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Recent oxygen depletion and benthic faunal change in shallow areas of Sannäs Fjord, Swedish west coast

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ABSTRACT

Sannäs Fjord is a shallow fjord (<32 m w.d.) with a sill depth of 8 m, located at the Swedish west coast of the Skagerrak (North Sea). The anthropogenic impact on the fjord represents combination of sewage from the local village of Sannäs and land run-off from agricultural areas. Sewage impact has been reduced since 1991 and today the fjord is included into several nature conservation programs administrated by the European Union. Yet, observations during the summers of 2008–2011 show that the shallow inner fjord inlet experiences severe oxygen depletion at 5–12 m water depth. To explore if the oxygen depletion is only a recent phenomenon and to evaluate the potential of fjord sediments to archive such environmental changes, in 2008 and 2009 seven sediment cores were taken along a transect oriented lengthwise in the fjord. The cores were analysed for organic carbon, C/N, benthic foraminifera and lead pollution records (as relative age marker). Carbon content increases in most of the cores since the ~1970–80s, while C/N ratio decreases from the core base upward since ~1995. Foraminiferal assemblages in most core stratigraphies are dominated by agglutinated species. Calcareous species (mainly elphidiids) have become dominant in the upper part of the records since the ~late 1990s or 2000 (the inner fjord and the deepest basin) and since the ~1950–70s (the outer fjord). In the inner Sannäs Fjord, an increase of agglutinated foraminiferal species (e.g. *Eggerelloides scaber*) and organic inner linings occurred since the ~1970s, suggesting an intensification of taphonomic processes affecting postmortem calcareous shell preservation. A study of living vs. dead foraminiferal assemblages undertaken during June–August 2013 demonstrates that in the shallow inner fjord, strong carbonate dissolution occurs within 1–3 months following the foraminiferal growth. The dissolution is linked to corrosive conditions present within the sediment - bottom water interface, and is likely caused by the organic matter decay, resulting in severe hypoxia to anoxia. Oxygen depletion at <10 m w.d. develops fast due to the small water volume and limited bottom water exchange caused by a close proximity of pycnocline to the fjord bottom. Sediment cores from the deep fjord basin and the outer fjord are, on the contrary, characterized by good to excellent preservation of foraminiferal shells, higher sediment accumulation rates, and the greatest potential for high-resolution paleoenvironmental studies. Increased frequencies of low-oxygen tolerant species (e.g. *Stainforthia fusiformis*) in the outer fjord after ~ the 1970s suggests that increased primary productivity and seasonal oxygen deficiency have existed in the area over the last century. Recent milder winters, absent sediment reworking by freezing and grounding of sea-ice, increased nutrient load due to higher precipitation and land run-off, and the luxuriant growth of filamentous green algae followed by the organic matter decay are discussed among the mechanisms driving formation of recent oxygen deficiency in the shallow fjord inlets.

1. Introduction

Fjords are semi-enclosed basins, which act as natural sediment traps receiving large amounts of biogenic material generated in situ and sediments originating both from the catchment area and the adjacent continental margins and shelves (Howe et al., 2010; Smith et al., 2015). Due to the presence of shallow sills, long bottom water residence time, high oxygen consumption and a slow ongoing isostatic sill shoaling, fjords often naturally develop stagnant conditions in their deeper basins (Syvitski et al., 1987; Gustafsson and Nordberg, 2002; Stigebrandt, 2012). Such conditions are a necessary prerequisite for low activity of burrowing benthic macrofauna and, hence, a low degree of sediment disturbance (e.g. Gooday et al., 2009). Therefore, fjord sediments provide at annual to decadal resolution continuous high-

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resolution temporal records of changes in local primary productivity and biogeochemical processes (e.g. Knies et al., 2003; Harland et al., 2013a, 2013b; Kjennbakken, 2013), atmosphere-land-ocean interactions (e.g. Filipsson and Nordberg, 2010; Polovodova Asteman et al., 2013) and regional variations of climate and hydrography (e.g. Nordberg et al., 2000; Filipsson and Nordberg, 2004; Harland et al., 2004, 2006; Pätzel and Dale, 2010; Faust et al., 2014). Located within coastal zones, which are often characterized by increased urbanization, industry and tourism, fjords and their sediments also record detailed history of human-induced environmental modifications and are thus increasingly used as environmental archives (e.g. Filipsson et al., 2005; Dolven et al., 2013; Polovodova Asteman et al., 2015).

Over the past 30 years, many fjords along the Swedish west coast have experienced periodic low-oxygen conditions in their deep basins (e.g. Nordberg et al., 2000; Gustafsson and Nordberg, 2000). In the summer 2008, severe low-oxygen conditions and laminated sediments were also recorded in Sannäs Fjord, where unlike other localities severe oxygen depletion persisted in the shallow areas (5–12 m w.d.) and not in the deepest basin (Nordberg et al., 2012).

This paper investigates the potential of the Sannäs Fjord sediments to archive at high-resolution such environmental changes back in time. To do so, we present, geochemical and benthic foraminiferal data from 7 short sediment cores representing the last 1–3 centuries and discuss causes driving environmental and benthic changes in the area.

