanation would likely entail somewhat increased turbidity closest to the drill hole which could explain presence of an opportunistic species like *E. e.* f. *clavata* (Hald and Korsun, 1997) in cores 5 and 30 (Figs. 5).

In cores 30 and 60 elevated Ba (and S) values, representing strongly drill cutting influenced sediments, decline sharply reaching relatively low values at 0-2 cm core depths (Fig. 3). This observation suggests that in the aftermath of drilling cessation and commencement of a natural sedimentation regime (Junttila et al., 2014) (Fig. 2; Table 2) less influence from reactivated up-stream sediments and limited mixing of sediments from below via bioturbation occurred, which allowed reestablishment of a natural fauna (Dijkstra et al., 2013; 2015) (Figs. 5, 6).

6.4 Live (vs. fossil) foraminiferal fauna assessment

Live (rose bengal stained) benthic calcareous and agglutinated foraminiferal fauna is observed down to 5 cm sediment depth in all the studied cores (Figs, 5, 6, 7). The sediment depth distribution of living forms at the time of coring in November 2014 shows highest abundances at 0-1 cm sediment depth followed by an overall decreasing trend down core. Exception is core 5 where abundance at 2-3 cm core depth is almost as high at within the topmost 0-1 cm. (Fig. 6). This overall distribution pattern is common for live benthic foraminifera within sediments (e.g. Castignetti and Manley, 1998; Alve and Murray, 2001) which is largely controlled by oxygen and food availability (Jorissen et al., 1995). TOC levels recorded in the top sediments across the study transect are within the range observed in the SW Barents Sea (Knies and Martinez, 2009; Dijkstra et al., 2013; 2015) (Fig. 3). TOC levels vary only slightly between cores and therefore have insignificant influence on the differences observed in live foraminiferal fauna compositions (Figs. 3, 5, 6).

The relatively most abundant live species found in all five cores are *E. nipponica, T. angulosa, C. laevigata* and *C. lobatulus* (Figs. 5, 7). All four species commonly co-dominate in the Atlantic water influenced SW Barents Sea (Sejrup et al., 2004; Saher et al., 2009), while *C. lobatulus* and *T. angulosa* furthermore are associated with areas of elevated hydrodynamic activity and coarser sediments (e.g. Hald and Steinsund, 1992). *C. lobatulus* and *T. angulosa* constitute 24-29 % of the live fauna closest to the drill site but are most prevalent furthest away from the drill site constituting 42-45% at core sites 125 and 250 (Fig. 5, 7) which may be tentatively linked to somewhat coarser surface sediment in the outer cores (Fig. 4). This is not the case for core 5 which has the highest top sediment sand content (Fig. 3) but does not hold relatively more live *C. lobatulus* and/or *T. angulosa* (Figs 5, 6, 7). This may instead be an expression of natural faunal variability/patchiness (e.g. Swallow, 2000; Griveaud et al., 2010) and/or somewhat different environmental conditions at 5 meters from the drill hole. The latter assertion is supported by the presence of live *E. e.* f. *clavata*, albeit at low relative abundance, indicating that turbidity could be a factor influencing the fauna composition (Hald and Korsun, 1997 and refs therein) near the drill hole in the aftermath of drilling cessation (see section 5.3) up until today. Calculated live faunal diversity and evenness values are highest in core 5 with both parameters declining with distance from the drill hole (Fig 5, 7). Furthermore total abundance of calcareous benthic foraminifera are slightly elevated in the three cores (5, 30 & 60) closest to the drill hole while agglutinated forms are present at approximately the same total abundance across the transect (Fig. 6). These observations collectively show that in the present setting a diverse (and numerous) benthic foraminiferal community was/is able to live and reproduce in the area despite lingering influence from drill cuttings. Other studies have shown similar diverse foraminiferal faunas at low pollution impact levels at intermediate distances from a polluting source (Mojtahid et al., 2006; 2008; Jorissen et al., 2009).

When comparing the relative abundance of live and ambient fossil calcareous foraminiferal species a large degree of similarity is observed most pronouncedly as the same four species, *E. nipponica*, *T. angulosa*, *C. laevigata* and *C. lobatulus* dominate in both assemblages (Figs. 5, 7). This observation suggests that an approximate natural benthic foraminiferal fauna reestablished after cessation of drill cutting release. This is confirmed by the observable similarity between the reestablished fauna in the top of the cores and 1) the pre-impacted faunal compositions in the lower part of cores 30 and 60 (Fig. 5), 2) the non-impacted faunas in cores 125 and 250 (Fig. 5) and 3) the faunas in local non-impacted sediments (Dijkstra et al., 2015). Several other species (*N. labradorica* (Figs. 6 and 7), *P. bulloides, M. barleeanus,* (Fig. 7), *Cassidulina neoteretis* and *Nonionella auricula* (Data not shown; see supplementary data)) are observed at lower relative abundance in both the live and fossil assemblage, but none show changes with distance from the drill hole that can be linked to drill cutting influence. However, these species are common at low relative abundance in the SW Barents Sea (Sejrup et al., 2004) and their presence in the top sediments therefore further supports the assertion that a natural fauna reestablished in all five cores after drilling cessation.

There are, however, some observable differences between the live and ambient fossil calcareous foraminiferal assemblage in the top sediments. Compared to the fossil record, the relative abundances of *C. laevigata* and *T. angulosa* are consequently lower and higher in the live assemblage, respectively (Fig. 6). These differences tentatively suggest that *T. angulosa* lives and reproduces in the area around the time of coring (i.e. late fall/early winter) while *C. laevigata*`s primary living/reproduction season likely is earlier in the year and therefore living species are underrepresented in the early winter fauna. Another marked difference between the live and fossil assemblage is presence of two species found at relatively high abundance in the live fauna, namely *Quinqueloculina seminula* observed in all cores (6.4-15.5%) and *Sphaeroidina bulloides* found only in cores 30 and 60 (3.2-9.1%) (Fig. 7). Both species are infrequently present at very low relative abundance or missing from large sections of the fossil record (see appendix). It could be construed that *Q. seminulum* and *S. bulloides*, which both are thin walled species, are particularly vulnerable to post mortem dissolution/destruction, which could explain their rarity in the fossil assemblage. However, frequent observations of the dissolution susceptible planktic foraminifera *Turborotalita quinqueloba* (Conan et al., 2002) in the sediments (data not shown) seems to negate post mortem dissolution as a sole explanation. Neither *Q. seminula* nor *S. bulloides* are reported at high abundance in the fossil fauna in the SW Barents Sea (e.g. Hald and Steinsund, 1992; Aagaard-Sørensen et al., 2010; Chistyakova et al., 2010; Risebrobakken et al., 2010; Dijkstra et al., 2015). Live *Q. seminula* is observed locally at low abundance by Dijkstra et al. (2013) and sporadically in surface sediments in the Barents Sea (Sejrup et al., 2004 and ref therein). Live *S. bulloides,* to our knowledge, remain undocumented in the Barents Sea area although the species is noted in studies spanning the globe from the Nordic and Arctic Seas (Goës, 1894; Gabel, 1971), Mediterranean Sea and Iberian Margin (Rasmussen, 2005 and ref therein) over the tropics (Cushman et al., 1954). In the literature neither *Q. seminula* nor *S. bulloides* are documented as indicator species for polluted or otherwise stresses environmental conditions, although Alve et al. (2016) ascribes *Q. seminula* to an ecological group that represents species that are absent at very high organic matter concentrations. The discrepancy that *Q. seminula* and *S. bulloides* are observed at somewhat high relative abundances in the present live assemblage, but at low relative abundances in the fossil assemblage could be an artefact related to the time of coring (Nov 2014). Given the distribution of the two species within the live and fossil assemblages, we find no evidence linking their presence/absence to either immediate or lingering long-term effects of the drill cutting release in 2006/07. Likewise, although the live benthic foraminiferal fauna observed across the transect portrays a composition that holds some marked differences compared to the ambient fossil fauna we ascribe most of this difference to seasonal influence over lingering impact from the 2006/07 drill cutting release.

