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Monitoring environmental impacts of fish farms: Comparing reference conditions of sediment geochemistry and benthic foraminifera with the present

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ABSTRACT

Intensive fish farming is a major industry, but the extent of organic matter (OM) and heavy metal pollution by fish farms is debated. This study established in situ reference conditions using geochemical parameters and fossil benthic foraminiferal assemblages in dated sediment cores to identify potential impacts of fish farming in two basins of the inner Øksfjord, Northern Norway. Living (rose Bengal stained) benthic foraminifera were used to assess the present day environmental conditions. The fossil foraminiferal records were compared with the living foraminifera, which in turn were compared with macrofaunal data. Long-term (> 100 yrs) sediment core records of the geochemical parameters (TOC_{63}, C/N, $\delta^{13}C_{VPDB}$ TOC and heavy metals) and foraminiferal indices (Norwegian Quality Index (fNQI), AZTI's Marine Biotic Index (fAMBI), $fHlog_2$, ES_{100}) did not indicate an impact from fish farming through time. Long-term changes in foraminiferal absolute abundances and relative abundances of ecological groups (EGs) reflecting organic matter (OM) tolerance suggest that the OM supply slightly increased compared to reference conditions. Relative abundances of *Brizalina skagerrakensis* and *Epistominella vitrea*, previously associated with phytodetrital input, suggest a minor increase in primary productivity compared to reference conditions. The *Stainforthia* group (*S. fusiformis* and *S. feylingi*), indicative of OM enrichment, in the living foraminiferal assemblages may indicate a response to fish farming activities, but foraminiferal seasonality could not be excluded as a potential cause. The indices of both fossil and living foraminifera, in addition to the macrofauna showed a good to high Ecological Quality Status (EcoQS) through time and at present. This indicates that environmental conditions have been and still are acceptable.

1. Introduction

Since the industrial revolution, population growth has led to increased inputs of anthropogenic organic carbon (OC) in many coastal areas. One major but relatively little studied source of anthropogenic OC and nutrients is intensive fish farming (Henderson et al., 1997; Husa et al., 2014; Johnsen and Lunestad, 1993; Kutti et al., 2008). It is estimated that a fish farm with 2910 tonnes of salmon produces 300 tonnes of organic waste per 2-year growth cycle (Kutti et al., 2007a; Zhulay et al., 2015). Previous studies suggest that OC emissions from fish farming have increased the primary productivity and OC loading of fjord sediments, with consequences for ecosystem functioning and benthic community structure (Holmer, 2010; Husa et al., 2014; Kutti et al., 2007b; Sweetman et al., 2016, 2014). Currently these studies based on spatial differences are difficult to interpret, as long time-series (spanning pre-anthropogenic impact conditions) have not been established. This makes it challenging to exclude natural gradients as causes of observed variabilities.

As a tool to manage and protect coastal water bodies in Europe, the Water Framework Directive (WDF, 2000/60/EC) was introduced. The WFD uses five categories (high, good, moderate, poor or bad) to classify a water body in order to define the Ecological Quality Status (EcoQS). According to the WFD it is mandatory that water bodies are returned to so called "reference conditions", defined as good or high EcoQS that

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presumably existed before human impact. From the WFD the Norwegian guidelines (Veileder, 02:2018) were derived based on the same principles but adjusted to fit the Norwegian coastal ecosystems. Currently reference conditions are established from seemingly un-impacted “pristine sites”, historical data, modelling or expert judgement (WDF, 2000/60/EC, p. 36–47). The first two options are often not available, so expert judgement is the best broadly available approach to constrain reference conditions (Borja et al., 2012). The latter, however, lacks transparency and is often incomprehensible for non-experts (Borja et al., 2012).

Benthic foraminiferal assemblages can provide estimates of in situ reference conditions (Alve et al., 2009), as the empty tests of many species preserve in the sediment forming fossil assemblages. Previous studies have shown that benthic foraminifera rapidly respond to changing environmental conditions, and steps have been made to implement them as a biomonitoing tool (e.g. Alve et al., 2009; Bouchet et al., 2012; Dolven et al., 2013; Schönfeld et al., 2012). Foraminifera can also provide environmental information at locations where a low abundance of macrofauna hampers their usability (Schönfeld et al., 2012). In environmental monitoring, benthic macrofauna is the traditionally used biological quality element. Whilst selected heavy metals and total organic carbon (TOC) are used as supporting elements to define the chemical status (Veileder, 02:2018, p. 30). In aquaculture related biomonitoring, geochemical parameters like sediment stable carbon isotopes ratios ($\delta^{13}C_{VPDB}$ TOC) and organic Carbon and total Nitrogen (C/N) ratios have shown potential to determine the dispersal of fish-farm waste (Kutti et al., 2007a). These parameters are well documented for successfully tracing sources of the organic matter (OM) in coastal systems (Kuliński et al., 2014; Mayr et al., 2011; Meyers, 1994; Sauer et al., 2016).

The main objectives of this study are to establish reference conditions and assess the potential environmental impacts of fish farming activities on the benthic environment of the Øksfjord, northern Norway. The study is based on the long-term ($>$ 100 yrs) records of geochemical parameters and benthic foraminifera in dated sediment cores. This is the first combined down-core application of geochemical parameters (TOC_{63}, $\delta^{13}C_{VPDB}$ TOC, C/N ratios and heavy metals) with foraminiferal indices (Shannon-Wiener; fH'_{log2}, Hurlberts rarefaction; fES_{100}, multimetric Norwegian Quality Index; fNQI; fAMBI (Alve et al., 2019, 2016)), to investigate potential temporal changes introduced by fish farming. An additional aim is to assess the present day EcoQS based on living (rose Bengal (rB) stained) benthic foraminiferal assemblages and compare it with ecological assessments based on macrofauna and the fossil foraminiferal record. This study is another step towards integrating foraminifera in the governmental monitoring protocols.

2. Study area

This study was carried out in the inner Øksfjord, Loppa kommune, Northern Norway (Fig. 1). The inner fjord is separated from the outer fjord by a ca. 120 m deep sill, and the inner fjord consists of two basins separated by a ca. 100 m sill. The basins in the inner Øksfjord are referred to as the main basin and the sub-basin, and have maximum depths of 240 and 160 m, respectively (Fig. 1). The fjord area is characterized by a steep topography and bathymetry with rocky slopes (Krauskopf, 1954). The glacier Øksfjordjøkelen drains into the inner and outer fjord from the western side, but apart from that, no other substantial rivers drain into the inner fjord. Water column stratification in northern Norway is at a minimum during early spring followed by an increase in May-September, after which it decreases during late fall and winter (Keck and Wassmann, 1996; Wassmann et al., 1996). The stratification is also less and the water exchange is stronger compared to Norway’s boreal fjords (Holte et al., 2005).

There are no large settlements, heavy industry or agricultural activities along the inner Øksfjord. The fjord is, however, one of the most intensively fish farmed fjords in northern Norway (Bjørn et al., 2009). Norway’s aquaculture pioneered in the early 1970s (Berge, 2000), but fish farming in the Øksfjord started in 1996 (Per-Arne Emaus, pers. com. 2020). Since the start of production, licences increased from 1500 tonnes of fish per fish farm to 2700 tonnes in 2006 (Per-Arne Emaus, pers. com. 2020). Grieg Seafood ASA obtained the licences in 2005 and has since increased the production to 4000–8000 tonnes of fish per year (Odd Leknes, Grieg Seafood, pers. com. 2020). From 2011 to 2013, five fish farms were operating simultaneously in the inner Øksfjord (Fig. 1). Since 2013, one location (Lille Skognes) has been permanently closed due to deteriorating environmental conditions in the innermost part of the fjord (Odd Leknes, pers. com. 2020). During sampling in September 2017, the fish farms Auskarnes and Storvik were both being fallowed. The fallowing period started in 2016. In September 2017, two farms (Steinviknes and Kjøsen) were in active use (Fig. 1). In total, Grieg Seafood ASA produced 62,700 tonnes of salmon using 75,500 tonnes of fish feed between 2005 and 2017 in the inner Øksfjord (Odd Leknes, Grieg Seafood, pers. com. 2020).

