Recent changes in environmental conditions in the southwestern Kattegat, Scandinavia

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Short cores (20-30 cm) were taken from two sites in the southwestern Kattegat at similar water depths (<20 m; under the pycnocline) but with different exposures and resuspension rates (gross sedimentation rates: 3419 and 6275 g m^{-2} y^{-1}, net sedimentation rates: 469 and 479 g m^{-2} y^{-1}, respectively). They were dated by ^{210}Pb and analysed for their content of organic matter, bulk density, foraminifera, selected elements and grain-size distribution. Drastic changes in the foraminiferal fauna (from a nearly 100% agglutinated to about 75% hyaline fauna) as well as in bulk sediment density and contents of especially Ba (0.7-0.2%), Ca (0.8-4.0%), K (1.2-2.4%), Ti (0.3-0.5%) and Zr (0.3-0.16%) were observed in detail along one of the cores, at levels dated to the early 1970'ies. More summary foraminiferal and element analyses of two other cores taken below the pycnocline corroborate these observations. In contrast, there were no clear changes in the foraminiferal and element contents in a much more sandy core taken above the pycnocline.

During the past 30 years, daily wind observations and salinity measurements have shown a change in the local wind regime to a higher frequency of strong winds followed by an increase in salinity. Monthly oxygen measurements taken since 1976 have also shown a decline in the bottom-water oxygen concentrations. The present observations of down-core changes are explained by changes to more advection and a smaller local water mass oxygen content.

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Introduction

Paleoenvironmetal reconstruction and information on paleocirculation are commonly based on biological indicators (see Nordberg (1991), for a review of paleo-oceanographic conditions in the Skagerrak/-Kattegat over the last 8000 years). Similarly, Conradsen (1993), Conradsen et al. (1994) and Alve (1994) have used foraminifers to infer sub-recent and recent environmental conditions.

A number of non-biological indicators have, however, also been used to infer paleosalinity, i.e., to distinguish between freshwater and marine sediment deposition. Berner et al. (1979) showed good correlations between sediment FeS_2/FeS ratios and overlying water salinities. Also, Berner & Raiswell (1984) devised a C/S method to distinguish between freshwater and marine sediments, and C/N ratios were normally found to be much higher in terrestrial sediments than in marine sediments. Emelyanov (1982) showed that Na is generally fixed in larger quantities in marine than in freshwater sediments and that Mn, Ba and P contents in especially Baltic Sea sediments may serve as indicators for changes from lacustrine to marine environments. Recently, Christiansen et al. (1994) suggested that the relatively high Ca content in Kattegat surface sediments may be caused by inflows from the Skagerrak/North Sea. In line with such a suggestion, Christiansen & Kunzendorf (1995) found that high contents of Ca in Baltic Sea sediments correlated with known periods of strong inflow to the Baltic Sea. Additionally, sediments enriched in Mo are often regarded as indicative of anoxic conditions, e.g., as observed in the central and most H_2S-enriched parts of the Baltic Sea (Wedepohl 1978).

In this paper we present the results of studies on short sediment cores from the southwestern Kattegat. We then discuss both the biological and the non-biological evidence of near-recent to recent changes in environmental conditions in the southern Kattegat.

Study area

The study area in the southwestern Kattegat (Fig. 1) is situated in the transition zone between inflowing bottom water of high density (normal salinity) from the North Sea and outflowing low density (low salinity) surface water from the Baltic. The background concentration of suspended matter in the study area is lower than in the North Sea and higher than in the Baltic. Therefore, the concentration of suspended matter and the rate of sedimentation in the western part of the southern Kattegat are both highest when the area is dominated by an inflow of North Sea water (Lund-Hansen et al. 1993).

Because of the circulation, the water column has a strong pycnocline at a depth of 10-20 m in spring and summer (Stigebrandt 1983), whereas it is generally less stratified during autumn and winter.

