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RECENT AND LATE HOLOCENE DEVELOPMENT OF THE MARINE ENVIRONMENT IN THREE FJORDS ON THE SWEDISH WEST COAST

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Akademisk avhandling

För vinnande av filosofie doktorsexamen i Oceanografi (examinator professor Anders Stigebrandt) som enligt beslut av Tjänsteförslagsnämnden, Institutionen för Geovetenskaper vid Göteborgs Universitet, kommer att offentligt försvaras fredagen den 31 mars 2000, kl. 10.00 i Hörsalen, Geovetarcentrum, Guldhedsgatan 5 A, 405 30 Göteborg.

Fakultetsopponent: Dr Antoon Kuijpers, Danmarks og Grønlands Geologiske Undersøgelse, Köpenhamn, Danmark

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ABSTRACT

Oxygen depletion in the bottom water of many Scandinavian fjords is often considered to be a modern problem, caused by human induced eutrophication. That also includes Gullmar Fjord, Koljö Fjord and Havstens Fjord on the Swedish west coast which are investigated here. However, major reasons for periodic or permanent oxygen deficiency in fjords are the existence of a sill, the stratified water column and slow vertical mixing. The problems of determining the causes of oxygen depletion in the bottom water of stagnant basins are not trivial, but Scandinavian fjords are characterized by high sediment accumulation rates, minor tidal activity and low abundances of turbating macrofauna. The prerequisites for the formation of a high-resolution environmental archive in the sediment record are therefore good. Together with long-term instrumental hydrographic data series and meteorological data, requirements are fulfilled for an interesting study of the causes of oxygen deficiency in the bottom water, natural or anthropogenic.

The aim of this thesis is to reconstruct the recent and late Holocene environmental history of Gullmar Fjord, Koljö Fjord and Havstens Fjord and to correlate modern and older oceanographic and climatic data with stratigraphic information from sediment records to bridge the gap between present and past. The research will hopefully contribute to our understanding of the relationships between natural variations in the climate and oceanography, the land uplift of the sill areas, ecological parameters and anthropogenic impact on the environment and interactions between these.

A wide range of methods have been used, including hydrographic measurements, sediment sampling, X-ray radiography, foraminiferal analysis, organic carbon content, ^{210}Pb dating, ^{14}C dating, long-term hydrographic and meteorological data processing and sediment correlations.

To achieve the aims of the study, we started the project by improving one of the most important tools here, study of the benthic foraminifera. We performed a 17-months-long monthly record of living (stained) foraminifera together with oxygen, salt and temperature measurements from ten sites at different depths in the fjords. The results of this seasonal study, together with monthly instrumental hydrographic and meteorological records extending over decades, make up the basis for the stratigraphic work.

The access to foraminiferal assemblages that have grown under known environmental conditions in a well-documented *in situ* situation together with very high-resolution sediment records including an absolute, almost year-based, chronology make this study unique. The study is an important step towards development of a tool for quantitative reconstruction of the environment, beyond all measurement programmes, in most fjords and estuaries.

The results of the stratigraphic part of the thesis suggest that natural processes controlling the fjord environments are possibly more important than the human impact in these not so heavily populated areas. The results contrast with general opinions about the marine environment in the area and underline the importance of high-resolution paleo work in combination with studies of recent material.

Key words: Sweden, Skagerrak, fjord, benthic foraminifera, sediment record, laminated sediments, hydrography, primary production, hypoxia, anoxia, stratigraphy, eutrophication, climate, NAO-index.

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PREFACE

This thesis comprises the following six papers, which are referred to by their Roman numerals.

I: Gustafsson, M. and Nordberg, K., 1999: Benthic foraminifera and their response to hydrography, periodic hypoxic conditions and primary production in the Koljö fjord on the Swedish west coast. *Journal of Sea Research*, 41: 163-178.

II: Gustafsson, M., and Nordberg, K. Living (stained) benthic foraminifera and their response to the seasonal hydrographic cycle, periodic hypoxia and to primary production in the Havstens Fjord on the Swedish west coast. Submitted to *Estuarine, Coastal and Shelf Science.*

III: Gustafsson, M., and Nordberg, K. Living (stained) benthic foraminiferal response to primary production and hydrography in the deepest part of the Gullmar Fjord, on the Swedish west coast; including comparisons with Höglund's material from 1927. Submitted to *Journal of Foraminiferal Research.*

IV: Nordberg, K., Gustafsson, M., and Krantz, A-L., 2000: Decreasing oxygen concentrations in the Gullmar Fjord, Sweden, as confirmed by benthic foraminifera, and the possible association with NAO. *Journal of Marine Systems*, 23: 303-316.

V: Nordberg, K., Gustafsson, M., Filipsson, H. Harland, R. and Roos, P. Marine benthic hypoxia in Koljö Fjord, Sweden: Natural causes challenging the significance of human impact. Submitted to *Limnology and Oceanography.*

VI: Gustafsson, M. and Nordberg, K. The impact of climate and shore level displacement on the late Holocene environmental development of the Havstens Fjord and the Koljö Fjord, on the Swedish west coast. To be submitted to *The Holocene.*

INTRODUCTION

Oxygen depletion in the bottom water of many Scandinavian fjords, the southern Kattegat and the Baltic Sea is considered to be a modern problem, caused by anthropogenic eutrophication. This also includes Gullmar Fjord, Koljö Fjord and Havstens Fjord on the Swedish west coast (Figure 1). However, major reasons for