7. Summary and conclusions

The objective of the present study was to examine the potential past and present-day environmental impact linked to water based drill cuttings (DC) release during drilling of an exploration well in 2006/07 within the Goliat oil field, SW Barents Sea. The examined material consists of sediment cores obtained at 5, 30, 60, 125 and 250 meters from the wellhead in the downstream eastward direction. The cores were retrieved (Nov 2014) almost a decade after cessation of exploration drilling (Jan 2007).

DC influenced sediments were identified by detection of elevated Ba (and S) concentrations and changes in sediment grain size. DC influenced sediments spread to at least a distance of 60 m from the wellhead with thicknesses decreasing away from the wellhead reaching minimum 20cm at 5m, ~8cm at 30m and 2-3cm at 60m. At 5m the DC influenced sediment reaches the surface, while at 30 and 60m it is covered by ~2 cm almost un-impacted sediment suggesting a post-impact sedimentation rate of ~2.5 mm/yr, while sedimentations rates in non-impacted sediment sections established via ^{210}Pb dating on average were ~0.6-1.7 mm/yr.

The foraminiferal fauna composition observed within the strongly DC influenced core 5 (below 5 cm core depth) and in parts of core 30 (~2-11 cm core depth) shows high relative abundance of arctic species like *E. e.* f. *clavata* and *C. reniforme*. This fauna composition is markedly different from the live and the fossil fauna composition observed before and after drilling ended. As it is unlikely that these arctic species lived (to the extent that they could dominate the fauna composition) in the area during the few month of drilling activity it therefore can be asserted that they more likely were part of the released DC material. A similar link between DC influenced material and arctic fauna is not observed in core 60 likely due to settling of coarser sediment fractions, to which foraminifera typically adhere, closer to the wellhead.

The abundance and composition of the fossil fauna observed within the minimally impacted ~2 cm surface sediment in cores 30 and 60 furthermore suggest that a natural fauna likely reestablish soon after drilling ended. The immediate impact of DC releases is observed in core 30 where an abrupt and market shift in sediment properties indicates a stop of bioturbation due to delivery of ~8 cm drill cuttings smothering the benthic foraminiferal fauna. In core 60 delivery of ~2-3 cm DC related sediments and a less abrupt shift in most notably sediment Ba concentrations suggests continued bioturbation and likely partial survival of the foraminiferal fauna.

The live foraminiferal fauna observed at all distances from the drill site is dominated by of *E. nipponica*, *T. angulosa*, *C. laevigata* and *C. lobatulus*, alongside a range of lesser frequent species, resembling live fauna distributions from non-impacted local studies. This indicates that a natural foraminiferal fauna had reestablished at the time of coring. The live fauna also resembles the post- and pre-impacted fossil fauna observed in the non-DC influenced sediments of the cores, which shows that the environment in the area was the same prior to and after DC release.

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Captions

Table 1. Examined push cores with distance from drill hole, core length, applied proxies, sampling and dating method. Abbreviations: TOC=Total Organic Carbon; S= Sulphur; HM=Heavy Metal; X-ray=X-ray photograph; Forams=Foraminiferal analysis; Water %=Sediment water content; GS=Grain Size. *^{210}Pb dating unsuccessful (see table 2).

Table 2. Excess ^{210}Pb measurements, CRS calculated age and calculated sedimentation rates. *Sedimentation rate estimated based on post-impacted sediment thickness (See discussion). `Years before 2006. `` Years before 2014.

Table 3. Species list

Figure 1. Study area, water masses, push core transect and CTD. (A) Regional study area with dominant ocean currents of the Norwegian Sea and western Barents Sea. Abbreviations: NAC=North Atlantic Current; NCC=Norwegian Coastal Current; NCaC=North Cape Current; BIC=Bear Island Current; ESC=East Spitsbergen Current. (B) Local study area with detailed bathymetry. (C) The Goliat field with exploration wells sites (Modified from Norwegian petroleum Directorate factmaps, 2016). X and black box mark examined exploration well 7122/7-5 and downstream push core transect. (D) X-ray images of push cores with distance from exploration well (0m). (E) Conductivity, temperature, and depth (CTD) of the water column in November 2014.

Figure 2. Age reconstruction and sedimentation rate of cores 30 and 250. (A, C) Top sediment age models of the cores (black dots) based on the Constant Rate of Supply (CRS) model (Appleby and Oldfield, 1992) and excess ^{210}Pb profiles (open gray dots) and measurement uncertainty represented by vertical error bars. (B, D) Average sediment accumulation rates developed by linear interpolation between Pb-210 dated levels. *Estimated post depositional accumulation rate (see table 2). **Estimated thickness of drill cuttings accumulated during 2006/7.

Figure 3. Heavy metal (Ba, Hg, Cd, Cr, Cu, Pb, Zn, Ti) concentrations (mg/kg TS) and TOC and S content (wt.%) in cores 5, 30, 60, 125, 250 vs depth. For Hg, Cd, Cr, Pb, Zn no coloring depicts heavy metal concentrations of environmental class I (background) and red shading depicts concentrations of environmental class II (good), none of which are considered toxic (Bakke et al., 2010). For metals Ba and Ti (not included in the above referenced class system) a simplified classification system is used, with values either above (red shading) or below (no shading) observed background levels (<200 mg/kg) in non-impacted regional sediments (Dijkstra et al., 2015). (Middle) ^{210}Pb age.