Water depths vary between 10 and 15 m in the western and northern parts of the study area and between 20 and

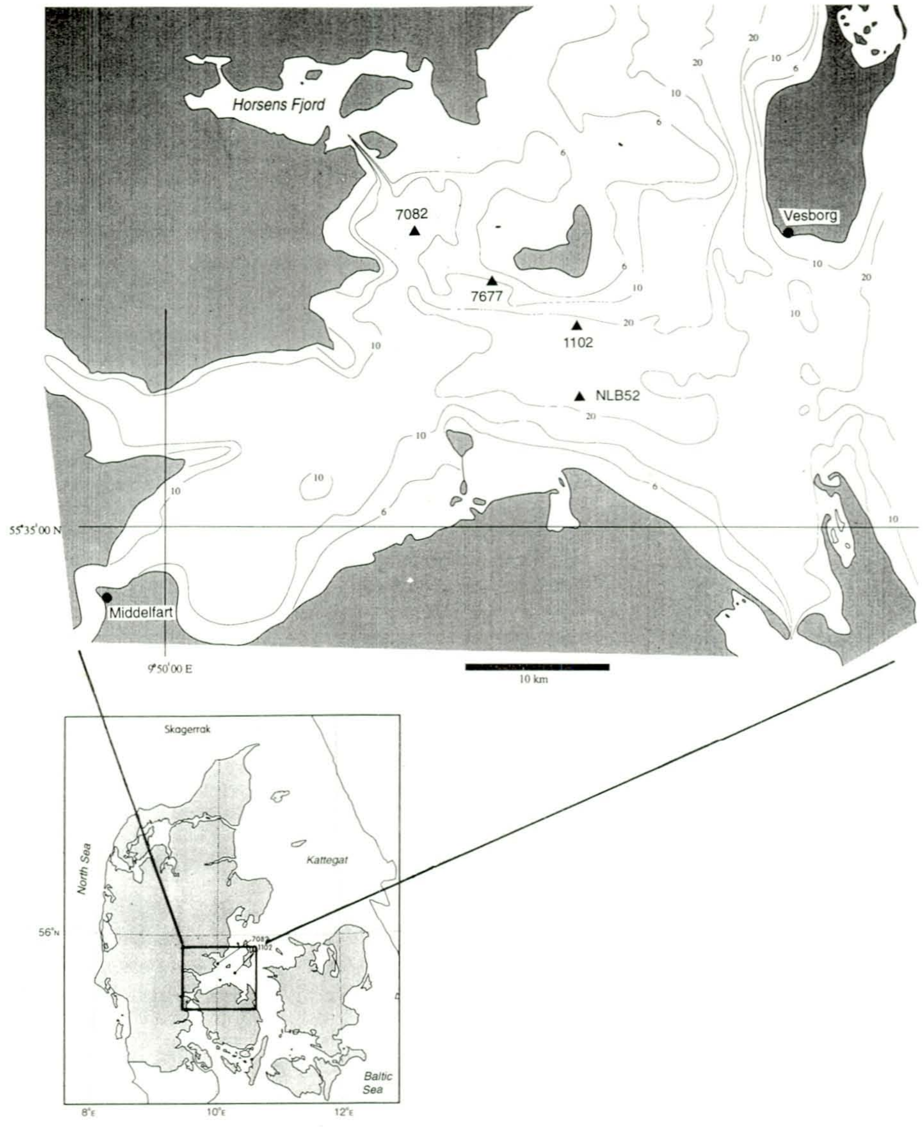

Fig. 1. Location map showing sampling positions and localities mentioned in the text.

25 m in its central part. Because of this depth distribution, wave-induced resuspension of the sediments is more frequent in the western and northern than in the central part (Floderus 1989, Christiansen et al. 1993). This results in pronounced depth-dependent grain-size distributions of sediments (Skov & Natur-styrelsen 1992). The tidal range is small (<0.4 m), and these relatively small sea-level variations are by far exceeded by meteorologically induced variations which may amount to 1.7 m above and 1.5 m below mean sea-level (Christiansen et al. 1981). Wind-induced mixing and resuspension are important factors in the nutrient cycling of the study area.

