Rapid environmental responses to climate-induced hydrographic changes in the Baltic Sea entrance

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Abstract

The Öresund (the Sound), which is a part of the Danish straits, is linking the marine North Sea and the brackish Baltic Sea. It is a transition zone where ecosystems are subjected to large gradients in terms of salinity, temperature, carbonate chemistry, and dissolved oxygen concentration. In addition to the highly variable environmental conditions, the area is responding to anthropogenic disturbances in e.g. nutrient loading, temperature, and pH. We have reconstructed environmental changes in the Öresund during the last c. 200 years, and especially dissolved oxygen concentration, salinity, organic matter content, and pollution levels, using benthic foraminifera and sediment geochemistry. Five zones with characteristic foraminiferal assemblages were identified, each reflecting the environmental conditions for respective period.

The largest changes occurred around 1950, when the foraminiferal assemblage shifted from a low diversity fauna, dominated by the species *Stainforthia fusiformis* to higher diversity and abundance, and dominance of the *Elphidium* species. Concurrently, the grain-size distribution shifted from clayey — to sandier sediment. To explore the causes for the environmental changes, we used time-series of reconstructed wind conditions coupled with large-scale climate variations as recorded by the North Atlantic Oscillation (NAO) index, as well as the ECOSMO II model of currents in the Öresund area. The results indicate increased changes in the water circulation towards stronger currents in the area after the 1950's. The foraminiferal fauna responded quickly (< 10 years) to the environmental changes. Notably, when the wind conditions, and thereby the current system, returned in the 1980's to the previous pattern, the foraminiferal assemblage did not rebound. Instead, the foraminiferal faunas displayed a new equilibrium state.

1 – Introduction

The Öresund (the Sound) is one part of the Danish straits between Sweden and Denmark. Together with the Great — and Little Belt, they link the open-ocean waters of the North Sea and the brackish waters of the Baltic Sea. The confluence of the water masses creates a north-south gradient as well as a strong vertical stratification of the water in terms of salinity, carbonate chemistry and dissolved oxygen concentration ([O_2]) (Leppäranta and Myrberg 2009). The depth of the halocline mainly depends of the outflows from the Baltic Sea; a strong thermocline develops during spring and summer, which further strengthens the vertical stratification. Thus, the ecosystems in the Öresund are exposed — and adapted — to a unique transitional environment. The region is also characterized by intense human activities, with 4 million people living in the vicinity of the Öresund and 85 million people living in the catchment area of the Baltic Sea (HELCOM, 2009). Discharge from agriculture, industry, and urban areas on both the

Swedish and Danish sides of the strait, and the considerable impact of marine traffic – the strait is one of the busiest waterways in the world – generate pollution and eutrophication of the water (HELCOM 2009; ICES 2010). Since the 1980's, the implementation of efficient wastewater treatment and measures in agriculture contributed to markedly reduce the amount of nutrients coming from river run-off (Nausch et al. 1999; Carstensen et al. 2006; Rydberg et al. 2006). However, these efforts in decreasing nutrient loads have not resulted in improved water quality, due to the long time scales of biogeochemical cycles to reach equilibrium in the Baltic Sea region (Gustafsson et al. 2012). The Öresund, like most of the Baltic Sea, is still assessed to be eutrophic, and hypoxic events are frequent (Rosenberg et al. 1996; Conley et al. 2007, 2011; HELCOM 2009; Wesslander et al. 2016). Moreover, increasing temperatures and declining pH, linked to global climate change and ocean acidification, have been reported for surface and bottom waters in the area (Andersson et al. 2008; Göransson 2017). As a result, ecosystems in the Öresund are currently under the combined impact of natural and anthropogenic stressors (Henriksson 1969; Göransson et al. 2002; HELCOM 2009; ICES 2010). The multiple stressors currently affecting the environment make this region particularly interesting to study, and also highlight the need to obtain records of decadal and centennial environmental changes. As noted above, both recent human-induced impacts and climate variability have been substantial in the region. Therefore the question arises whether these factors have affected the benthic environment. Furthermore, sediment records of past environmental changes can provide crucial context for ongoing and future predicted changes in the Öresund and Baltic Sea regions.

We used the marine sediment record and its contents of foraminifera as well as sediment geochemistry to obtain records of decadal environmental changes. Benthic foraminifera are widely used for environmental reconstructions, based on their rapid response to environmental changes, broad distribution, high densities, and often well-preserved tests (shells) in the sediment (e.g. Sen Gupta 1999b; Murray 2006). For instance, distribution of benthic foraminifera have been used for historical environmental reconstructions of fjords on decadal to centennial timescales on the Swedish west coast (Nordberg et al. 2000; Filipsson and Nordberg 2004a, 2004b; Polovodova Asteman and Nordberg 2013; Polovodova Asteman et al. 2015), and in the Kattegat (Seidenkrantz 1993; Christiansen et al. 1996). In the Öresund, living foraminiferal assemblages have been studied (Hansen 1965; Charrieau et al. 2018), but to the best of our knowledge, no studies of past foraminiferal assemblages have been performed. The objective of this study was to reconstruct the environmental conditions of benthic systems during the last two centuries in the Öresund, by using foraminiferal fauna analysis in combination with sediment geochemistry and grain-size. Furthermore, we analyzed long time series of wind conditions in the area to evaluate the coupling between local changes in ecosystem variables and variations in atmospheric and subsequent hydrographic conditions, and a possible link with large-scale variations expressed through the North Atlantic Oscillation (NAO) index. Finally, we compared our data with the model ECOSMO II (Daewel and Schrum 2013; 2017) of currents and water circulation changes in the Öresund area during the period 1948—2013.

2 – Study site

The Öresund is a 118 km long narrow strait (Figure 1). The water depth in the northern part is on average 24 m but it reaches 53 m south of the Island of Ven. The Öresund is an important link between the North Sea, Skagerrak, Kattegat and the Baltic Sea (Figure 1), and up to 30 % of the water exchange in the region goes through the Öresund (Sayin and Krauß 1996; Leppäranta and Myrberg 2009). The remaining part goes through the Great and Little Belt. The width of the Öresund varies between 4 and 28 km, and the water has overall high current velocities, up to 1.5

$m.s^{-1}$ at the upper water layer in the northern part (Nielsen 2001). The fully marine Skagerrak consists of water masses from the North Sea and the North Atlantic and in general a thin surface layer with water originating from the Baltic Sea and rivers draining into the sea; the water circulation forms a cyclonic gyre (cf. Erbs-Hansen et al. 2012). Part of the Skagerrak waters reach the Kattegat and the Baltic Sea, where they are successively diluted with the large amounts of freshwater (around 15,000 m^3/s, Bergström and Carlsson 1994) draining into the Baltic Sea from numerous large rivers. The low-saline Baltic Sea surface water is transported by the Baltic Current, which is typically confined along the Swedish west coast in the Kattegat but may cover a larger surface area towards the west, depending on wind direction. The Baltic Current later joins the Norwegian Coastal Current in the Skagerrak (Figure 1). The large fresh water input and the subsequent large salinity difference between the Kattegat and Baltic Sea result in a two-layer structure in the Öresund (Figure 2) (She et al. 2007; Leppäranta and Myrberg 2009). The water stratification is influenced by the surface water from Arkona Basin (salinity 7.5—8.5), the surface water from the Kattegat upper layer (salinity 18—26) and the lower layer of the Kattegat (salinity 32—34).

Salinity, temperature, pH, [O_2] and nutrient content, here represented by dissolved inorganic nitrogen concentration [DIN] (nitrate + nitrite + ammonium), in the surface and bottom waters of the Öresund vary seasonally (Figure 3, Appendix A). At the surface and bottom water, salinity ranges between ~8 and ~18 and between ~29 and ~34, respectively, and it is more stable between April and July, when the stratification is the strongest (Figure 3). Temperature ranges between ~1 °C in February and ~19 °C in July in the surface water, while in the bottom water, the lowest temperature is found in March—April with ~5° C, and the highest temperature in October—November with ~13 °C. The pH varies between ~8.1 and ~8.6 in the surface water, and between

~7.8 and ~8.6 in the bottom water, without a clear seasonal pattern (Figure 3). [O_2] in the bottom water reaches ~7 $mL.L^{-1}$ in January, and it is typically below 2 $mL.L^{-1}$ in October, approaching hypoxic values. In the surface water, [DIN] can reach ~7 $\mu mol.L^{-1}$ in January, and it is ~0 $\mu mol.L^{-1}$ between April and August (Figure 3).

3 – Materials and Methods

3.1 Sampling

A suite of sediment cores, as well as water samples from the water column, were collected in November 2013 during a cruise with r/v *Skagerak*. Here we present the data from two sediment cores sampled at the Öresund station DV-1 (55°55.59' N, 12°42.66' E) (Figure 1), north of the Island of Ven. The water depth was 45 m, and CTD (Conductivity, Temperature, Depth) casts were taken to measure salinity, temperature and [O_2] in the water column. Water samples were collected at 10, 15, 20, 30 and 43 m from the Niskin bottles for carbonate chemistry analyses. The CTD and carbonate chemistry data are presented in Charrieau et al. (2018). In general, it is challenging to obtain sediment cores in the Öresund, due to the high current velocities up to 1.5 $m.s^{-1}$ (Nielsen 2001), human-induced disturbances, and limited areas of recent sediment deposition (Lumborg 2005), but our site north of Ven represents an accumulation area. The cores (9-cm-inner-diameter) were collected using a GEMAX twin barrel corer. The corer allowed sampling of 30 and 36 cm long sediment cores (referred in this study as core DV1-G and DV1-I, respectively), which were sliced into one centimeter sections. The samples from the DV1-G core were analyzed for carbon and nitrogen content, grain size distribution, and dated using Gamma spectroscopy. The samples from the DV1-I core were analyzed with respect to foraminiferal fauna and carbon and nitrogen content. The distinct carbon content profiles, measured on both cores, were used to correlate the ^{210}Pb dated DV1-G core to the DV1-I core used for foraminiferal analyses.

