Ecological Indicators 131 (2021) 108162

Contents lists available at ScienceDirect

Ecological Indicators

journal homepage: www.elsevier.com/locate/ecolind

Naturally changing reference conditions: Evidence of isostatic uplift being the main cause of changes in ecological status in a SW Norwegian fjord system

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ARTICLE INFO

Keywords:
Ecological quality status
Reference conditions
Natural changing environment
Water framework directive (WFD)
Benthic foraminifera

ABSTRACT

According to the European Water Framework Directive (WFD), restoration actions are needed if the present-day ecological quality status (EcoQS) is worse than good. However, less stringent environmental objectives may be allowed if the water body's natural condition is such that it may be unfeasible or unreasonably expensive to achieve good conditions.

In the Inner Skjolda- and Grindefjord, an isolated and shallow silled fjordsystem on the SW coast of Norway, the present EcoQS (based on benthic foraminifera and macroinvertebrates) is bad due to anoxic conditions in the bottom water. Paleoecological foraminiferal data in two dated sediment records were used to establish in situ reference conditions. The data revealed that the current bad EcoQS did not deviate from the natural reference condition which existed just prior to the onset of the industrial revolution. Further back in time, the record showed poor EcoQS and a strong dominance of the opportunistic foraminiferal species *Stainforthia fusiformis*, indicating unfavorable conditions for benthic foraminifera already >2000 years ago. The changing ecological status during the pre-industrial period was probably caused by the inner fjordsystem becoming gradually more isolated and stratified, and the bottom water more stagnant with decreasing oxygen concentrations, in response to isostatic uplift. Our study shows that reference conditions at a location may represent a natural succession of environmental changes i.e., the natural baseline does not have to represent only one environmental condition but may vary naturally over time. We therefore suggest that the conditions just prior to the onset of the industrial revolution should be used when defining reference conditions according to the WFD.

1. Introduction

The Norwegian coastline is about 83300 km long (Nesje, 2014) and divided into>1730 fjords (Kartverket, 2018). No fjords are alike. They all have their own characteristics, such as bathymetrical-, physical and chemical properties, different local or regional climate, and anthropogenic impact. This has complicated the work concerning typification and classification of Norwegian marine water bodies according to the European Water Framework Directive (WFD, 2000) standards, and resulted in challenges with intercalibration on a European scale. The WFD was adopted to protect, restore, and regulate European waters, and describes steps and common sets of intercalibrated quality criteria for defining ecological and chemical status (WFD, 2003). The objectives have been to characterize, classify, and assign an environmental goal for each European water body. When defining ecological status, emphasis has been put on "biological quality elements" with specific sensitivity to different environmental pressures. According to the WFD, restoration actions are needed to reinstate the reference condition if the present-day ecological quality status (EcoQS) significantly deviates from the reference conditions. Establishing the reference status is done by collecting biological information from reference sites in an equivalently low-impacted water body, by use of historical- or "palaeological" data, modelling, and in some cases through expert judgements (WFD, 2000, p. 27). Defining reference conditions is especially difficult for the water body types lacking credible natural reference sites (Nõges et al., 2009). However, paleoecological data on benthic foraminifera from dated sediment cores have successfully been applied to define in situ reference conditions in anthropogenically impacted Norwegian- and Swedish

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https://doi.org/10.1016/j.ecolind.2021.108162
Received 21 May 2021; Received in revised form 27 August 2021; Accepted 28 August 2021

fjord systems (e.g., Alve, 1991; Alve, 2000; Alve et al., 2009; Dolven et al., 2013; Polovodova Asteman et al., 2015), as well as globally, (e.g., Cearreta et al., 2002; Francescangeli et al., 2016; Hayward et al., 2004; Nikulina et al., 2008; Tsujimoto et al., 2006). Subfossil foraminifera have also been used to define reference conditions in naturally stressed areas (Barbieri et al., 2020; Hess et al., 2020) and as proxies for natural environmental developments in silled fjords caused by changing climate and shore-level displacement (Gustafsson and Nordberg, 2002). But, how to define the reference conditions according to the WFD for water bodies where the natural environment is continuously changing?

1.1. *Investigation area and aim of study*

This study was carried out in the Grindefjord and Inner Skjoldafjord (Fig. 1), located in Tysvær and Vindafjord municipalities in the Rogaland County, Norway. The two fjords are parts of an isolated inner fjord system connected through a long, narrow sound to the outer fjord system including the outer Skjoldafjord, the Hervikfjord, and the Boknafjord. At Skjoldastraumen, the water passage is partly blocked by a small island (Holmen; Fig. 1) and a shallow sill (2–3 m water depth) causing strong currents (= “straum” in Norwegian). To allow larger boats to pass through Skjoldastraumen, a 42 m long, 7 m wide and 3.5 m deep saltwater lock was constructed and opened in 1908 (Store norske leksikon, 2020). The lock is kept closed when not in use, and have therefore limited effect on the water exchange through Skjoldastraumen.

The long, narrow sound and shallow sill at Skjoldastraumen limit the water exchange between the inner and outer fjord systems. The maximum water depth is 95 m in the Grindefjord and 102 m in the Inner Skjoldafjord, with a 50 m sill in between. The drainage areas surrounding the fjords do not include any major rivers, only small rivers and streams. The water column is stratified with low saline water in the surface (upper 5–10 m) and more dense marine water masses below (Strøm, 1936). Data from 1972 (NIVA, 1973), 1986 (Stokland, 1987) and 1992-93 (Vea, 1994) have shown salinities between 10 and 19 in the upper 0–1 m, between 22 and 26 at 10 m water depth, and between 26 and 27 in the water column below 15 m water depth. Vertical mixing occurs but is not strong enough to influence and renew the deepest water masses. Limited tidal differences and currents, as well as reduced inflow of normal marine water from the outer fjord system has resulted in stagnant and hypoxic to anoxic conditions in the water masses below 20 m in the inner fjord system. Anoxic bottom water masses were observed already in 1935 (Strøm, 1936), and several later monitoring programs have confirmed these observations, with only small variations in the upper extension of the anoxic layer (NIVA, 1973; Birkeland, 2002; Sømme and Kaurin, 2013).

Most of the area around Boknafjord became ice free around 14000 yrs BP (years before present), at the end of the Weichselian glaciation (Anundsen, 1985; Paus, 1989). The postglacial rebound in Rogaland was smaller compared to many other areas in Norway as the down pressure of the ice on land had been weak (Prøsch-Danielsen, 2006). During the Late Weichselian and Holocene, the area experienced a complex shoreline displacement due to alternating transgressions and regressions, with the Late Weichselian (Younger Dryas age)- and the Tapes transgressions (ca. 6500 yrs BP) being the two most prominent sea level rises (Prøsch-Danielsen, 2006). Due to the dominance of isostatic uplift, early postglacial shore lines are today found far above the present sea-level in the area (Prøsch-Danielsen, 2006).