An increase in the concentration of organic matter (OM) in the youngest sediment (<300 yrs. BP) is commonly observed in cores from the Kattegat (Nordberg & Bergsten 1988, Christiansen et al. 1993). Seidenkrantz (1993) explained the OM increase in the eastern part of the Kattegat as a result of anthropogenic activity, and found that the distribution of foraminifers also was affected. Madsen & Larsen (1986) showed that surface sediments were generally enriched in trace metal concentrations by a factor of 2-3 for Zn, Cd and Pb, and 4-9 for Hg as compared to pre-1850 samples. Olausson (1975) also documented an increase in Cu, Ni, Zn and Po_4-P during recent decades.

In the Kattegat there is a north to south decreasing gradient in the content of Ca in the water column. Bernard & Van Grieken (1989), in their study of suspended matter from the Skagerrak to the Baltic Sea, found that the North Sea acts as a source of $CaCO_3$ for the Baltic Sea. On the other hand, Ingri et al. (1990) observed a rise in the suspended matter content of Ba in a profile from the Baltic Sea to the Danish Belt area.

Methods

Four short (20-30 cm) cores were obtained by a 'Haps' corer (Kanneworff & Nicolaisen 1973). Gamma-spectrometric measurements of ^{210}Pb, ^{137}Cs and ^{226}Ra were carried out on two of the cores using a reverse-electrode coaxial Ge-detector (10% rel. efficiency) with energy resolution values of 640 eV (at 5.9 keV) and 1.7 keV (at 1332 keV). Subtracting ^{210}Pb-supported activity, i.e. an amount equivalent to the ^{226}Ra activity, the unsupported activity $^{210}Pb_{unsup}$ is used to estimate linear sedimentation rates for the cores using the constant initial concentration (CIC) model of interpretation. Historical profiles were constructed using petrophysical core data and the constant rate of supply (CRS) model for lead-210.

The uppermost 15 cm of core 7082 were sliced into 1 cm samples, and the foraminiferal content quantitatively analysed according to standard methods (Meldgård & Knudsen 1979). Each sample (70-80 g) was washed in sieves with mesh-sizes 0.1 mm and 1.0 mm, a minimum of 300 specimens were counted and the material screened for additional species. Paleoecological parameters such as the number of specimens in a 100 g wet sample, the percentages of agglutinated/calcareous species and the foraminiferal accumulation rates have been used to interpret the ecological conditions. The other cores were only analysed at 4 levels down the cores.

Salinity has been measured daily in Middelfart since 1930 (Fig. 1). Data from this time series since 1950 were filtered by a 12 month moving average in order to eliminate seasonal salinity variations and detect possible long-term changes. Wind directions and velocities were measured every three hours at the Vesborg lighthouse (Fig. 1). The concentration of dissolved oxygen in the water column has been measured monthly in the study area since 1970 by Vejle County as part of a monitoring programme.

Results

Sediment changes

Sediment changes were studied in four cores taken below the pycnocline. Results presented here are mainly from station 7082, but summary results from the other cores corroborate the findings from station 7082. The ^{210}Pb dating yields a sedimentation rate of 3 mm y^{-1} which is equivalent to a net deposition rate of 469 g m^{-2} y^{-1} (CIC model). This is much less than the gross deposition rate 3419 g m^{-2} y^{-1} measured in sediment traps 4 m above the bottom, suggesting a significant amount of resuspension. There is a bend in the dating curve (CRS model, Fig. 2) situated at a level of about -80 mm down-core, which corresponds to the beginning of the 1970'ies. The bend is associated with a significant change in sediment bulk density. The bulk density is on average 1.4 g cm^{-3} below the -80 mm level and less than 1.2 g cm^{-3} above the -80 mm level (Fig. 2). Also observed is a high content of organic matter increasing from about 10% at the -75 mm level to about 14% at the surface. At the same time the grain size (88-92 % < 63m) does not change with depth.