3.2 Chronology

The age-depth model was established using ^{210}Pb and ^{137}Cs techniques on samples from the DV1-G core. The samples were measured with an ORTEC HPGe (High-Purity Germanium) Gamma Detector at the Department of Geology at Lund University, Sweden. Corrections for self-absorption were made for ^{210}Pb following Cutshall et al. (1983). The instruments were calibrated against in-house standards and the maximum error was 0.5 year in the measurements. Excess (unsupported) ^{210}Pb was measured down to 23 cm and the age model was calculated based on the Constant Rate of ^{210}Pb Supply (CRS) model (Appleby 2001).

3.3 Foraminifera analyses

Approximately 10 g of freeze-dried sediment per sample were wet sieved thought a 63-µm mesh screen and dried on filter paper at room temperature. Subsequently, the samples were dried sieved through 100- and 500-µm mesh screens and separated into the fractions 100-500 µm and >500 µm. The foraminifera from every second centimeter of the core - plus from additional centimeters around key zones - were picked and sorted under a Nikon microscope (22 samples in total). A minimum of 300 specimens per sample were picked and identified, as recommended by Patterson and Fishbein (1989). If necessary the samples were split with an Otto splitter (Otto 1933). For taxonomy at the genus level, we mainly followed Loeblich and Tappan (1964) with some updates from more recent literature, e.g. Tappan and Loeblich (1988). For taxonomy at the species level, we mainly used Feyling-Hanssen (1964), Feyling-Hanssen et al. (1971) and

Murray and Alve (2011). For original descriptions of the species, see Ellis and Messina (1940 and supplements up to 2013).

Recently, the eastern Pacific morphospecies *Nonionella stella* has been presented as an invasive species in the Skagerrak-Kattegat region (Polovodova Asteman and Schönfeld 2015). However, a comparison of *N. stella* DNA sequences from the Santa Barbara Basin (USA) (Bernhard et al. 1997) with the Swedish west coast specimens demonstrates that they represent two closely related species but are not conspecific (Deldicq et al. in press). Therefore, we have referred to the species found here as *Nonionella* sp. T1, following Deldicq et al. (2019). The species *Verneuilina media* (here referred to the genus *Eggerelloides*), which has often been reported in previous studies from the Skagerrak-Kattegat area (e.g. Conradsen et al. 1994), was morphologically close to *Eggerelloides scabrus* in the present material, and these two species have been grouped as *E. medius/scabrus*. The taxon *Elphidium excavatum* forma *clavata* (cf. Feyling-Hanssen 1972), was referred to as *Elphidium clavatum* following Darling et al. (2016). *Elphidium clavatum* and *Elphidium selseyense* (Heron-Allen and Earland) were morphologically difficult to separate in this region, as transitional forms occur. The dominant species was *E. clavatum*, but we acknowledge that a few individuals of *E. selseyense* could have been included in the counts. The taxon *Ammonia beccarii* was referred to as *Ammonia batava*, following recent molecular work done on the taxon *Ammonia* in the Kattegat region (Groeneveld et al. 2018; Bird et al. 2019)

Foraminiferal density was calculated and normalized to the number of specimens per 50 cm^3. Data of densities for the first two centimeters of the core are from Charrieau et al. (2018). Some specimens displayed decalcified tests, however the inner organic linings were preserved. These inner organic linings were reported separately and not included in the total foraminiferal counts. Benthic foraminiferal accumulation rates were calculated as follows:

BFAR (number of specimens.cm^{-2}.yr^{-1}) = BF x SAR,

where BF is the number of benthic foraminifera per cm^3 and SAR is the sediment accumulation rate (cm.yr^{-1}). Foraminiferal species that accounted for >5 % of the total fauna in at least one of the samples were considered as major species, and their density was used in statistical analysis. The Shannon index was calculated to describe the foraminiferal diversity. To determine foraminiferal zones, stratigraphically constrained cluster analysis was performed, using the size-independent Morisita's index to account for the large differences in the densities between samples (e.g. Krebs 1998). A dendrogram was then constructed based on arithmetic averages with the UPGMA method (Unweighted Pair Group Method with Arithmetic Mean). Correspondence analysis was also performed, to determine significant foraminiferal species in each zone. Statistical analyses were performed using the PAST software (Hammer et al. 2001).

3.4 Organic matter analyses

Total Organic Carbon (TOC) and Total Nitrogen (TN) content were measured for both DV1-G and DV1-I. Approximately 8 mg of freeze-dried sediment was homogenized for each centimeter and placed in silver capsules. Removal of inorganic carbon was carried out by in-situ acidification (2M HCl) method based on Brodie et al. (2011). TOC and TN content were analyzed on a Costech ECS 4010 Elemental Analyzer at the Department of Geology, Lund University. The instrument was calibrated against in-house standards. The analytical precisions showed a reproducibility of 0.2 % and 0.03 % for TOC and TN contents, respectively. The molar C/N ratio was calculated.

3.5 Grain-size analyses

Grain-size analyses were performed on core DV1-G using 3.5 to 5 g of freeze-dried sediment for each centimeter. Organic matter was removed by adding 15 mL of 30 % H_2O_2 and heating during 3 to 4 minutes until the reaction ceased. After the samples had cooled down, 10 mL of 10 % HCl was added to remove carbonates; thereafter the sediment was washed with milli-Q until its pH was neutral. In the last step, biogenic silica was removed by boiling the sediment in 100 mL 8 % NaOH, and then washed until neutral pH was reached. The sand fraction (>63 µm) was separated by sieving and the mass fraction of sand of each sample was calculated. Grain sizes <63 µm were analyzed by laser diffraction using a Sedigraph III Particle Size Analyzer at the Department of Geology, Lund University. The data were categorized into three size groups, <4 µm (clay), 4–63 µm (silt) and 63–2000 µm (sand).

3.6 Climate data and numerical modeling

Data from the dataset High Resolution Atmospheric Forcing Fields (HiResAFF) covering the time period 1850–2008 (Schenk and Zorita 2012; Schenk 2015) were used to study the variations of near-surface (10 m) wind conditions during the winter half of the year (October to March). The daily dataset can be downloaded from WDC Climate (Schenk 2017). Wind conditions over the Öresund are represented by the closest grid point of HiResAFF at 55° N and 12.5° E. The North Atlantic Oscillation (NAO) index as defined by Jones et al. (1997) for boreal winter (December to March) was used, with updates taken from the Climatic Research Unit (CRU, https://crudata.uea.ac.uk/cru/data/nao/). To allow comparison, the NAO and wind data were normalized relative to the period 1850–2008. Changes in the currents through the Öresund and the Kattegat were taken from the fully coupled physical biogeochemical model ECOSMO II

(Daewel and Schrum 2013, 2017), which was forced by NCEP/NCAR reanalysis data and covers the period 1950–2013. On model ECOSMO II, the simulated South-North currents are represented as VAV (vertically averaged V- component) and the simulated West-East currents as UAV (vertically averaged U - component).

4 – Results

4.1 Age model

The unsupported ^{210}Pb showed a decreasing trend with depth in the DV1-G core (Figures 4A, 4B). The peak observed in the ^{137}Cs around 9 cm corresponds to the Chernobyl accident in 1986 (Figure 4C). The unsupported ^{210}Pb allowed direct dating of the core between 2013 and 1913. The sedimentation rate ranged between 1 and 5.6 $mm.y^{-1}$, with an average of 2.2 $mm.y^{-1}$, and was decreased with depth. The ages of the lower part of the sediment record were deduced by linear extrapolation based on a sedimentation rate of 1.4 $mm.y^{-1}$, corresponding to the linear mean sedimentation rate between the years 1913 and 1946 (Figure 4D).

4.2 Foraminiferal assemblages and sediment features

The foraminiferal assemblages were composed of 76 species from the porcelaneous, hyalines and agglutinated forms (0.3, 54.5 and 45.2 %, respectively) (Appendix B). Eleven foraminiferal species had relative abundance higher than 5 % in at least one sample and were considered as major species (Plate 1, Figure 5).

The cluster analysis revealed three main foraminiferal zones (FOR-A, FOR-B, and FOR-C) (Figures 5, 6). The correspondence analysis resulted in three factors explaining 92 % of the variance, and in assemblages consisting in seven significant species, presented in order of contribution: *Nonionella* sp. T1, *Nonionoides turgida*, *Ammonia batava*, *Stainforthia fusiformis*, *Elphidium albiumbilicatum*, *E. clavatum* and *Elphidium magellanicum* (Table 1). Based both on the cluster and the correspondence analyses, five subzones could be separated to which we assigned dates according to the age model: FOR-A1 (1807–1870), FOR-A2 (1870–1953), FOR-B1 (1953–1998), FOR-B2 (1998–2009), and FOR-C (2009–2013) (Figures 5, 6).

4.2.1 Zone FOR-A1 (1807–1870)

The foraminiferal accumulation rate (BFAR) was on average 5 ±3 specimens.cm^{-2}.y^{-1} in zone FOR-A1 (Figure 5). The Shannon index was stable and low, around 1.77 ±0.1 (Figure 5). The agglutinated species *Eggerelloides medius/scabrus* and the hyaline species *Stainforthia fusiformis* made major contributions to the assemblages (relative abundances up to 53 % and 34 %, respectively; Figure 5A). *Ammonia batava*, the three *Elphidium* species (*E. albiumbilicatum*, *E. clavatum*, and *E. magellanicum*), *Nonionellina labradorica* and the agglutinated species *Reophax subfusiformis* were also major species with abundances up to 7 %. The TOC and C/N values on this period were stable and were on average 3.36 % and 8.8 %, respectively (Figure 7). The clay size fraction dominated the sediment at the end of this period with a mean value of 63 %, and the sand content was around 7 % (Figure 7).