3. Materials and methods

Sediment cores were collected from the main basin (D2) and the sub-basin (D3) in early September 2017 (Fig. 1, Table 1). Sediment coring was performed using a twin-barrelled Gemini gravity corer (inner diameter 8 cm, Niemistö, 1974). Two sediment cores from each basin were sectioned on deck, slicing the upper 20 cm into 1 cm thick slices and below 20 cm into 2 cm slices. In addition, three replicate surface samples (0–1 cm) were obtained from each station for living (rB stained) foraminiferal assemblage analyses. These samples were preserved and stored in a 70% ethanol/2 g L^{-1} rB mixture (Schönfeld et al., 2012). Three replicate grab samples were taken at each station for macrofaunal analysis using a van Veen grab (0.1 m^2, 36 × 28 cm). The macrofauna samples were carefully washed on deck using a 1 mm sieve and preserved in a rB stained 4% formaldehyde mixture neutralized with borax. Hydrographic measurements (temperature, salinity, oxygen concentration) were performed in each basin using a SAIV CTD model SD204.

All sediment core samples were freeze dried to obtain the down-core porosity records that were used to assess the quality of the cores. Cores D2-6A (main basin) and D3-3B (sub-basin) were sent to the Environmental Radioactivity Research Centre, University of Liverpool, UK, and analysed for ^{210}Pb, ^{226}Ra and ^{137}Cs by direct gamma assay on Ortec HPGe GWL series well-type coaxial low background intrinsic germanium detectors (Appleby et al., 1986). ^{210}Pb dates were calculated using both the Constant Rate of Supply (CRS) and Constant Initial Concentration (CIC) models (Appleby and Oldfield, 1978), and possible chronostratigraphic dates determined from the ^{137}Cs records. The dating results of D3-3B showed that reference conditions might not have been reached. Therefore the longer, not radiometrically dated, D3-13A core was used as an extension of the shorter D3-3B core (from here on D3-3B/13A) as the sediment porosities of both cores showed a good correlation. This correlation was further strengthened by good correlations between the geochemical parameters (bulk sediment TOC, C/N ratios and $\delta^{13}C_{VPDB}$ TOC).

Grain size distributions were determined using a Beckman Coulter LS13320 with laser diffraction at the Department of Geoscience, University of Oslo. The bulk sediment TOC, total nitrogen and $\delta^{13}C_{VPDB}$

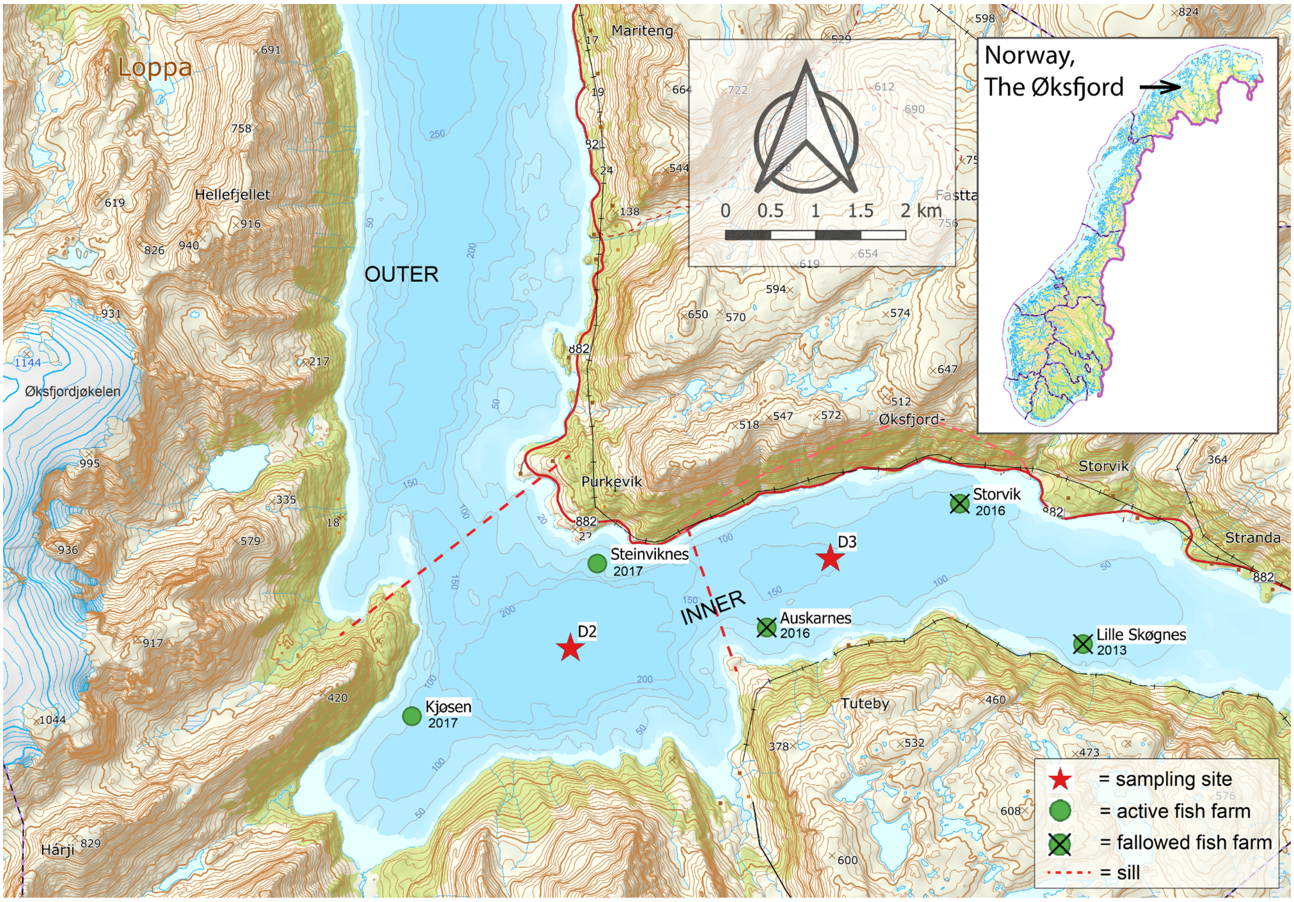

Fig. 1. Map of the outer and inner Øksfjord. The inner fjord consist of a main (D2) and a sub-basin (D3). The years under the names of the fish farms indicate the year at which they were active, or since when they were fallowed. (Modified from the QGIS Development Team (3.4.14-Madeira, 2020), map from Statens kartverk (2007)).

TOC, samples were analysed using an Elemental Analyser–Isotope Ratio Mass Spectrometry (EA-IRMS) at the ISO-Analytical Ltd. stable isotope analysis laboratory in Crewe, UK. Prior to the TOC and $\delta^{13}C_{VPDB}$ TOC, analyses samples were acidified with 1 M HCl. The TOC was normalized to the sediment fine fraction (% < 63 µm), as only the TOC_{63} can be used for classification in the Norwegian guidelines (TOC_{63} = TOC + 18 × 1 − % < 63 µm; Veileder, 02:2018). After initially starting with every second sample, the % < 63 µm fraction varied only little in the 42–22 cm interval of core D2-6A. Grain size measurements were therefore interpolated for the samples not analysed in this interval. Samples were treated with 7 M HNO_3 prior to the analyses of copper (Cu), zinc (Zn) and nickel (Ni) on a Gas Chromatography ICP Sector Field Mass Spectrometer by the ALS Laboratory Group Norway AS. Heavy metal concentrations were analysed from the undated D3-13A and D2-5A core, as the sediment porosity records were highly similar to those of the other cores taken in the basins.

For the fossil foraminiferal analyses, approximately 2 g of freeze-dried, gently homogenized sediment to ensure the aliquot represented the sample, was washed over 500 µm and 63 µm sieves and dried. From the 63–500 µm fraction, material was taken at random and fully picked, until > 250 specimens could be mounted on microfossil slides and identified to species level. The total number of specimens > 500 µm in the assemblages was small (< 6%) and therefore not included. For the living foraminiferal analyses, samples were washed through 63 µm and 500 µm sieves after which the 63–500 µm fraction was split using a modified Elmgren wet splitter (Elmgren, 1973). For one eighth of the sample, all living (rB stained) foraminifera were picked and mounted. To compare living foraminiferal assemblages with fossil foraminiferal records, non-fossilizable species were excluded from living assemblages (Bouchet et al., 2012). Due to large numbers of juvenile *Stainforthia*

Table 1
Basin, location, water depth, CTD results obtained at the sampling sites, the obtained cores and their length.

Site	Basin	Coordinates	Water depth (m)	BW* O_2 (ml/L^{-1})	BW* O_2 (mol/L^{-1})	BW* Salinity	BW* Temperature (°C)	Sediment cores + length
D2	Main	70°08.6456 N 22°17.7542 E	240	5.13	0.23	35	5.1	D2-6A = 42 cm D2-5B = 46 cm
D3	Sub-	70°08.8295 N 22°22.5421 E	160	5.77	0.26	35	5.6	D3-3B = 14 cm D3-13A = 30 cm

* Bottom Water.

fusiformis and *S. feylingi*, and *Cibicides refulgens* and *C. lobatulus*, the *Stainforthia* and *Cibicides* species were grouped into a *Stainforthia* group and a *Cibicides* group.