2. Study area

2.1. Geographical and geological background

Sannäs Fjord is one of Sweden's few silled fjords located along a fault line in the Precambrian bedrock, which was carved out by the Scandinavian Ice Sheet during the Pleistocene and was later, during the Late Weichselian and the Holocene, partially filled with sediments. The fjord is located on the Swedish west coast, approximately 25 km south of Strömstad (Fig. 1). It extends in a NNW-SSE direction and is approximately 7.5 km long and 100–800 m wide. The bathymetry in the fjord steepens gradually from 1 to 6 m water depth in the shallow inner part towards the Saltpannan deep basin (Fig. 1) where the water depth reaches 32 m. The fjord has an 8-m deep sill, located in its narrowest part. Outside the sill, water depths increase and reach 36 m in the outermost part forming the Västbacken basin (Fig. 1). The outermost part of Sannäs Fjord is partially sheltered by skerries and faces the adjacent Skagerrak Sea.

The coastal area in the outer Sannäs Fjord mainly consists of rocky shores with steep cliffs of Bohus granite. In the inner fjord, the shores are partly covered by vegetation, and rubble, gravel and sandy pocket beaches often alternate with steep cliffs. In turn, the sheltered shallow bays are characterized by fine-grained organic-rich muddy and silty sediments, which in the north-eastern part of the fjord are overgrown by eelgrass meadows marked by *Zostera marina* and *Ruppia* spp. (Appelqvist and Fröjmark, 2000).

In the deeper areas of the fjord on the inner slope of the sill, gravel, sand and silt prevail. The Saltpannan Basin sediments are mainly characterized by fine and organic-rich gyttja clay. Strong water exchanges and cascading inflow events, which take place across the sill, often have a high energy, which causes erosion of bottom sediments. As a result, a coarser sediment fraction is transported from the sill and the sill slope and may eventually be deposited in the deeper basin (Olsson, 2007; Johansson, 2010; Robijn, 2012).

One hundred years ago, the fjord's catchment area was deforested. Today it consists primarily of rocky granite hills with lean pines, mixed forests and agricultural land together with a single golf course and scattered small settlements (including the small village of Sannäs - Fig. 1). Though, the fresh water inflow to the fjord is generally minor, in the shallow inner part it is high enough to significantly reduce salinity of the upper water layer. The largest freshwater inflow occurs through the Skärboälven River, the largest stream in the area (Fig. 1), which has an average discharge of 0.5–1 m^3/s (Olsson, 2007). The Skärboälven River has a catchment area of 42 km^2 and passes through a number of agricultural areas on its way to Sannäs Fjord (CAB, 2005; Johansson, 2010; Ödalen, 2012).

The anthropogenic impact on the fjord environment from the Sannäs village has been reduced since 1991 when all wastewater from households was routed to a water treatment facility in nearby small town of Grebbestad (Ödalen, 2012). The fjord is rich in marine life; has a large stock of flat oysters (*Ostrea edulis*), and therefore has been included into the local nature management program "Tanums Coast III" and into the Nature Conservation Network "NATURA 2000" administrated by the European Union. Due to its environmental characteristics the fjord attracts hundreds of visitors for recreational boating and fishing. This results in a seasonal population boom in small settlements surrounding the fjord, i.e. population in the village of Sannäs reaches ~500 individuals during the summer months, as compared to its ~50 year-round residents.

2.2. Hydrography

The hydrography of Sannäs Fjord (Fig. 1) follows a complex fjord circulation pattern (Stigebrandt, 2012). The freshwater supplied by precipitation and run-off mixes with seawater to create the upper, ~1-m thick brackish ($S < 20$) water layer, which is separated by a halocline at 8–10 m depth from more saline ($S > 25$) water underneath. The halocline depth is generally controlled by the presence of 8-m deep sill. Wind mixing causes entrainment of the underlying seawater into the surface brackish layer and leads to a halocline deepening. This process creates an estuarine circulation when an outflow of the brackish surface water is caused by a difference in surface layer pressure inside and outside the fjord (Stigebrandt, 2012). At the same time there is an inflow of more saline water below the halocline. Water between the brackish surface water and the sill depth is often referred as intermediate water. Exchange of the intermediate water layer in Sannäs Fjord, and especially outside the Saltpannan Basin (Fig. 1), usually mirrors the density gradient between the fjord water and the coastal water of the adjacent Skagerrak. If changes in the coastal water density occur, the fjord responds by creating water stratification similar to that of the coastal water. This kind of adjustment causes strong inflows and outflows at different depths above the sill level (Pettersson, 1920) and is often referred to as intermediate circulation (Stigebrandt, 2012).

In addition to estuarine and intermediate circulation, variations of the local sea level (barotropic forcing) also play an important role for the water exchange across the sill in Sannäs Fjord (Johansson, 2010). When the sea level in the open sea exceeds that of the fjord, an inflow across the sill takes place and vice versa. Along the Swedish west coast, such mechanism of water exchange in the fjords is often dominated by tidal activity despite its relatively low amplitude (~20 cm) as compared to air pressure- and wind- driven variations of water level (Johansson, 2010). Tides in the study area are semi-diurnal, i.e. almost two cycles are completed in 24 h, which usually contributes more to the water exchange than the large-scale but long-term meteorological variations (Nordberg et al., 2012). According to Johansson (2010), the mean residence time of the fjord water above the sill is 6 days and the water exchanges due to tides, intermediate circulation and estuarine circulation constitute 5 m^3/s, 7.5 m^3/s and 7.5 m^3/s, respectively.

The fjord water mass below the sill level is often referred to as deep water or basin water (Stigebrandt, 2012). According to the measurements performed during 2003–2006 (Olsson, 2007), deep-water exchange in Sannäs Fjord occurs ~5 times per year. The deep-water renewal in the fjord takes place when coastal water of high density and speed flows over the sill and replaces less dense deep water in the fjord. Such water exchange is often driven by prevailing northerly to easterly winds and co-occurs with upwelling, which at the Swedish

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