4.2.2 Zone FOR-A2 (1870–1953)

The BFAR was on average 9 ±5 specimens.cm^{-2}.y^{-1} in zone FOR-A2 (Figure 5). The Shannon index was stable and low, around 1.94 ±0.15 (Figure 5). *Stainforthia fusiformis* dominated the assemblage with relative abundances up to 56 % and BFAR up to 608 specimens.cm^{-2}.y^{-1} (Figures 5A, 5B), which is the highest BFAR observed for this species along the core. *Egerelloides medius/scabrus* was still very abundant, up to 48 % (Figure 5A). *Ammonia batava*, the three *Elphidium* species and *N. labradorica* were present but with lower abundances than in the zone FOR-A1 (maximum 5 %). *Bulimina marginata* started to be more abundant with an average relative abundance of 2 % in the zone. *Reophax subfusiformis* was still a part of the assemblage and ranged between 1 and 8 %. The TOC and C/N values were stable and were on average 3.5 % and 8.74 %, respectively (Figure 7). The clay size fraction dominated the sediment during this period with a mean value of 63 %, and the sand content was around 6 % (Figure 7).

4.2.3 Zone FOR-B1 (1953–1998)

The BFAR increased massively during the zone FOR-B1 with on average 54 ±31 specimens.cm^{-2}.y^{-1} and with a peak at 93 specimens.cm^{-2}.y^{-1} around 1965 (Figure 5). It is lower during the second part of the zone. The Shannon index was higher than in previous zones and it progressively increased towards the top of the zone (Shannon index average 2.34 ±0.3) (Figure 5). The highest BFAR along the core were observed for all the dominant species of the previous zone FOR-A2, except for *S. fusiformis* (Figure 5B). The zone was then also characterized by a drastic drop in the relative abundance of *S. fusiformis* from 31 to 2 % (Figure 5A). *Eggerrelloides medius/scabrus* gradually decreased in the zone, with relative abundances from 49 to 24 %. The highest relative abundance of *A. batava* for the entire record was in this zone but it was slowly decreasing as well, from 10 to 3 %. The *Elphidium* species were more abundant than in the FOR-A zones and their relative abundance was increasing, especially for *E. clavatum* (increasing up to 23 %). *Bulimina marginata*, *N. labradorica* and *R. subfusiformis* had a relative abundance between 2 and 6 %. A period of lower TOC values was observed during zone FOR-B1 between 1953 and 1981, with an average of 2.38 % (Figure 7). On the same period, the sand content showed a pronounced increase, with an average of 24 % (Figure 7).

4.2.4 Zone FOR-B2 (1998–2009)

In zone FOR-B2 the BFAR was still high, on average 55 ±6 specimens.cm^{-2}.y^{-1} (Figure 5). The Shannon index was high with an average of 2.8 ±0.2 (Figure 5). The dominant species in the zone were *E. clavatum* (up to 25 %) and *Eggerelloides medius/scabrus* (up to 15 %; Figure 5A). The other two *Elphidium* species reached their highest relative abundances over the core (up to 6 %). *Nonionella* sp. T1, which had not occurred in the record until now, appeared in this zone with a relative abundance of 1 %. *Nonionoides turgida*, which was present in very low abundances along the core, had a mean abundance of 1 % in the zone (Figure 6A). *Stainforthia fusiformis* was present with up to 9 % in relative abundance and a BFAR higher than in zone FOR-B1 (up to 570 specimens.cm^{-2}.y^{-1}). *Ammonia batava*, *B. marginata*, *N. labradorica*, and *R. subfusiformis* were present and ranged between 2 and 8 %. The TOC values were increasing, with on average 3.05 % (Figure 7). The sediment was dominated by the clay fraction that was increasing (mean value of 58 %), and the sand content was around 17 % (Figure 7).

4.2.5 Zone FOR-C (2009–2013)

The BFAR was lower than in previous zones FOR-B1 and FOR-B2, with on average 21 ±5 specimens.cm^{-2}.y^{-1} (Figure 5). The Shannon index was the highest during FOR-C (Shannon index average 2.93 ±0.07) (Figure 5). *Nonionella* sp. T1 was a dominant specie in the zone with a strong increase in relative abundance (from 1 to 14 %) and in BFAR (from 61 to 137 specimens.cm^{-2}.y^{-1}) (Figures 5A, 5B). *Elphidium clavatum* and *R. subfusiformis* were also dominant species with abundances up to 13%. *Nonionoides turgida* had its highest relative abundance and BFAR over the core during the zone, with up to 9 % and 342 specimens.cm^{-2}.y^{-1}, respectively (Figures 5A, 5B). *Eggerelloides medius/scabrus* had its lowest relative abundance over the core (up to 9 %). *Bulimina marginata*, the other two *Elphidium* species, *N. labradorica* and *S. fusiformis* were still present (between 1 and 6 %), while *Ammonia batava* was absent during the zone. The TOC and C/N values were on average 3.71 % and 8.17 %, respectively (Figure 7). The clay size fraction dominated the sediment with a mean value of 66 % and the sand fraction was 7 % (Figure 7).

4.2.6 Inner organic linings

Decalcified specimens were few and ranged between 0 and 4 specimens.cm^{-2}.y^{-1} with an average of 1 specimen.cm^{-2}.y^{-1} (Fig. 5). They were observed throughout the core and especially during zone FOR-B2, and the morphology of the remaining inner organic linings allowed the identification of the taxon *Ammonia* (Plate 1).

4.3 Simulated data from model ECOSMO II

The VAV (vertically averaged South-North current velocity) through the Öresund from the model ECOSMO II showed a reversed pattern compared to the UAV (vertically averaged West-East current velocity) through the Kattegat (Figure 8). Thus, higher VAV through the Öresund translates to an increase in the East to West flow in the Kattegat (lower UAV), suggesting a stronger outflow from the Baltic Sea. The VAV through the Öresund had the lowest values around 1955 (Figure 8), followed by a shift to very high values, which dominated throughout 1960–70. A comparable period with increased outflow from the Baltic into the Kattegat re-occurred during the period 1993–2000.

5 – Discussion

Our environmental interpretations of the foraminiferal assemblages were based on the ecological characteristics of each major species (Table 2). Based on our environmental reconstructions, we could infer environmental changes regarding [O_2], salinity, organic matter content, and pollution levels. Furthermore, we linked local environmental changes to larger atmospheric and hydrographic conditions.

5.1 1807 – 1870

All the major species found in this period are tolerant to low oxygen conditions, especially the two main species: *S. fusiformis* and *E. medius/scabrus* (Table 2). *Stainforthia fusiformis* is an opportunistic species used to hypoxic and potentially anoxic conditions (Alve 1994), and *E. medius/scabrus* specimens have been found alive down to 10 cm in the sediment, where no oxygen was available (Cesbron et al. 2016). *Stainforthia fusiformis* and *N. labradorica* are also able to denitrify (Piña-Ochoa et al. 2010). The fact that species tolerant to low oxygen conditions dominated, and the presence of species that have the capacity to denitrify, suggest that low oxygen conditions were prevailing during this period. Furthermore, *S. fusiformis* prefers organic rich substrate and clayey sediment, which was measured in our core during this time period (Figure 7). The low species diversity, as indicated by the low Shannon index in this section of the core, can sometimes be linked with low salinity (Sen Gupta 1999a). Most of the major species found during this period, such as the *Elphidium* species, *R. subfusiformis* and *A. batava* tolerate lower salinities, and are typical of brackish environments (Table 2). The low occurrence of *B. marginata*, a typical marine species, also suggests a salinity lower than in the open ocean. However, the salinity was probably not below ~30, which is the lower limit for *N. labradorica* and *S. fusiformis*, which were present throughout the period (Figure 5, Table 2). In summary, this period appears to have been characterized by low [O_2], high organic matter content, and salinity around 30.

5.2 1870 – 1953

Stainforthia fusiformis was largely dominating the assemblage during this period, which may suggest even lower oxygen conditions than during the previous period. This would also go along with the low species diversity, which is sometimes linked to low salinity. In the Öresund, low salinity can be caused by less influence of more saline marine waters from the Kattegat, and changes in the water transport through the strait is a possible explanation for both lower salinity and oxygen levels. However, the occurrence of the marine species *B. marginata* suggests that the salinity was at least ~30 (Table 2). Low oxygen can also be associated with high organic matter contents, since oxygen is consumed during remineralization of organic matter. However, the TOC levels observed in our core in this zone were high, but not higher than in the previous zone (Figure 7). At the time of the industrial revolution, the Öresund, as the Baltic Sea in general, was used as a sewage recipient for a mixture of domestic and industrial wastes, industrial cooling water and drainage water (Henriksson 1968), and the amount of marine traffic increased considerably during this time period. Across the Baltic Sea, this notably caused increased deposition of heavy metals (Borg and Jonsson 1996). This diverse type of pollution could have modified the water properties, for example regarding the carbonate chemistry and pH. Indeed, this zone is characterized by the presence of organic linings in the core (see also section 5.6). Moreover, heavy metals, fuel ash (black carbon) and pesticides have been demonstrated to generally have a negative effect on foraminiferal abundance and diversity (Yanko et al 1999; Geslin et al. 2002). Pollution and low oxygen concentration could explain the low species BFAR and diversity as well as the dissolution of tests during this period. Some species that were present, i.e. the agglutinated species *E. medius/scabrus* and *R. subfusiformis*, are known to be tolerant to various kind of pollution (Table 2).