Figure 4. Detailed sediment grain size distribution and water content in cores 5, 30, 60, 125, 250 vs depth. Grain sizes divided into clay, silt and very fine, fine and coarse sand fractions. (Right) Accumulated grain size. (Right) Water content (wt.%).

Figure 5. Relative abundance of fossil and live calcareous benthic foraminifera (Rel.%) and faunal diversity index values in cores 5, 30, 60, 125, 250 vs depth. (Left) Shannon index (H) and Simpson`s index of Diversity (1-D). (Middle – Right) Relative abundance (Rel.%) of calcareous benthic foraminiferal species (>8 Rel.% in fossil assemblage in at least one sample). Red Diamonds= Relative species abundance and diversity index values for live calcareous benthic foraminifera in top sediment at 0-5 cm core depth.

Figure 6. Foraminiferal abundance (specimens per gram dry sediment) in cores 5, 30, 60, 125, 250 vs depth. (Left – Middle) Abundance of relatively most abundant (Showing data with fossil species >8 Rel.% in at least one sample) fossil and live calcareous benthic foraminiferal species. Red Diamonds= Live species abundance in top sediment at 0-5 cm core depth. (Right) Total abundance of fossil and live (red line) calcareous and agglutinated foraminifera in addition to fossil planktic foraminifera. Flux of fossil foraminifera (blue line).

Figure 7. Relative abundance of most abundant (>8 Rel.% in at least one sample + *E.e.*f. *clavata*) live benthic foraminifera (Rel. %) at 0-5 cm core depth in cores 5, 30, 60, 125 and 250. (Right) Live calcareous benthic foraminifera diversity index values (Shannon index (H) and Simpson`s index of Diversity (1-D)).

Table 1

Date of coring	Distance from drill hole (m)	Core name	Core treatment onboard vessel	Analytical methods	Short core/ station name	Position	Water depth (m)
30.11.2014	5	ED50-5.4.5.PuC	Frozen	TOC, S, HM, X-ray, ^{210}Pb*	Core 5	71.274° N; 22.276° E	371
30.11.2014	5	ED50-5.5.5.PuC	Subsampled, frozen	Forams, GS, Water %	Core 5	71.274° N; 22.276° E	371
30.11.2014	30	ED50-4.1.30.PuC	Frozen	TOC, S, HM, X-ray, ^{210}Pb	Core 30	71.274° N; 22.277° E	371
30.11.2014	30	ED50-4.3.30.PuC	Subsampled, frozen	Forams, GS, Water %	Core 30	71.274° N; 22.277° E	371
29.11.2014	60	ED50-3.2.60.PuC	Frozen	TOC, S, HM, X-ray, ^{210}Pb*	Core 60	71.274° N; 22.278° E	372
29.11.2014	60	ED50-3.4.60.PuC	Subsampled, frozen	Forams, GS, Water %	Core 60	71.274° N; 22.278° E	372
29.11.2014	125	ED50-2.2.125.PuC	Frozen	TOC, S, HM, X-ray, ^{210}Pb*	Core 125	71.274° N; 22.280° E	372
29.11.2014	125	ED50-2.4.125.PuC	Subsampled, frozen	Forams, GS, Water %	Core 125	71.274° N; 22.280° E	372
29.11.2014	250	ED50-1.2.250.PuC	Frozen	TOC, S, HM, X-ray, ^{210}Pb	Core 250	71.274° N; 22.283° E	373
29.11.2014	250	ED50-1.1.250.PuC	Subsampled, frozen	Forams, GS, Water %	Core 250	71.273° N; 22.282° E	373

Table 2

Core name	Short name	Distance from wellhead (m)	Measured core depth (cm)	Decay-Corrected Excess Pb-210 (pCi/g)	CRS calc. age Midpoint (Years)	CRS date (Calendar years)	Sedimentation rate (mm/yr)
ED50-5.4.5.PuC	Core 5b	5	5.5	0.35±0.65			
			10.5	-0.09±0.31			
			19.5	0.08±0.27			
ED50-4.1.30.PuC	Core 30b	30	0.5	1.51±0.65	0	2014	2.5*
			1.5	1.15±0.18	0	2010	2.5*
			2.5	2.57±0.23	0	2006/7	0
			3.5	1.07±0.18	0	2006/7	0
			4.5	0.38±0.20	0	2006/7	0
			5.5	0.04±0.12	0	2006/7	0
			6.5	0.05±0.09	0	2006/7	0
			7.5	0.13±0.13	0	2006/7	0
			8.5	0.14±0.11	0	2006/7	0
			9.5	0.50±0.55	0	2006/7	0
			10.5	0.27±0.14	0	2006/7	0
			11.5	1.21±0.60	11.39’	1995	0.91
			12.5	0.27±0.48	14.84’	1991	2.5
			13.5	0.25±0.38	18.39’	1988	3.33
			14.5	0.13±0.21	20.33’	1986	5
			15.5	0.39±0.48	27.06’	1979	1.43
			16.5	0.19±0.10	31.07’	1975	2.5
			17.5	0.33±0.12	39.55’	1966	1.11
			18.5	0.27±0.12	48.53’	1957	1.11
			19.5	0.09±0.10	52.35’	1954	3.33
ED50-3.2.60.PuC	Core 60b	60	0.5	1.37±0.63		2014	2.5*
			3.5	1.78±0.77			
			6.5	3.24±0.679			
			7.5	3.02±0.89			
			8.5	2.96±1.05			
			9.5	4.48±0.67			
ED50-2.2.125.PuC	Core 125b	125	0.5	2.79±0.67			
			1.5	2.44±0.67			
			2.5	2.22±0.67			
			3.5	1.71±0.64			
			4.5	1.20±0.61			
			5.5	0.87±0.47			
			6.5	0.93±0.53			
			7.5	0.27±0.47			
ED50-1.2.250.PuC	Core 250b	250	0.5	2.58±0.88	6.15’’	2008	1.62
			1.5	2.31±0.9	21.33’’	1993	0.66
			2.5	1.61±0.82	38.81’’	1975	0.57
			3.5	1.40±0.79	71.60’’	1942	0.31
			4.5	0.20±0.45	81.00’’	1933	1.06
			5.5	0.22±0.45	96.27’’	1918	0.65
			6.5	0.10±0.46			
			7.5	-0.06±0.3			
			8.5	-0.03±0.47			