After fixation, macrofaunal samples were sorted in the laboratory under 10× magnification. Living specimens were identified to the lowest practical taxonomic level and counted in the EN ISO-IEC 17025 accredited laboratories at Akvaplan-niva, Tromsø, Norway. The EN ISO-IEC 17025 is set of internationally accepted standards for laboratories that perform testing, sampling or calibration.

Species diversity indices $H'_{\log 2}$ (Shannon and Weaver, 1963) and ES_{100} (Hurlbert, 1971) were calculated using the R-data software program (R Core team, 2020). The OM sensitivity index AMBI was calculated according to Alve et al. (2016) for foraminifera (fAMBI) and Borja et al. (2000) for the macrofauna (mAMBI). For the calculation of fAMBI and mAMBI only taxa and groups assigned to the ecological groups (EGs) were used, as described in Alve et al. (2016) and Borja et al. (2000). The multi-metric Norwegian Quality Index (NQI) for foraminifera was calculated after Alve et al., 2019 (fNQI) and for macrofauna *sensu* the Norwegian guidelines (Veileder 02:2018 (mNQI)). For both the living foraminiferal assemblages and macrofauna, index values represent the arithmetic mean of three replicates after which only the averages were reported and, when applicable, used to assess EcoQS (Borja and Muxika, 2005). To further explore the palaeo-environmental conditions the five EGs of Alve et al. (2016), representing different responses to OM enrichment, were used. For the EGs, the relative abundances of assigned species, and species groups, were calculated using the sum of assigned species and groups only, after which the relative abundances were summed for each EG. Absolute abundances of the fossil foraminifera were calculated as the number of tests per gram dry sediment (test/g sediment). For the radiometrically dated upper 6 cm of core D3-3B, the Benthic Foraminifera Accumulation Rates (BFAR) were calculated according to Herguera and Berger (1991). *Stainforthia fusiformis*, a member of the *Stainforthia* group, is considered a first order opportunist, indicative of excess OM enrichment according to Alve et al. (2016). *Brizalina skagerrakensis* and *Epistominella vitrea* were used as species indicative of increased phytodetrital input (Asteman et al., 2018 and sources therein; Duffield et al., 2015). For the foraminifera taxonomic references, see Appendix A.

4. Results

4.1. Hydrocast data

The salinity in the water column increased from ~33 in the surface to 35 in both the Øksfjord basins (Supplementary Appendix A, Table 1). The temperature decreased from 9 °C in the surface to 5.5 °C in the bottom waters (Supplementary Appendix A, Table 1). The oxygen concentrations in the fjord decreased from 6 mL/L (0.27 µmol/L^{-1}) in the surface to 5.5 mL/L (0.25 µmol/L^{-1}) in the bottom waters (Supplementary Appendix A, Table 1).

4.2. Chronologies of the sediment cores

The sediment cores D2-6A and D3-3B could be radiometrically dated back to the mid-1800s and 1920s, respectively (Table 2, Fig. 2). In the main basin D2-6A core, the ^{210}Pb and ^{137}Cs records were both dominated by a major non-monotonic feature, between 13 and 5 cm, in which concentrations were significantly lower than in samples directly above and below (Table 2, Fig. 2). This feature coincides closely with a layer of dense, compact sediment amounting to around 73 kg m^{-2} in a ± 8 cm thick layer. ^{210}Pb calculations using the CRS model showed that the otherwise exponentially declining ^{137}Cs record was split into two distinct peaks, one immediately above the dense layer and the other immediately below. In the sub-basin D3-3B core concentrations of fallout ^{210}Pb declined exponentially with depth down to 6 cm, after which the signal was lost. Excluding the 13–5 cm interval in the main basin D2-6A core, sedimentation rates and sediment accumulation rates in both basins appear to have been relatively stable, averaging 0.9 mm yr^{-1} and 0.35 kg m^{-2} yr^{-1} in core D2-6A and 0.6 mm yr^{-1} and 0.53 kg m^{-2} yr^{-1} in core D3-3B.

4.3. Geochemical parameters and grain size

In core D2-6A from the main basin, the TOC_{63} concentrations from 42 to 14 cm varied between 29 and 38 mg/g (2.8–3.3% TOC) (Fig. 3). Between 13 and 5 cm, values were lower and varied between 9 and 17 mg/g (0.2–2.3% TOC) (Fig. 3). In the upper 5 cm of core D2-6A the concentration gradually increased from 22 to 28 mg/g (2.0–2.7% TOC). In the D3-3B/13A core from the sub-basin the TOC_{63} concentrations

Table 2
The radiometric dates, sediment accumulation rates (kg m^{-2} yr^{-1}) and sedimentation rates (mm yr^{-1}) from the D2-6A and D3-3B core.

Main basin D2-6A				Sub basin D3-3B			
Depth (cm)	Date AD	Sedimentation		Depth (cm)	Date AD	Sedimentation	
		kg m^{-2} $^{-1}$	mm yr^{-1}			kg m^{-2} yr^{-1}	mm yr^{-1}
0	2017			0	2017		
0.5	2013	0.37	1.1	0.5	2012	0.53	0.9
2.5	1995	0.37	1	1.5	1999	0.53	0.7
3.5	1983	0.37	0.8	2.5	1985	0.53	0.6
4.5	1969	0.37	1.2	3.5	1967	0.53	0.5
5.5	1967	3.58	5.6	4.5	1948	0.53	0.5
6.5	1965	9.86	13.1	5.5	1926	0.53	0.5
8.5	1964	20.65	24.6				
10.5	1964	20.65	23.8				
12.5	1963	10.39	10.5				
14.5	1960	0.34	1.2				
16.5	1928	0.34	0.6				
18.5	1897	0.34	0.6				
21	1858	0.34	0.6				