5.3 1953 – 1998

The large increase in general BFAR from 1953 suggests either more favorable growth conditions or significant deposition of transported specimens into the area. The coarser grain size observed during this period indicates possible changes in the current system, which could affect both growing conditions and transport of specimens (Figure 7). However, the dating of our core showed continuous sediment accumulation without any interruption during this period (Figure 4). Moreover, all the new dominating species were already present in the core, even if in lower relative abundances (Figure 5A). This indicates that the BFAR increase is most likely not due to specimens transport, but rather as a result of a change in substrate and environmental conditions that became favorable for a different foraminiferal assemblage. The higher foraminiferal diversity compared to previous periods and the decrease in the relative abundance of *S. fusiformis* may indicate more oxic conditions. *Elphidium clavatum* has been found in coarse sediment in the area (Bergsten et al. 1996), and other species that tolerate sandy environments and varying TOC dominated the assemblage, such as *A. batava*, the other species in the *Elphidium* species, *B. marginata*, and *E. medius/scabrus*. Furthermore, anthropogenic activities such as agricultural practices were intensified during this period until the 1980s, which resulted in increased nutrient loads and resulting eutrophication (i.e. Rydberg et al. 2006). The increase in organic matter may have been beneficial for foraminifera as food source. Food webs and species interaction like intra and inter competition might also have been modified, giving the advantage to some species such as the *Elphidium* species to develop in these new environmental conditions.

The temporal coincidence with the shifts seen in the sediment record and the anomalous wind conditions suggests a notable change of the currents through the Öresund (Figures 8, 9). The simulated currents through the Öresund confirm such an abrupt change characterized by a shift from very limited outflow from the Baltic to the Kattegat before ~1960 to more than a decade of high relative outflow (high VAV) from the Öresund to the Kattegat and high current velocities (Figure 8). While the simulation only covers the period after 1950, the analysis of wind conditions and the NAO index suggest that the anomalies in the current and sediment pattern from ~mid 1950's might have been unprecedented since at least the middle of the 19th century (Figure 9). The shift in local sediment properties and the shift to higher BFAR and species diversity suggest a combination of anomalous currents during a period of unusually negative NAO index and the abrupt first advection of anthropogenic eutrophication from the Baltic Sea towards the Kattegat. Consistent with our findings, long-term variations in Large Volume Changes in the Baltic Sea (LVC, Lehmann and Post 2015; Lehmann et al. 2017), which are calculated from >29 cm (~100 km^3) daily sea-level changes at Landsort (58.74° N; 17.87° E) for 1887–2015, show an unusual cluster of both, more frequent and also larger LVCs during the 1970's to 1980's relative to the entire time period. Notably, this period coincides with the most dramatic shift in foraminiferal BFAR and species diversity as well as an increase in sand content. The period before the "regime shift" of the 1950's to 1960's is dominated by very infrequent and few large LVC events. After the shift, the 1990's show also very few or partly no LVC events with generally record-low Major Baltic Inflow events.

Thus, during this period, the ecosystems were affected both by climatic effects through sedimentation changes, and human impact. At the end of the period, after ~1980, the general BFAR was lower during a short time (Figures 5, 9). This could be linked to the measures that were taken in agriculture and water treatments in order to reduce the nutrients discharge (Carstensen et al. 2006; Conley et al. 2007), which could have reduced the food input. Interestingly, when the sedimentation pattern changes again and the sand content decreases markedly (Figure 7), the new species in the foraminiferal fauna do not return to previous relative abundances as one could have expected (Figure 5A). This suggests that once the foraminiferal fauna was established in the Öresund area after the ~1953 shift, it created a new state of equilibrium.

5.4 1998 – 2009

The foraminiferal assemblage in this zone was similar to the previous one, with high BFAR, high diversity, and the *Elphidium* species as dominating species. This period is, however, characterized by the appearance of two new major species: *N. turgida* and *Nonionella* sp. T1. *Nonionella* sp. T1 is suggested to be an invasive species in the region which arrived by ship ballast tanks around 1985, and rapidly expanded to the Kattegat and Öresund (Polovodova Asteman and Schönfeld 2015). According to our dated core, the species arrived in the Öresund ~2000 CE (Figure 5). The species is also present on the south coast of Norway since ~2009 (Deldicq et al. 2019), but additional genetic analyses are necessary to have a better overview of the species' origin and expansion. *Nonionoides turgida* is an opportunistic species that prefers high levels of organic matter in the sediment, as observed in our core during this period (Figure 7). The increase in the *S. fusiformis* BFAR suggest lower [O_2] than in the previous zone, which was indeed a general trend in the Danish waters during this time period (Conley et al. 2007). The salinity was probably marine during this period, as suggested by the high occurrence of the marine species *B. marginata* (Figure 5). This period was then characterized by low [O_2], high organic matter content, and open ocean salinity.

5.5 2009 – 2013

The ability of *Nonionella* sp. T1 to denitrify and its tolerance to varying environment may explain its rapid increase during this period. The increase of *N. turgida* also suggests higher levels of organic matter in the sediment. The dominance of these two species and the lower BFAR compared to previous periods suggest low oxygen levels. This period is thus characterized by low [O_2], high organic matter content, and open ocean salinity.

5.6 Dissolution

The inner organic linings of the taxon *Ammonia* were observed (in low numbers, < 5 units) along the whole core, except in the top two centimeters (Figure 5). Inner organic linings of the taxa *Ammonia* and/or *Elphidium* were noticed in previous studies among dead fauna in the region (Jarke 1961; Hermelin 1987: Baltic Sea; Christiansen et al. 1996; Murray and Alve 1999: Kattegat and Skagerrak; Filipsson and Nordberg 2004b: Koljö Fjord). Dissolution of calcareous foraminiferal tests has been considered as a taphonomic process, affecting the test of the specimens after their death (Martin 1999; Berkeley et al. 2007). However, living decalcified foraminifera have been observed in their natural environment in the south Baltic Sea (Charrieau et al. 2018) and the Arcachon Bay, France (Cesbron et al. 2016) and, proving that test dissolution can also occur while the specimens live. In any case, low pH and low calcium carbonate saturation are suggested as involved in the observed dissolution (Jarke 1961; Christiansen et al. 1996; Murray and Alve 1999; Cesbron et al. 2016; Charrieau et al. 2018). Test dissolution may occur in all calcitic species, but only the organic linings of *Ammonia* were found in our study, probably because these were more robust to physical stress such as abrasion.

6 – Conclusion

In this study, we described an environmental record from the Öresund, based on benthic foraminifera – and geochemical data and we link the results with reconstructed wind data, NAO index and currents from a hydrodynamic model. Five foraminiferal zones were differentiated and associated with environmental changes in terms of salinity, [O_2], and organic matter content. The main event is a major shift in the foraminiferal assemblage ~1950, when the BFAR massively increased and *S. fusiformis* stopped dominating the assemblage. This period also corresponds to an increase in grain-size, resulting in a higher sand content. The grain-size distribution suggests changes in the current velocities which are confirmed by simulated current velocity through the Öresund. Human activities through increased eutrophication also influenced the foraminiferal fauna changes during this period. Organic linings of *Ammonia* were observed throughout the core, probably linked to low pH and calcium carbonate saturation, affecting test preservation.

The long-term reconstruction of sediment – and ecosystem parameters since ~1807 suggests that the onset of increased anthropogenic eutrophication of the eastern Kattegat started with an abrupt shift ~1960 during a period of strongly negative NAO index. With unusually calm wind conditions during the winter half and increased easterly winds, the conditions were ideal for larger Baltic outflow events which is a prerequisite for more frequent and stronger major Baltic inflow events (Lehmann et al. 2017), as calculated from LVC events during this period. Our high-resolution sediment record points towards the importance of considering also large Baltic outflow events for the Kattegat environment. Since the Baltic Sea is much more eutrophic, less oxygenated and less saline, large outflow events may have a significant impact also on the Kattegat ecosystem. Periods with a negative NAO or conditions with intense atmospheric blocking over Scandinavia like in 2018 may also increase the influence of Baltic Sea's environmental problems into the Kattegat region.

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Supplementary data

Appendix A, with time series of salinity, temperature and dissolved oxygen concentration at the bottom water of the Öresund, and Appendix B, with total foraminiferal faunas normalized to 50 cm^3 along the DV core, are available in the online version of the article.

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Figures

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Figure 2. CTD profiles of temperature, salinity, pH and dissolved oxygen concentration in the water column for the DV-1 station (modified from Charrieau et al. 2018).

Figure 3. Seasonal variability of salinity, temperature, pH and dissolved inorganic nitrogen (DIN) concentration at the surface water (light grey), and seasonal variability of salinity, temperature, pH and dissolved oxygen concentration at the bottom water (40-50 m) (dark grey) of the Öresund. The data were measured between 1965 and 2016 by the SMHI (Swedish Meteorological and Hydrological Institute) at the station W LANDSKRONA. The number of measurements is indicated for each month.

Figure 4. Age-depth calibration for the sediment sequence from the Öresund (DV-1). A) Total and supported ^{210}Pb activity. B) Unsupported ^{210}Pb activity and the associated age-model. C) ^{137}Cs activity. The peak corresponds to the Chernobyl reactor accident in 1986. D) Age-depth model for the whole sediment sequence based on ^{210}Pb dates and calculated sediment accumulation rates (SAR).

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Figure 6. Dendrogram produced by the cluster analysis based on the Morisita index and the UPGMA clustering method.