Table 3

Alabaminella weddellensis (Earland, 1936)
Asterigerinata mamilla (Williamson, 1858)
Astrononion gallowayi Loeblich and Tappan, 1953
Bolivina variabilis (Williamson, 1858)
Brizalina pseudopunctata (Höglund, 1947)
Buccella frigida (Cushman 1922)
Buccella hannai (Phleger and Parker) subsp. *arctica* Voloshinova, 1960
Buccella tenerrima (Bandy, 1950)
Bulimina marginata d'Orbigny, 1826
Cassidulina laevigata d'Orbigny, 1826
Cassidulina neoteretis Seidenkrantz, 1995
Cassidulina reniforme (Nørvang, 1975)
Cassidulina obtusa Williamson, 1858
Cassidulina sp.
Cibicides lobatulus (Walker & Jacob, 1798)
Cibicides refulgens Montfort, 1808
Dentalina pauperata (d'Orbigny, 1846)
Dentalina subsoluta (Cushman, 1923)
Discorbinella spp.
Elphidium albiumbilicatum (Weiss, 1954)
Elphidium asklundi Brotzen, 1943
Elphidium excavatum (Terquem) forma *clavata* Cushman, 1944
Elphidium frigidum Cushman, 1933
Elphidium magellanicum Heron-Allen and Earland, 1932
Eponides spp.
Epistominella vitrea Parker, 1953
Epistominella exigua (Brady, 1884)
Epistominella nipponica (Kuwano, 1962)
Epistominella sp.
Fissurina orbignyana Seguenza, 1862
Fissurina spp.
Glandulina laevigata (d'Orbigny, 1826)
Globobulimina auriculata arctica Höglund, 1947
Globobulimina turgida (Bailey, 1851)
Guttulina spp.
Haynesina orbiculare (Brady, 1881)
Islandiella helenae Feyling-Hanssen & Buzas, 1976
Lagena sp.
Lagena striata (d'Orbigny, 1839)
Laryngosigma spp.
Lenticulina spp.
Melonis barleeanus (Williamson, 1858)
Melonis umbilicatulus (Walker & Jacob, 1798)
Miliolinella subrotunda (Montagu, 1803)
Nodosaria spp.
Nonionella auricula Heron-Allen & Earland, 1930
Nonionellina labradorica (Dawson, 1860)
Nonionoides turgida (Williamson, 1858)
Oolina melo d'Orbigny, 1839
Oolina spp.

Parafissurina spp.
Patellina corrugata Williamson, 1858
Pseudopolymorphina spp.
Pullenia bulloides (d'Orbigny, 1846)
Pullenia osloensis Feyling-Hanssen, 1954
Pullenia subcarinata (d'Orbigny, 1839)
Pyrgo williamsoni (Silvestri, 1923)
Quinqueloculina seminula (Linnaeus, 1758)
Quinqueloculina spp.
Robertinoides charlottensis (Cushman, 1925)
Rosalina williamsoni (Chapman & Parr, 1932)
Sphaeroidina bulloides d'Orbigny, 1826
Spirillina vivipara Ehrenberg, 1843
Stainforthia feylingi Knudsen & Seidenkrantz, 1994
Stainforthia fusiformis (Williamson, 1848)
Stainforthia loeblichi Feyling-Hanssen, 1954
Triloculina spp.
Triloculina trihedra Loeblich & Tappan, 1953
Triloculina trigonula (Lamarck, 1804)
Trifarina angulosa (Williamson, 1858)
Uvigerina peregrina Cushman, 1923