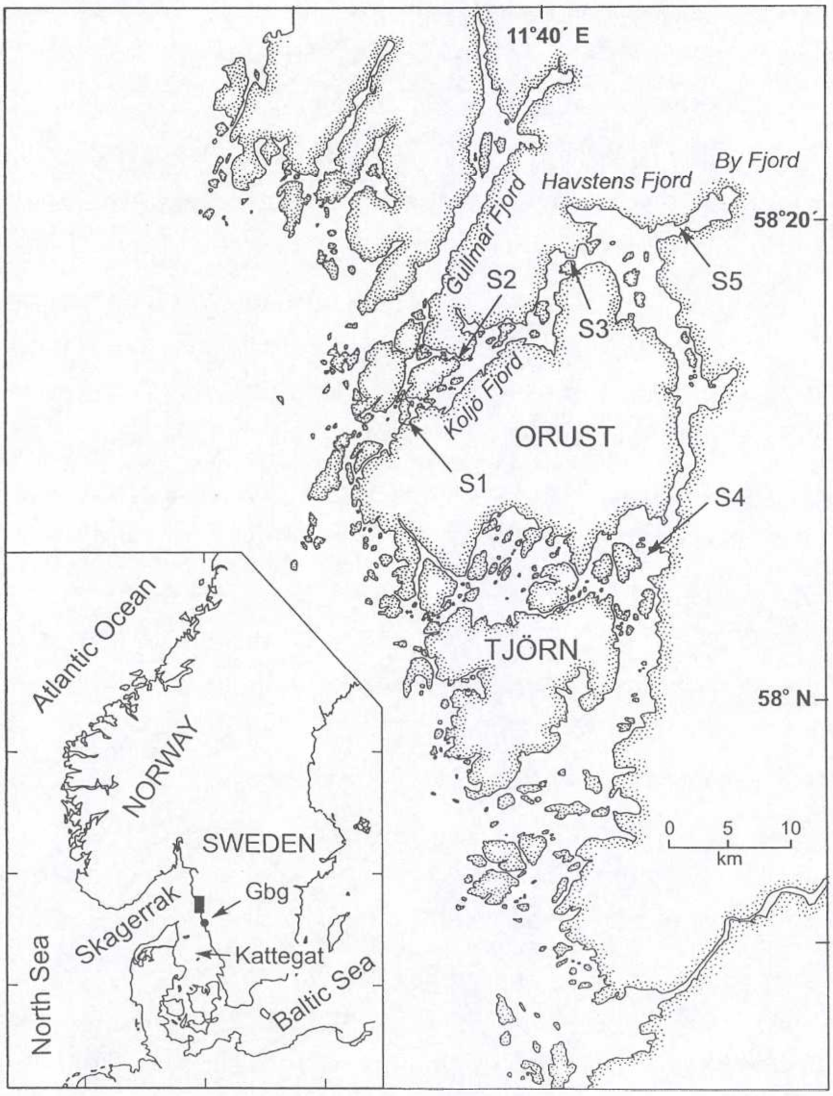

Figure 1 Location map of the investigated fjord system. The Koljö Fjord's western sill at Malöströmmar (S1), the northern sill at Nordströmmarna (S2) and the eastern sill at Nötesund (S3) are indicated. In the Havstens Fjord the southern sill (S4) and the By Fjord sill (S5) are indicated.

periodic or permanent oxygen deficiency in fjords the existence of a sill, vertical density stratification and weak tidal activity. In addition the climate is a major driving mechanism for the fjord environment and its oxygen status.
Scandinavian waters, including these three fjords, are also unique in, that they have been subject to continuous hydrographical measurements for fifty years or more. This is also the case for meteorological measurements, which have been performed for more than a hundred years.

The aim of this study is to reconstruct the recent and late Holocene environmental history of Gullmar Fjord, Koljö Fjord and Havstens Fjord and to correlate modern and older oceanographic, climatic, and biological/ecological data with stratigraphic information from sediment records. The research will hopefully contribute to our understanding of the relationships between variations in the climate and oceanography, the land uplift of the sill areas, ecological parameters and anthropogenic impact on the environment and interactions between these.

To achieve the aims of the study, we started the project by improving one of the most important tools here, the benthic foraminifera. We performed a 17-months-long monthly record of living (stained) foraminifera together with oxygen, salt and temperature measurements from ten sites at different depths in the fjords. The results of this seasonal study (Papers I, II and III), together with monthly instrumental hydrographic and meteorological records extended over decades, make up the basis for the stratigraphic work (Papers IV, V and VI).

The study of living benthic foraminifera is very important and essential for an understanding of the past. In areas that are subject to seasonal variations in most variables, like shelf and fjord environments, it is very important to know what time of the year a certain species is flourishing and how, when and why it responds to specific variables like oxygen concentration, salinity, temperature and primary production. This kind of information is essential for accurate down-core environmental reconstructions. The access to foraminiferal assemblages that have grown under known environmental conditions in a well-documented *in situ* situation together with very high-resolution sediment records including an absolute, almost year-based, chronology make this study unique. The study is an important step towards development of a tool for quantitative reconstruction of the environment, beyond all measurement programmes, in most fjords and estuaries.

The results of the stratigraphic part of the thesis suggest that natural processes controlling the fjord environments are possibly more important than the human impact in these not so heavily populated areas. The results contrast with general opinions about the marine environment in this area and underline the importance of high-resolution paleo work in combination with studies of recent material. To understand the environmental development and to improve our tools, we need to bridge the gap between now and then.

HYDROGRAPHY OF THE INVESTIGATED AREA

The Kattegat forms an estuary between the Baltic and the Skagerrak. While the Kattegat is shallow, with a mean depth of 23 m and a maximum of about 100 m in the north-eastern part, the Skagerrak has a mean depth of about 200 m and a maximum depth of about 700 m. In the Skagerrak, an upper brackish water mass (about 25‰) is separated from the marine Skagerrak water by a pycnocline at 15 to 20 m depth (Svansson, 1984). Below the pycnocline the water is of normal salinity (35‰) and derives from the North Sea and the Atlantic (e.g. Rodhe, 1987). In the deeper part of the Skagerrak there is a continuous cyclonic circulation and the advective residence time for the water down to 400-500 m is about 100 days (Rodhe, 1987). Most of the brackish surface water flows northwards along the Swedish west coast (e.g. Gustafsson and Stigebrandt, 1996). The Skagerrak receives large amounts of fresh water, both in the form of rather low-saline waters from the Baltic Sea (about 15000 m^3/s in terms of fresh water) and in fresh form from local rivers (about 2500 m^3/s) (Svansson, 1975). From the southern North Sea, rather low-saline waters from continental river discharge of about 4500 m^3/s pass through the Skagerrak (Gustafsson and Stigebrandt, 1996). These waters, mixed with the underlying Skagerrak water, participate in a variable, during the winter mainly wind-driven, cyclonic surface circulation in the Skagerrak (e.g. Gustafsson, 1999). South-westerly winds may induce transversal Ekman flows that hinder outflow of the Norwegian coastal current (Aure and Sætre, 1981). When the wind weakens or changes direction, there may be large outbreaks of fresh-water-influenced surface-water to the Norwegian coastal current. During calmer summer weather conditions it takes about one week to establish a fresh-water-driven cyclonic circulation, with baroclinic current and geostrophic balance in the coastal current along the Swedish west coast (Gustafsson, 1999).

Like other Scandinavian fjords, the Havstens Fjord and the Koljö Fjord (Figure 1) have a strong pycnocline between the brackish surface layer and the deep-water, which fluctuates between 15 and 20 m. The pycnocline and a 5 to 10 m thick layer with intermediate physical properties more or less inhibits the brackish surface water from mixing with the more saline deep-water. The sills prevent communication of deep water between the fjords and the sea. Below about 25 m stagnant conditions usually prevail and low-oxygen conditions also evolve during autumn and winter. A semi-diurnal tide with 0.15-0.2 m amplitude contributes to the exchange of the fjord's, surface water with the Skagerrak. Steric height difference and a northward inclining salinity gradient induce a net transport of 70 m^3/s of surface water northwards in the fjord system (Björk et al., 2000). Deep-water inflows into the Havstens Fjord occur annually over a 20 m deep sill in the southern part of the fjord. Deep-water inflows to the Koljö Fjord are often annual, but stagnation periods several years long sometimes occur. Deep-water inflows to the Koljö Fjord generally come from the Havstens Fjord over the 12 m deep sill. The shallow sill results in a brackish deep-water in the Koljö Fjord (26-28‰) compared to the Havstens Fjord's almost normal saline (31-33‰). Koljö Fjord's deep-water most likely comprises intermediate water from the Havstens Fjord. To the west, Koljö Fjord meets the Skagerrak over an 8 m deep sill. The maximum depth is 42 m in the Havstens Fjord and 56 m in the Koljö Fjord. During history the fjord morphology and especially the sills have changed as a consequence of the shore-level displacement. The shore-level displacement in this area is caused by the combination of isostatic land uplift, about 2.25 mm/year (RAK, 1971), and global sea-level variations. In this area, the shore-level displacement has been considerable (Påsse, 1997), which has had a significant effect on the fjords with shallow sills. For instance, the Koljö Fjord's deepest sill has halved its depth during the last 3000 years or so.