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Tables

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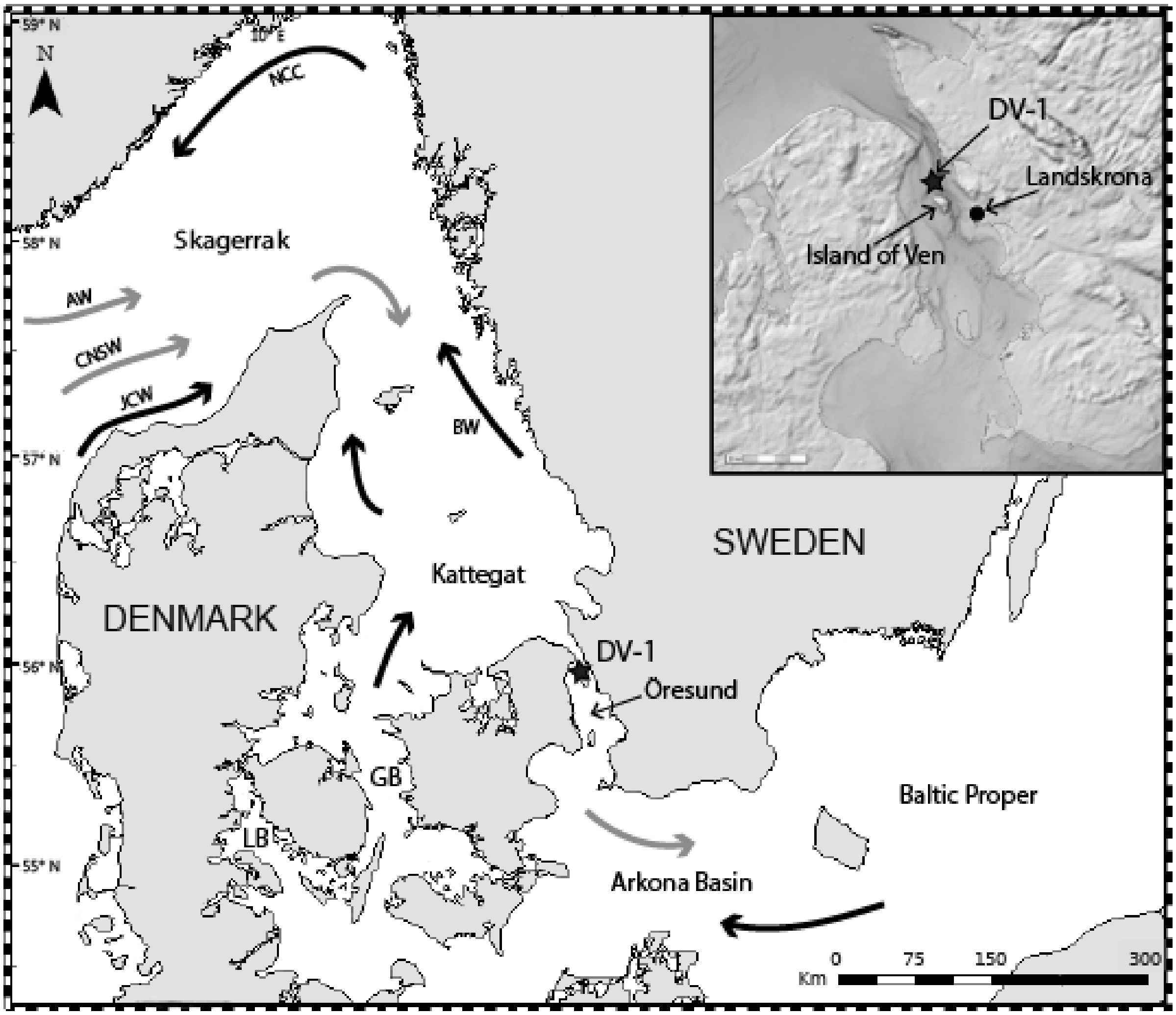
Table 2. Ecological significance of the benthic foraminiferal assemblages (major species).



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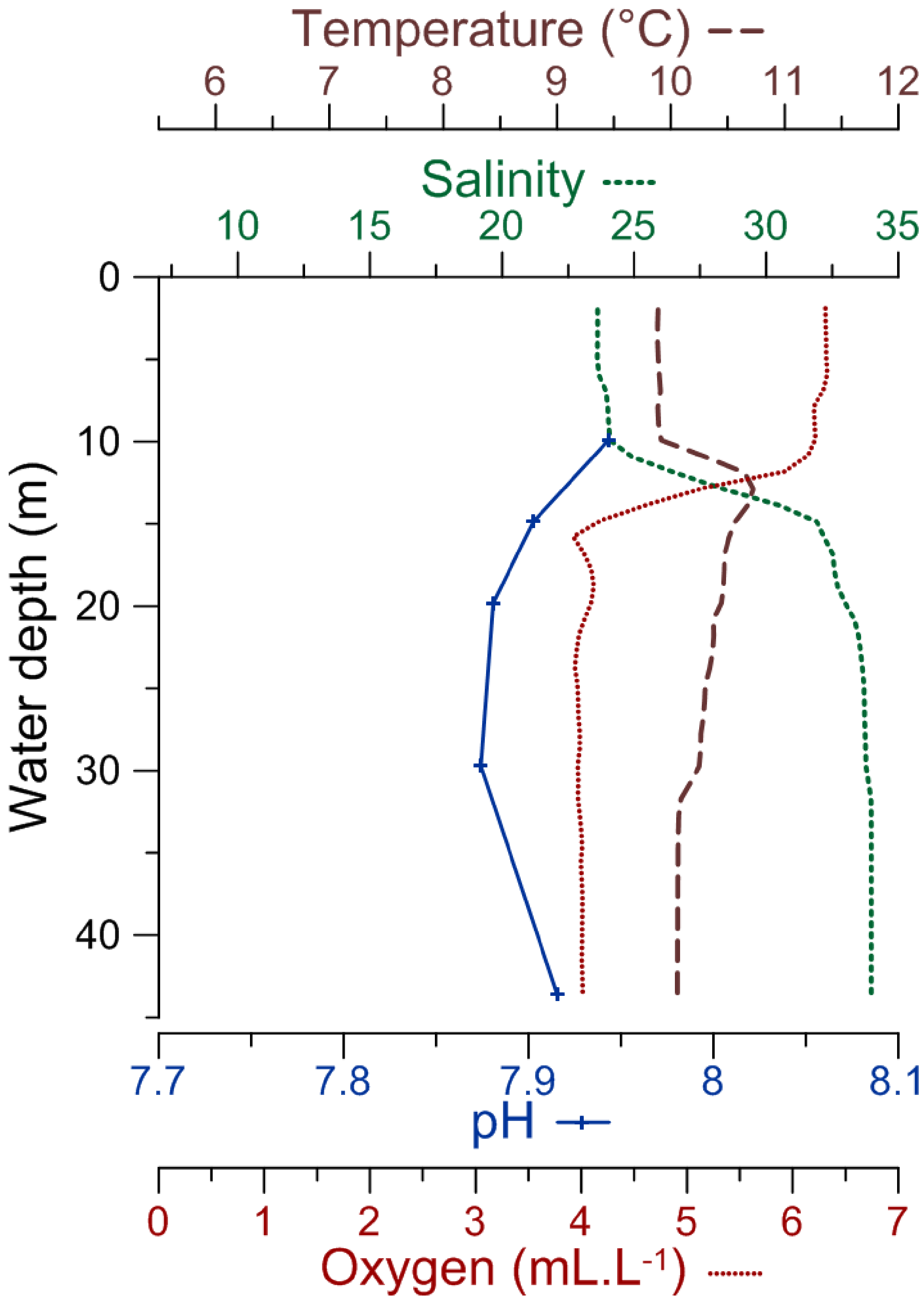

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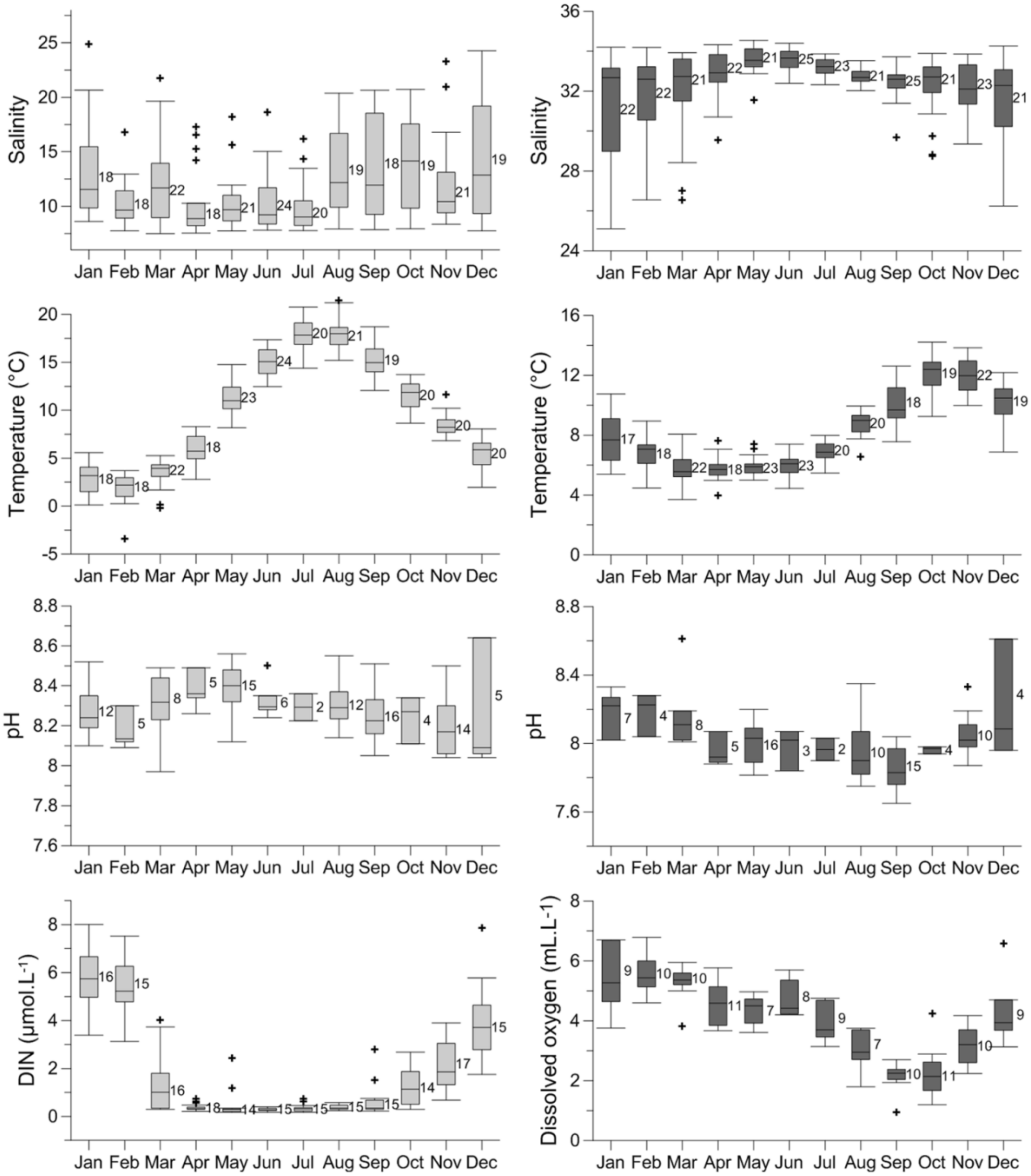