Figure 1
Click here to download high resolution image

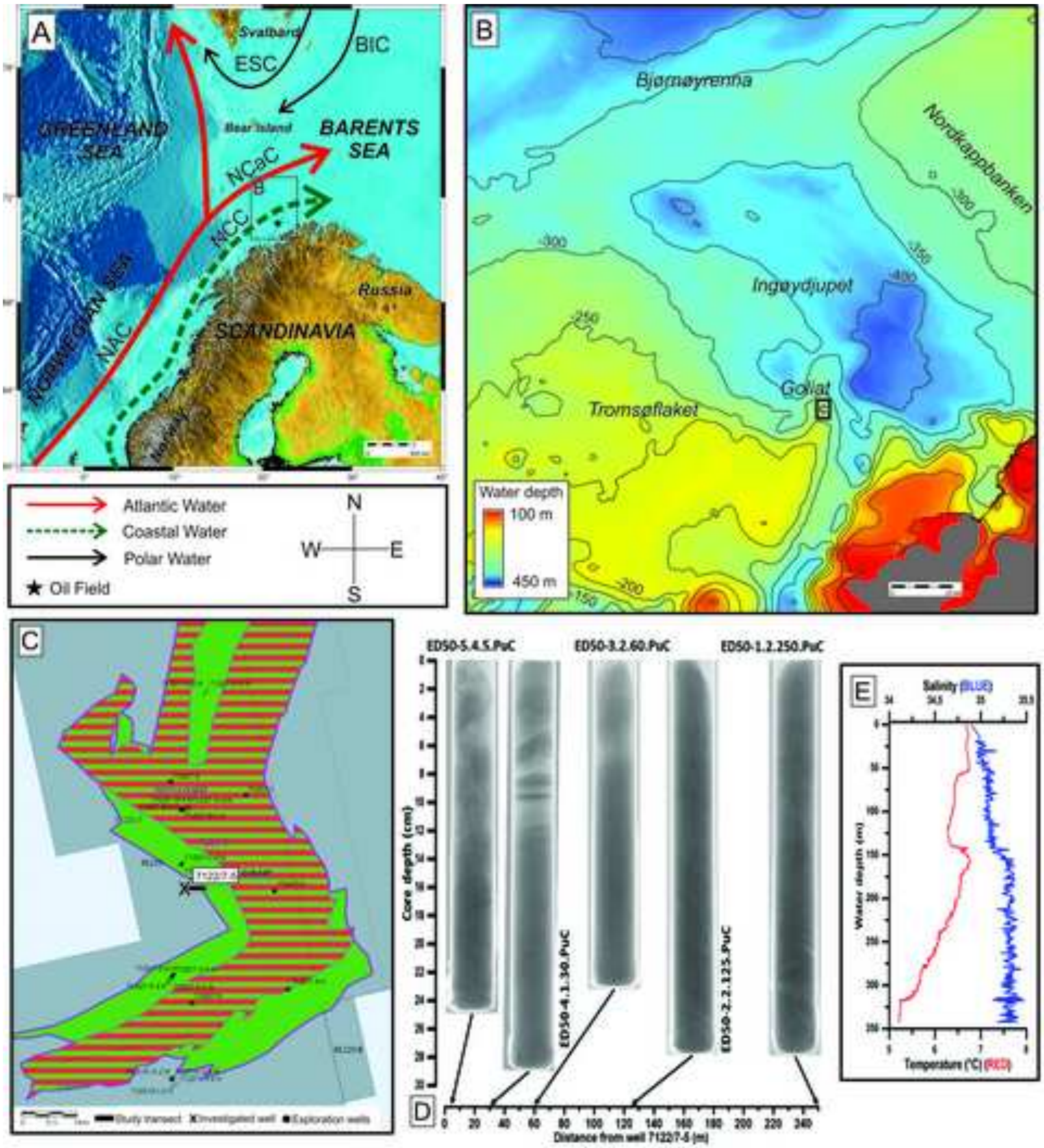


Figure 2

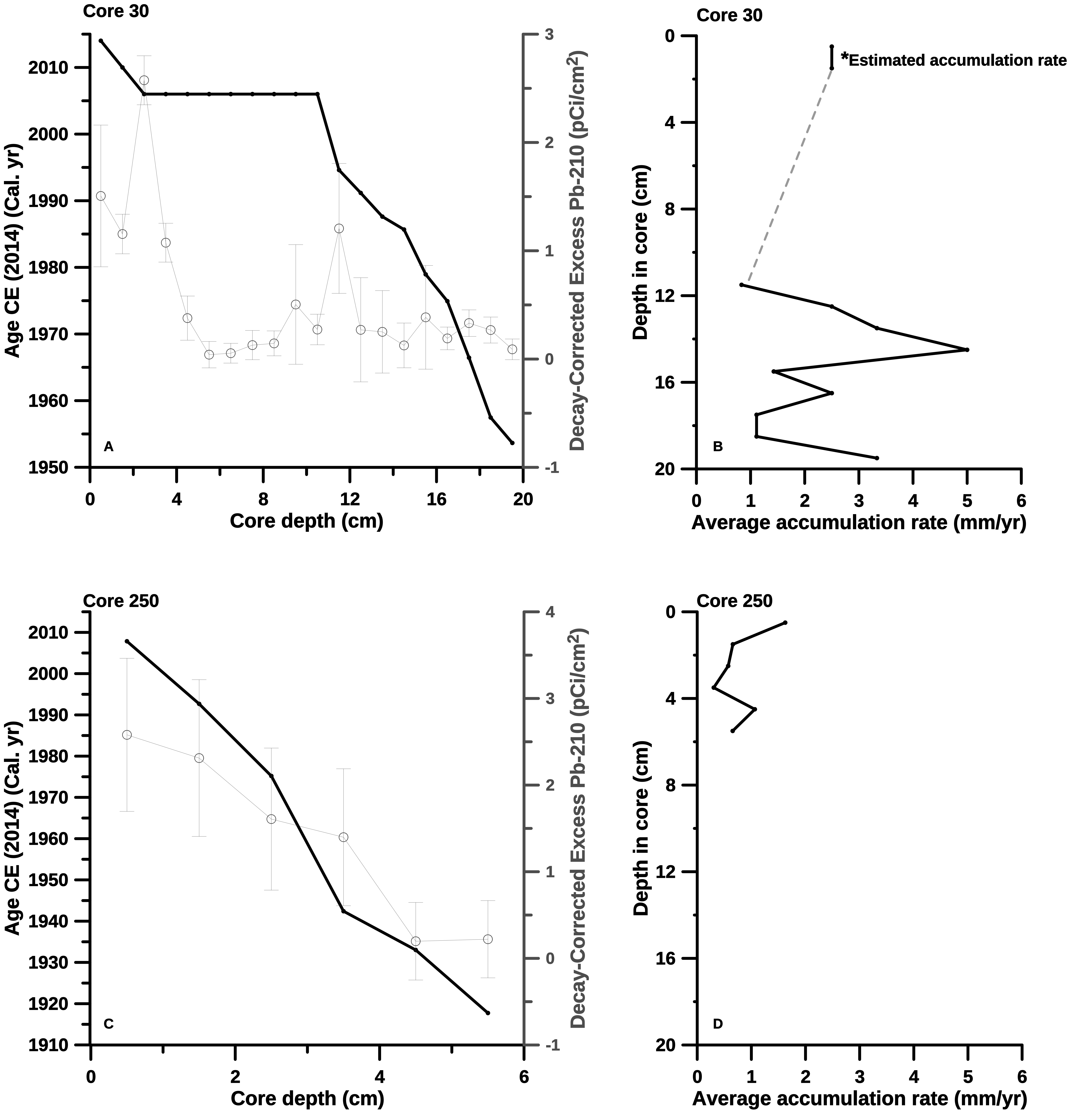

Core 30
Age CE (2014) (Cal. yr)
2010
2000
1990
1980
1970
1960
1950
Decay-Corrected Excess Pb-210 (pCi/cm2)
3
2
1
0
-1
A
0
4
8
12
16
20
Core depth (cm)
Core 30
*Estimated accumulation rate
Depth in core (cm)
0
4
8
12
16
20
B
0
1
2
3
4
5
6
Average accumulation rate (mm/yr)
Core 250
Age CE (2014) (Cal. yr)
2010
2000
1990
1980
1970
1960
1950
1940
1930
1920
1910
Decay-Corrected Excess Pb-210 (pCi/cm2)
4
3
2
1
0
-1
C
0
2
4
6
Core depth (cm)
Core 250
Depth in core (cm)
0
4
8
12
16
20
D
0
1
2
3
4
5
6
Average accumulation rate (mm/yr)