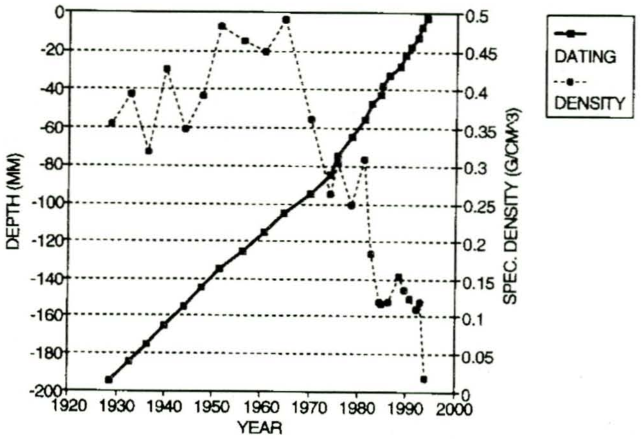

Fig. 2. Down-core datings (heavy line) of the sediments (core 7082). Also shown is the sediment bulk density as a function of time (dashed line).

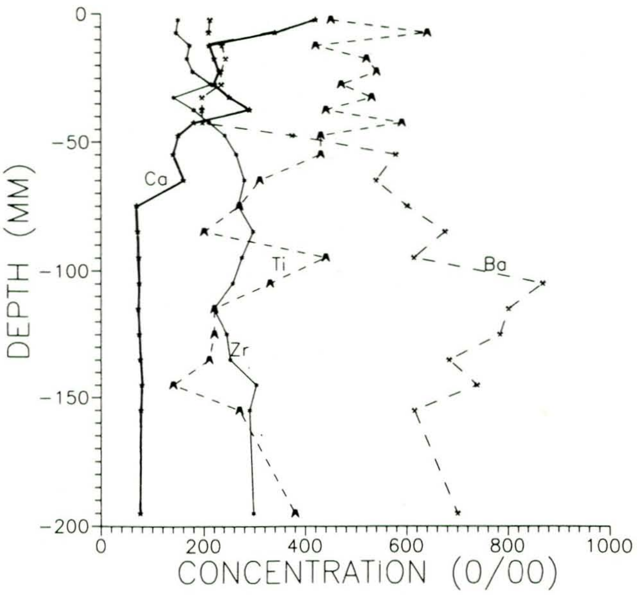

Fig. 3. Down-core variations in Ca, Ti, Zr and Ba concentrations (Station 7082). Note the strong changes in the core at 80 mm depth.

From the -80 mm level upward, there are also significant changes in the concentrations of a number of elements (Fig. 3). There is an increase in the content of Ca (from 0.8 to 4.2 %), K (1.2 to 2.4 %) and Ti (0.3 to 0.5 %). In contrast to this, Ba (0.7 to 0.2 %) and Zr contents (0.3 to 0.2 %) decrease. Other elements such as Fe, Zn, Rb, Sr and Y have also been analysed, but no significant changes in their concentrations are observed in sediments from the early 1970'ies.

One coarse-grained (16-20 % < 63m) core (station 7677) with a significantly lower organic matter content (1.2-1.4 %) taken at a water depth of 14 m, which normally is above the pycnocline, showed no clear systematic changes in element concentrations (Fig. 4).

Foraminiferal changes

The 15 analysed samples contain a total of 11 species, all benthonic. Five of these species have hyaline calcareous tests, while 6 species belong to agglutinated genera.