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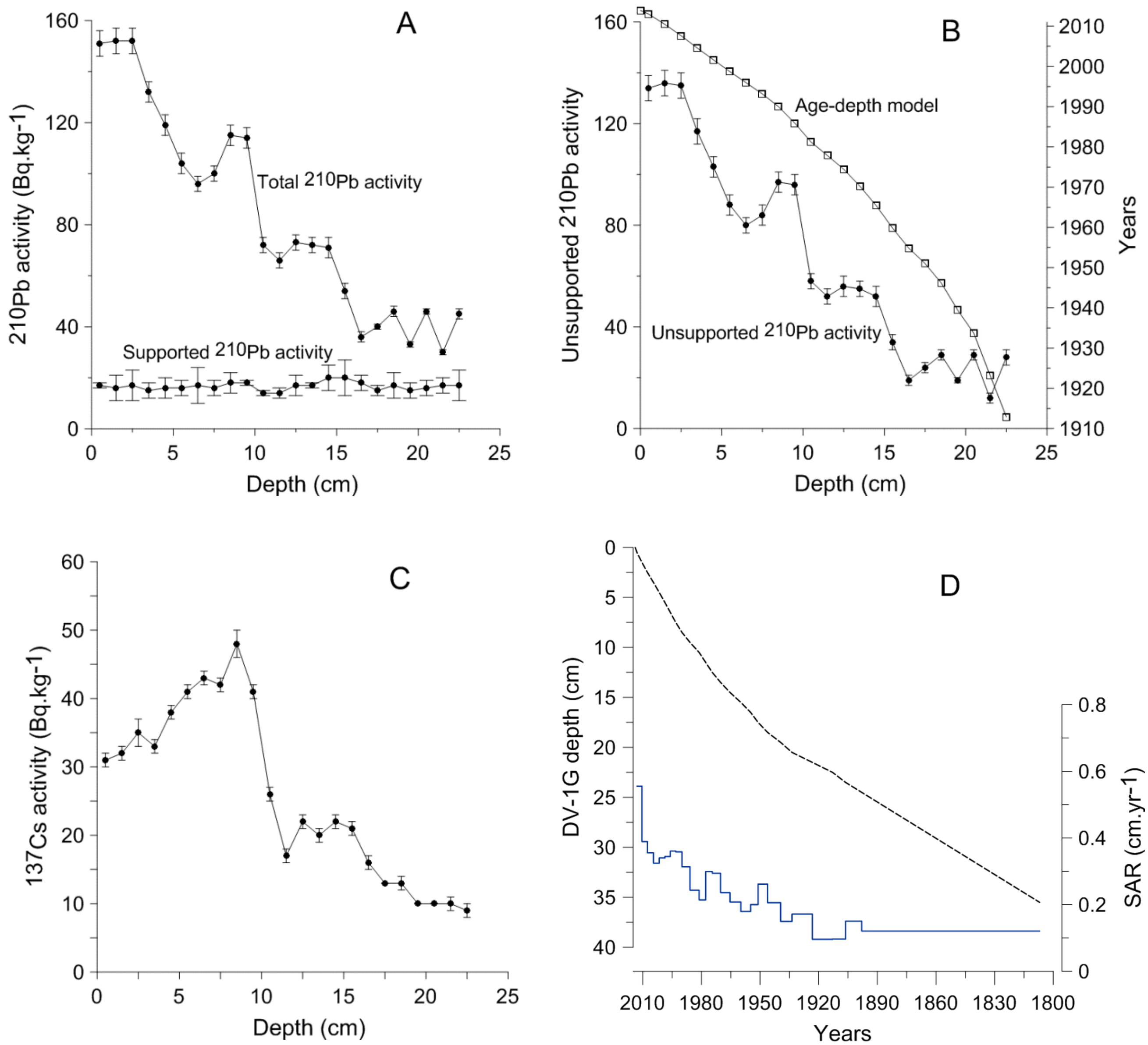

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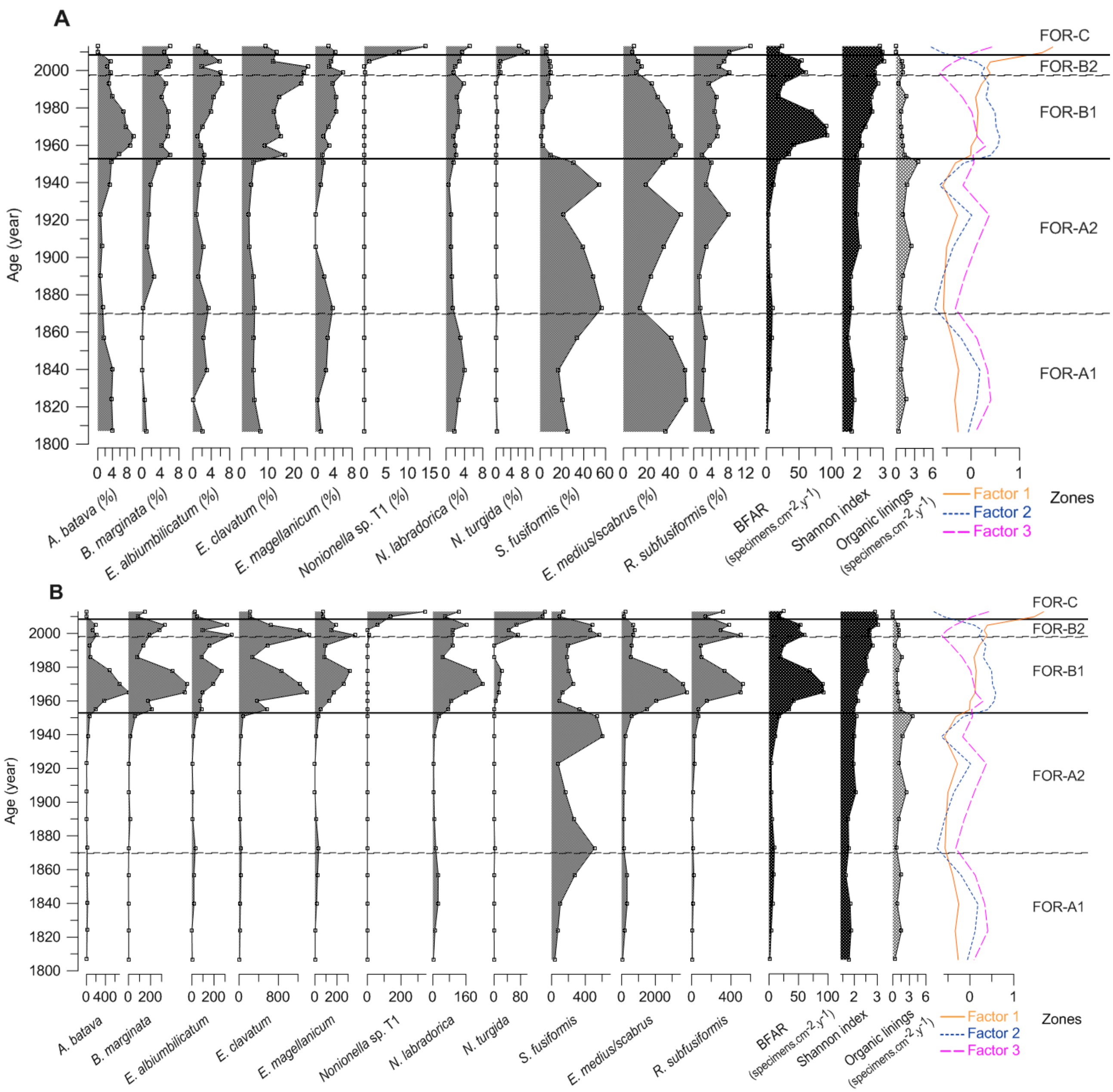