Archaeological evidence shows that people have been hunting,

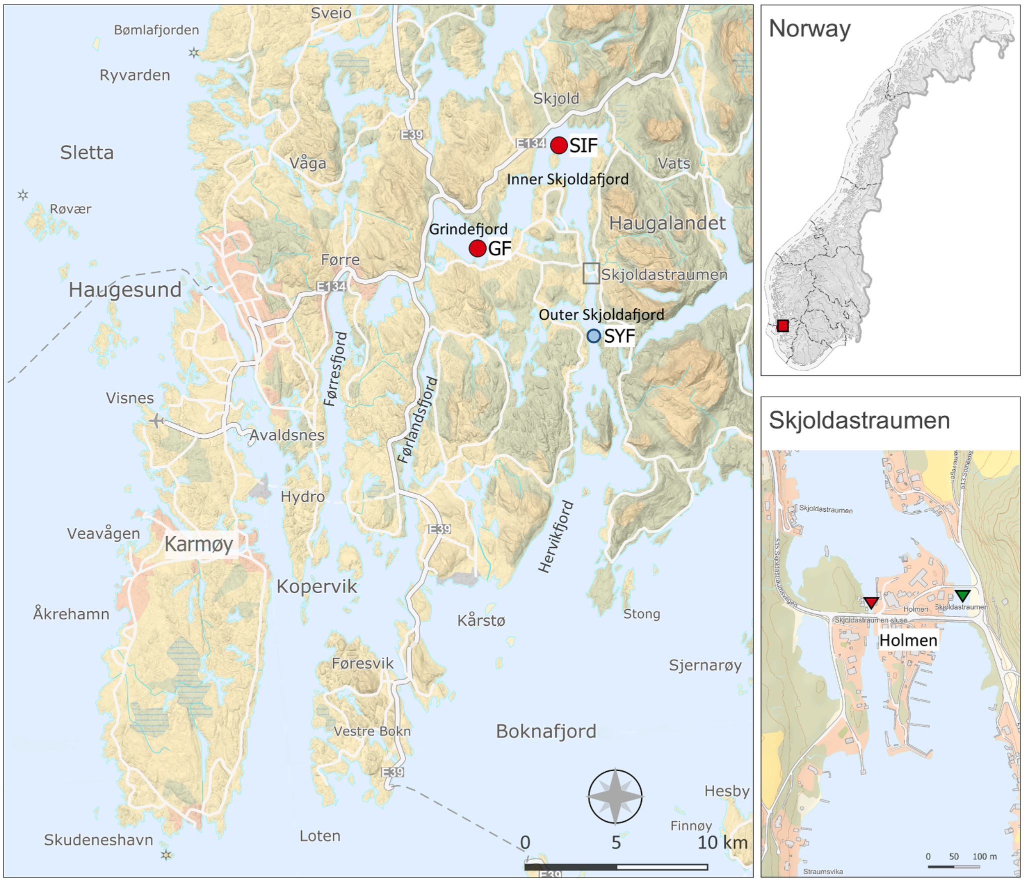

Fig. 1. The study area in the south-western part of Norway, showing the position of station GF in the Grindefjord and SIF in the Inner Skjoldafjord. The position of SYF in the Outer Skjoldafjord where hydrographical data were collected is also shown. The narrow sound in the Skjoldastraumen area is indicated by a grey box (enlarged map on the lower right). All maps are based on Statens kartverk (2007).

fishing, and gathering, in the area, in the vicinity of the changing shoreline, for>11000 years (Midtbø, 2011). However, from about 4000 calendar yrs BP the hunter-gathering way of living changed to become more sedentary, and the settlement became more permanent and stable (Olsen, 1995). Agropastoralism changed the settlement patterns to become more focused on inland sites and less on maritime resources (Prøsch-Danielsen, 2006). Some archaeological sites in the area indicate that a farming practice based on cattle where fodder from broadleaved trees was used, became increasingly important (Simonsen and Prøsch-Danielsen, 2005). Due to human impact, there was a slow transition from mixed oak-forest to birch-and-pine-forest (Midtbø, 2000; Simonsen and Prøsch-Danielsen, 2005). The deforestation expanded 2880–2000 yrs BP, gradually ending up with heathland and/or grassland, maintained by burning and grazing. The studies of former settlements, distinct raised beach ridges, marine shell layers, as well as litho-, pollen- and diatom- stratigraphy in old beach ridges or dated lake sediment cores have revealed in-depth information on the shore-level displacement history of the area (Prøsch-Danielsen, 2006).

Today, about 2250 people live around the Grindefjord and Inner Skjoldafjord. Heath- and grassland still constitute most of the cultural landscape with sheep being the most common livestock. Nutrients and organic matter from farming and wastewater are the main human impacting factors on the inner fjord systems (NIVA, 1973). The drainage area around the inner fjord system is about 160 km^2, and the water volume in the inner fjord system (inside Skjoldastraumen) is estimated to about 1040 million m^3 (NIVA, 1973). A simplified model has showed that the local anthropogenic impact on the fjord is limited (NIVA, 1973). Still there was a growing concern about the low oxygen conditions in the inner fjord system in the 1980s. This led to a test project in April 1992, performed by Rogalandsforskning supported by Norsk Hydro, pumping oxygen-rich air into the bottom water masses in a restricted part of the inner fjord system. Unfortunately, the oxygenation of the bottom water masses did not have any documented effect on improving the water quality, and the project was terminated after one year in operation (Vea, 1994).

With the implementations of the WFD, and the knowledge of oxygen depleted water masses and the bad ecological status (based on benthic macroinvertebrates) in the Grindefjord and Inner Skjoldafjord (Sømme and Kaurin, 2013), the need for information about the in situ reference conditions arose. The aims of the study have therefore been to find out: How and when did the bad environmental conditions evolve? Is the ecological status in the inner fjord system deviating from the natural reference condition? Are the present-day oxygen depleted conditions caused by human impact, or are there other influencing factors impacting on the inner fjord system?

The present study tries to find answers to the above questions by investigating benthic foraminifera (protists) and supporting parameters (e.g. metals and organic matter content) in dated sediment cores from the Grindefjord and Inner Skjoldafjord.

2. Materials and methods

Sediment samples were collected from the deepest basins in the Grindefjord (GF) and the Inner Skjoldafjord (SIF) in early August 2019 (Fig. 1 and Table 1) onboard the boat "Scallop" owned by Kvitsøy Sjøtjenester. Eight sediment cores were collected at each station using a twin-barreled Gemini gravity corer (inner diameter 8 cm, modified from Niemistö, 1974). For the down-core studies two cores were chosen at each site to obtain enough material for analyses and dating. Each core was divided into 1 cm thick slices between 0 and 20 cm and 2 cm think slices thereafter. All sub-samples were freeze dried at the University of Oslo, wet- and dry-weighed, and the water content was calculated to correlate the two cores from the same site. Three additional cores were sampled for living foraminifera (see description below). The remaining cores were extruded on deck, vertically split in two halves, and described and photographed to get a lithological description of the sediment profile.

Table 1
Coordinates (WGS 84, decimal degrees) and water depth (m) at investigated stations in the Grindefjord and inner Skjoldafjord. *Position of the hydrographical station in the outer Skjoldafjord.

Station	Area	North	East	Water depth	Core length (cm)
GF	Grindefjord	59.43835	5.51046	95 m	64 cm (GF-1)/ 68 cm (GF-2)
SIF	Inner Skjoldafjord	59.49116	5.58393	102 m	66 cm (SIF-1)/ 62 cm (SIF-2)
SYF*	Outer Skjoldafjord	59.39819	5.62695	58 m	

Subsamples of about 2 g of dried sediment from each slice in the main cores (GF-1 and SIF-1) were sent to Liverpool University Environmental Radioactivity Research Centre (ERRC, England) for radiometric (^{210}Pb, ^{226}Ra, ^{137}C) dating. The sub-samples from each core were analyzed (by P. Appleby and G.T. Piliposian) for ^{210}Pb, ^{226}Ra, ^{137}Cs, and ^{241}Am by direct gamma assay, using Ortec HPGe GWL series well-type coaxial low background intrinsic germanium detectors (Appleby et al. 1986). Content of ^{210}Pb was determined via its gamma emissions at 46.5 keV, and ^{226}Ra by the 295 keV and 352 keV ɣ-rays emitted by its daughter radionuclide ^{214}Pb following 3 weeks storage in sealed containers to allow radioactive equilibration. Radionuclides ^{137}Cs and ^{241}Am were measured by their emissions at 662 keV and 59.5 keV, respectively. The absolute efficiencies of the detectors were determined using calibrated sources and sediment samples of known activity. Corrections were made for the effect of self-absorption of low energy ɣ-rays within the sample (Appleby et al. 1992). Best chronologies for each core were determined following an assessment of all the data using the methods outlined in Appleby (2001).

Calcium carbonate, in the form of foraminifera-shells or bivalves, from two subsamples in the lower part of each of the two main cores (GF-1 and SIF-1) were ^{14}C-dated at the MICADAS-lab at Alfred Wegener Institute (Germany). The ^{14}C-dates (Stuiver and Polach, 1977; Stuiver et al. 1998) were calibrated with IntCal20, a newly developed curve for the northern hemisphere (Heaton et al., 2020).

About 2 g of dry sediment were analysed for total organic carbon (TOC, %), total nitrogen (TN, %) and δ^{13}C (‰). Due to the semiliquid nature of the sediment in the GF-1 and SIF-1, core top samples provided only a very small weight of dry sediment. Selected samples from the uppermost 0–18 cm of the twin-cores (GF-2 and SIF-2, respectively) were used instead. All samples were analyzed using an Elemental Analyzer–Isotope Ratio Mass Spectrometry (EA-IRMS) at the ISO-Analytical Ltd. stable isotope analysis laboratory in Crewe, UK. Selected samples were analyzed twice to check the accuracy of the measurement. All data are plotted in the result-figures (including measured values for the check samples). The measurement uncertainties were ± 0.3 % for TOC, ± 0.014 % for N, and ± 0,03 ‰ for δ^{13}C.