Figure 3

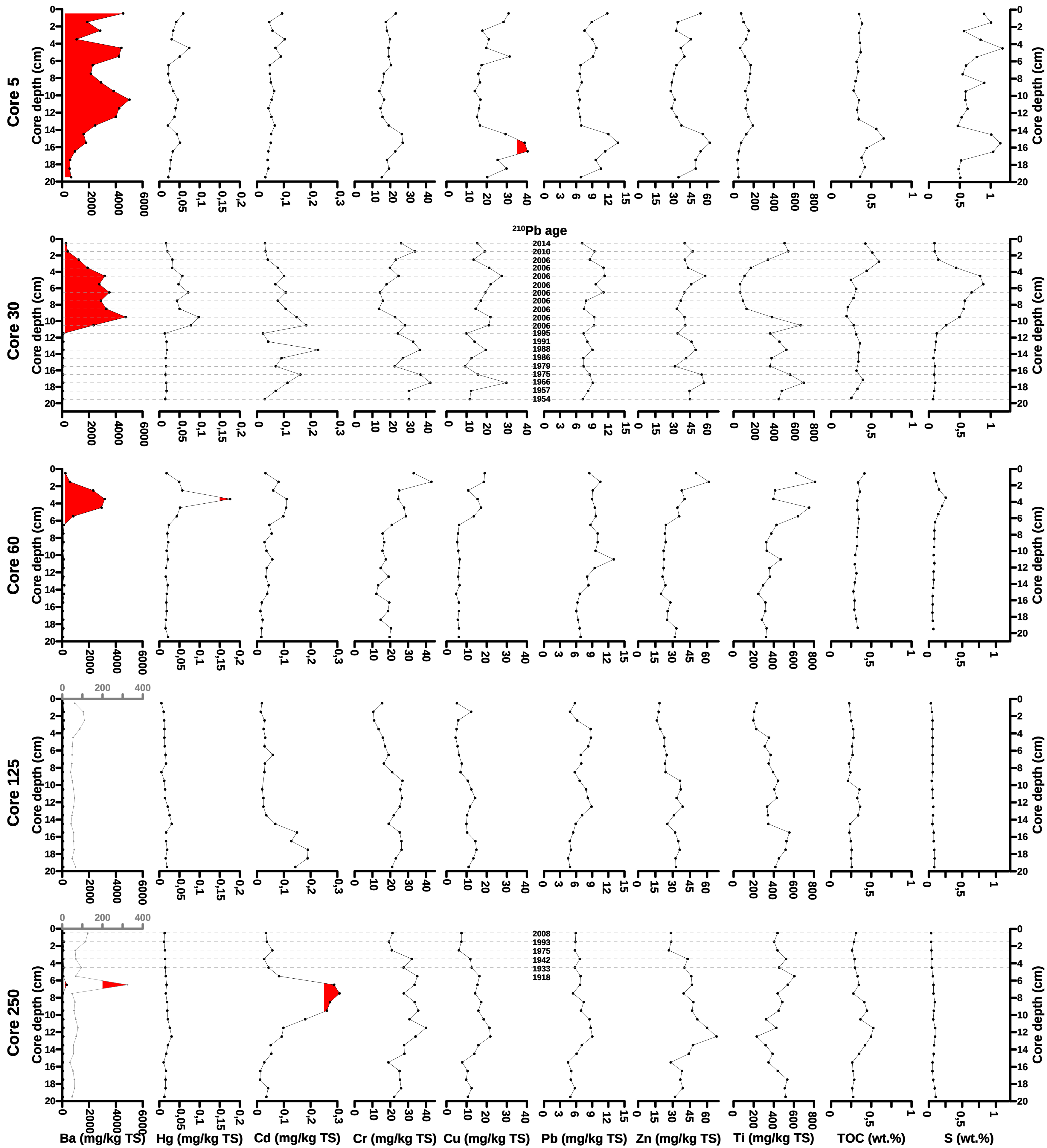
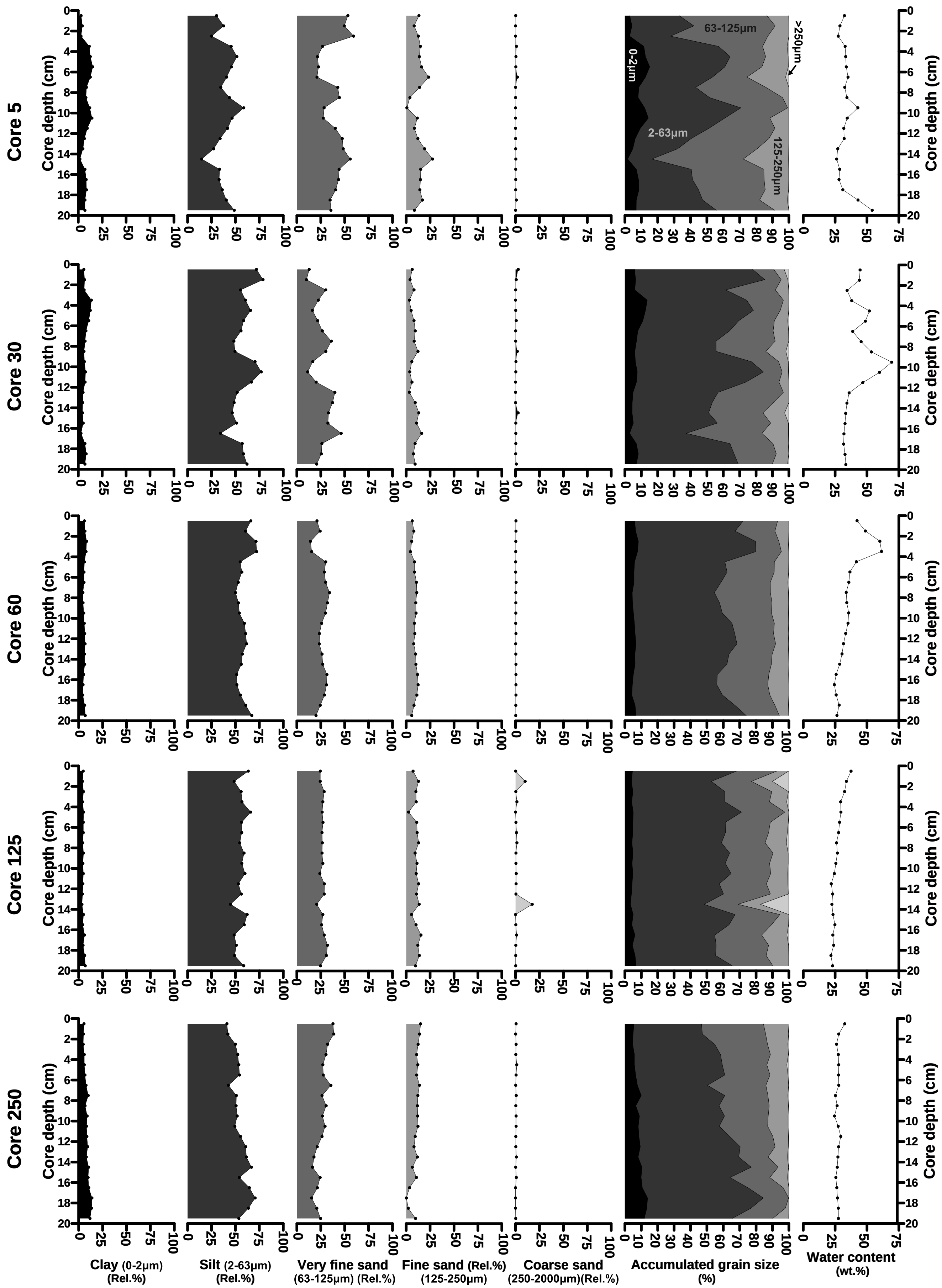
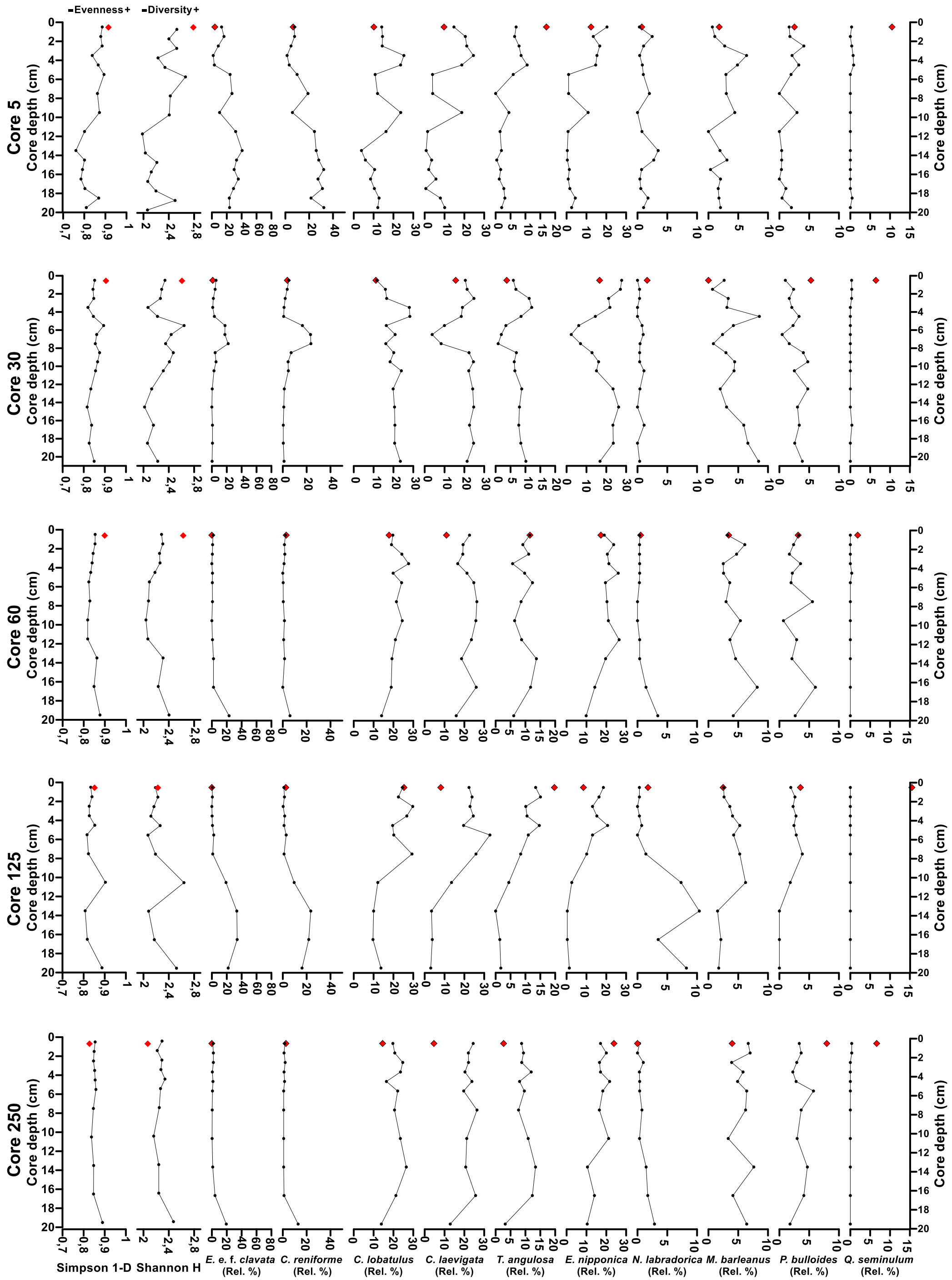