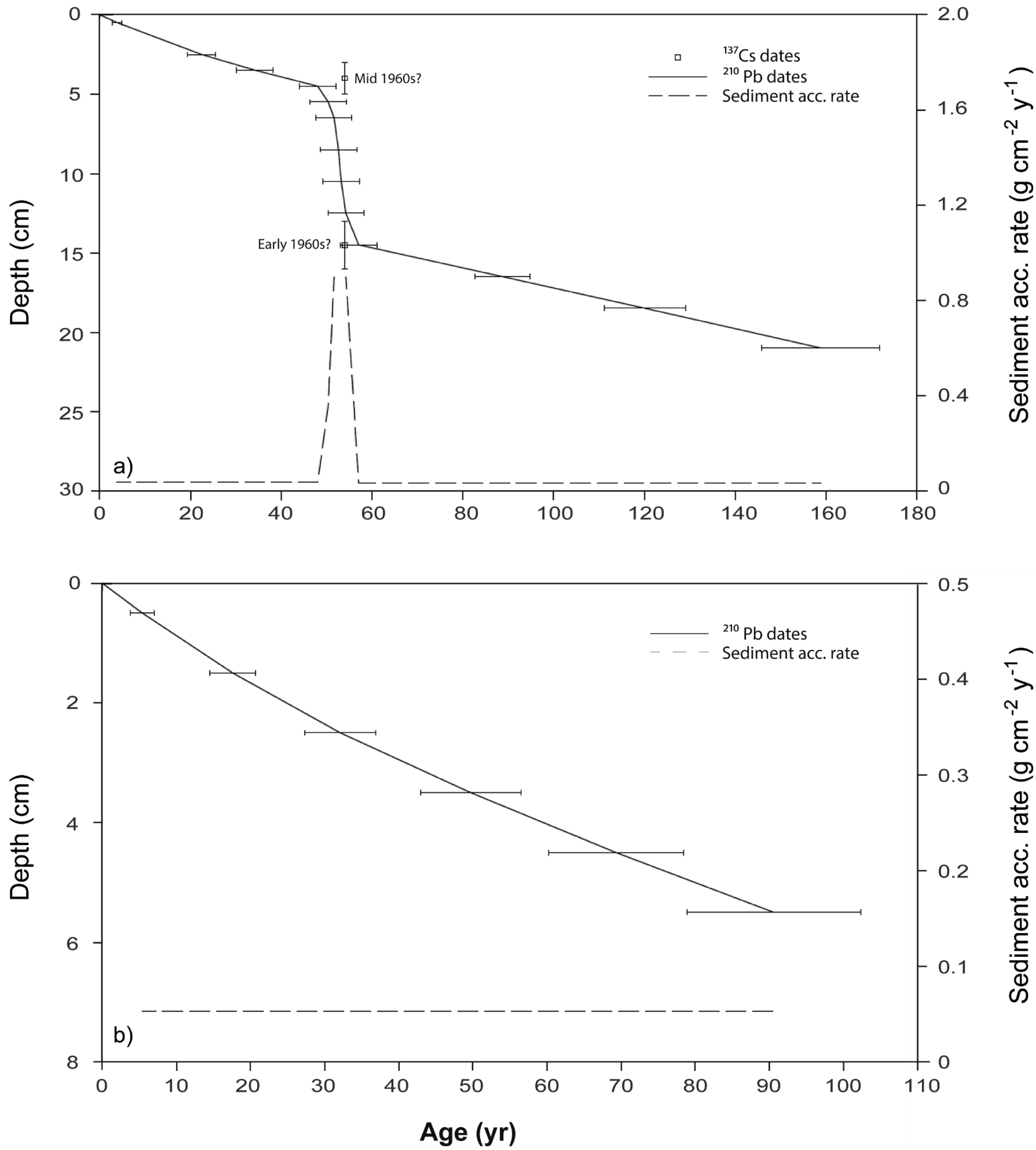

Fig. 2. Radiometric chronologies for a) core D2-6A from the main basin, and b) core D3-3B from the sub-basin. NB: axes have different scales.

showed a minor increase from ± 7 mg/g (0.5% TOC) to 17 mg/g (1.3% TOC) (Fig. 3) in the uppermost part (0–1 cm). The uncorrected % TOC values in parentheses are shown in Appendix B Tables B.1 and B.2.

The $\delta^{13}C_{VPDB}$ TOC and C/N ratios in the sediment cores from both basins, not including the 13–5 cm interval in D2-6A, showed no major changes (Fig. 3), and the concentrations of Cu, Zn and Ni showed only small variations through time (Fig. 3). In both basins, concentrations including the 13–5 cm interval in D2-6A, varied as follows: Cu = 16–75, Zn = 31–130 and Ni = 27–87 mg/kg.

The sediment fraction < 63 μm in core D2-6A had the lowest values in the 13–5 cm interval (28–80%), with only 28% fine fraction between 12 and 11 cm (Fig. 3). In core D3-3B/13A the sediment fraction < 63 μm fraction varied between 50 and 96% (Fig. 3).

4.4. Fossil foraminiferal assemblages

The fossil foraminiferal indices showed no clear tendency in both cores and varied as follows; fH'_{log2} = 3.3–4.5, fES_{100} = 17–28, fNQI = 0.57–0.76 (Fig. 4). In the D2-6A core, the fAMBI scores ranged from 1.4 to 2.6, apart from in the 13–5 cm interval where they ranged from 0.7 to 1.8 (Fig. 4). In the upper 3 cm of core D3-3B/13A, the fAMBI scores were somewhat higher compared to the lower part, ranging from 2.9 to 3.1 compared 1.2 to 2.5 below (Fig. 4). For most samples > 85% of the fossil foraminiferal assemblages could be assigned to one of the five EGs defined in the fAMBI. For the 8–4 cm interval in core D3-3B only between 77 and 79% could be assigned. The EG distributions showed that in both cores, D2-6A and D3-3B/13A, relative abundance of EG III were higher than EG I in the upper 5–6 cm (Fig. 5).

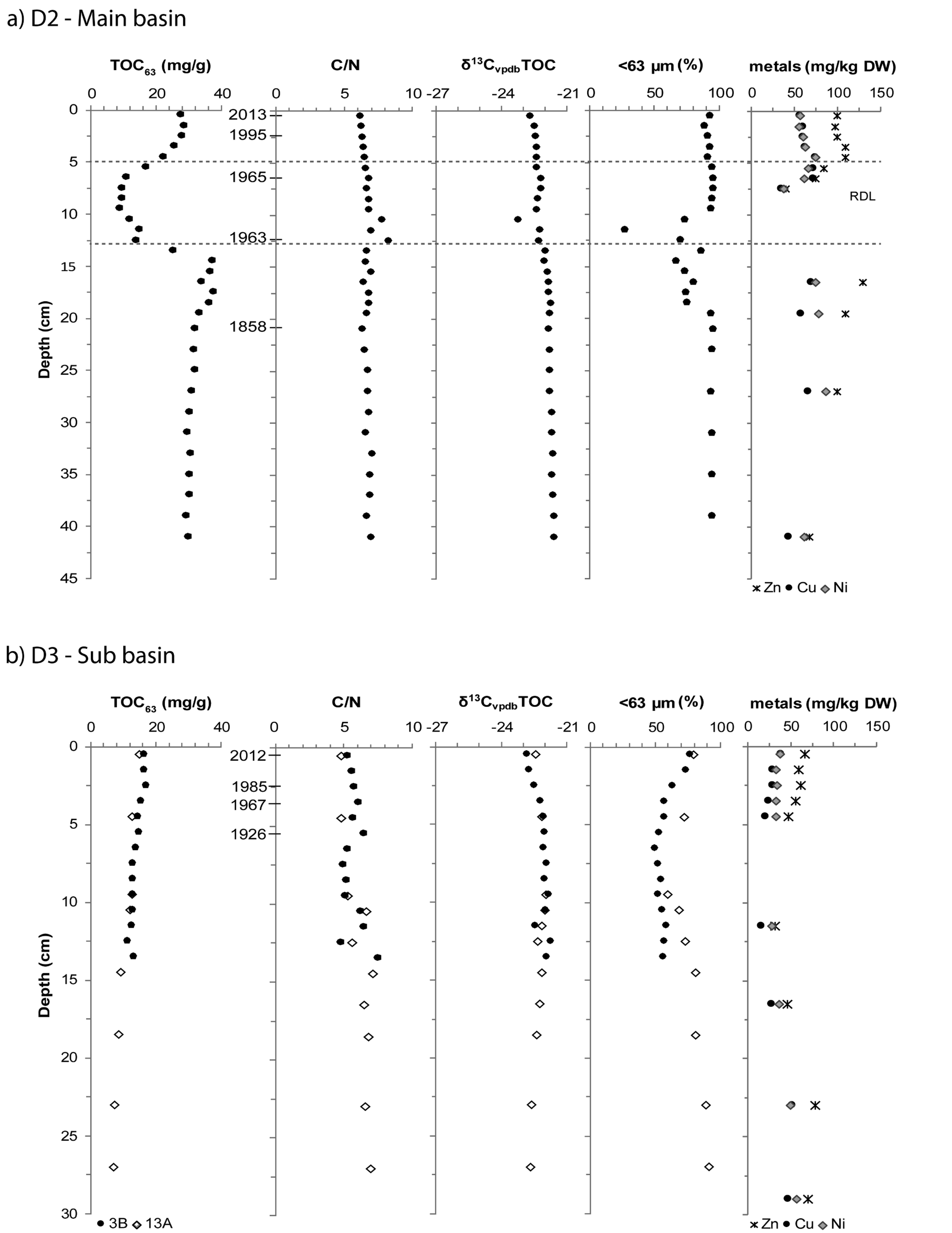

Fig. 3. The geochemical parameters, TOC_{63} (mg/g), C/N ratios, bulk sediment carbon isotopes ($\delta^{13}C_{VPDB}$ TOC), fraction < 63 µm (%) and heavy metal concentrations of Zinc (Zn), Copper (Cu) and Nickel (Ni) (mg/kg Dry Weight) plotted for a) the main and b) the sub-basin. RDL = re-deposited layer.