About 2 g, from selected slices in GF-1 and SIF-1, were used for the analyses of lead, zinc, and mercury at the accredited lab Eurofins Environment Testing Norway AS using Inductively Coupled Plastma-Mass Spectrometry (ICP-MS) and the following standards SS28311: 2017mod/SS-EN ISO 17294:2016. The measurement uncertainties were 25 % for lead and zinc, and 20 % for mercury. Lead and mercury are priority substances (WFD 2000 Annex X emended in Directive 2013/39/EU) used to define the chemical status of a water body, while Zn is included among regionally or locally important pollutants (Specific substances, Annex VIII in WFD 2000). Therefore, only lead and mercury were classified according to the environmental quality standards (EQS), i.e. AA-EQS in Veileder 02 (2018).

Biotic indices (ES_{100}, H_{log2} and NQI_f) based on foraminiferal assemblage data from the dated cores were used to assess the in situ paleo-EcoQS and the normalized Ecological Quality Ratio (nEQR).

For the foraminiferal analyses 1.5–2 g of dry sediment from selected subsamples were washed through a 63 µm sieve. When possible, about 300 foraminiferal specimens from the > 63 µm fraction were picked, mounted on microfossil slides, identified to species level, and counted. 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 sensitivity index $AMBI_f$ and multi-metric Norwegian Quality Index (NQI_f) were calculated according to Alve et al. (2016). The nEQR was calculated according to the formula presented in Hess et al. (2020). The class boundaries for each index are presented in Table 2.

At each station, 3 replicate surface sediment samples (0–1 cm) were collected and preserved in > 70 % ethanol stained with rose Bengal (rB) (Schönfeld et al., 2012). The samples were wet-sieved to identify and count living (rB stained) individuals > 63 µm. The entire sample > 63 µm from each replicate was studied (i.e. no sample splitting was performed).

During the sampling campaign, hydrographical parameters (temperature, salinity, and dissolved oxygen) were measured throughout the water column at the two stations GF and SIF by use of a CTD, i.e. a SAIV SD208 sonde with an optical oxygen sensor (RINKO-III ARO-CAV). One station (SYF) from the outer Skjoldafjord was also measured to assess differences in hydrographical conditions between the inner and outer fjord systems.

3. Results

3.1. Hydrographical data

The hydrographical data from GF and SIF showed almost identical measurements for density, salinity, temperature, and oxygen throughout the water column in the inner fjord system (Fig. 2). The pycnocline was found between ca. 2 m and 6 m in the inner fjord system (GF and SIF; Fig. 2). The salinity increased from about 19.5 in the surface water (0–2 m) to about 24 at 5 m, and from there it slowly increased to 26.7 toward the bottom (100 m water depth). The temperature rapidly decreased from 21 °C in the surface to ca. 10 °C at 10 m water depth. Below 10 m the temperature decreased and stabilized around 8.8 °C (below 45 m). The oxygen concentration dropped rapidly from a maximum (>6 ml/l) in the surface water to under the detection limit (0.06 ml/l) below 18 m.

In the outer fjord system (SYF; Fig. 2), the salinity quickly increased from 24 in the surface to ca. 31 at 7 m water depth and remained stable between 7 and 23 m. Below 23 m the salinity once again increased rapidly to 34.2 at 28 m water depth. It remained stable around 32.4 below 28 m. The temperature was 19.7 °C in surface water (i.e. the upper 1.5 m), and gradually dropped 11.6 °C between 1.5 and 27 m. From 28 m and below the temperature remained stable at 8.1 °C. The oxygen concentrations were relatively stable around 5.7 ml/l in the upper part of the water column (between 0 and 25 m). Between 25 m and 30 m it rapidly dropped and stabilized around 4.5 ml/l in the lowermost part of the water column (below 30 m).

Table 2
Classification system for biotic indices and oxygen based on Alve et al. (2019) and Veileder 02 (2018).

Biotic indices and oxygen	Classification status				
	I High	II Good	II Moderat	IV Poor	V Bad
ES_{100}	35–18	18–13	13–11	11–9	9–0
H'($\log_2$)	5–3.4	3.4–2.4	2.4–1.8	1.8–1.2	1.2–0
NQI-f	1–0.54	0.54–0.45	0.45–0.31	0.31–0.13	0.13–0
nEQR	1–0.8	0.8–0.6	0.6–0.4	0.4–0.2	0.2–0
O_2 (ml/l)	>4.5	4.5–3.5	3.5–2.5	2.5–1.5	< 1.5

3.2. Sediment characteristics

The two studied sediment cores (GF-1 and GF-2) from the Grindefjord were 64 and 68 cm, respectively, while the two cores (SIF-1 and SIF-2) from the Inner Skjoldafjord were 66 and 62 cm, respectively. Additional replicate cores collected and split on deck in the field, revealed changes in colors and texture (Appendix 1).

In the Grindefjord core the sediments below ca. 50 cm were brownish, relatively homogeneous, and with an increasing water content from 75 to 80 % (in the lowermost parts) to about 90 % just below 50 cm core depth. Between 50 and 15 cm the sediments were dark grey mud with 84–91 % water-content. White laminas were present in the otherwise dark sediments. The upper 15 cm consisted of black, H_2S-smelly mud with a very high (>95 %) water-content (Appendix 1).

The two split cores from the Inner Skjoldafjord both showed brownish colored sediments below 55 cm. From 55 cm and up to about 15 cm the sediments became gradually darker grey. One of the split cores revealed the same thin white laminas as in the Grindefjord cores. The upper 15 cm of the Inner Skjoldafjord core consisted of black mud with a water-content close to 95 % and a characteristic H_2S smell (Appendix 1).

3.3. Core chronologies

Core GF-1 from the Grindefjord and core SIF-1from the Inner Skjoldafjord, were radiometrically dated back to the mid-1800 s at 18.5 cm and 21 cm, respectively (Tables 3 and 4; Appendix 2).

In the Grindefjord core GF-1 two distinct peaks of ^{137}Cs occurred i.e., one at 9–10 cm probably due to the 1986 Chernobyl accident, and one between 12 and 14 cm corresponding to the atmospheric testing of nuclear weapons. The latter interpretation was supported by a peak in ^{241}Am at the same depth (Appleby et al., 1992). The ^{210}Pb dates were calculated (Appleby and Piliposian, Appendix 2) using the CRS model which placed the 1986-event within the 8–9 cm sample and the 1963-event within the 12–13 cm which was in reasonable agreement with the ^{137}Cs/^{241}Am record (Fig. 3). A small correction of the ^{210}Pb dates were made using the ^{137}Cs dates as reference points.

In the Inner Skjoldafjord core two distinct peaks of ^{137}Cs were found i.e., one between 8 and 10 cm corresponding to the 1986 Chernobyl accident, and one at 12–14 cm related to the atmospheric testing of nuclear weapons. Using the CRS model, Appleby calculated the ^{210}Pb date for the 1986-event at approximately 10 cm and the 1963-event around 14 cm which was in good agreement with the ^{137}Cs/^{241}Am record (Fig. 3). A small correction of the ^{210}Pb dates were made using the 1963 ^{137}Cs date as reference point.

The ^{14}C-datings of bivalves or bulk foraminifera in two core samples from each of GF-1 and SIF-1 are shown in Table 5. Corresponding calibrated years BP (found in IntCal20) as well as CE/BCE-dates are also presented. The bulk-foraminifera based ^{14}C-dating has a 4 times higher uncertainty than the bivalve based ^{14}C-dating (i.e. ± 79 yrs and ± 22 yrs respectively).

Ages between datum points in the upper part of the cores (0–18.5 cm for GF and 0–21 cm for SIF) were calculated by interpolation between ^{210}Pb-dates. To get an idea of approximate ages for the sediment samples in the middle part of the cores, an interpolation was performed between the lowermost dated ^{210}Pb-sample and the uppermost dated bivalve based ^{14}C sample in each core (i.e. samples 21 cm and 50–52 cm in GF and samples 18.5 and 56–56 cm in SIF) using calendar years. Interpolation between the two ^{14}C-datum points (using calendar yrs) in each core were done to get an indication of ages of sediment samples between 52 and 62 cm in GF and between 56 and 64 cm in SIF.