The Gullmar Fjord is located north of the Koljö Fjord (Figure 1). It is about 30 km long, about 2 km wide and is oriented in a south-west to north-east direction. The fjord has a maximum depth of 119 m. A strong thermohaline stratification with a pycnocline between 15 and 20 m is imported from the Skagerrak (Svansson, 1984). During the summer the stratification is strengthened as a consequence of the developing thermohaline stratification. The outflow of fresh water from the Örekil River, sea-ice during cold winters and the rather small tidal activity also contribute to the formation of a stable water column in the Gullmar Fjord. The mean residence time for the intermediate water is about 1 month (Rydberg 1977). Below the pycnocline the salinity is normal marine. The sill depth is 42 m and from about 50 m and deeper the water mass is usually stagnant (Svansson, 1984). The water mass below 50 m is usually exchanged once every winter or early spring, when Skagerrak deep water enters the fjord. This happens when the thermocline is weak, and after a period of northerly to easterly winds that induce upwelling along the coast through Ekman transport and subsequent deep-water inflow (Rydberg, 1977). In the deepest parts of the fjord, below 80 m depth, hypoxic conditions evolve occasionally during the autumn and winter.

Modelling vertical mixing in the fjord basins

It is well known that oscillating barotropic tidal currents over a ridge or sill will generate internal waves in vertically stratified water. In fjords, internal tides are assumed to break where they meet the bottom and the energy dissipates while mixing the water masses (Stigebrandt, 1976). During stagnant conditions in a fjord basin, internal tides are usually the major contributor to turbulence mixing oxygen into the deep-water. This mixing is also crucial for the decrease in the deep-water salinity and density. Since deep-water inflow will only occur when denser water from outside reaches over the sill, a continuous decrease of the deep-water salinity and density will increase the probability of deep-water exchange (Aure and Stigebrandt, 1989).

Internal tidal waves generated at sills in stratified fjords may generate a significant amount of mixing. The parameters necessary to calculate the energy transfer from internal waves (E) are: fjord area (A_f), sill depth (H_t), basin water mean depth (H_b), vertical cross-sectional area above the sill (A_s), tidal amplitude (a_i), tidal frequency (ω), phase velocity of internal waves (C_i) and the density difference ($\Delta\rho$)for a two-layer vertical stratification. These parameters are used in the equation described by Stigebrandt and Aure (1989) in Figure 2.

$$C_i = \sqrt{g\frac{\Delta\rho}{\rho} \cdot \frac{H_t \cdot H_b}{H_t + H_b}}$$

$$E = \rho \cdot \omega^2 \cdot a_i^2 \cdot \frac{A_f^2}{2 \cdot A_s} \cdot \frac{H_b}{H_b + H_t} \cdot c_i$$

Figure 2 The equations for calculation of energy transfer to internal tides, from Stigebrandt and Aure (1989).

Maps (scale 1:10000) and sea charts (scale 1:50000) were used to calculate ancient as well as present shorelines and vertical sill areas. The energy transfer to each of the two fjords is calculated for the recent shoreline and for a shoreline raised 20 m and 10 m, which represent the fjord system 4500 and 2500 years ago. It should be noted that the sediment accumulation was compensated for while calculating the paleo-basin depth. Also, the changed salinity in the deep-water of the Koljö Fjord was estimated. All parameters necessary for the calculation of the internal tide energy in the fjords are presented in Table 1.

Koljö Fjord	C_i	H_t (m)	H_b (m)	A_s (m^2)	A_f (km^2)	$\Delta\rho$	E (kW)	Tot. E (kW)	Sce.
Present, Nsill	1.15	6	22.6	1410	46.7	3	5.9		
Present, E sill	0.99	12	16.6	2506	14.0	3	18.9	24.8	
+ 10m, W sill	1.46	18	21.6	3830	18.3	5	29.2		1
+ 10m, E sill	1.52	16	23.6	4346	18.3	5	29.4	58.6	1
+ 10m, W sill	1.46	18	21.6	3830	36.6	5	116.8		2
+ 10m, E sill	1.52	16	23.6	4346	36.6	5	117.5	234.3	2
+ 20m, W sill	1.50	28	23	9200	23.5	5	17.1		1
+ 20m, E sill	1.57	26	25	8260	23.5	5	21.6	38.7	1
+ 20m, W sill	1.50	28	23	9200	47.0	5	68.4		2
+ 20m, E sill	1.57	26	25	8260	47.0	5	86.3	154.7	2
Havstens Fjord									
Present, S sill	0.69	20	4.9	7780	82.6	5	50.3		
Present, By sill	1.29	8	16.9	2290	6.0	5	5.7		
Present, E sill	1.12	12	12.9	2506	14.0	5	19.2	75.2	
+ 10m, By sill	1.33	18	17.9	7690	7.2	5	1.9		1
+ 10m, S sill	0.76	30	5.9	12900	87.6	5	31.3	33.1	1
+ 10m, By sill	1.33	18	17.9	7690	7.2	5	1.9		2
+ 10m, E sill	1.17	22	13.9	6012	36.6	5	42.4		2
+ 10m, S sill	0.76	30	5.9	12900	51.0	5	10.6	54.8	2
+ 20m, W sill	1.36	28	18.9	19200	8.6	5	0.9		1
+ 20m, E sill	0.82	40	6.9	37400	112.6	5	17.3	18.1	1
+ 20m, W sill	1.36	28	18.9	19200	8.6	5	0.9		2
+ 20m, E sill	1.21	32	14.9	11400	47.0	5	31.3		2
+ 20m, S sill	0.82	40	6.9	24500	65.6	5	8.9	41.1	2

Table 1.The parameters necessary to calculate the energy transfer from internal waves generated at sills in stratified fjords.

Half of the tidal volume comes to the Koljö Fjord via the eastern sill, while one sixth of the tidal volume comes via the narrow northern sill (Björk et al., 2000). At both these sills internal waves should be generated since the fjord sills are closely connected to the deep-water of the fjords. At the narrow western sill, where one third of the tidal water is exchanged, there is probably an insignificant generation of internal waves since the sill area is shallow and not in contact with the deep-water.

All the tidal water to Havstens Fjord plus half the Koljö Fjord's tidal volume and the tidal water to the By Fjord comes via the southern sill of the Havstens Fjord.