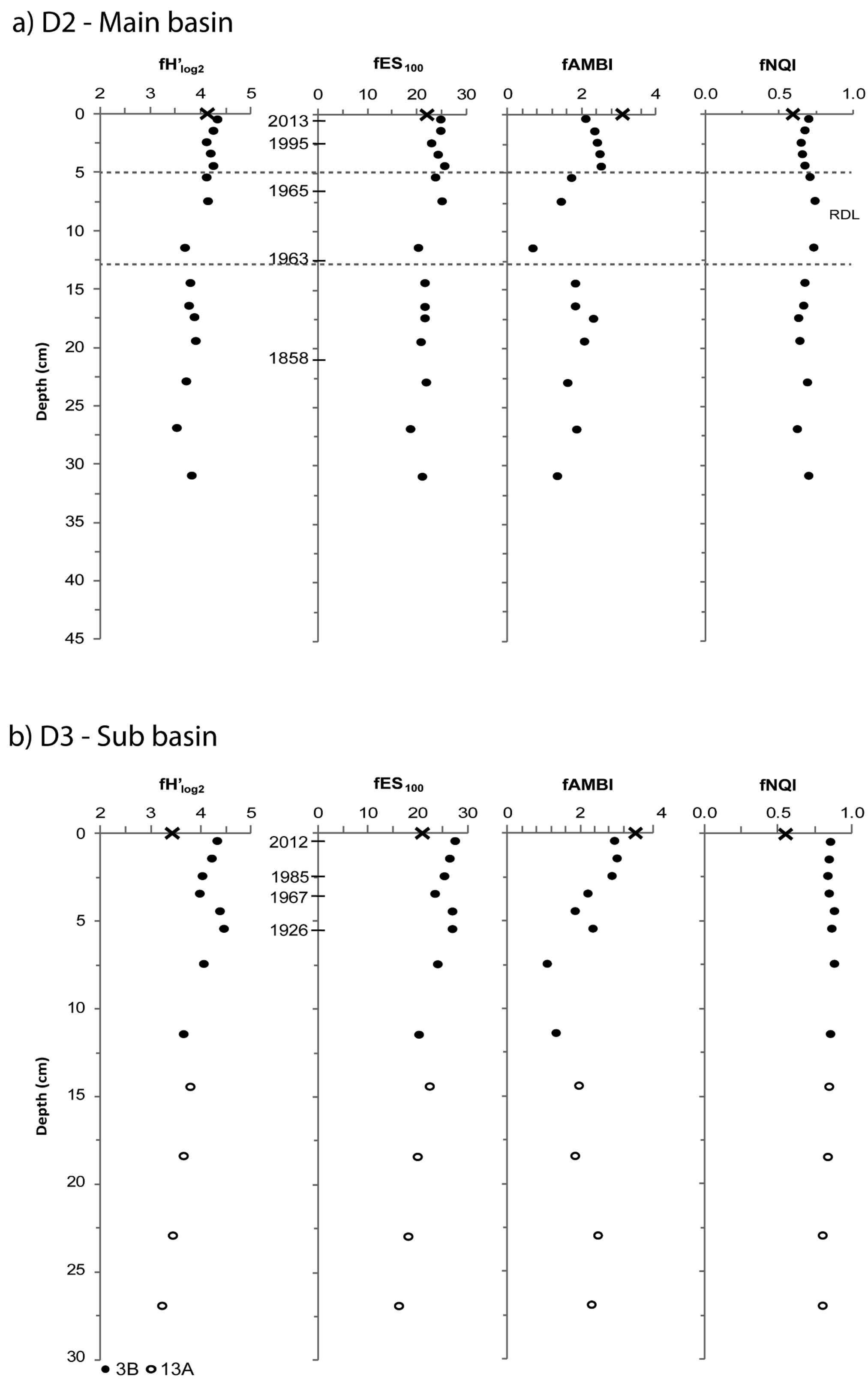

Fig. 4. The diversity indices (fH'_{log2} and fES_{100}), sensitivity index fAMBI and the fNQI plotted for a) the main and b) the sub-basin. Circles = fossil data and crosses = living foraminiferal assemblage data. RDL = re-deposited layer.

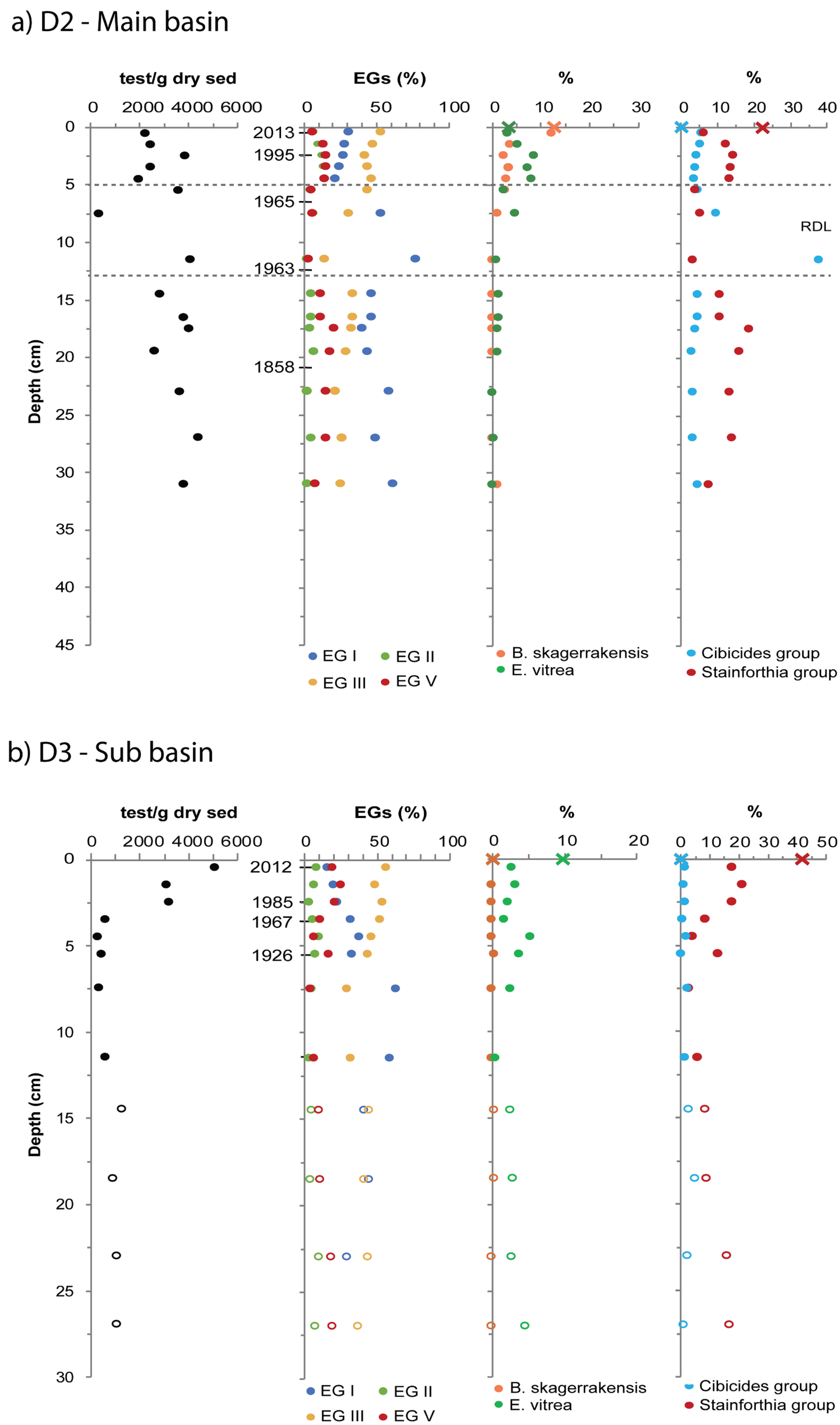

Fig. 5. The foraminiferal absolute abundances (test/g dry sediment), relative abundances of the Ecological Groups (EGs %) and relative abundances of the indicator species (%) plotted for a) the main and b) the sub-basin. Circles represent = fossil data and crosses = the living foraminiferal assemblage data. In b) D3 – Sub basin open circles = D3-13A and filled circles = D3-3B. RDL = re-deposited layer.

Table 3
Macrofauna and living foraminiferal indices, averages of three replicates. Colour coding of the classification according to Norwegian guidelines (Veileder, 02:2018) and Alve et al., 2019. Colour coding of the statuses is shown in the legend below the table.

Site	D2	D3	D2	D3
Indices	*macrofauna*	*macrofauna*	*foraminifera*	*foraminifera*
H'_{log2}	3.3	2.6	4.0	3.4
ES_{100}	18	19	22	20
AMBI	2.1	2.3	3.1	3.5
NQI	0.69	0.71	0.58	0.54

Status	High	Good	Moderate	Poor	Bad

The absolute abundances of the fossil assemblages in the D2-6A core varied between 1975 and 4436 tests/g dry sediment, except for one sample at 7–8 cm where 388 tests/g dry sediment were found (Fig. 5). In core D3-3B/13A, absolute abundances were relatively stable in the lower part (30–6 cm), ranging between 372 and 1299 tests/gr dry sediment, compared to the rapid increase in the upper 3 cm from 625 till 5074 tests/g dry sediment (Fig. 5). The BFAR were only calculated for the radiometrically dated upper 6 cm of core D3-3B/13A, as the absolute abundances only changed in D3-3B/13A. In this interval, they increased from 18 to 33 test/cm^2/year to 165–269 test/cm^2/year.