3.4. Geochemical parameters

Below 25 cm, the concentrations of lead (Pb), mercury (Hg), and zinc (Zn) were low, corresponding to background values representing good

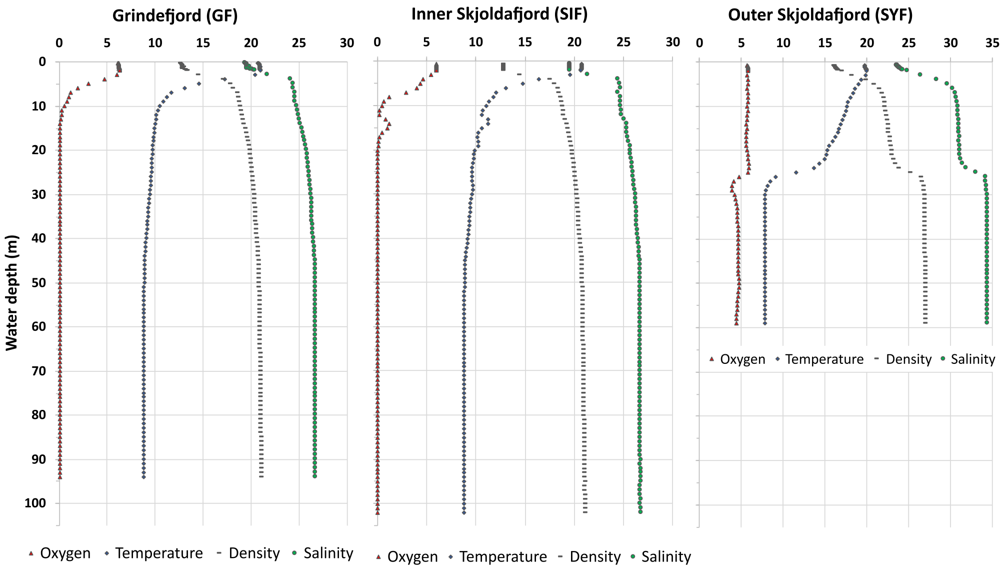

Fig. 2. Hydrographical profiles through the water column in the Grindefjord (GF), the Inner Skjoldafjord (SIF) and the outer Skjoldafjord (SYF) showing oxygen (ml/l), temperature (°C), density (sigma-T = kg/m^3-1000) and salinity (ppt). Data collected in August 2019.

Table 3
Age model (sediment depths, ages, and sediment accumulation rates) in GF-1 from the Grindefjord based on lead (^{210}Pb)- and cesium (^{137}Cs) dates (Appleby and Piliposian; Appendix 2).

Depth	Chronology GF1			Sediment accumulation rates	
cm	Data AD	years	±	g cm-2 y-1	± (%)
0	2019	0	0		
0.5	2017	2	2	0.017	3.9
2.5	2012	7	2	0.016	5.2
4.5	2005	14	2	0.013	5.4
6.5	1997	22	2	0.013	6.9
7.5	1993	26	2	0.015	6.9
8.5	1990	29	2	0.014	8.2
9.5	1986	33	3	0.013	8.7
10.5	1982	37	3	0.011	10.1
11.5	1976	43	3	0.0085	10.3
12.5	1968	51	3	0.0068	12.4
13.5	1957	62	4	0.0056	14.3
14.5	1944	75	5	0.0056	14.3
16.5	1909	110	8	0.0056	14.3
18.5	1866	153	14	0.0056	14.3

Table 4
Age model (sediment depths, ages, and sediment accumulation rates) in SIF-1 from the inner Skjoldafjord based on lead (^{210}Pb)- and cesium (^{137}Cs) dates (Appleby and Piliposian; Appendix 2).

Depth	Chronology SIF-1			Sediment accumulation rates	
cm	Data AD	years	±	g cm-2 y-1	±(%)
0	2019	0	0		
0.5	2018	1	2	0.022	5.5
2.5	2014	5	2	0.018	4.8
4.5	2007	12	2	0.013	4.9
6.5	1999	20	2	0.012	5.3
7.5	1994	25	2	0.012	6.2
8.5	1990	29	2	0.011	6.9
9.5	1985	34	2	0.011	7.4
10.5	1980	39	3	0.012	8.7
11.5	1975	44	3	0.011	9.5
12.5	1968	51	4	0.0092	11
13.5	1959	60	4	0.0088	10.8
14.5	1949	70	5	0.0088	10.8
16.5	1923	96	6	0.0088	10.8
18.5	1893	126	9	0.0088	10.8
21	1857	162	13	0.0088	10.8

status in both GF and SIF (Fig. 4). From 25 cm and up, the concentrations increased reaching maximums values at around 14–16 cm depth in both cores. Peak concentrations of Pb corresponded to bad chemical status (Veileder 02, 2018). Hg reflected good chemical status throughout the core. Above the peaks the concentration gradually decreased in both cores reaching background levels in the uppermost samples (0–1 cm).

The total organic carbon (TOC) content below 30 cm core depth varied mainly between 8 and 12 % in GF and 8 and 10 % in SIF (Fig. 5). Above 30 cm the TOC concentration increased to a peak (15 %) at 18–19 cm. From the peak and upwards the amount of TOC gradually decreased reaching about 4 % in the upper sample (0–1 cm). Below 30 cm the TOC/TN-ratio (from now termed C/N) was relatively stable around 9 in both cores. From 30 cm and upwards the ratio increased and reached a maximum of 12 in GF and 14 in SIF at around 18–19 cm. Above this the ratio gradually decreased ending at 6 in GF and 8 in SIF in the surface sediment (0–1 cm). The C/N-ratio in the lowermost sample in GF-1 is considered an artefact (not included in Fig. 8). Below 30 cm, the δ^{13}C values showed background levels of –23 ‰ and −24 ‰, the values got more negative up-core to 18–19 cm where the values peaked between −25.5 ‰ and −26 ‰, and reached values of −25 ‰ to −25.5 ‰ in the surface sediments at both stations (Fig. 5).

3.5. Fossil and living (stained) foraminiferal assemblages

The fossil foraminiferal content in nine sediment samples from the GF-1 core and ten samples from the SIF-1 core, revealed a total of 46 different species (33 in GF-1 and 35 in SIF-1). The faunas (in both cores) were dominated by calcareous species (ca. 98 %). The most common species in GF-1 were *Stainforthia fusiformis* (Williamson, 1858) with 71.7 %, *Elphidium albiumbilicatum* (Weiss, 1954) with 7.8 %, *Elphidium margaritaceum* Cushman (1930) with 3.4 %, and *Bulimina marginata* (d'Orbigny, 1826) with 2.6%. In SIF-1 the most common species were *S. fusiformis* with 73.7 %, *E. albiumbilicatum* with 7.8 %, *Elphidium excavatum* (Terquem, 1875) with 2.7 % and *B. marginata* with 2.6 %.

The number of foraminiferal tests pr gram dry sediment rapidly decreased from 940 at 63 cm core depth to 142 at 53 cm in GF-1, and from 1464 at 65 cm to 197 at 55 cm in SIF-1 (Fig. 6; Appendix 3). The number of species in the same samples were reduced from 26 to 14 in GF-1 and 22 to 9 in SIF-1. In both the Grindefjord (GF-1) and