If we compare the situation today with that of 4500 and 2500 years ago, the sill depths were 20 m and 10 m deeper and the vertical sill areas were considerably larger. To make a precise reconstruction of the tidal flow 4500 and 2500 years ago, calculations for the whole fjord system must be made, using the actual topography of the fjords. That is beyond the scope of the present work. However, two scenarios are modelled here for the tidal flow and energy transfer to internal waves. The real situation was probably within the range spanned by the two scenarios.

It is obvious that the tidal inflow to the Koljö Fjord over the northern and western sills must have been more effective than today. In the first scenario (Table 1), we suggest that the Koljö Fjord is filled by equal contributions from the western and northern sills and thus with insignificant tidal flow over the eastern sill. This means that the tidal flow in the Havstens Fjord coming from the south meets the tidal flow from the Koljö Fjord at the eastern sill. In this situation, the Koljö Fjord basin water receives about twice the energy it receives at present from internal tides, while in the Havstens Fjord the energy was about one third to half of that at present. In the second scenario (Table 1), twice the Koljö Fjord tidal volume is filled from the western and northern sills, which means that there was a flow of one such volume to the Havstens Fjord over the eastern sill. This situation may be somewhat extreme since the flow resistance in the straits of the Koljö Fjord would be quite large. In this case the energy from internal tides should have been about 5 to 10 times greater than at present in the Koljö Fjord and about one third lower than at present in the Havstens Fjord.

From the computations presented above, we can say that the energy transfer to deep-water mixing from internal tides in the Koljö Fjord at present should be less than half that 2500 years ago, while the corresponding transfer should have increased somewhat in the Havstens Fjord. This means that there should be a trend of decreasing mixing in the Koljö Fjord and hence, a decreasing probability of deep-water exchange. In the Havstens Fjord, the trend should be the opposite.

However, these trends are not easily found in the sediment records of the fjords. Instead, there are obvious variations caused by climate fluctuations (Paper VI). It is interesting to note that the climatic variability has been so dominating that a long term significant change of energy from internal tides is not found in the sediment record. In future model calculations, the tidally-induced flow in the fjord system as well as fjord paleo-morphology will be considered for different periods to compute variations in the basin-water density. It should then be possible to quantify the climatic impact on the fjord environment in relation to the impact from internal tides.

MATERIAL AND METHODS

Work at sea was performed on board *R/V Arne Tiselius* and *R/V Skagerak.*

In this study, water and surface sediment samples were collected at five sites along a depth transect (12 to 43 m) in the Koljö fjord and at four sites along a depth transect (12 to 40 m) in the Havstens Fjord (Figure 1, Papers I and II). In the Gullmar Fjord, one site at 116 m depth was sampled (Paper III). Sampling was done monthly from August 1993 to December 1994, thus spanning both hypoxic and oxic conditions. Apart from sediment sampling, hydrographic data including salinity, temperature and oxygen content, were also obtained at each site during every sampling occasion. Monthly values of primary production (chlorophyll *a*) in the surface water in all three fjords were also available (Göteborgs och Bohusläns Vattenvårdsförbund årssammanfattning, 1993, 1994).

Sediment samples were collected with a multiple corer (Mark III-400), described by Barnett et al., (1984) and later modified by Barnett. Sediment colour was determined using the Munsell soil colour chart. The organic carbon and total nitrogen content of sediment was determined using a Carlo Erba NA 1500 analyser.

Temperature and salinity in the water column were recorded with a CTD-probe complemented with a rosette-sampler for water samples. To avoid contamination of resuspended sediments in the water samples, all samples were collected 1 m above the sediment surface. Water samples were analysed for salinity and oxygen content. The oxygen content was analysed by standard Winkler titration and salinity was measured with a high-precision laboratory salinometer (Minisal 2100). Optical landmarks and the DGPS navigation system were used to relocate the exact positions on every sampling occasion.

The sediment cores were sliced at 1 cm (75.4 cm^3) intervals down to 7 cm and each slice was preserved in an equal amount of 95% ethanol. To the sediment and ethanol mixture, 1 g/l of Rose Bengal was added overnight and the samples were then sieved through 1000 µm and 63 µm sieves. The samples were stored in 70% ethanol buffered to pH 9 with borax. All stained foraminifera in the 63 µm fractions were counted in each sample. In the Koljö Fjord the 63 - 100 µm fraction was counted separately. The foraminifera were picked up with a Pasteur pipette and dried at 20°C on a filter paper.

Sediment records

Short, high-quality sediment cores of were collected using a Multiple Corer Mark III-400 (Barnett et al. 1984), which gives a virtually undisturbed sediment surface. The core diameter was 100 mm and the tube length was 500 mm. For deeper penetration of the sea floor, a 4 m long piston corer with a diameter of 70 mm was used parallel with the multiple corer. After collection, the sediment cores were X-rayed on board the ship, using an Andrex BV (155 140kV/10mA) portable X-ray machine.

After X-raying, some of the cores were sliced at 1 or 2 cm intervals and analyzed for organic carbon, using a Carlo Erba NA 1500 analyser, as well as for foraminifera and dinoflagellate cysts and dated by the ^{210}Pb method and the AMS method.

Foraminiferal stratigraphy

After the sediment cores were X-rayed, they were sectioned in 10 or 20 mm slices. All samples were freeze-dried, washed over a set of sieves (1000 and 63 μm) and investigated for their foraminiferal content and approximately 300 randomly picked specimens where identified and counted in each sample. The sand-sized fractions (>63 μm) were dried and weighed to obtain an estimate of the sand content.

Dinoflagellate cyst analysis

Forty-four samples for dinoflagellate cyst analysis were taken at 1 cm intervals from one core from the Koljö Fjord encompassing depths from 0 to 43.5 cm. The samples were naturally moist and the palynological preparations were carried out at the Centre for Palynology, University of Sheffield, UK. In order to preserve and concentrate as many of the dinoflagellate cysts as possible, and to avoid any loss of the more fragile peridiniacean and congruentidiacean cysts (Dale 1976), the following technique was employed.

Each sample was dried and the resulting 'mud sheet' was crumbled to powder. The sample was weighed and approximately 2 g of material was utilised for further preparation. Samples were soaked in hot water with detergent with a short period (10-30 sec) of ultrasonic sound until disaggregated. All mineral matter was removed by separation in a heavy liquid (Zinc chloride solution, 1.96 g/cm3). The resulting residuals were strew mounted.

Stable isotopes

Stable isotopes δ^{18}O and δ^{13}C were analysed in foraminiferal shells from both Koljö Fjord and Havstens Fjord, at the Department of Marine Geology at Göteborg University. We used a VG Prism Series II mass spectrometer with a VG Isocarb preparation system. Isotope values are presented in per mill (‰) to the Vienna Pee Dee Belemnite standard (V-PDB). The equation from O´Neil et al. (1969), modified by Hays and Grossman (1991), was used to calculate the paleotemperature and for calculation of estimated δ^{18}O values. Estimated δ^{18}O values were calculated from instrumental salinity and temperature data from the Koljö Fjord and Havstens Fjord (40 m depth) which were provided by the Swedish Meteorological and Hydrographical Institute (SMHI) and the Bohuslän water Conservation Association (in Swedish: Göteborgs och Bohusläns Vattenvårdsförbund). In the equation, we used the relationship between salinity and $\delta^{18}O$ for this region (Frölich et al. 1988) to calculate paleotemperatures and to calculate estimated $\delta^{18}O$ values from temperature and salinity measurements. When calculating estimated $\delta^{18}O$ values, 0.27‰ was subtracted to convert the estimated value from SMOW (Standard Mean Ocean Water) to V-PDB (Bemis et al., 1998).