In both sediment cores, the *Stainforthia* group showed no overall trend and varied in relative abundance between 5 and 20% (Fig. 5). Relative abundances of the *Cibicides* group were generally below 10% in both cores, except for a peak at 11–12 cm in core D2-6A where the abundance was 38% (Fig. 5). In the upper 5 cm of core D2-6A, the combined relative abundances of *B. skagerrakensis* and *E. vitrea* ranged from 5 to 15% compared to 0–1% in the lower part (Fig. 5). In core D3-3B/13A, relative abundances of *E. vitrea* exhibited small changes and *B. skagerrakensis* was almost absent (Fig. 5).

4.5. Living foraminiferal assemblages

Living foraminifera indices were as follows; fH'_{log2} = 4.1 and 3.4, fES_{100} = 22 and 21, fNQI = 0.59 and 0.56, fAMBI 3.1 and 3.5 for D2 and D3, respectively (Fig. 4). Relative abundances of *B. skagerrakensis* and *E. vitrea* in the living assemblages were 13% and 4% at D2 and 0.1% and 10% at D3 (Fig. 5). For the *Stainforthia* group relative abundances in the living assemblages were 22% at D2 and 42% at D3 (Fig. 5).

4.6. Macrofauna

The macrofaunal diversity indices (mH'_{log2}, mES_{100}) and the mNQI were as follows; at D2, mH'_{log2} = 3.3, mES_{100} = 18, mNQI = 0.69, and at D3, mH'_{log2} = 2.6, mES_{100} = 19, mNQI = 0.71 (Table 3). The mAMBI scores were similar at both sites, 2.1 at D2 and 2.3 at D3. Of the macrofauna, between 96% and 98% could be assigned to the five EGs that were used to calculate the mAMBI for D2 and D3, respectively.

5. Discussion

5.1. Continuity of the sedimentary record

The ^{210}Pb concentrations declined exponentially in both cores, giving no indication of dredging or trawling activities in the inner-Øksfjord (Fig. 2). The interruption of the ^{137}Cs and ^{210}Pb records suggests that the 13–5 cm interval in the D2-6A core is a re-deposited layer (RDL) (Supplementary Appendix B, Table 2, Fig. 2). This re-deposited layer was deposited during an event in the early 1960s, as is shown by the maximum ^{137}Cs fallout from the atmospheric testing of nuclear weapons. Shell fragments, coarse grains, and high relative abundances of the *Cibicides* group at the base of the RDL indicate that the event was a sub-aqueous slide (Figs. 3 and 5). Members of the *Cibicides* group prefer high-energy areas with coarse sediment and hard substrates (Mackensen et al., 1985; Schönfeld, 2002), suggesting that the RDL material came from the shallower areas of the Øksfjord with more suitable conditions for these taxa. Fossil *Cibicides* specimens appeared worn and in some instances missed the final chambers throughout both cores, which supports the hypotheses regarding transportation.

In the sub-basin D3-3B core, there was no evidence of a peak in the ^{137}Cs record for the 1963 fallout maximum. This could be the result of large standard errors in the measurements, low isotope concentrations, or minor bioturbation as suggested by width of the peak in the ^{137}Cs dating record. In core D3-3B, no evidence of an RDL was found in the percent < 63 μm fraction or the foraminiferal record itself either.

5.2. Establishing reference conditions

There are no large settlements, heavy industry or agricultural activities along the inner-Øksfjord. This leaves fish farming activities the most noticeable remaining source of human impact on the fjord. Fish farming was conducted on a relatively small scale, until Grieg Seafood ASA rapidly increased the production in 2005 (Odd Leknes, pers. com. 2020). It is thus reasonable to assume that the relatively stable conditions in pre-1960 sediment records from D2 and D3 are only minimally affected by human activities, and thus represent the reference conditions.

5.3. Temporal patterns of the abiotic parameters

The fish farms in the Øksfjord are situated in rocky, steeply inclined areas that could not be sampled (Fig. 1). The sampling sites in the Øksfjord were thus between 1 and 2 km away from the farms. Previously no changes in TOC concentrations, and particulate organic matter and carbon (POM and POC) fluxes have been observed outside a 100 to 500 m radius from fish farms (Brooks and Mahnken, 2003a; Carroll et al., 2003; Kutti et al., 2007a; Lalande et al., 2020). A previous study using fatty acids, $\delta^{13}C_{VPDB}$, and C/N ratios, however, suggested that some of the organic fish farming waste was transported > 1 km away (Kutti et al., 2007a), though this is less than < 2.7% of the total waste (Bannister et al., 2016). The lack of major changes in the $\delta^{13}C_{VPDB}$ TOC, and C/N ratios (Fig. 3), suggest that the sampling locations in the Øksfjord are probably too far away to have a realistic impact on these parameters. Furthermore, the sedimentation rates in the Øksfjord are relatively low (between 0.5 and 1.1 mm yr^{-1}, Table 2) compared to e.g. 1.4–5.1 mm yr^{-1} in Lysefjorden (Duffield et al., 2017) or 2–10 mm yr^{-1} in the Inner Oslofjord (Dolven et al., 2013). In addition, the bottom waters in the Øksfjord are well oxygenated in autumn as shown in this study (Table 1), and previous biomonitoring reports (Velvin and Emaus, 2015). The oxygenated bottom waters in combination with low sedimentation rates could have affected the preservation of any potential fish farm OM in the Øksfjord basins.

In nearby Repparfjorden no fish farm is present and TOC_{63} concentrations ranged from 8.4 mg/g to 27.3 mg/g (Sternal et al., 2017). The Øksfjord TOC_{63} concentrations are predominantly within this range, but below the RDL (19–14 cm) in core D2-6A concentrations were higher. The sediments below the RDL in D2-6A, however, were deposited pre 1960s when no fish farms were present in the Øksfjord during reference conditions. Furthermore, according to the Norwegian guidelines, the TOC_{63} concentrations in sediments from the upper 3 cm of core D2-6A are classified as indicating a moderate impact (Appendix B Table B.1, Supplementary Appendix C, Veileder 02:2018). During the time interval these sediments were deposited (± 1995–2017), fish farms were active. The long-term sediment core records, however, showed that the moderate status reflects the reference conditions at site D2, as TOC_{63} concentrations in pre-1960s sediments have a moderate status as well. Overall, sediment geochemistry records suggest that the environmental conditions in the Øksfjord basins have remained relatively stable during at least the past century (Fig. 3).

The heavy metals Cu and Zn are used in monitoring studies to detect the impact of fish farming as their main sources are assumed to be anti-biofouling paint on the cages and fish feed (Brooks and Mahnken, 2003b; Burridge et al., 2010; Dean et al., 2007). However, a study investigating Cu concentrations in sediments near fish farm cages found that in most cases Cu concentrations in sediments under anti-biofouling paint treated cages were within the range found under untreated cages (Brooks and Mahnken, 2003b). The metal concentrations of Cu, Zn and Ni in the Øksfjord could reflect the surrounding bedrock. The bedrock surrounding the Øksfjord is comprised of gabbro (Krauskopf, 1954; Rea et al., 1996), which is known for its high concentrations of up to 90 mg/kg Cu, 100 mg/kg Zn and 130 mg/kg Ni (Reimann and Caritat, 1998). Biomonitoring studies only use the acid leached portion of the metals (e.g. Turner and Olsen, 2000), which is probably the main reason for the lower metal concentrations in the Øksfjord sediments compared to the bedrock. The Ni concentrations in core D2-6A have a moderate status according to the Norwegian guidelines, which would require governmental intervention to lower the concentrations (Appendix B Table B.1, Supplementary Appendix D, Veileder 02:2018). However, the sediment core records, again, showed that this reflects the natural background status in the Øksfjord. The lack of major variations in the heavy metal concentrations throughout the Øksfjord sediment cores (Fig. 3), suggests that the metal concentrations reflect bedrock rather than fish farming.

5.4. The use of biotic indices

Time averaging of the fossil assemblages could have influenced the fossil foraminiferal indices in the Øksfjord. Time averaging is the accumulation of foraminiferal tests from a succession of previous living assemblages over multiple years into one fossil assemblage (Murray, 2000). Due to low sedimentation rates, the fossil foraminiferal assemblages in each sample are time averaged over 10 to 15 years in the Øksfjord. Fish farming waste fluxes strongly vary depending on the farm's production cycle, usually 2-years, and the fallowing periods (Kutti et al., 2007a; Zhulay et al., 2015). As time averaging dampens such short-term variability (Duffield et al., 2017; Martin, 1999; Schafer, 2000), any potential responses of the fossil foraminifera indices that would occur on these time scales potentially lost in the Øksfjord records (Fig. 4).

