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A short note on a present-day benthic recovery status in the formerly heavily polluted Idefjord (Sweden/Norway)

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A B S T R A C T

Idefjord (Skagerrak, North Sea) has had a long pollution history due to a heavy exposure to effluents from sawmills and pulp and paper industry, which had a detrimental effect on fjord life. Earlier we presented a paper on the pollution history and benthic recovery in the fjord by studying sediment geochemistry (TOC and heavy metals) and benthic foraminifera in the sediment cores taken in the inner and the outer Idefjord. At that stage the foraminiferal (∼benthic recovery) record was limited to years 2000 (inner fjord) and 2002 (outer fjord), in contrast to pollutant data reaching all the way up to 2014. In this short note we extend the foraminiferal record to year 2014 and fill the gap in the benthic recovery in the inner and the outer fjord over the last 12 years. The results show that both inner and outer fjord inlets currently undergo a steady benthic recovery reflected in comeback of transitional and pre-pollution benthic foraminiferal species after 2000–2002 and towards 2014. The recovery is also supported by increasing faunal diversity, low dominance and since 2000–2002 re-appearance of calcareous foraminiferal species (*Bulimina marginata, Elphidium* spp., *Epistominella vitrea*, *Hyalinea balthica* and *Lagena* spp), which all disappeared during the period of maximum effluent discharges. At the same time, detection of opportunistic newcomers (e.g. *Stainforthia fusiformis*) and persisting absence of some transitional species such as *Ammoscalaria tenuimargo* suggests a recolonization by foraminiferal population with a different species composition as compared to the original pre-pollution community either due to changed environmental conditions or/and increased competition.

1. Introduction

Idefjord (Fig. 1) is a fjord located at the border between Sweden and Norway ("*Ringdalsfjord and Iddefjord*" in Norwegian). It is known for its long pollution history due to heavy discharges of effluents from saw mills, pulp and paper industry from the sixteenth century until the 1990s (Polovodova Asteman et al., 2015 and references therein). The most heavy load on the fjord environment occurred during the 20th century and especially between 1915 and 1975, when hundreds thousands tons of oxygen consuming organic material (wood fibers, chips and saw dust) together with domestic sewage effluents were released into the fjord from the cellulose-manufacturing factory and the town of Halden (Fig.1). Huge amounts of organic matter increased oxygen consumption and caused widespread and severe anoxia in the fjord. During 1964–1968 wastes with high concentrations of phenyl-mercury, used for cleaning the paper manufacturing machines, were released into the fjord (Berge, 1994), which created an independent time-marker in fjord sediment (Knutzen et al., 1978; Syvitski et al., 1987). Among other industrial effluents were heavy metals such as e.g. Zn, Cd, Pb and Cu, contained in a sulphide ore sludge discharged into the fjord and also chloro-organic compounds, dioxins and furans. The pollution had a detrimental effect on fjord life and attracted wide public and governmental attention. Following introduction of the Clean Water Act in 1970, and the first paper and pulp industry regulations of 1974 (Sæter, 1998) the discharges to the fjord started to decrease. The old chemical pulp mill at Halden operated until 1992 and a new rebuilt thermomechanical pulp mill with a four-stage wastewater treatment was introduced after 1994 (Sæter, 1998). This resulted in a discharge reduction by > 90%, which significantly improved water quality (Berge, 1994).

A couple of years ago we presented a paper on the temporal development of the pollution and benthic recovery in the fjord by studying sediment geochemistry (total organic carbon (TOC), C/N, Zn, Cd, Pb, Cu and Hg) and benthic foraminifera in the sediment cores taken in the inner and the outer Idefjord (Polovodova Asteman et al., 2015). Results showed that the fjord was close to a complete benthic recovery and recovery from pollution and anoxia in its outer part, whilst the inner part still remained subjected to severe hypoxic to