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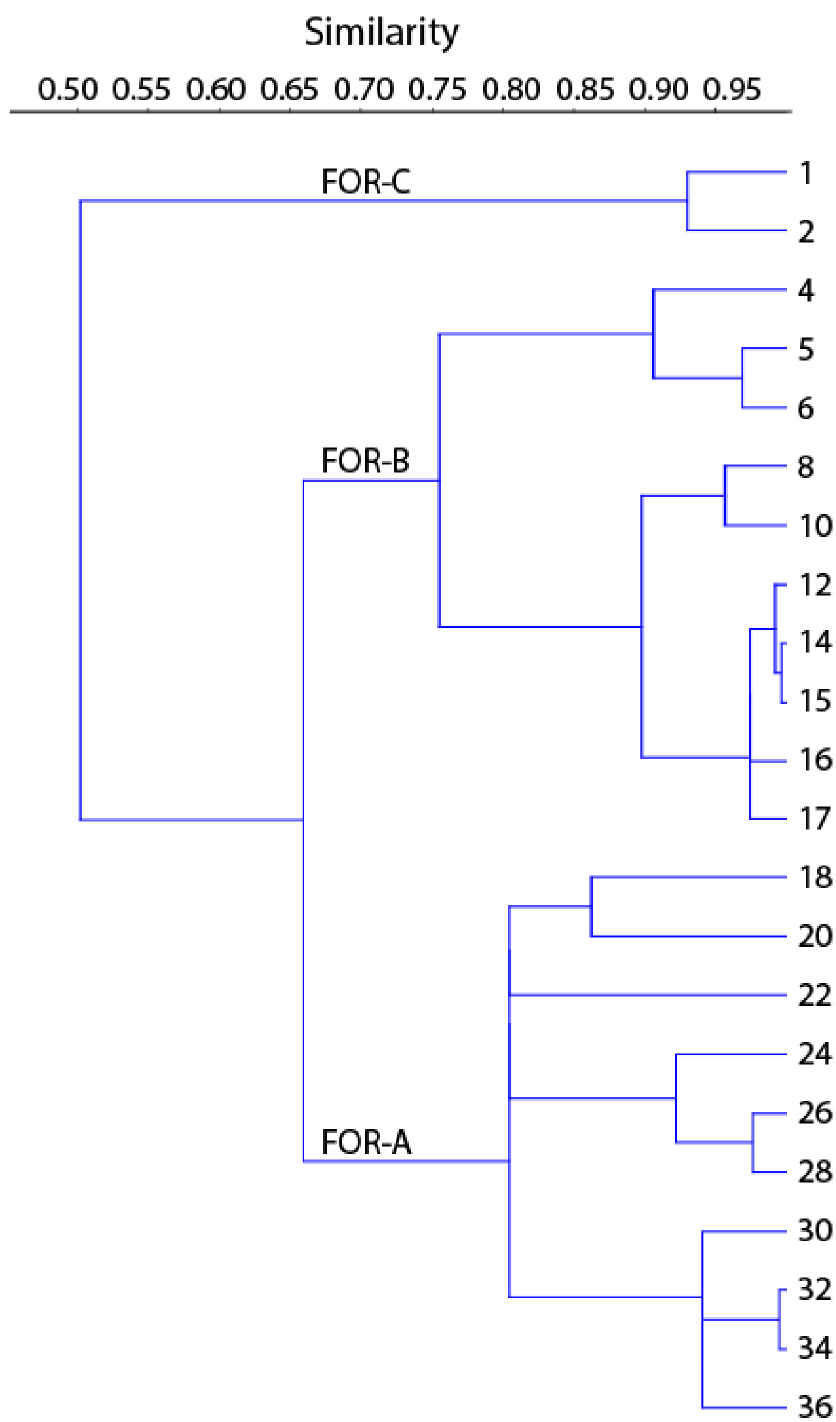

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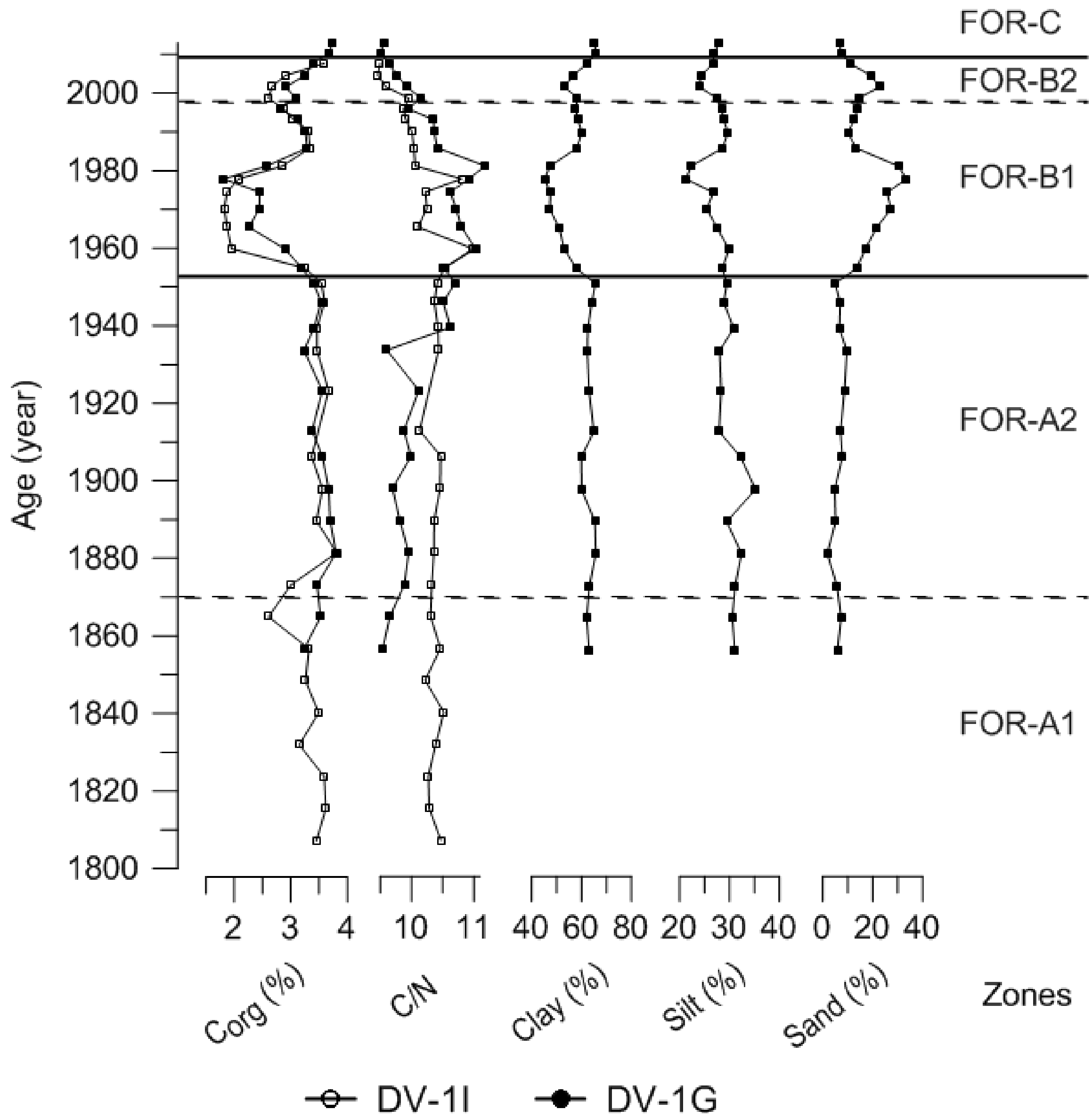

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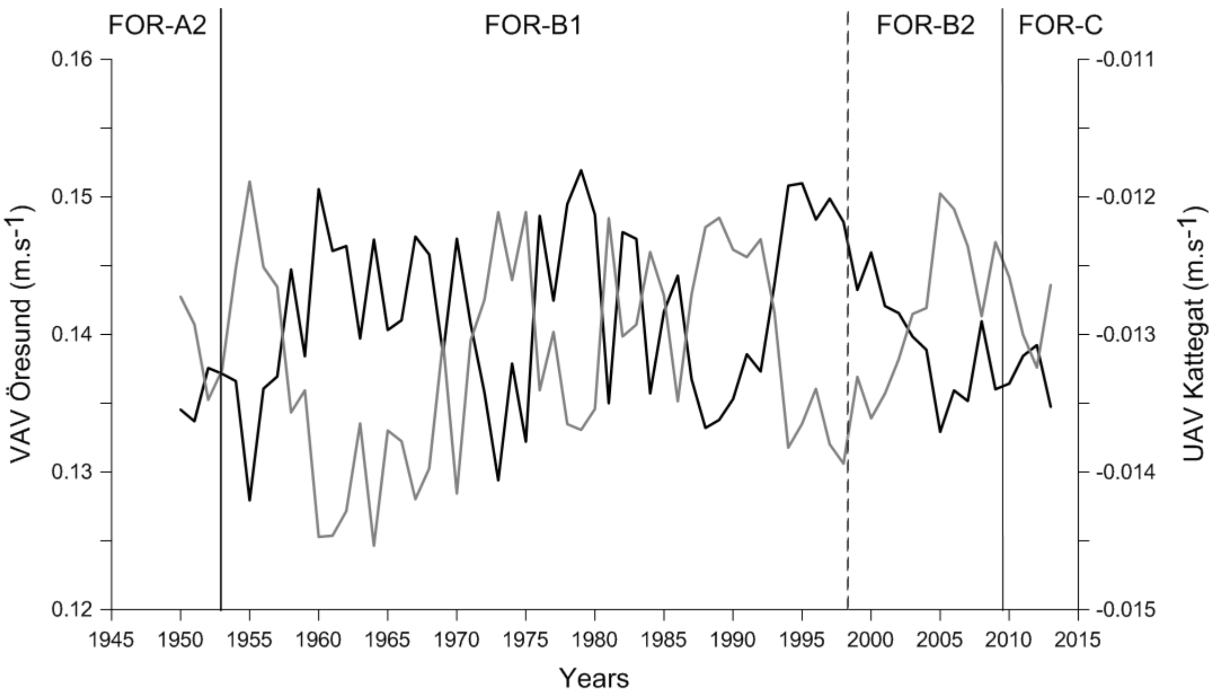