The analysed samples are divided into two zones; a

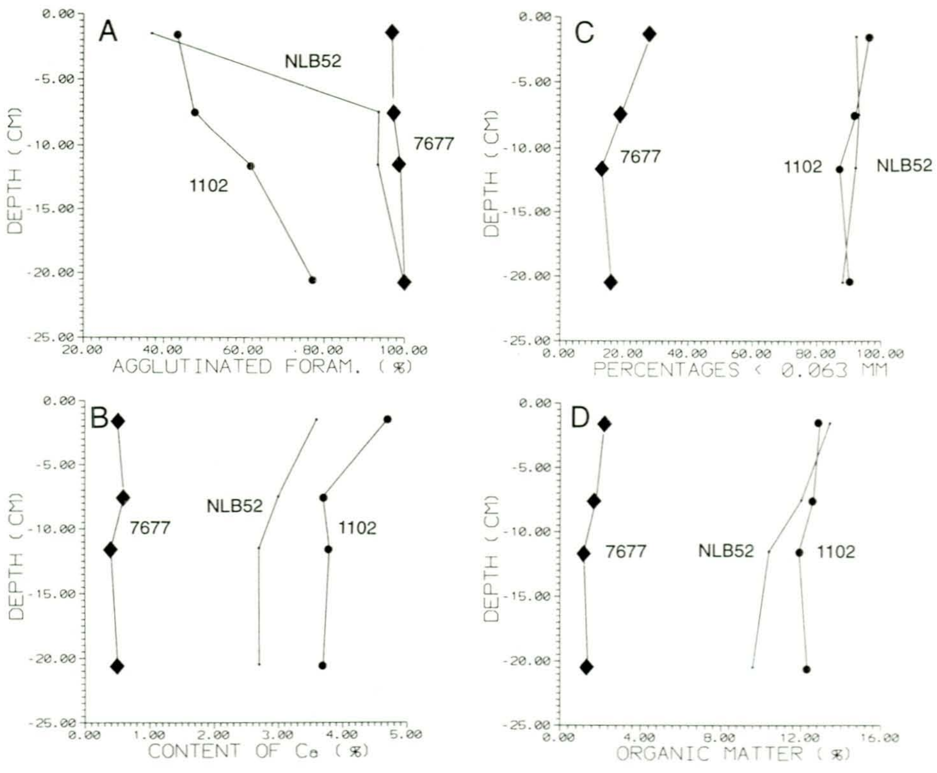

Fig. 4. Down-core variations at stations 1102, nlb52 and 7677 in A) Percentages of agglutinated foraminifera, B) Content of Ca, C) Grain-size, and D) Organic matter.

lower zone (Zone I) with faunal assemblages consisting of 60-99 % agglutinated specimens, and an upper zone (Zone II) with a content of calcareous specimens increasing to about 75% of the total fauna (Fig. 5a). The zonal boundary is placed at the -90 mm level, where the calcareous content increases from about 10 % of the total fauna to more than 30 %. However, the change to >50 % of calcareous specimens takes place at the -70 mm level. The 90-70 mm interval can thus be regarded as transitory.

Dissolution of calcareous tests commonly leaves behind a residue of free organic linings from certain species, and in the core 7082 all such linings appear to be from the species *Ammonia batava*. In Zone I, where the agglutinated species dominate, the content of free organic linings is around 6 per sample (70-80 g wet sediment), while immediately above the zonal boundary it rises to 25-30 linings per sample. Stratigraphically higher in the core the content of free organic linings declines, and above the -60 mm level they disappear. As the free organic linings are not counted as calcareous specimens, this suggests that the faunistic change from mainly agglutinated to mainly calcareous, in reality was less gradual than the range-chart (Fig. 5a) indicates. The apparently transitory interval, 90-70 mm, is thus included in Zone II.

The total number of species in each of the samples is fairly constant, between 7 and 10, and, except for the 130-140 mm sample, both the total number of specimens per 100 g wet sample and the total flux may also be considered as constant (Figs. 5A and 5B). The faunal assemblage in the 130-140 mm sample consists of 91% small, probably juvenile specimens of *Eggerelloides scabrus*, and the foraminiferal biomass at the time of deposition was probably the same in this sample as in the rest of the analysed samples.

Wind and hydrographical changes

An analysis of wind data from the Vesborg lighthouse (Fig. 6) shows that substantial changes in the frequency of strong winds have occurred especially during the last 20-30 years. The frequency of high-velocity winds (>11 m s^{-1}) has increased from less than 10% of the year in the 1960'ies to more than 15% of the year in the 1980'ies. During the same period of time, the frequency of even stronger winds (>19 m s^{-1}) has doubled from less than 0.5% to about 1% per year. The average prevailing wind direction has, however, remained around southwest. Southwesterly winds may increase the magnitude of the Jutland Current in the North Sea (Bolding 1991) and they may also favour the inflow of more highly saline bottom water into the Kattegat (Aarkrog 1988).