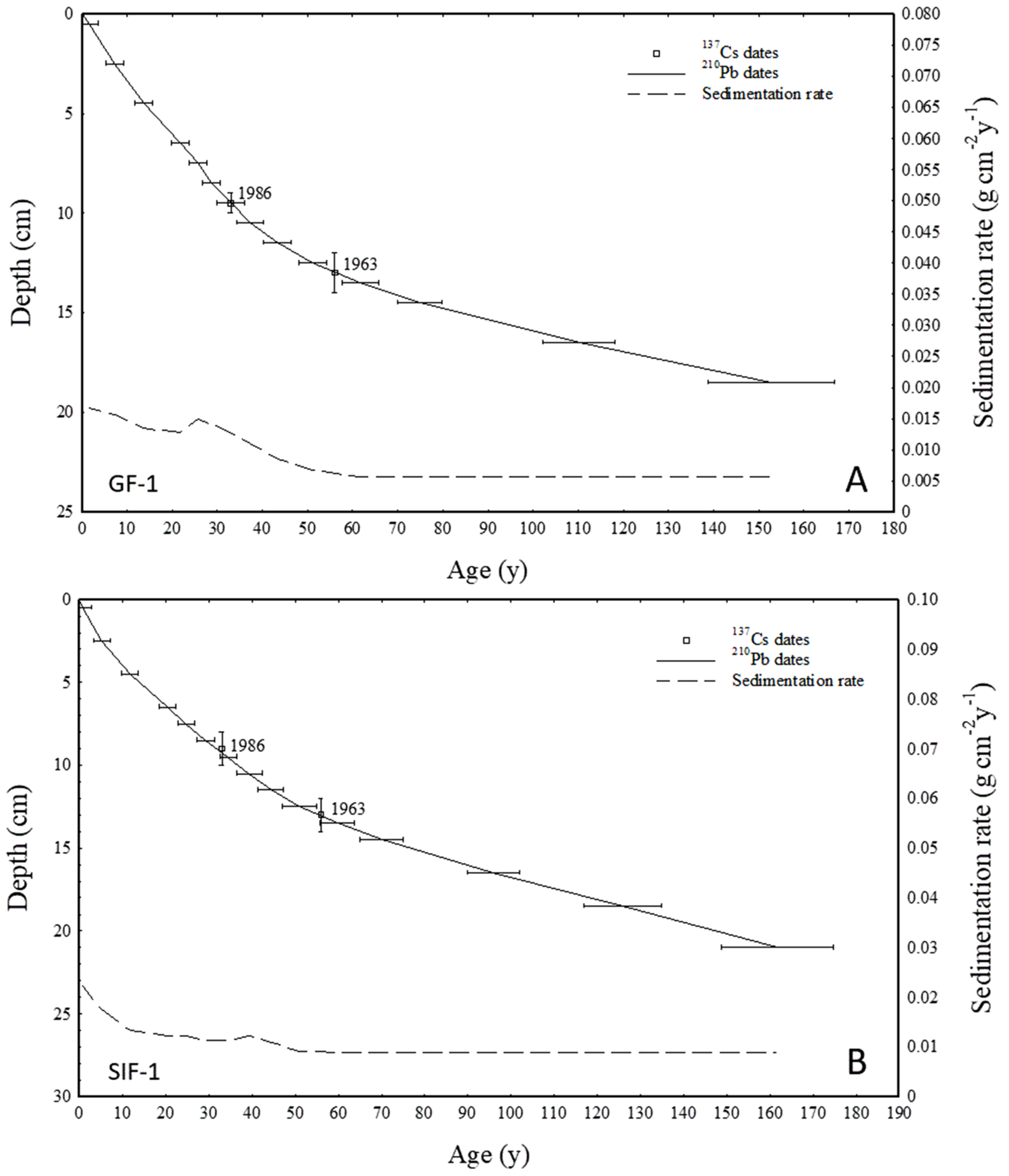

Fig. 3. Radiometric chronologies for A) GF-1 (Grindefjord) and B) SIF-1 (Inner Skjoldafjord) (Appleby and Piliposian, Appendix 2).

Table 5
Uncorrected ^{14}C ages found by ^{14}C-dating bivalves or bulk foraminifera (mainly specimens of *Stainforthia fusiformis*) and corresponding calibrated calendar years BP (BP = 1950).

Sample	^{14}C yrs	± yrs	Calendar yrs BP	CE/BCE	Matrix
GF-1: 50–52 cm	2017	22	1400	550 CE	Bivalve
GF-1: 62–64 cm	3616	79	3360	1410 BCE	Bulk foraminifera
SIF-1: 54–56 cm	1999	22	1380	570 CE	Bivalve
SIF-1: 64–66 cm	2840	22	2380	430 BCE	Bivalve

Skjoldafjord (SIF-1) *S. fusiformis* dominated the assemblage in the lowermost parts of the cores (below 30–40 cm), and *E. albiumbilicatum* dominated the fauna found between ca 15–30 cm (Fig. 6). Foraminifera were absent in the upper 11 cm of the cores (Appendix 4).

The abundance of *Elphidium albiumbilicatum* (Weiss, 1954) was low (<5 test/g sediment) in the lowermost part of both cores (below 50 cm). At 41 cm, the abundance increased to 17 and 15 test/g sediment in GF and SIF, respectively. Above this, the abundance of *E. albiumbilicatum* gradually decreased and became absent above 11 cm. In SIF there was a peak of *E. albiumbilicatum* (108 test/g sed; Fig. 6) and *Elphidium excavatum* (Terquem, 1875) (32 test/g sed) at 17 cm. Only four other species were present in the same sample, however in very low numbers.

Below 50 cm sediment depth, roughly corresponding to the time 1400 BCE to 200 CE in the Grindefjord and 430 BCE to 570 CE in the Inner Skjoldafjord, the diversity index H'$_{\log2}$ showed values between 1.3 and 1.7 in the Grindefjord (GF-1) and 0.8–1.5 in the Inner Skjoldafjord (SIF-1) (Fig. 7). The ES$_{100}$-values varied between 9.9 and 14 in GF-1 and

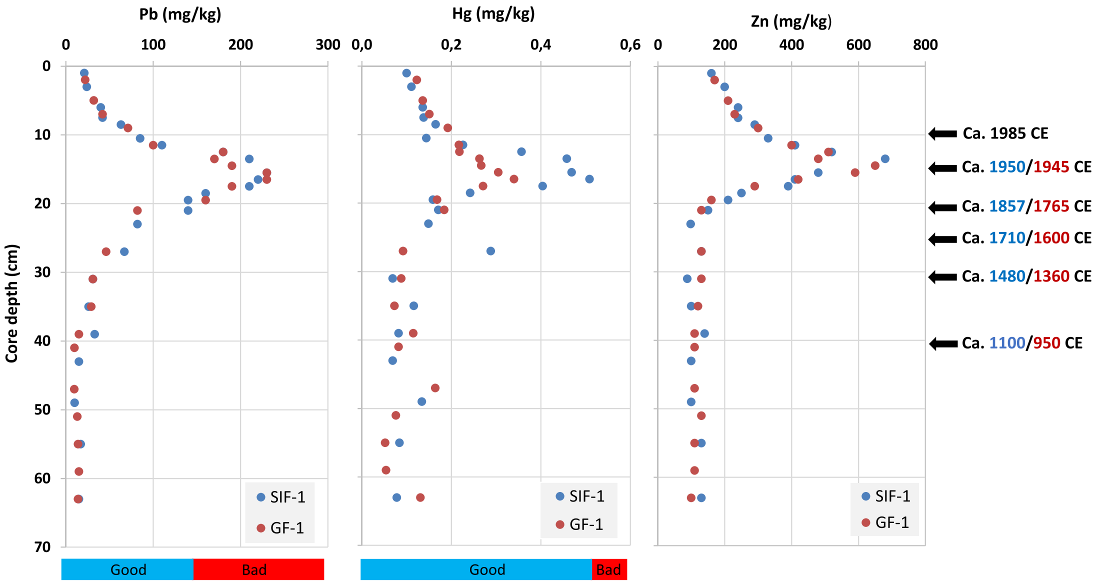

Fig. 4. The concentration (mg/kg) of lead (Pb), zinc (Zn), and mercury (Hg) vs core depth in the Grindefjord (GF – red circles) and the inner Skjoldafjord (SIF – blue circles). Pb and Hg are prioritized substances according to WFD (2013). The AA-EQS (environmental quality standard) for Pb = 150 mg/kg and Hg = 0.52 mg/kg (Veileder 02, 2018). Concentrations above AA-EQS = bad chemical status (red) and below AA-EQS = good chemical status (blue). On the right-hand side: approximate ages shown in black numbers = both fjords; blue numbers = Skjoldafjord; red numbers = Grindefjord. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

between 6.6 and 12.4 in SIF-1. The NQI-values were between 0.25 and 0.32 for the GF-1 and 0.18 and 0.29 for the SIF-1. The calculated normalized ecological quality ratio (nEQR) indicated poor to bad ecological status. As the abundance of foraminifera gradually decreased upwards in the sediments, it was not possible to calculate index-values from samples between 0 and 40 cm neither in GF-1 nor in SIF-1, except for at 17–18 cm (corresponding to about 1910 CE) in SIF-1. This sample revealed poor ecological status (nEQR = 0.36; Fig. 7).

No living (rB stained) nor dead specimens of foraminifera were found in the entire > 63 μm fraction of 3 replicate surface sediment samples (0–1 cm) from GF and SIF. There was no indication of other benthic organisms in the processed samples either. No soft-bottom macro-invertebrates were observed during the field sampling in 2019 nor in 2013 (Sømme and Kaurin, 2013).

4. Discussion

4.1. Establishing reference conditions

Humans have had an impact on nature for several thousand years, but not as severe as from the onset of the industrial revolution when chemical parameters such as metals and toxic organic compounds started spreading to the environment by air and water. Reference conditions according to the WFD are therefore often defined as the pre-industrial conditions (Willis and Birks, 2006; Alve et al., 2009; Hess et al., 2020), in other words, the background status prevailing before the industrial pollution started. In the present study, selected chemical parameters (Pb, Zn, and Hg) in the sediments showed background concentrations roughly below about 20–25 cm core depth (before the 19th century, Fig. 4), interpreted to correspond to the pre-impacted, pre-industrial period, i.e. representing the reference conditions. The upper core sections, between 0 and about 25 cm, reflect the industrial period.

4.2. Reference conditions in the pre-industrial period

According to the WFD, the boundary between good and moderate ecological quality status (EcoQS) is crucial for whether or not action is needed to improve the conditions in a water body. In the present study, however, foraminifera based biotic indices summarized as nEQR (Fig. 7), reflect an overall poor EcoQS even in the oldest parts of the cores. Hence, these old deposits should not be accepted to represent the reference conditions unless it can be shown that the conditions were poor for natural reasons (WFD, 2000, p. 3). The stable, low background concentrations of metals clearly indicate that the latter is the case (Fig. 4). Consequently, the poor EcoQS in the oldest investigated sediments may indeed represent the reference conditions.