Core 5
Core 30
Core 60
Core 125
Core 250
Core depth (cm)
210Pb age
2014
2010
2006
2006
2006
2006
2006
2006
2006
2006
2006
1995
1991
1988
1986
1979
1975
1966
1957
1954
2008
1993
1975
1942
1933
1918
Ba (mg/kg TS)
Hg (mg/kg TS)
Cd (mg/kg TS)
Cr (mg/kg TS)
Cu (mg/kg TS)
Pb (mg/kg TS)
Zn (mg/kg TS)
Ti (mg/kg TS)
TOC (wt.%)
S (wt.%)

Figure 4



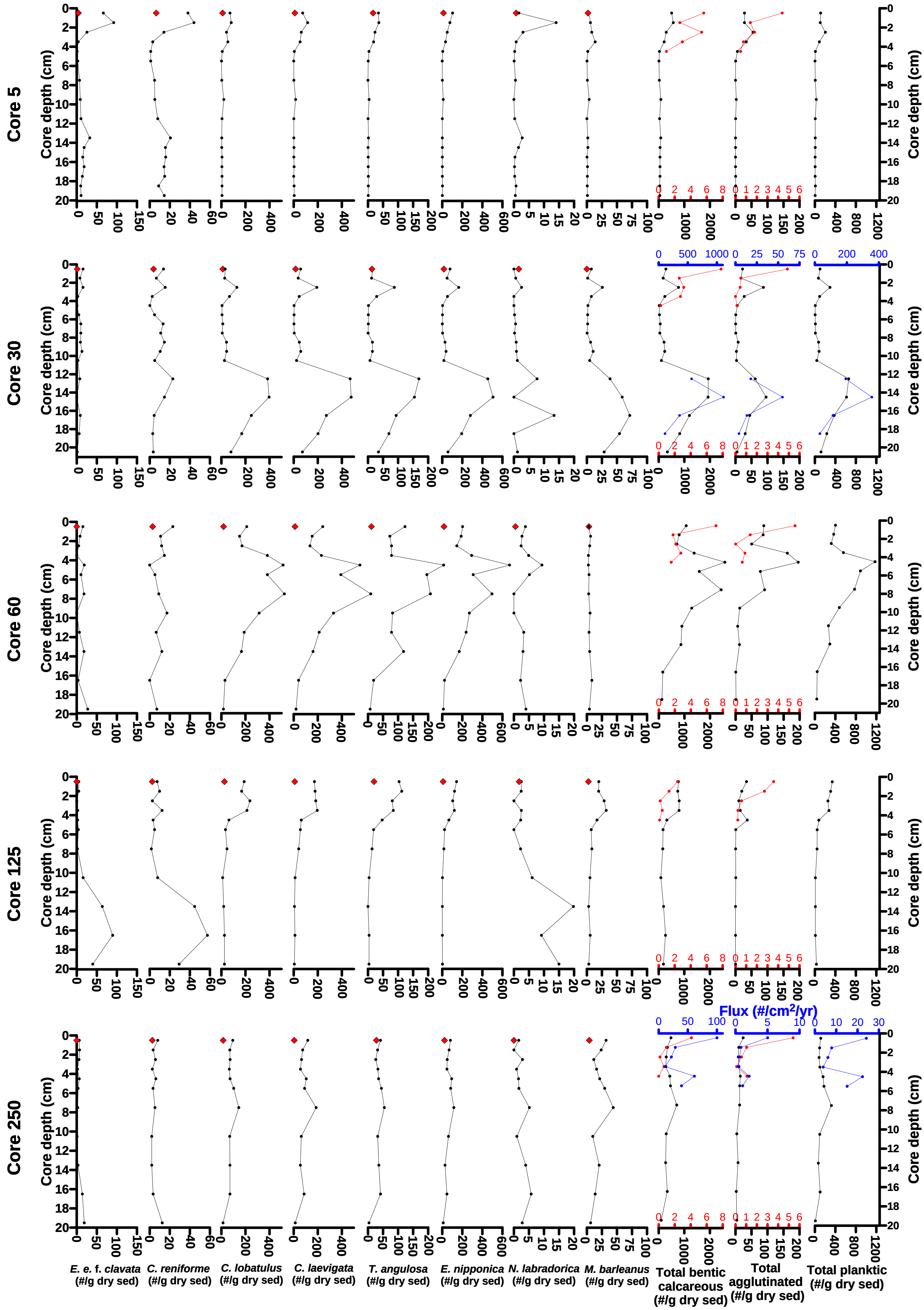
Core 5
Core 30
Core 60
Core 125
Core 250
Core depth (cm)
0-2μm
2-63μm
63-125μm
125-250μm
>250μm
Clay (0-2μm) (Rel.%)
Silt (2-63μm) (Rel.%)
Very fine sand (63-125μm) (Rel.%)
Fine sand (Rel.%) (125-250μm)
Coarse sand (250-2000μm)(Rel.%)
Accumulated grain size (%)
Water content (wt.%)