Average salinities in the study period (Fig. 7) also show a rising tendency, from 19.5 psu in the 1950'ies to 20 psu at present. It is evident from Fig. 7 that strong fluctuations in salinity prevailed up to 1970, but since 1970 salinity fluctuations have become smaller.

The average oxygen content of the August-October water column has gradually declined from about 8 mg l^{-1} in 1970 to about 3 mg l^{-1} at present. Oxygen deficiencies (< 4 mg l^{-1}) in the study area have also become more increasingly common and widespread since 1970 (Schwærter et al. 1990).

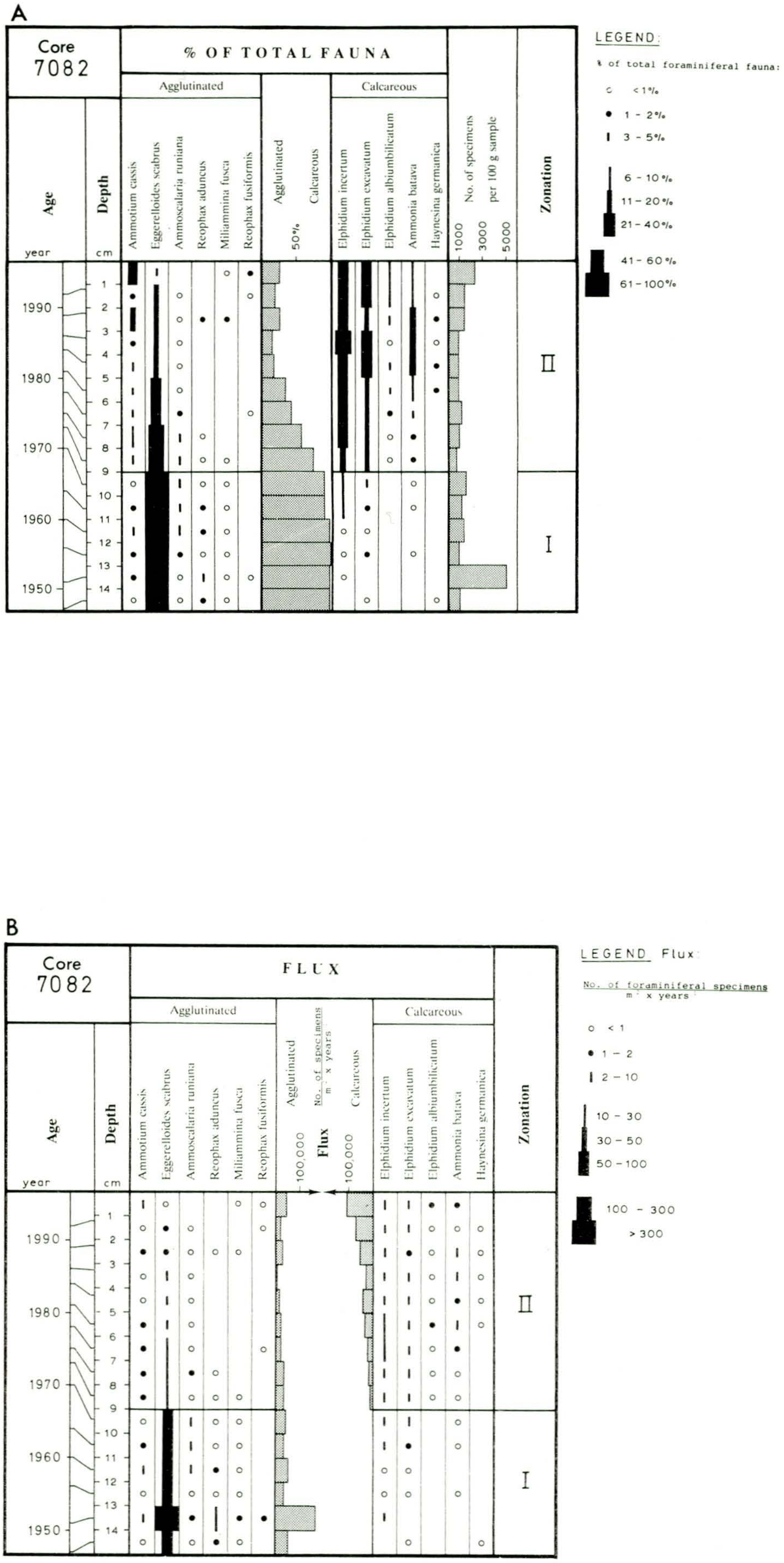