The oldest sediments (>430 BCE) showed the highest abundances of foraminifera and the assemblages were strongly dominated by the opportunistic species *Stainforthia fusiformis* (Fig. 6). This species prefers salinities of at least 29–30 ppt (Gustafsson and Nordberg, 2000) and is the most abundant living species in low-oxygen conditions in Scandinavian fjords (e.g., Gustafsson and Nordberg, 1999, Gustafsson and Nordberg, 2000; Alve, 2003; Bouchet et al., 2012). Hence, the dominance of *S. fusiformis* indicates oxygen depleted conditions with close to normal marine salinities, and that the water quality in the Inner Skjoldafjord and the Grindefjord basins was unfavorable for most benthic foraminifera species already > 2,000 years ago, long before the start of the industrial period. Around 1000 CE the *S. fusiformis*-dominated fauna was gradually replaced by a low-diverse population dominated by elphidiids, particularly *Elphidium albiumilicatum.* The latter is known to thrive in low-saline, shallow, intertidal to subtidal, Boreal, Lusitanean, and Arcitc waters (Darling et al., 2016). Living specimens have been found in salinities between 0.2 and 25.0 (between 5 m and 45 m water depth) in the partly brackish Drammensfjord, S Norway (Alve, 1995). This suggests that a strong stratification had been established in the inner fjord system already 1000 years ago, and that the deep-water renewal and exchange of more dense normal marine water masse (as found in outer Skjoldafjord) through Skjoldastraumen had become limited. As time went by, the negative development in oxygen conditions continued, and the EcoQS of the deeper fjord basins went from poor to bad (Fig. 7). Finally, already before the start of the industrial period, the conditions went to nearly permanently anoxic bottom water as demonstrated by the almost complete absence of foraminifera (Fig. 6).

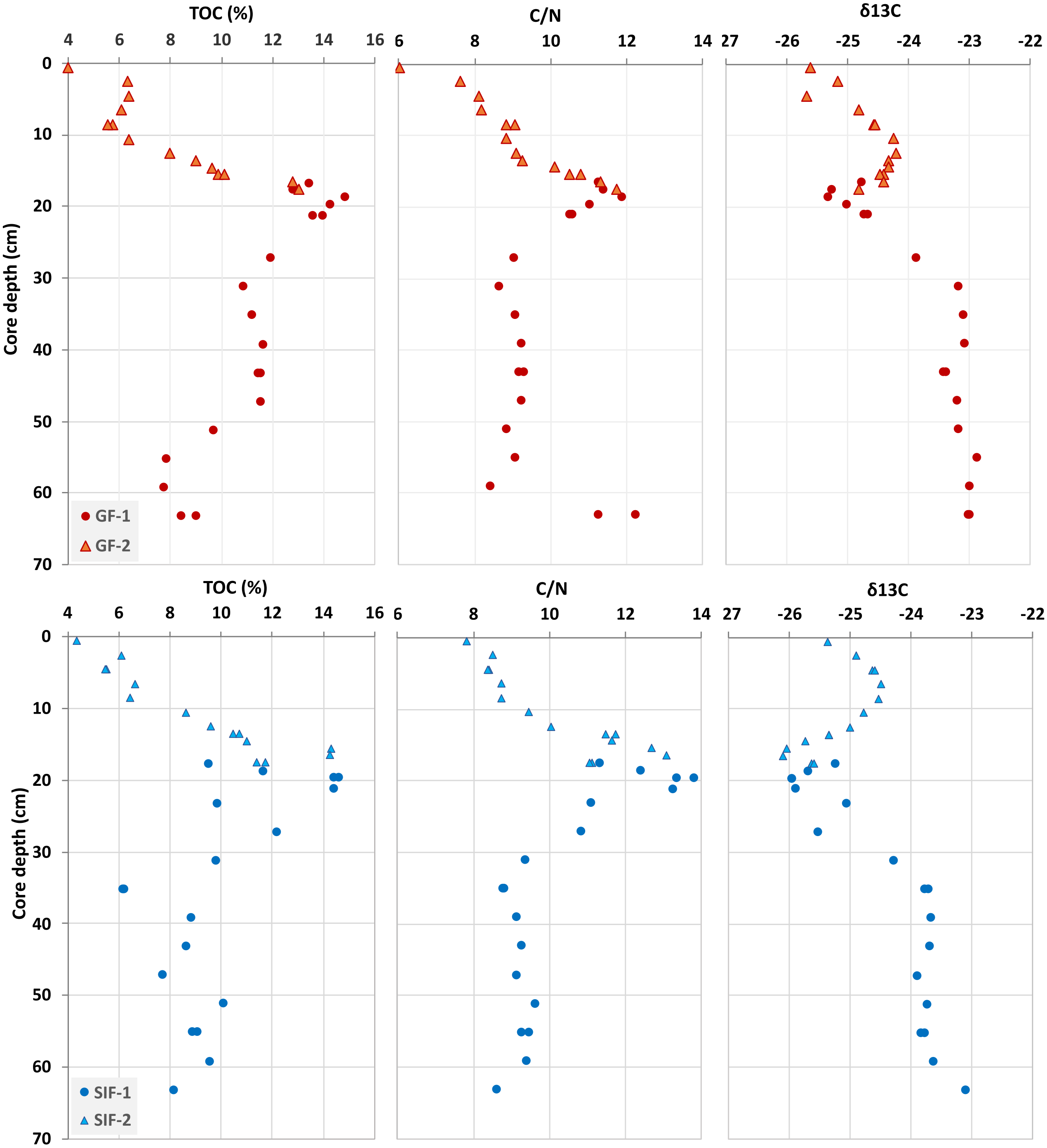

Fig. 5. Total organic carbon (%), the carbon–nitrogen ratio (C/N) and δ^{13}C (‰) values in the Grindefjord (GF) and the inner Skjoldafjord (SIF). The measurement uncertainties for TOC were ± 0.3%, ± 0.014 % for N and ± 0,03 ‰ for δ^{13}C. Sediment samples from parallel cores (diamonds) were used in the uppermost 20 cm.

4.3. The industrial period

The sediments deposited during the industrial period was characterized by gradually increasing concentrations of metals and TOC in both fjords during the 19th century, with maximum values during the middle part of the 20th century (Figs. 4 and 5). This was followed by a decrease towards background values in the uppermost, recently deposited sediments. The overall development seems to follow a recurring pattern commonly seen in Norwegian fjords which had been exposed to industrial pollution and sewage (e.g., Drammensfjord: Alve, 1991; Frierfjord: Alve, 2000; Inner Oslofjord: Lepland et al., 2010, Dolven et al., 2013; Horten Inner Harbor: Hess et al., 2020; Iddefjord: Polovodova Asteman et al., 2015).

Pb and Hg belong to the priority substances (WFD 2000 Annex X emended in Directive 2013/39/EU) used to define the chemical status of a water body, while Zn is included among regionally or locally important pollutants (Specific substances, Annex VIII in WFD, 2000). The chemical status is defined as “good” or “failing to achieve good” (the latter was also referred to as “bad” in the WFD, 2003) depending on whether the concentrations of the priority substances are below or above their environmental quality standard (AA-EQS). Both the present and the background concentrations for Pb and Hg were below EQS

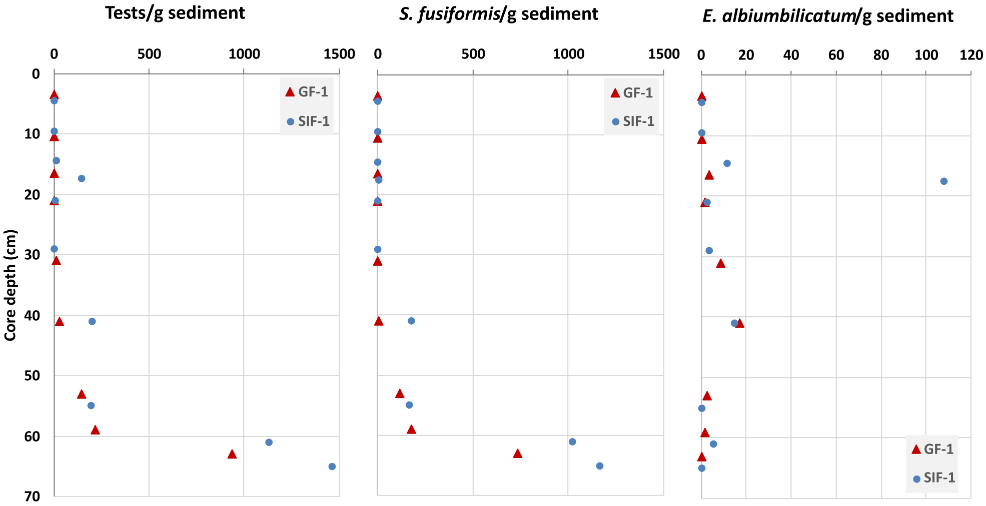

Fig. 6. The foraminiferal abundance of the complete assemblages and of two of the most abundant species, *Stainforthia fusiformis* and *Elphidium albiumbilicatum*, plotted as tests/g dry sediment. NB: The x-axes have different scales.