^{210}Pb dating

Sediment samples of 0.5-1 gram were completely dissolved using hot $HF/HNO_3/HCl$ in the presence of ^{209}Po, acting as a yield determinant for the ^{210}Pb daughter isotope ^{210}Po. The polonium isotopes were plated on polished nickel discs from dilute hydrochloric acid in the presence of ascorbic acid to complex iron. The discs were analysed for ^{210}Po and ^{209}Po using alpha spectrometry, counting over at least two days. The mass of each sample was corrected for its salt content by using known porosity and assuming a salinity of 28. Radium-226 was measured by gamma spectrometry in order to determine the supported ^{210}Pb levels.

Dating of the core was performed using the constant rate of supply (CRS) model (Appleby and Oldfield, 1978).

AMS dating

AMS dating was performed on intact bivalve shells from the Koljö Fjord and the Havstens Fjord records. The samples were analysed at the Ångström laboratory, Uppsala, Sweden. The ^{14}C age was transformed to calendar years by the use of the upgraded program from Stuvier and Reimer (1993) CALIB 4.2, which uses the 1998 international calibration datasets using a reservoir age of 400 years.

Instrumental records

The Swedish Meteorological and Hydrographical Institute (SMHI) and the Bohuslän water Conservation Association provided the hydrographical data including salinity, temperature and dissolved oxygen content. Positions of the monitoring sites are: 58°13’83N/11°34’80E in Koljö Fjord and 58°18’75N/11°46’40E in Havstens Fjord, which is about 0.5 km and 1.5 km from each coring site respectively. In the Gullmar Fjord, the monitoring site is 58°19’40N/11°32’82E. SMHI provided the air temperature data from the Vinga Island, located approximately 10 km west of the city of Göteborg (Gbg, in Fig. 1). Temperature data were treated by using a three-year moving average.

We have also calculated the three-year moving average of the North Atlantic Oscillation indices (NAO), January to March, as an indication of the predominating weather conditions during the winters of the investigated time interval. Most of the deep-water exchange events occur during these winter months.

Normalised monthly NAO-indices were taken from Web site http://www.cgd.ucar.edu/cas/climind/nao_monthly.html and as presented by Hurrell (1995).

SUMMARY OF PUBLICATIONS

Paper I:

The aim of this study was to find out how living benthic foraminifera react to hydrographic variations, periodic oxygen deficiency and variations in primary production. A uniquely long series of monthly hydrographic measurements was made from August 1993 to December, 1994, combined with sediment sampling along a (12-43 m) depth transect at five different sites. Monthly values of surface chlorophyll *a* were available. Periods of hypoxia to anoxia with one intervening period of oxic conditions, together with phytoplankton blooms, made it possible to achieve the aims of this study. Low salinity (<27‰) is the main reason for low foraminiferal diversity in the Koljö Fjord. At the deeper stations, hypoxic conditions cause even lower faunal diversity. During the autumn of 1993 we registered bottom water oxygen contents 1 m above the sea floor between 1.0 and 0.2 ml/l. A small foraminiferal population, dominated by *Elphidium excavatum clavatum, E. incertum* and *E. magellanicum,* was able to withstand these conditions.

During a major deep-water inflow in January 1994 the bottom-water oxygen content rose above 5 ml/l in the entire fjord area. Despite the well-oxygenated conditions at the deeper sites, the foraminiferal populations did not respond positively until about 3 months later, when the spring phytoplankton bloom was sedimented (Figure 3). This suggests that food shortage was the limiting factor for growth. Freshly deposited phytoplankton appear to be the significant triggering mechanism for foraminiferal population growth, when oxygen is not a limiting factor. In this study, we have clearly shown that, in certain situations and/or places, the general belief that foraminifera feed on organic-rich sediments or detritus (i.e. disintegrating organic material) is wrong. This investigation shows that *Elphidium excavatum clavatum, E. incertum* and *E. magellanicum* can react quickly to environmental change. Reproduction and growth from juvenile to adult occurred in less than one month, taking advantage of the rich food supply from sedimenting phytoplankton blooms.

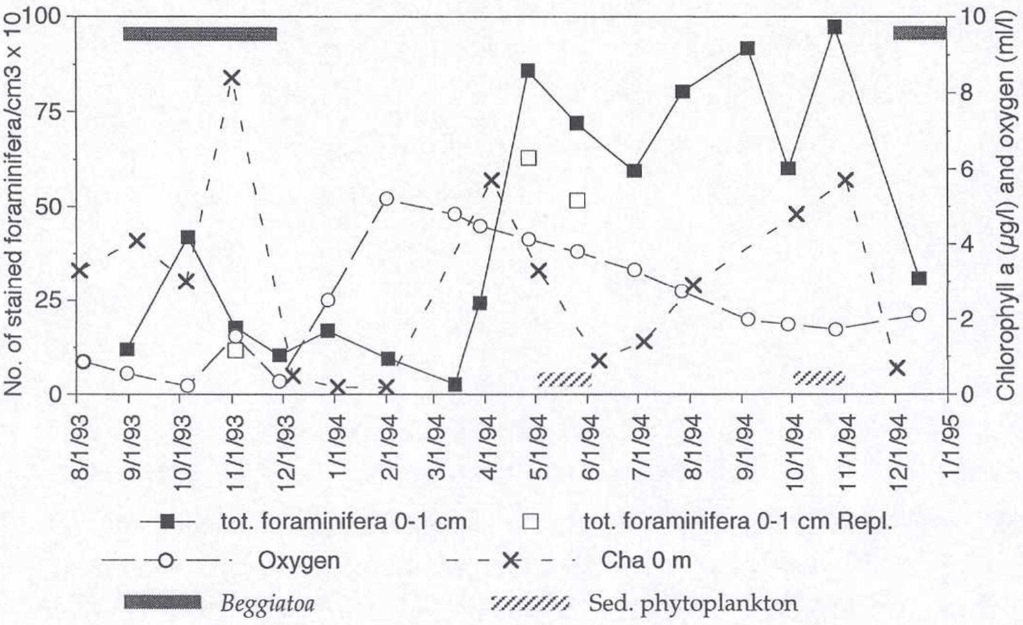

Figure 3 Summary diagram showing: total stained foraminifera per 10 cm^3 (0-1 cm depth) at 28 m depth in the Koljö Fjord (K28), bottom-water oxygen content, chlorophyll a *in the surface water, observed sedimentation events of phytoplankton and the occurence of* Beggiatoa *bacterial mats.*

Paper II:

From the shallowest station at 12 m depth in the Havstens Fjord to the deepest at 40 m, the marine environment changes from brackish and well-oxygenated conditions to near normal saline conditions and periods of low oxygen conditions. We have noted a clear succession, from shallow water towards deeper sites, of foraminiferal species that can withstand increased exposure to severe hypoxia or even anoxia. At the deepest station, H40, hypoxic or anoxic conditions are the most important reason for low foraminiferal diversity and abundance. Below the brackish surface water (>15 m), the dominating foraminiferal species is the low-oxygen-tolerant opportunistic species *Stainforthia fusiformis*. This species is able to withstand several months, severe hypoxia to anoxic conditions, while *Elphidium magellanicum*, followed by *Elphidium incertum* and *Epistominella vitrea*, seems to be slightly less tolerant (Figure 4). Other tolerant species are *Bulimina marginata, Buliminella elegantissima, Eggerelloides scaber, Leptohalysis catella, Quinqueloculina seminula* and *Spiroplectammina* *biformis*. At station H30 (30 m depth) the periodic hypoxia were severe enough to prevent a rich benthic macrofauna from establishing, but there was enough oxygen for a large and diverse foraminiferal fauna to thrive. Minor food competition and predation from benthic macrofauna at station H30, together with stable hydrographic conditions, explain the presence of the most abundant foraminiferal population within this study.

During oxic conditions, the availability of freshly sedimented phytoplankton is a major controlling factor for foraminiferal faunas, especially for the opportunistic species *S. fusiformis* (Figure 5).

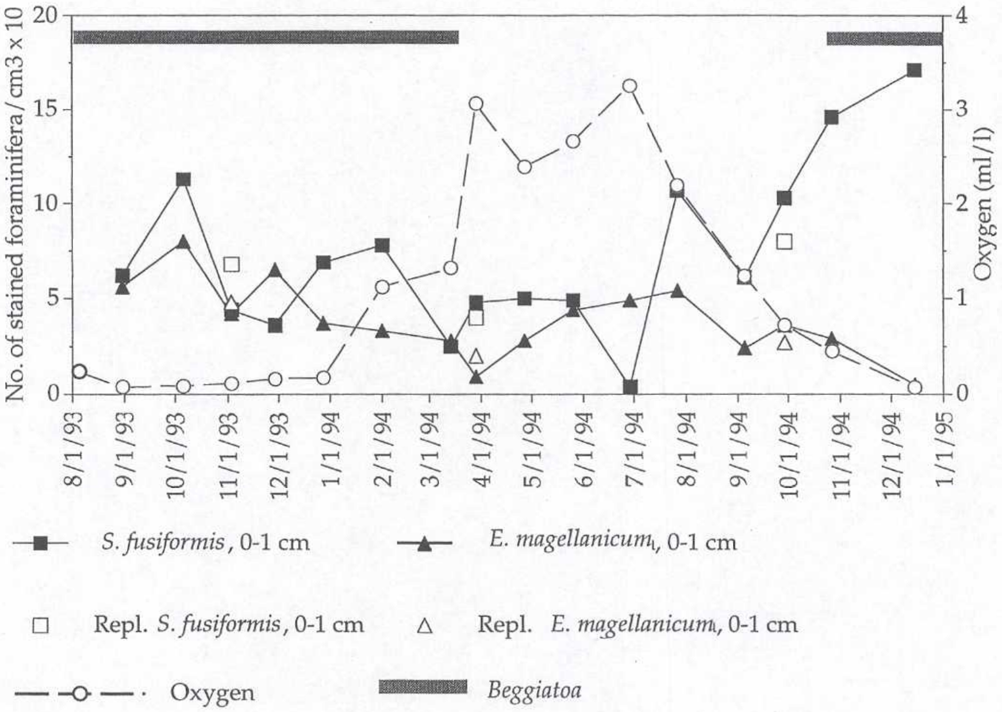

Figure 4 Summary diagram showing: stained S. fusiformis *and* E. magellanicum *per 10 cm*^{3} *(0-1 cm depth) at 40 m depth in the Havstens Fjord (H40), bottom-water oxygen content, chlorophyll* a *in the surface water, observed sedimentation events of phytoplankton and the occurence of* Beggiatoa *bacterial mats.*

Paper III:

Living (stained) benthic foraminifera were studied in the deepest part (116 m) of the classic marine investigation area, the Gullmar Fjord. After the spring phytoplankton bloom of 1994, the small and thin-shelled *Stainforthia fusiformis* was able to multiply its population size seven times in one month (Figure 6), while the larger and more thick-shelled species *Nonionellina labradorica* reached its maximum two months later. For most of the foraminiferal taxa, reproduction was probably triggered by a deep-water inflow and a temperature drop in the bottom water by

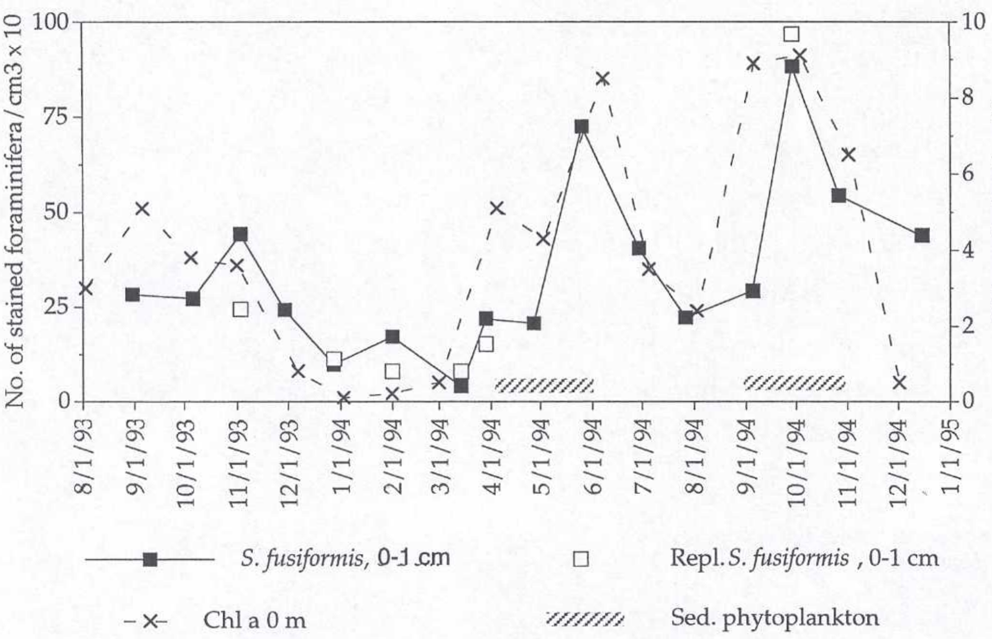

Figure 5 Summary diagram showing: total stained S. fusiformis *per 10 cm*^{3} *(0-1 cm depth) at 20 m depth in the Havstens Fjord (H20), chlorophyll a in the surface water and observed sedimentation events of phytoplankton.*