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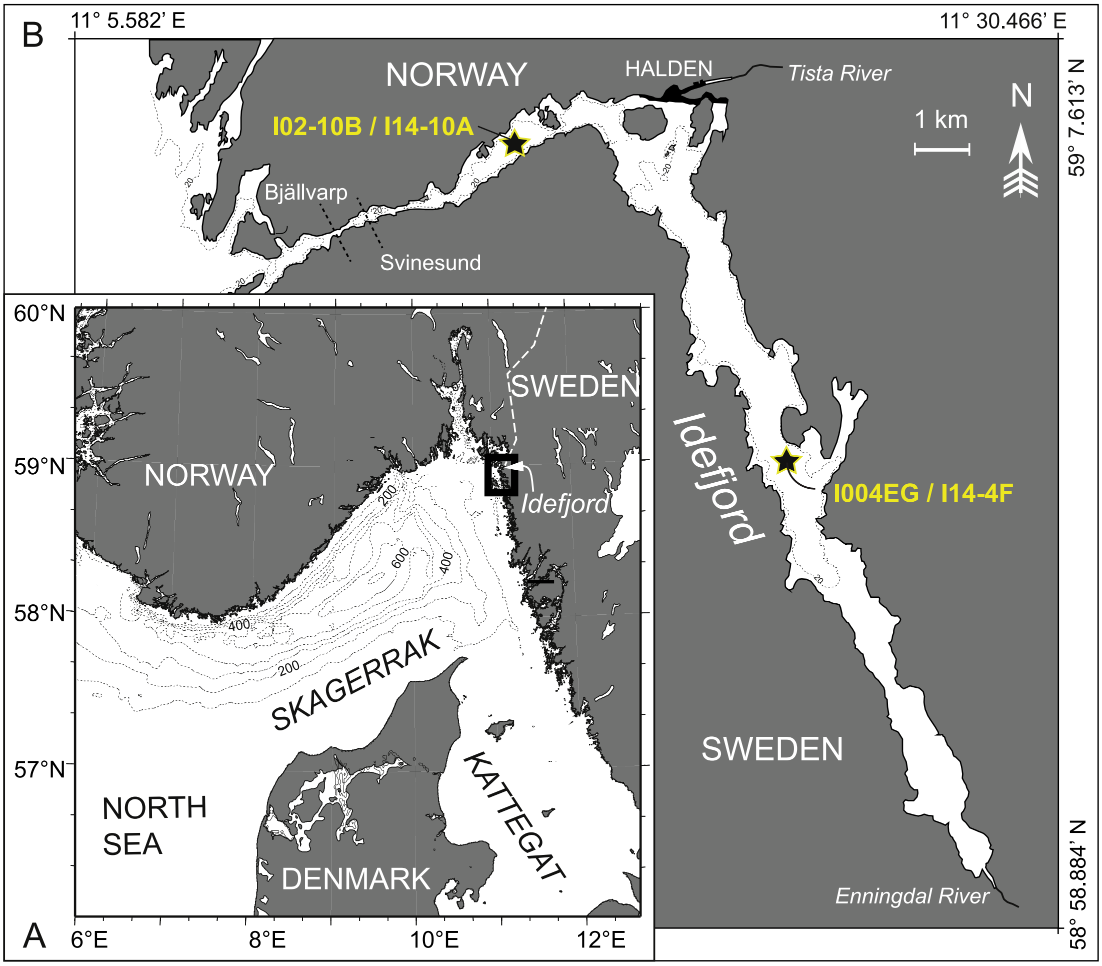

Fig. 1. A: Location of Idefjord within the North Sea and the Skagerrak-Kattegat region; B: Position of the sampling sites and sediment cores from the inner and the outer fjord discussed in the text. Dashed lines at the fjord entrance show location of the two closely spaced sills at Bjällvarp and Svinesund, which facilitate generation of internal waves discussed in the text.

anoxic conditions and was barren of benthic foraminifera despite low pollutant levels. However at that stage the foraminiferal record was limited to years 2000 (inner fjord) and 2002 (outer fjord), in contrast to pollutant data reaching all the way up to 2014. In this short note we aim to extend the foraminiferal record to year 2014 as well and fill the gap in the benthic recovery in the fjord over the last 12 years.

2. Study area

Two shallow sills at 9 m and 10 m cut off the Idefjord basin from the adjacent Skagerrak (Fig. 1). The deepest basin of the fjord reaches 48 m in the outer part. Two rivers contribute to the fresh-water runoff: the Enningdal River in the innermost part and the Tista River, which drains into the fjord by the town of Halden (Fig. 1). The fjord water column is subdivided into three water masses (Johnsson et al., 2007). On top there is a ~2-m thick brackish surface layer with a salinity of < 10. Below it there is a layer of intermediate water mass between ~2 m and 17–22 m, which consists of coastal Skagerrak water with salinity of 15–25. Finally, the deep basin water is found below 17–22 m and represents the imported saline water with salinity of ~30.

The hydrography in the Idefjord is largely influenced by a frequency of water exchange with the adjacent Single Fjord and the Skagerrak. The residence time of surface water in the inner and outer fjord corresponds to 29 and 3–4 days, respectively (Magnusson et al., 1996; Knutzen, 1986; Berge, 1994). The intermediate water mass exchanges every ~75 days for the inner fjord, and ~9 days for the outer fjord (Johnsson et al., 2007). Such different residence times are due to generation of frequent internal waves at two closely spaced sills in the outer fjord, which cause wave trapping and, hence, the more regular mixing in the outer part in contrast to the inner fjord (Johnsson et al., 2007). The deep-water exchange was estimated to 2–3 times year^{-1} for the outer fjord (Berge, 1994) and 1 time year^{-1} for the inner fjord (Stigebrandt, pers. communication, 2014). For further details regarding fjord hydrography see Johnsson et al. (2007).

Due to a specific bottom topography, long residence time of bottom water and the on-going shoaling of the sill depth due to isostatic uplift, the fjords are naturally subject to development of bottom water oxygen depletion, especially in their inner basins (Inall and Gillibrand, 2010). The strong and long-lasting pollution by organic effluents from Halden accelerated development of anoxia in the Idefjord, which along with pollution had a detrimental effect on fjord's life (Skei, 1976; Syvitski et al., 1987; Berge, 1994; Berge et al., 1997).

3. Material and method

The study is based on 20 samples from two sediment cores I14-4F (inner fjord, 9 samples) and I14-10A (outer fjord, 11 samples), which were subsampled at 2-cm resolution. One to two grams of wet sediment were sieved over a 63-μm sieve and wet analysed for total (living + dead) benthic foraminifera with counts of at least 300 specimens per sample (where possible). Both relative (%) and absolute abundances (ind./g dry sed.) for various benthic species were calculated. The taxonomic identification was based on Höglund (1947), Feyling-Hanssen (1964) and Murray (1971). Fisher alpha, evenness and