corresponding to good chemical status. The maximum concentration of lead (Pb) was above EQS in the mid-1900s, while the maximum Hg concentrations increased but remained within good chemical status. The same increase–decrease pattern as Pb and Hg was also found for Zn. As there are no known history of large industries directly around the inner fjord system, it is suggested that these metals have been transported to the area mainly by air and possibly by ocean currents. Karmøy (an island west of Grindefjord) is known for it's long mining history (of e.g. pyrite and copper from 1866 to 1972) as well as metal industries and yard businesses. An increasing supply of untreated sewage (due to population growth) may also have contributed to the increased TOC and metal concentrations recorded during the late 1800s and early 1900s.

The bad EcoQS reflected in the black, sulfidic younger parts of the pre-industrial period continued through the industrial period and up to the time of collection in 2019 (Fig. 7) indicating more or less permanently hypoxic to anoxic oxygen conditions in the bottom water as demonstrated by the nearly complete absence of benthic foraminifera (Fig. 6). The only exception was a bloom in *Elphidium albiumbilicatum* and *Elipidium excavatum* in the Inner Skjoldafjord around 1910 CE (17.5 cm). In the latter case the anoxic intervals in the Inner Skjoldafjord may have been interrupted by occasional influxes of shallow water through Skjoldastraumen, carrying populations of e.g. juvenile *E. albiumbilicatum* (c.f. Alve and Goldstein, 2003) which settled and prospered until anoxia continued to prevail. Events of increased influx of costal water, causing temporarily improving bottom water conditions, have been described to take place occasionally (Strøm, 1936). However, the bottom water renewal probably only reached the Inner Skjoldafjord as no simultaneous bloom of *E. albiumbilicatum* was found in the Grindefjord.

The decreased metal concentrations in the sediments since the middle part of the 20th century reflect reduced emission from industry and agriculture. Despite the reduction in pollutants and organic load, and the improved chemical status the last 60 years, this has not had any apparent positive effect on the benthic fauna as demonstrated by the absence of both living foraminifera (present study) and macro-invertebrates (Sømme and Kaurin, 2013).

4.4. Naturally changing physical factors influence the reference conditions

The foraminifera in the Inner Skjoldafjord and the Grindefjord were affected several hundred years before the concentration of the geochemical parameters started increasing i.e., before the start of the industrial period (Figs. 4 and 6). This indicates that the industrial impact (as illustrated by the metal concentrations) was not responsible for the negative development in the foraminiferal assemblages. Rather, the initial strong dominance of *S. fusiformis* followed by a poor low-oxygen and brackish tolerant fauna (*E. albiumbilicatum*) before the fauna completely disappeared, points to oxygen depletion followed by anoxia, as the likely cause. But why should oxygen get depleted in these coastal waters?

Late Weichselian – Holocene sea-level displacement curves (Fig. 8A) have been reconstructed based on several sea-level studies in the area (Prøsch-Danielsen, 2006 and references therein). The shoreline displacement was a result of interactions between isostatic rebound and eustatic variations (Prøsch-Danielsen, 2006). Due to land rise the shoreline that prevailed around 10500 yr BP are now found 30 m above the present sea level. Plotting the 30 m contour line reveal that the in-/outlet, trough Skjoldastraumen, to the inner fjord system was much wider and deeper at the end of the late Weichselian (Fig. 8B). At that time, the inner fjord system also had communication with both the Førresfjord and the Førlandsfjord (see locations of fjords in Fig. 1). This probably allowed for well-circulated and well-oxygenated normal-marine conditions in both the Grindefjord and the Inner Skjoldafjord.

Archeological excavations and mapping of old shorelines in the study area revealed that the shoreline that prevailed around 3600 ^{14}C yrs BP, now found 5 m above the present sea level (Prøsch-Danielsen, 2006; Fig. 8A), correspond approximately to the oldest dated samples in the Grindefjord core. Already at that time, the contemporary foraminiferal fauna revealed poor ecological status. However, the 5 m contour line (Fig. 8C) shows that the inlet to the inner fjord system was broader, probably allowing for a better water exchange between the inner and outer fjord-system, compared to the almost closed situation with bad EcoQS as found today (Fig. 8 D). Narrowing of Skjoldastraumen was probably caused by the isostatic land rise which gradually isolated the fjord basins from the coastal water. Additionally, local supply of organic matter, combined with stratification of the water masses and restricted deep water renewals caused stagnant, oxygen depleted conditions in the bottom water.

The TOC-content in the studied cores was exceptionally high for Norwegian coastal waters, i.e. two to four times higher than what is commonly reported in Norwegian fjord basins (c.f. Alve, 1991; Alve, 2000, Dolven et al., 2013; Hess et al., 2020; Klootwijk et al. 2020). The fact that TOC, C/N and δ^{13}C showed the same temporal changes in both fjords indicates that the changes were not simply due to local phenomena but rather linked to more regional patterns (Fig. 5). The C/N and δ^{13}C values indicate a change in the dominant carbon source from

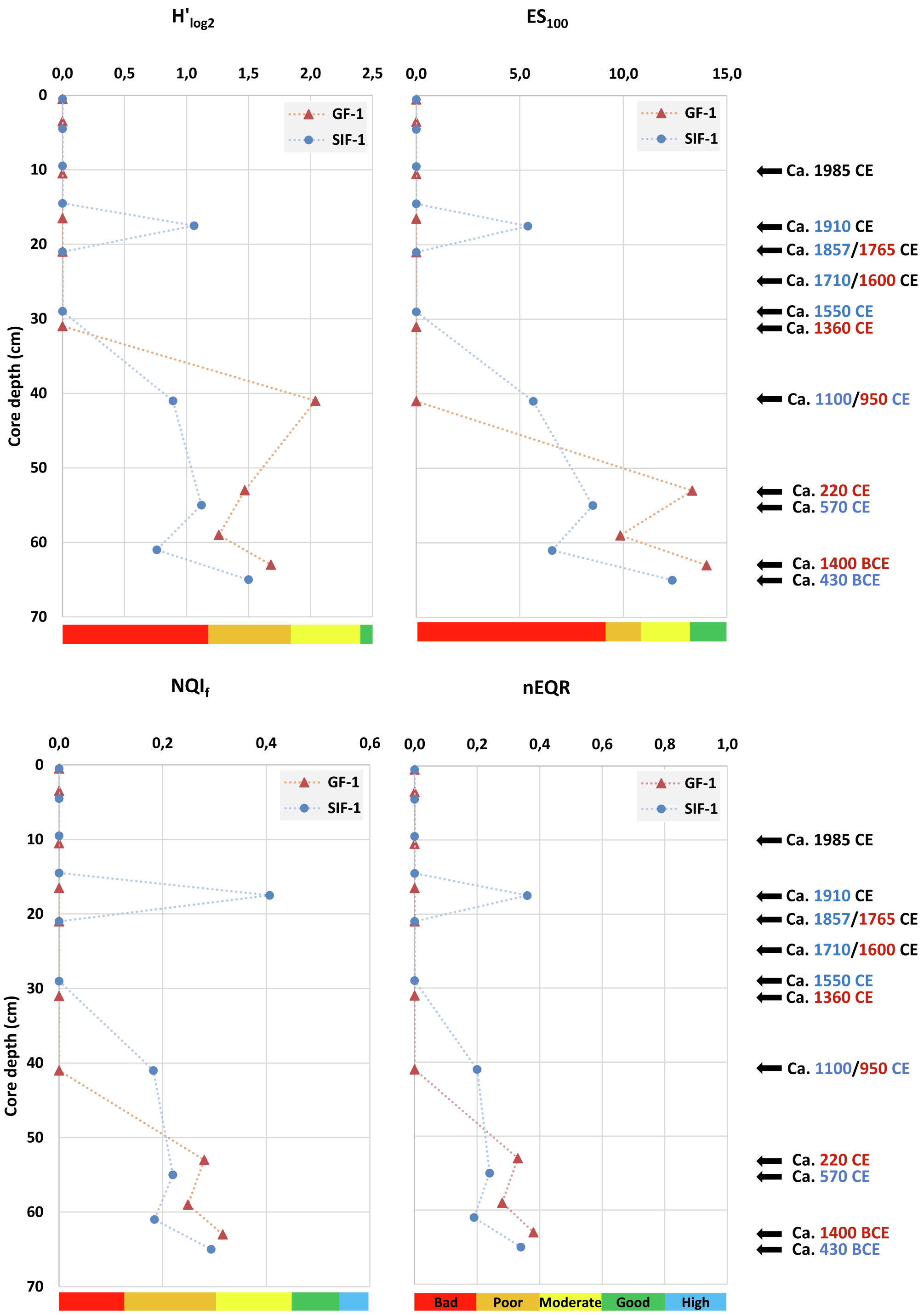

Fig. 7. Index-values of H'$_{log2}$, ES$_{100}$, NQI$_f$ and nEQR (nEQR is based on only H'$_{log2}$ and NQI$_f$) plotted against sediment depth (cm). For samples with too few individuals to calculate indices, the values were set to zero. On the right hand side: approximate age: in black = age for both fjords; blue = ages for Skjoldafjord; red = ages for Grindefjord. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