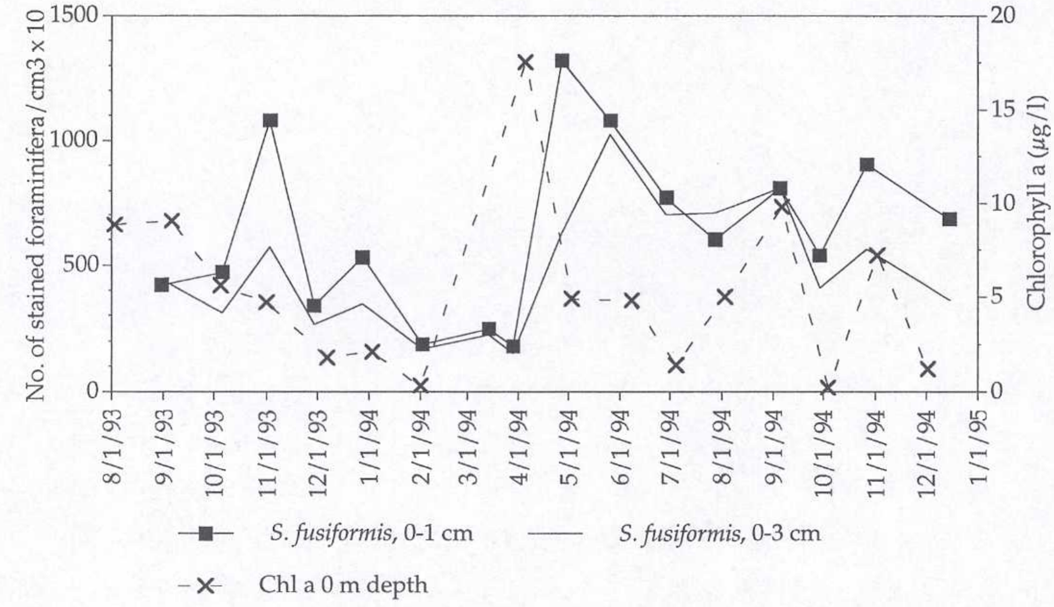

Figure 6 Summary diagram showing: total stained S. fusiformis *per 10 cm*^{3} *(0-1 and 0-3 cm depth) at 116 m depth in the Gullmar Fjord (G116) and chlorophyll a in the surface water.*

0.9°C in February 1994. The reproduction event was recognised as a temporal population decline of many taxa. When comparing this with Höglund's (1947) study of surficial sediments from the same area, it is clear that a major change in the foraminiferal fauna distribution has taken place since 1927. *Textularia earlandi, Eggerelloides scaber, Adercotryma glomerata, Haplophragmoides bradyi* and *Hyalinea balthica* dominated at that time but subsequently decreased or disappeared, together with several other species that are common in the Skagerrak and Kattegat region today. The low-oxygen-tolerant species *S. fusiformis* and *Bolivinellina pseudopunctata* have now become the dominating species. This faunal change coincides with a decreasing oxygen trend registered in the Gullmar Fjord deep-water where, since the mid 1970s, oxygen concentrations have frequently reached values below 0.5 ml/l.

Paper IV:

Several Scandinavian fjords and estuaries are subject to temporal hypoxia in the bottom water, leading to the escape of benthic macrofauna or benthic mortality. Since the late 1970s attention has been payed to oxygen deficiency in the bottom water of the classic marine biological and hydrographic investigation area, the Gullmar Fjord, on the Swedish west coast. The frequency of hydrographic measurements increased in 1980, so it is difficult to prove whether a declining oxygen trend in the instrumental record of the bottom water is real or not. By means of three ultra-high-resolution sediment records from the more than 100 m deep Alsbäck Depth in the Gullmar Fjord, we have established a foraminiferal record comprising the time interval 1930-1996. With a temporal resolution of only 1 year, we have documented a significant two-step faunal change during the mid 1970s and between 1979 and 1982. The foraminiferal faunas altered from a normal Skagerrak fauna to a characteristic, opportunistic low-oxygen fauna marked by an indicator species, *Stainfortia fusiformis* (Figure 7). This change shows that there has actually been a decrease in the oxygen content of the bottom water but if this is a trend or a change to a period characterized by temporal oxygen deficiency is not clear. The reason for this change is difficult to assess in detail but there is a striking concordance with the main features of the NAO-indices. During the seventies, these changed from mainly negative to mainly positive values. Translated into weather conditions, this alteration led to prevailing winter weather characterized by westerly winds, which normally prevent the exchange of bottom water in the fjords, and thus the oxygenation of the sea floor and the supply of oxygen to benthic life.

Paper V:

Since the late seventies, Scandinavian waters have been extensively investigated for human-induced marine pollution, especially marine eutrophication, oxygen deficiency in bottom waters and subsequent benthic mortality. Among the most serious oxygen deficiencies are those noted in the sill fjords along the Swedish west coast. One of these fjords, Koljö Fjord, is considered by marine scientists to be a good example of an eutrophicated fjord. The fjord is characterized by frequently occurring episodes of hypoxia/anoxia which last for months or even years. The anoxic conditions give rise to laminated sediments, which are preserved intact due to the lack of bioturbation. Here, for the first time, we present high-resolution sediment data together with long-term instrumental records of air temperatures, NAO-indices and hydrography from Koljö Fjord (Figure 8). These data show that the most important factors controlling the marine environment in this fjord over the last 200 years can be attributed to weather and hydrography, i.e. interactions between wind-driven water exchange and salinity.