Since they are not affected by time averaging, the living foraminiferal assemblages are more likely to reflect the recent OM input from the two active fish farms in the Øksfjord (Fig. 1). The indices of the living and fossil foraminiferal assemblages suggest no major change from the reference EcoQS in either basin (Appendix B Tables B.1 and B.2, Supplementary Appendix E, Fig. 4), reflecting good to high EcoQS according to Alve et al. (2019). The macrofauna indices from this study (Supplementary Appendix G, Table 3) and previous biomonitoring studies in the Øksfjord (Velvin and Emaus, 2015) also indicate good to high EcoQS according to the Norwegian guidelines (Veileder 02:2018).

Currently, comparing the fAMBI of the living foraminifera and the mAMBI is not straightforward. Species that are sensitive or indifferent to OM enrichment (Alve et al., 2016; Borja et al., 2000) are more abundant in the macrofauna compared to the living foraminiferal assemblages, as shown by the lower mAMBI than fAMBI (Table 3). Previous studies have shown that benthic foraminifera are potentially more sensitive to environmental degradation than macrofauna (Bouchet et al., 2020; Denoyelle et al., 2010). The mAMBI, however, may not optimally reflect environmental pressure gradients in Norwegian coastal waters (Rygg and Norling, 2013). This is thought to be due to using both Northern and Southern European data of macroinvertebrates to assign species to the five EGs (Rygg and Norling, 2013). This creates problems as species may exhibit varying sensitivity/tolerance levels along their different geographical distributions (Grémare et al., 2009; Zettler et al., 2013). This is less of a problem for the fAMBI as species are assigned to the EGs using data from the North Atlantic region only (Alve et al., 2016). However, both the living foraminifera fAMBI and mAMBI indicate that the present day conditions have deviated only minorly, if at all, from reference conditions in the Øksfjord basins.

5.5. Foraminiferal absolute abundances, Ecological groups and indicator species

The correlation between increased OM supply and increases in benthic foraminifera absolute abundances and BFAR is well known (e.g. Fontanier et al., 2002; Gooday, 1988; Rudnick, 1989). The use of these parameters for biomonitoring purposes was illustrated by Alve (1995), Duffield et al. (2017) and Hess et al. (2020), but they have not yet been systematically explored. Pearson and Rosenberg (1978) showed that when OM supply increases the number of individuals and biomass of macrofauna rise before a change in the number of taxa is observed. These increases in absolute abundances can occur rapidly. This is shown by the immediate response of the macrofauna after a pipe-line discharging organic waste was installed, and an immediate recovery when the pipe-line outlet was relocated (Borja et al., 2003). The abrupt increase of fossil foraminifera absolute abundances in the D3-3B/13A core could thus represent the first response to an increase in OM loading (Fig. 5). This is supported by the BFAR, which has been shown to reflect changes in OM supply (Herguera and Berger, 1991). In core D2-6A, the absolute abundances do not change throughout the core but they are higher than in most of the samples from core D3-3B/13A. A change in OM supply from reference conditions is also suggested by the sediment core records of the EGs. Foraminiferal species sensitive to OM input are in EG I (e.g. *Cassidulina reniforme*) whereas EG III (e.g. *B. marginata*) contains species tolerant to excess OM enrichment. For the EGs see Supplementary Appendices E and F, where species are assigned to EGs according to Alve et al. (2016). The shift of fossil assemblages dominated by EG I to EG III is subtle (Fig. 5), but suggests that the OM supply has changed compared to reference conditions.

The use of indicator species has been questioned due to differences in stress tolerance along natural environmental gradients and geographic regions (Grémare et al., 2009; Zettler et al., 2013). The species *B. skagerrakensis* and *E. vitrea* are considered indicator species for increased phytodetrital input (Asteman et al., 2018 and sources therein; Duffield et al., 2015). Relative abundances of these two species in long term sediment core records and living foraminiferal assemblages may suggests an increase in primary productivity compared to reference conditions in the Øksfjord (Fig. 5). Previous studies on the link between salmon farms, ambient nutrient levels and phytoplankton density are equivocal (Brooks and Mahnken, 2003a; Jansen et al., 2018; Quiñones et al., 2019), but nutrient inputs from fish farms may be one factor leading to increased productivity in the Øksfjord. Alternatively, changes in the water column as a result of global climate change could have affected the primary productivity (e.g. Sommer and Lengfellner, 2008; Winder and Sommer, 2012).

The *Stainforthia* group reflects the opportunistic life strategy of *S. fusiformis*, a member of EG V (Alve et al., 2016), which is considered highly adapted to deal environmental stress like for example OM enrichment (Alve, 2003). The *Stainforthia* group strongly influenced the diversity indices and fAMBI scores of the living foraminiferal assemblages in the Øksfjord. The high relative abundances of the *Stainforthia* group in the living assemblages are not observed in the fossil assemblages of the Øksfjord (Fig. 5). This could in part be due to time averaging dampening the present day signal in the fossil assemblages because of the low sedimentation rates. In addition, some of the thin *Stainforthia* tests disintegrated during picking which could point to a preservation issue. However, despite their relatively thin tests, members from the *Stainforthia* group were present throughout both sediment cores (Fig. 5). *S. fusiformis* has the ability to rapidly increase in abundance with seasonal changes showing the highest abundances from May till September in the Gullmarfjord (Gustafsson and Nordberg, 2001). This seasonal acme could have caused the high relative abundances observed in the living assemblages of the Øksfjord. In Malangen, a fjord just south of the Øksfjord, a seasonal study showed that the highest absolute foraminiferal abundances in northern Norway occurred during autumn (Gaute Rørvik Salomonsen pers. com.). In northern Norway, the main phytoplankton bloom occurs in April-May, but elevated fluxes of POC have also been observed during autumn (Lalande et al., 2020; Noji et al., 1993; Wassmann et al., 1996). The high relative abundances of the *Stainforthia* group in the living assemblages could thus be a result of seasonality, rather than a response to fish farming.

6. Conclusions

This study illustrated the importance of integrating sediment core records of geochemical parameters and benthic foraminifera in environmental monitoring systems. Sediment geochemistry and benthic foraminiferal indices from dated sediment cores showed no deviations from reference conditions. Long-term changes in foraminiferal absolute abundances, relative abundances of the EGs and indicator species suggest the OM supply slightly increased during recent decades compared to reference conditions. The sediment core records also showed that the moderate classification of TOC_{63} and Ni in core D2-6A reflected the natural background conditions. The Ecological Quality Status (EcoQS) from the fossil and living foraminifera, in addition to the macrofauna, classified as good to high. This indicates that good environmental conditions persisted during at least the past century and in the present. Overall, there is no clear indication of an impact of former and present fish farming in the Øksfjord basins.

CRediT authorship contribution statement

Anouk T. Klootwijk: Conceptualization, Investigation, Data curation, Formal analysis, Writing - original draft. **Elisabeth Alve:** Conceptualization, Funding acquisition, Project administration, Writing - review & editing. **Silvia Hess:** Conceptualization, Funding acquisition, Writing - review & editing. **Paul E. Renaud:** Conceptualization, Funding acquisition, Writing - review & editing. **Carsten Sørlie:** Data curation. **Jane K. Dolven:** Conceptualization, Funding acquisition, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Taxonomic list of the benthic foraminifera

Brizalina skagerrakensis (Qvale and Nigam) = *Bolivina skagerrakensis* Qvale and Nigam, 1985
Bulimina marginata d'Orbigny, 1826
Cassidulina reniforme Nørvang, 1945
Cibicides lobatulus (Walker and Jacob) = Nautilus lobatulus Walker and Jacob, 1798
Cibicides refulgens Montfort, 1808
Epistominella vitrea Parker, 1953
Stainforthia feylingi Knudsen and Seidenkrantz, 1994
Stainforthia fusiformis (Williamson) = Bulimina pupoides d'Orbigny var. fusiformis Williamson, 1858

Appendix B. Geochemical and foraminiferal parameters

Table B.1

The D2-6A porosity (%), uncorrected TOC (%), Fine fraction (% < 63 µm), TOC_{63} (mg/g), N (%), C/N ratios, $\delta^{13}C_{VPDB}$, fES_{100}, fAMBI, fNQI, $fHlog_2$, and the D2-5B porosity (%), Cu (mg/kg), Zn (mg/kg), Ni (mg/kg). Classification of the geochemical parameters and foraminiferal parameters are according to the Veileder (02:2018) and Alve et al. (2019), respectively.