marine (below 30 cm) to more terrestrial influenced (Meyers, 1994; Lamb et al., 2006) between 15 cm and 25 cm. This may be a consequence of the gradual shoreline displacement causing isolation of the basins and reduction of the communication with the open coastal waters. In this way the inner fjord system became more impacted by terrestrial input (Lamb et al., 2006) from the drainage area. In the upper part of the cores, the reduction in the C/N values once again indicate a change towards marine carbon sources (Appendix 5; Lamb et al., 2006), possibly due to eutrophication as a result of human induced nutrients from farming and wastewater (NIVA, 1973). The δ^{13}C values, however, are more difficult to interpret. Previous studies have shown that plankton has variable δ^{13}C and that plankton-dominated environments may pose problems to the interpretation of the δ^{13}C-signal (Lamb et al., 2006).

5. Conclusions

The present study has shown that the bad ecological status in the

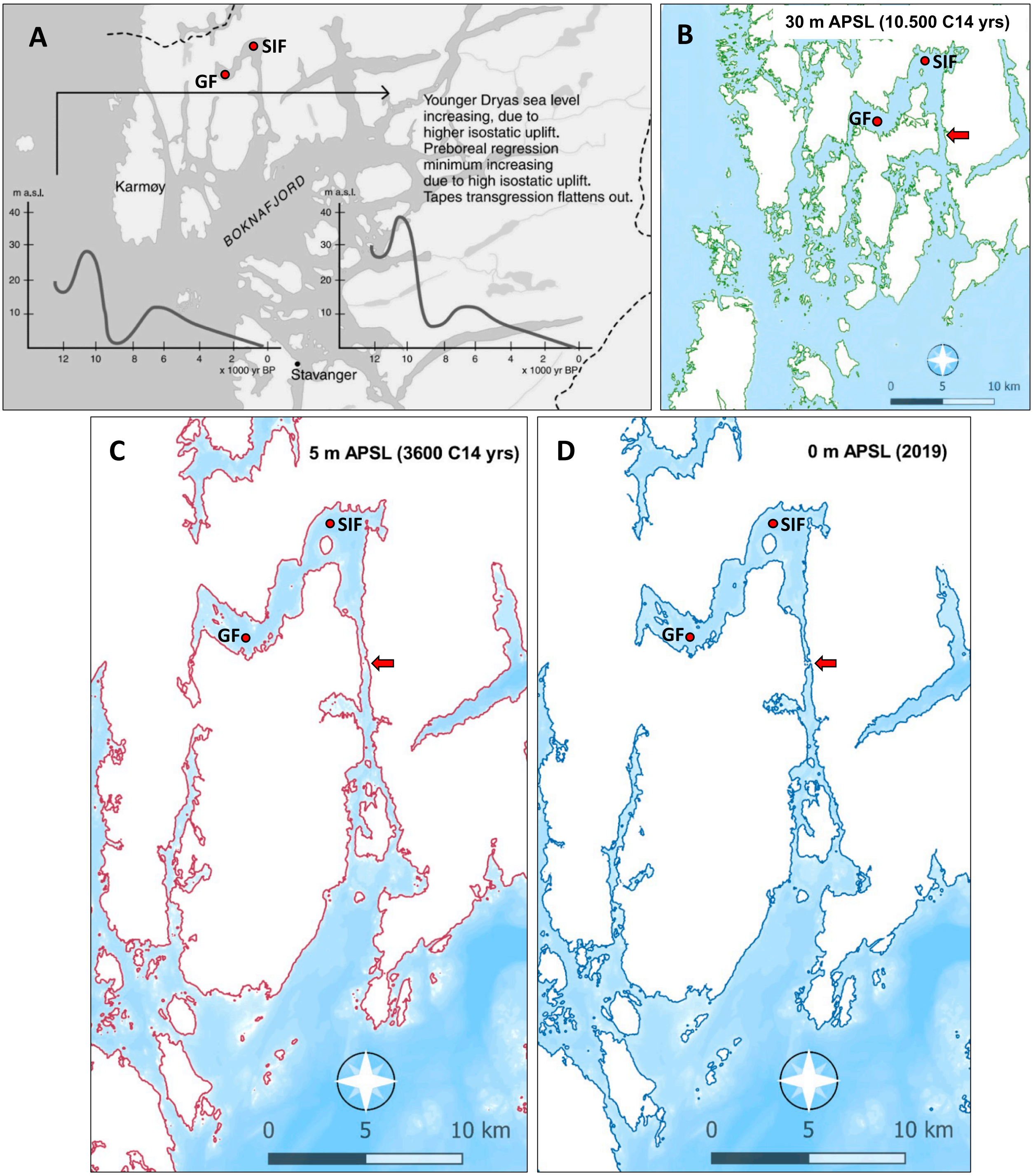

Fig. 8. Plotted contour lines for the A) Shoreline displacement curves slightly modified from Prøsch-Danielsen (2006). APSL = Above Present Sea Level. B) 30 m contour lines (=10500 14C yrs BP) C) 5 m contour lines (=3600 14C yrs BP) and D) present day situations 0 m (=2019). Red circles indicate the location of the investigated stations in the Grindefjord (GF) and Inner Skjoldafjord (SIF). Red arrow shows the position of Skjoldastraumen. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Grindefjord and Inner Skjoldafjord, an almost isolated fjordsystem on the SW coast of Norway, does not deviate from the natural in situ reference conditions which existed just prior to the onset of the industrial revolution. However, the ecological status was not static in the pre-industrial times. In response to isostatic uplift, the ecological status of the reference conditions changed from poor to bad for natural reasons. In our example, the deteriorating water quality was most likely caused by the inner fjord system becoming gradually more isolated, resulting in stagnant and anoxic bottom water masses, and inhabitable living conditions for the benthic fauna. This shows that reference conditions at one location may represent a natural succession of environmental change i.e., it does not only have to represent one particular environmental condition but may vary through time. We therefore suggest that the conditions just prior to the onset of the industrial revolution should be used when defining reference conditions according to the WFD.

Governmental actions, trying to reinstate the ecological quality status good in the Grindefjord and Inner Skjoldafjord will be too expensive in a cost-benefit perspective, and it is not guaranteed to succeed as long as the isostatic uplift proceeds and the entrance to the inner fjord system becomes increasingly restricted. However, all practical steps should be taken to limit human impact on the inner fjord system, to prevent any further deterioration of the status (WFD, 2000).

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.

Acknowledgements

Two anonymous reviewers are gratefully thanked for their comments and suggestions which highly improved the manuscript. We would like to thank Ørjan Simonsen (County Governor of Rogaland) for the project opportunity as well as valuable and positive feedback. We thank Julie Jacobi Jonstrup (County Governor of Rogaland), Øystein Karlsen (Kvitsøy sjøtjenester AS), and Marit S. Stange for help and facilitation during the fieldwork. We appreciate the assistance of Are Reiakvam (UiO) preparing/freeze drying the sediment samples. We are grateful to Peter Appleby and G.T. Piliposian at the University of Liverpool (UK) for the Pb-dating, Gesine Mollenhauer and Torben Gentz at the Alfred-Wegener Institute, Bremerhaven (Germany) for the ^{14}C-dating, as well as Ian Begley and Steven Brooks at the Iso-Analytical Ltd (UK) for analyzing the TOC, TN, and δ^{13}C, and Eurofins AS (Norway) for doing the metal analysis. This study was funded by the County Governor of Rogaland (Norway).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2021.108162.

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