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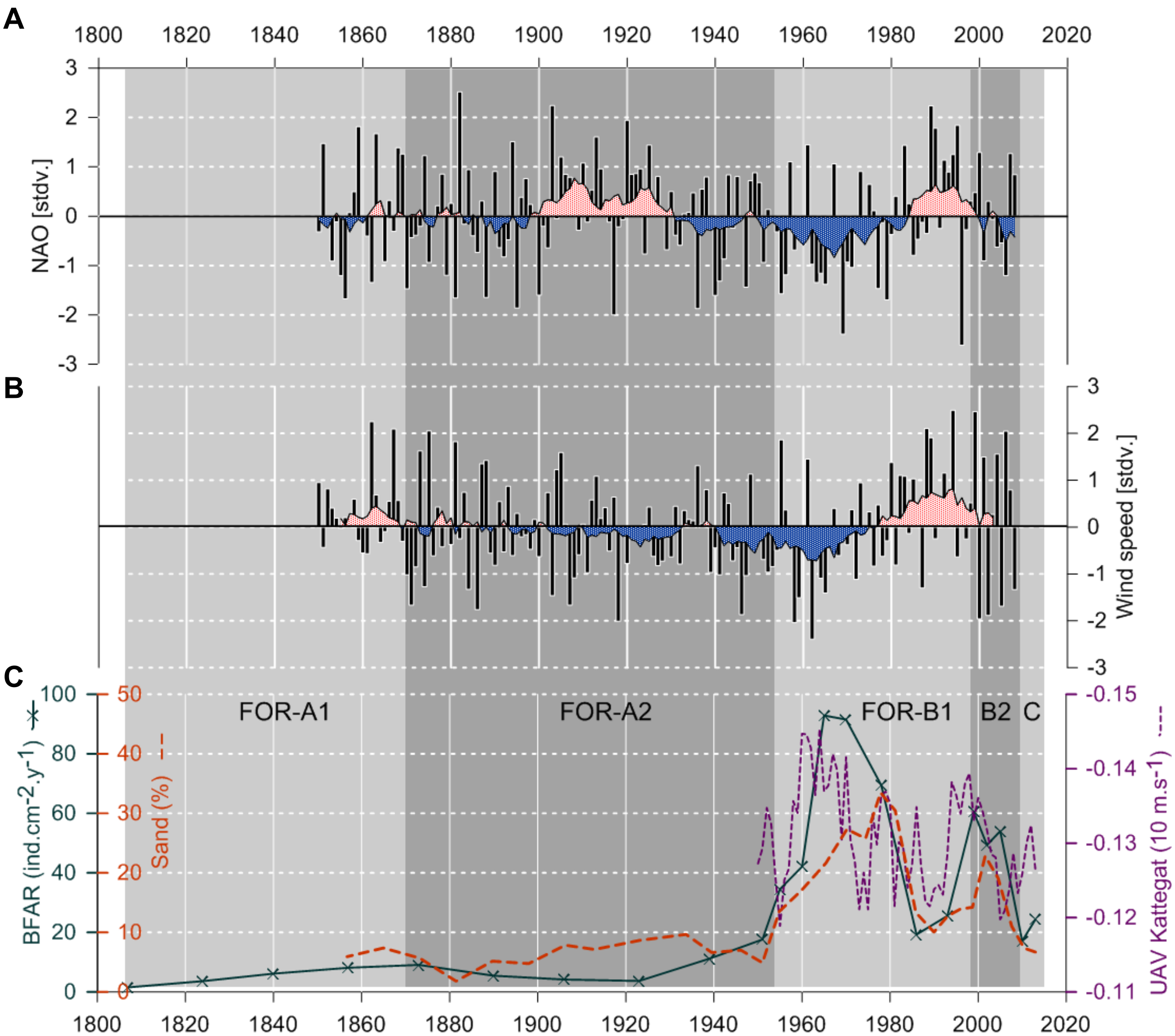

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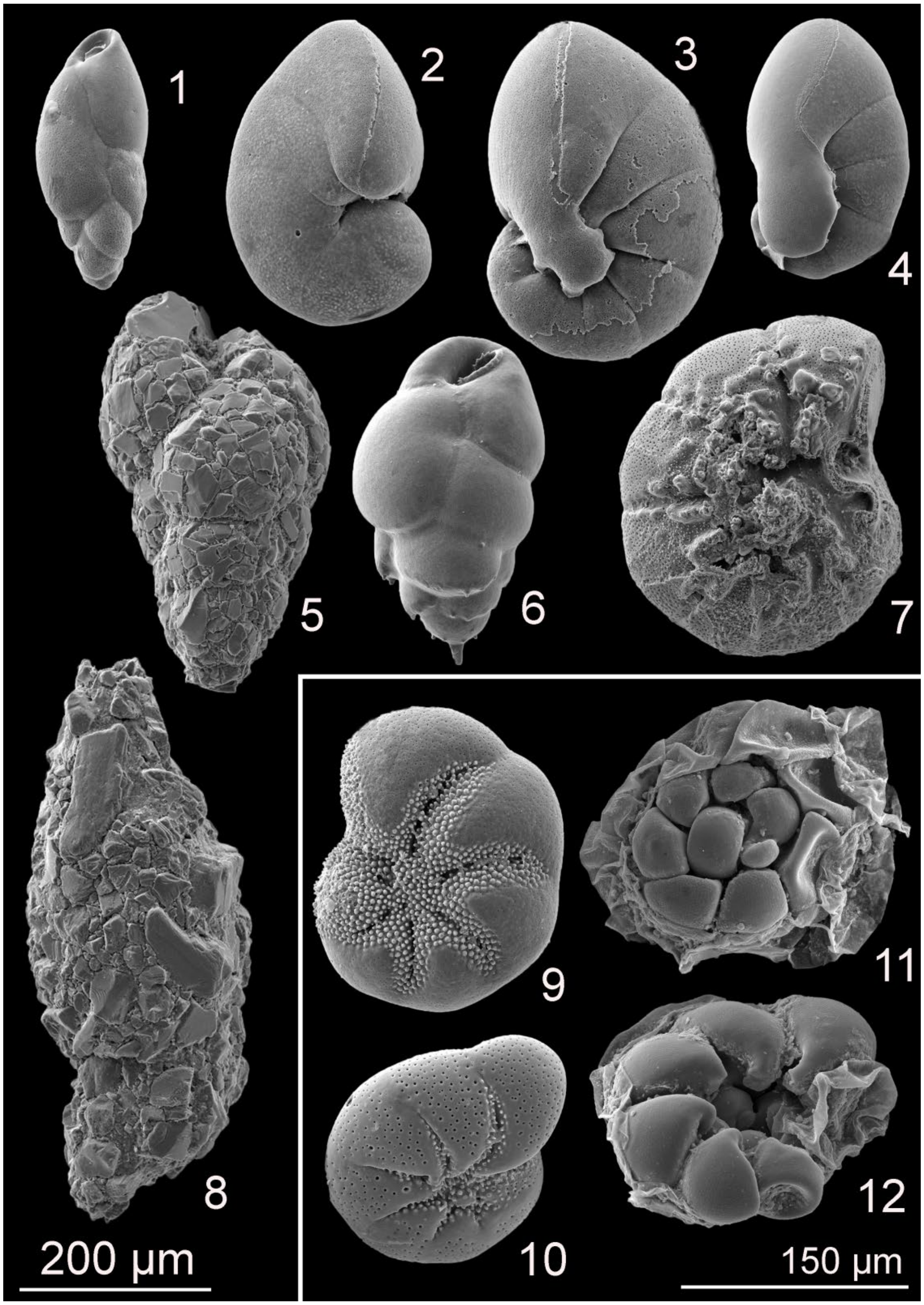

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Table 1. Significant foraminiferal species and scores according to the correspondence analysis.

Factor	Total variance (%)	Significant species	Score
1	48.18	*Nonionella* sp. T1	5.10
		Nonionoides turgida	4.14
2	30.88	*Ammonia batava*	1.34
		Stainforthia fusiformis	-1.41
3	13.36	*Elphidium albiumbilicatum*	-1.65
		Elphidium clavatum	-1.57
		Elphidium magellanicum	-1.32

Table 2. Ecological significance of the benthic foraminiferal assemblages (major species).

Species	Ecological significance	Reference
Ammonia batava	Salinity 15-35, T 0-29^{0}C, high tolerance to varying substrate and TOC	Alve and Murray (1999); Murray (2006)
Bulimina marginata	Tolerates low oxygen conditions, salinity 30-35, T 5-13^{0}C, muddy sand, prefers organic rich substrates	Conradsen (1993); Murray (2006)
Elphidium albiumbilicatum	Salinity 16-26, typical brackish species	Alve and Murray (1999)
Elphidium clavatum	Tolerates low oxygen conditions, salinity 10-35, T 0-7^{0}C, high tolerance to varying substrate and TOC, subtidal	Conradsen {Citation}(1993); Alve and Murray (1999); Murray (2006)
Elphidium magellanicum	Coastal species	Sen Gupta (1999)
Nonionella stella/aff. *stella*	Tolerates low oxygen conditions, kleptoplastidy, able of denitrification, invasive in the Skagerrak-Kattegat	Piña-Ochoa et al. (2010); Bernhard et al. (2012); Charrieau et al. (2018)
Nonionellina labradorica	Salinity >30, T 4-14^{0}C, high latitudes, kleptoplastidy, able of denitrification	Cedhagen (1991)
Nonionoides turgida	Opportunistic species, tolerates low oxygen conditions, prefers high food availability	Van der Zwaan and Jorissen (1991)
Stainforthia fusiformis	Opportunistic species, tolerates very low oxygen conditions, salinity >30, able of denitrification, prefers organic rich substrates, fast reproduction cycle	Alve (1994); Filipsson and Nordberg (2004); Piña-Ochoa et al. (2010)
Eggerelloides medius/scabrus	High tolerance to hypoxia, salinity 20-35, T 8-14^{0}C, sandy-muddy sand, tolerance to various kind of pollution	Alve and Murray (1999); Alve (1990); Murray (2006); Cesbron et al. (2016)
Reophax subfusiformis	Tolerance to environmental variations and fuel ash	Sen Gupta (1999)