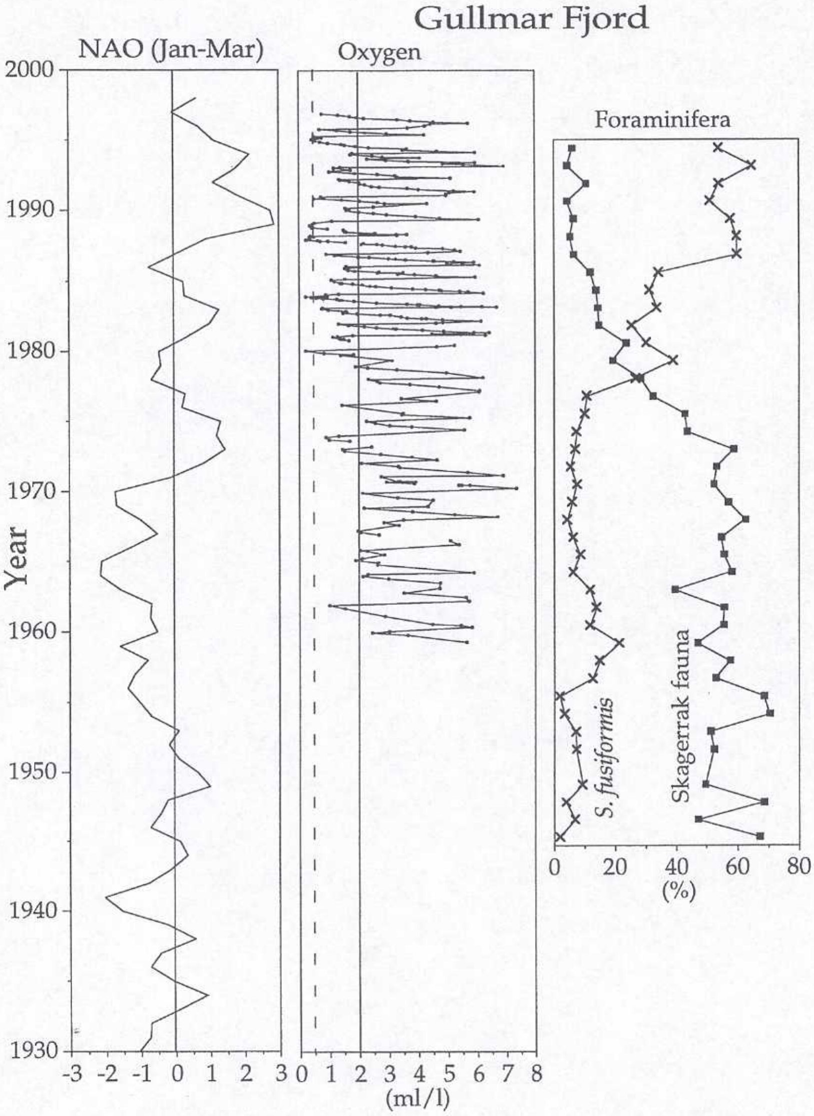

Figure 7. NAO-indices, oxygen time series from the Gullmar Fjord 119 m depth and foraminifera from one of three sediment cores. NAO-indices are filtered by a 3-years moving average. Skagerrak fauna includes species common in the Kattegat and the Skagerrak below the pycnocline, they are; Bulimina marginata, Cassidulina laevigata, Hyalinea balthica, Liebusella goësi, Nonionellina labradorica *and* Textularina earlandii

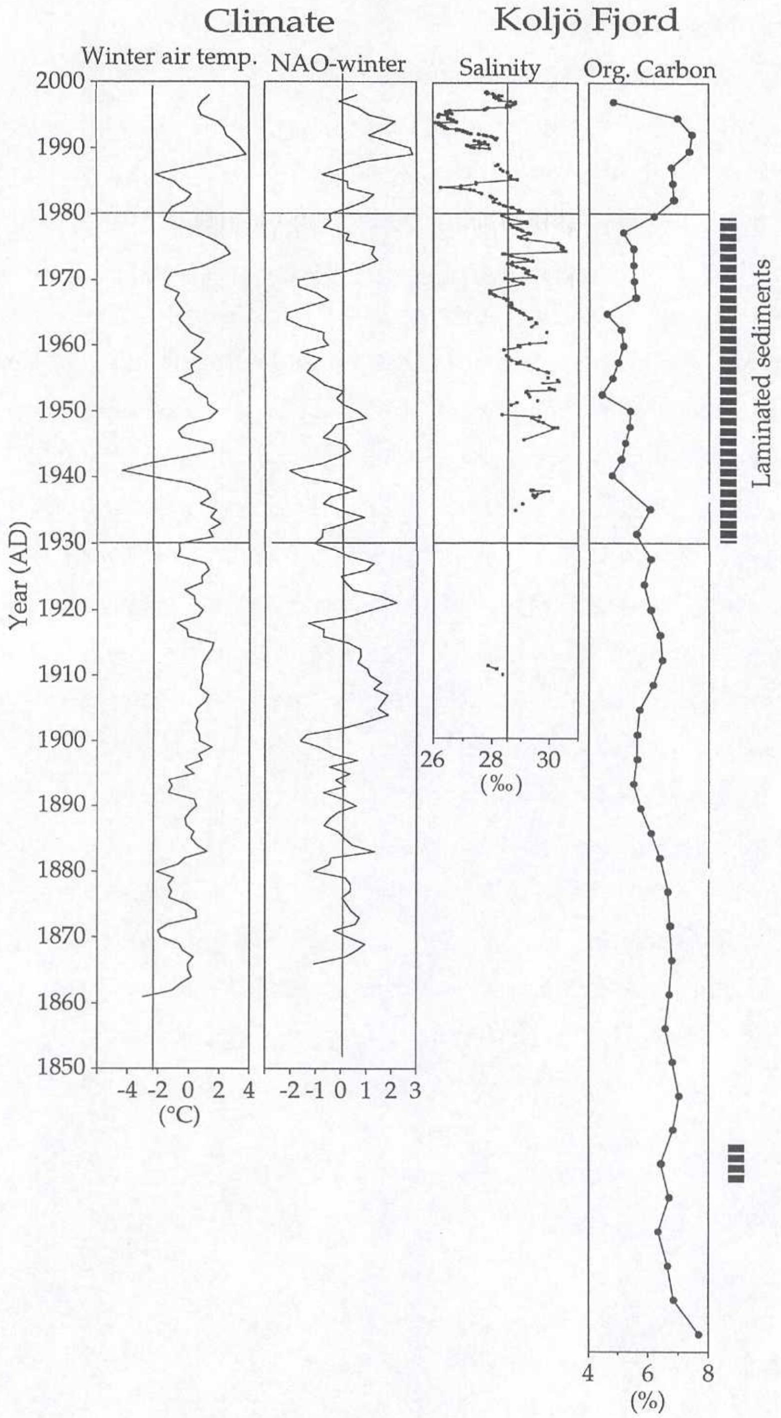

Figure 8 Composite diagram including air temperature data from Vinga island (three-year moving average), NAO-indices, winter values (three-year moving average), salinity data from the Koljö Fjord, sediment organic carbon from 40 m depth in the Koljö Fjord (K6A) and laminated sediment in core K6A.

Paper VI:

The fjord morphology and the sill have proved to be the most important factors controlling the fjord environment in the Koljö Fjord, but climatic factors are very important as well. In the Havstens Fjord, climatic variations have proved to be the main factor controlling the fjord environment, but here the climate appear to act more like a regulator of the primary production than a force influencing the temperature and salinity of the deep-water. More productive fjord conditions coincide with increased humidity, a phenomenon that has been observed in both fjords, in the past as well as currently. Abundant foraminiferal faunas, dominated by the opportunistic *S. fusiformis*, and increased organic carbon content suggest that increased run-off supplied the nutrients. In the Koljöfjord the decreasing sill depths, caused by the proceeding isostatic land-uplift, are the main explanation for the development of stagnant fjord basins. The most dramatic change occurred approximately 500 AD, when the Koljö Fjord became brackish, which happened when the sill crossed the 15 m water depth, which coincides with the mean level of the pycnocline. In recent times the formation of laminated sediments in both fjords is characteristic. In the Koljö Fjord laminated sediments have been formed between 1830 and 1860, between 1930 and 1980 and since 1996. These periods appear to coincide with increased salinities in the bottom water and strong pycnoclines. In Koljö Fjord, no evidence of human influence on the low oxygen conditions has been discovered. In Havstens Fjord, the lamination started considerably later, in approximately 1950 AD. In this fjord there is a general connection between climatic conditions and the fjord environment and we have not found positive evidence of human influence on the low-oxygen conditions. In Havstens Fjord, however, we can not exclude the possibility that human influence actually has an impact on the low-oxygen conditions but we are not able to distinghuish natural causes from anthropogenic effects here at present.

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