Figure 5



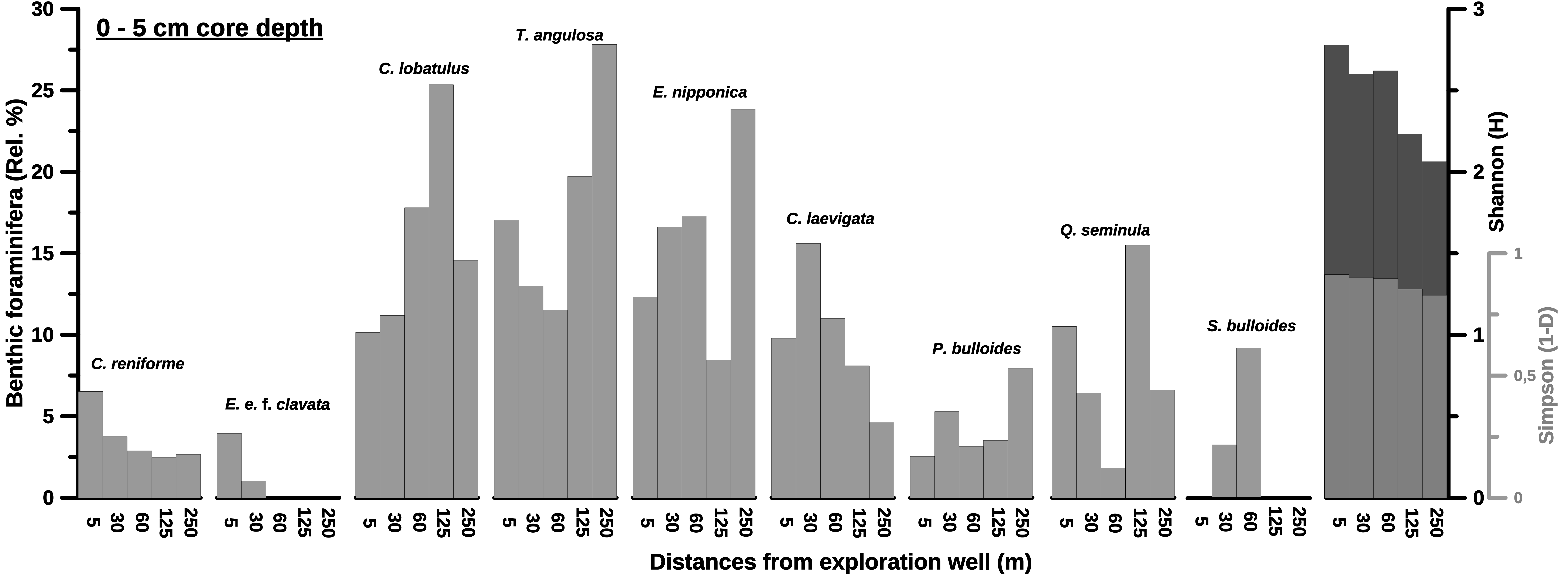
Evenness+
Diversity+
Core 5
Core 30
Core 60
Core 125
Core 250
Core depth (cm)
Simpson 1-D
Shannon H
E. e. f. clavata (Rel. %)
C. reniforme (Rel. %)
C. lobatulus (Rel. %)
C. laevigata (Rel. %)
T. angulosa (Rel. %)
E. nipponica (Rel. %)
N. labradorica (Rel. %)
M. barleanus (Rel. %)
P. bulloides (Rel. %)
Q. seminulum (Rel. %)

Figure 6



Core 5
Core 30
Core 60
Core 125
Core 250
Core depth (cm)
Flux (#/cm2/yr)
E. e. f. clavata (#/g dry sed)
C. reniforme (#/g dry sed)
C. lobatulus (#/g dry sed)
C. laevigata (#/g dry sed)
T. angulosa (#/g dry sed)
E. nipponica (#/g dry sed)
N. labradorica (#/g dry sed)
M. barleanus (#/g dry sed)
Total bentic calcareous (#/g dry sed)
Total agglutinated (#/g dry sed)
Total planktic (#/g dry sed)

Figure 7


0 - 5 cm core depth
Benthic foraminifera (Rel. %)
0
5
10
15
20
25
30
C. reniforme
E. e. f. clavata
C. lobatulus
T. angulosa
E. nipponica
C. laevigata
P. bulloides
Q. seminula
S. bulloides
5
30
60
125
250
Distances from exploration well (m)
Shannon (H)
0
1
2
3
Simpson (1-D)
0
0,5
1

Supplementary Data Abiotic

Click here to download Supplementary Data: Supplementary data_abiotic_Aagaard et al.xlsx

Supplementary Data Foraminifera

Click here to download Supplementary Data: Supplementary data_forams_Aagaard et al.xlsx