Status	High	Good	Moderate	Poor	Bad

Core	Interval (cm)	Porosity (%)	TOC (%)	Fine fraction (%<63µm)	TOC_{63} (mg/g)	N (%)	C/N	$\delta^{13}C_{V-PDB}$ (‰)	fES_{100}	fAMBI	fNQI	fH_{log2}	Core	Interval (cm)	Porosity (%)	Cu (mg/kg)	Zn (mg/kg)	Ni (mg/kg)
D2-6A	0-1	76	2.66	94	28	0.42	6.27	-22.67	25	2.14	0.71	4.36	D2-5B	0-1	76	57	100	57
D2-6A	1-2	71	2.66	89	29	0.42	6.32	-22.45	25	2.41	0.69	4.28	D2-5B	1-2	71	61	97	56
D2-6A	2-3	68	2.63	92	28	0.41	6.37	-22.41	23	2.45	0.66	4.16	D2-5B	2-3	65	60	100	60
D2-6A	3-4	64	2.42	93	25	0.37	6.47	-22.35	24	2.52	0.67	4.25	D2-5B	3-4	60	63	110	63
D2-6A	4-5	59	2.06	92	22	0.32	6.53	-22.36	26	2.57	0.69	4.30	D2-5B	4-5/5-6 A	55	75	110	75
D2-6A	5-6	54	1.62	95	17	0.25	6.59	-22.35	24	1.78	0.72	4.17	D2-5B	4-5/5-6 B	49	72	85	66
D2-6A	6-7	49	1.01	96	11	0.15	6.90	-22.18					D2-5B	6-7	45	72	75	62
D2-6A	7-8	46	0.87	96	9	0.13	6.68	-22.17	25	1.47	0.76	4.19	D2-5B	7-8	36	35	40	38
D2-6A	8-9	47	0.88	95	10	0.13	6.87	-22.30					D2-5B	8-9	26			
D2-6A	9-10	44	0.78	94	9	0.11	6.88	-22.37					D2-5B	9-10	45			
D2-6A	10-11	35	0.74	74	12	0.09	7.81	-23.20					D2-5B	10-11	59			
D2-6A	11-12	25	0.20	28	15	0.03	7.00	-22.22	21	0.72	0.74	3.74	D2-5B	11-12	60			
D2-6A	12-13	33	0.88	71	14	0.11	8.34	-22.28					D2-5B	12-13	61			
D2-6A	13-14	54	2.30	87	25	0.34	6.73	-21.95					D2-5B	13-14	61			
D2-6A	14-15	60	3.13	68	37	0.47	6.66	-22.04	22	1.85	0.68	3.83	D2-5B	14-15	62			
D2-6A	15-16	59	3.19	74	36	0.46	7.00	-21.89					D2-5B	15-16	62			
D2-6A	16-17	59	3.05	81	34	0.47	6.51	-21.80	22	1.85	0.68	3.81	D2-5B	16-17	54	70	130	75
D2-6A	17-18	60	3.31	75	38	0.48	6.89	-21.81	22	2.34	0.64	3.93	D2-5B	17-18	69			
D2-6A	18-19	61	3.20	75	36	0.47	6.85	-21.74					D2-5B	18-19	61			
D2-6A	19-20	61	3.21	94	33	0.48	6.73	-21.77	21	2.13	0.65	3.94	D2-5B	19-20	60	58	110	79
D2-6A	20-22	60	3.10	96	32	0.48	6.41	-21.82					D2-5B	20-22	60			
D2-6A	22-24	59	3.08	95	32	0.47	6.58	-21.76	22	1.64	0.70	3.76	D2-5B	22-24	60			
D2-6A	24-26	58	3.09	95	32	0.46	6.79	-21.78					D2-5B	24-26	61			
D2-6A	26-28	57	3.00	95	31	0.44	6.83	-21.79	19	1.89	0.64	3.56	D2-5B	26-28	59	66	100	87
D2-6A	28-30	57	2.95	95	30	0.43	6.89	-21.65					D2-5B	28-30	58			
D2-6A	30-32	56	2.86	95	29	0.43	6.60	-21.65	21	1.36	0.71	3.87	D2-5B	30-32	58			
D2-6A	32-34	56	2.96	95	30	0.42	7.08	-21.63					D2-5B	32-34	56			
D2-6A	34-36	56	2.93	95	30	0.42	6.95	-21.68					D2-5B	34-36	56			
D2-6A	36-38	55	2.93	95	30	0.42	6.95	-21.61					D2-5B	36-38	55			
D2-6A	38-40	54	2.85	95	29	0.42	6.75	-21.57					D2-5B	38-40	55			
D2-6A	40-42	55	2.92	95	30	0.41	7.06	-21.58					D2-5B	40-42	55	44	68	62

Table B.2
The D3-3B/13A porosity (%), uncorrected TOC (%), Grain size (% < 63 µm), TOC_{63} (mg/g), N (%), C/N ratios, $\delta^{13}C_{VPDB}$, fES_{100}, fAMBI, fNQI, $fHlog_2$ and the D3-13A porosity (%), Cu (mg/kg), Zn (mg/kg), Ni (mg/kg). Classification of the geochemical parameters and foraminiferal parameters are acording to the Veileder (02:2018) and Alve et al. (2019), respectively.

Status	High	Good	Moderate	Poor	Bad

Core	Interval (cm)	Porosity (%)	TOC (%)	Fine fraction (%<63µm)	TOC_{63} (mg/g)	N (%)	C/N	$\delta^{13}C_{V\text{-}PDB}$ (‰)	fES_{100}	fAMBI	fNQI	fH_{log2}	Core	Interval (cm)	Porosity (%)	Cu (mg/kg)	Zn (mg/kg)	Ni (mg/kg)
D3-3B	0-1	58	1.25	77	17	0.24	5.30	-22.81	28	2.99	0.69	4.35	D3-13A	0-1	63	38	66	37
D3-3B	1-2	50	1.19	74	17	0.21	5.60	-22.69	27	3.05	0.66	4.24	D3-13A	1-2	54	29	59	32
D3-3B	2-3	45	1.07	64	17	0.18	5.82	-22.45	26	2.91	0.66	4.06	D3-13A	2-3	50	29	61	34
D3-3B	3-4	37	0.80	58	16	0.13	6.10	-22.20	24	2.27	0.68	4.00	D3-13A	3-4	44	24	55	32
D3-3B	4-5	36	0.69	57	15	0.12	5.67	-22.04	27	1.92	0.75	4.40	D3-13A	4-5	41	20	47	32
D3-3B	5-6	30	0.65	53	15	0.10	6.48	-22.02	27	2.41	0.72	4.50	D3-13A	11-12	26	16	31	27
D3-3B	6-7	28	0.50	50	14	0.09	5.33	-22.06					D3-13A	16-17	41	27	46	36
D3-3B	7-8	27	0.47	53	13	0.09	5.01	-21.90	24	1.16	0.76	4.07	D3-13A	22-24	35	52	78	49
D3-3B	8-9	26	0.50	55	13	0.09	5.27	-21.98					D3-13A	28-30	36	47	70	56
D3-3B	9-10	25	0.45	53	13	0.09	5.17	-21.82										
D3-3B	10-11	24	0.50	56	13	0.08	6.26	-21.96										
D3-3B	11-12	26	0.55	59	13	0.09	6.47	-22.44	21	1.40	0.69	3.67						
D3-3B	12-13	26	0.39	57	12	0.08	4.84	-21.69										
D3-3B	13-14	24	0.55	56	13	0.07	7.52	-21.92										
D3-13A	0-1	63	1.14	80	15	0.24	4.79	-22.42										
D3-13A	4-5	41	0.79	73	13	0.16	4.86	-22.15										
D3-13A	9-10	29	0.54	60	13	0.10	5.28	-21.95										
D3-13A	10-11	27	0.65	69	12	0.10	6.65	-22.01										
D3-13A	12-13	27	0.52	73	10	0.09	5.60	-22.31										
D3-13A	14-15	29	0.59	82	9	0.08	7.17	-22.12	23	2.01	0.68	3.82						
D3-13A	16-17	29	0.53			0.08	6.54	-22.25										
D3-13A	18-19	29	0.52	81	9	0.08	6.83	-22.38	20	1.92	0.65	3.67						
D3-13A	22-24	35	0.54	89	7	0.08	6.61	-22.59	18	2.53	0.58	3.46						
D3-13A	26-28	35	0.55	92	7	0.08	7.00	-22.64	17	2.35	0.57	3.26						

Appendix C. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2020.106818.

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