Fig. 5 (A). Range chart showing each foraminiferal species and the combined agglutinated species as percentages of the total fauna. The figure also contains the age of the samples, the total number of specimens in 100 g sample, and the zonation. (B). Range chart showing the yearly flux of each foraminiferal species, the combined agglutinated species, and the combined calcareous species per m^2. The figure also shows the age of the samples and the zonation.

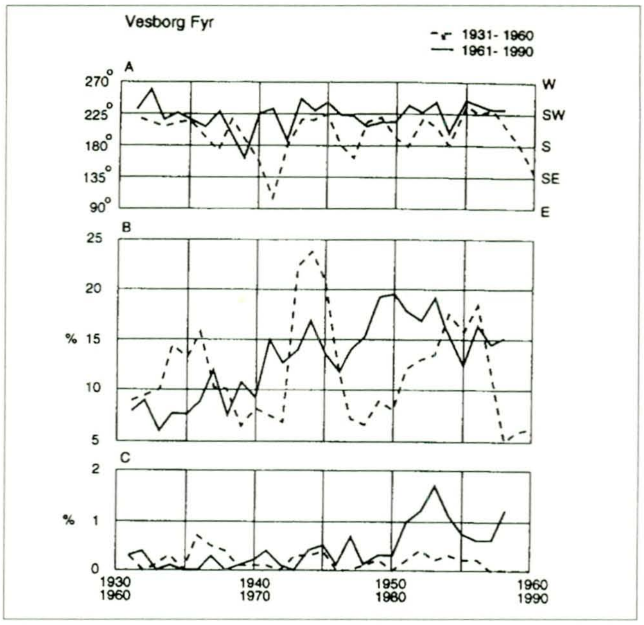

Fig. 6. Annual average wind direction (A) and frequencies of wind velocities exceeding 6 Beaufort (B) and 9 Beaufort (C).

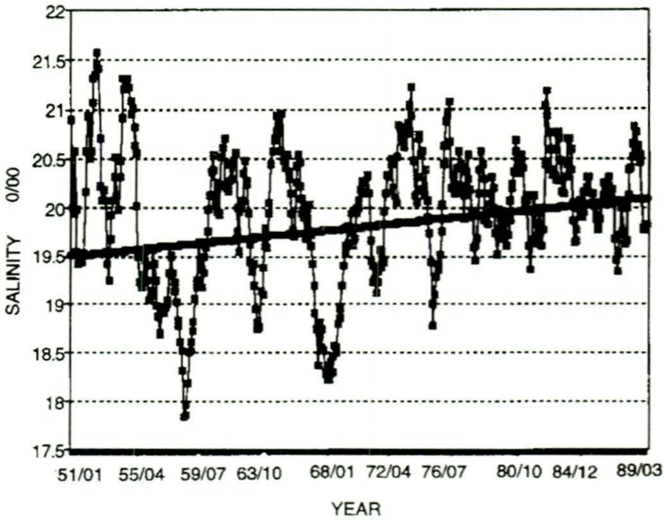

Fig. 7. Long-term monthly mean salinity variations in the period from January 1951 (51/01) to March 1989 (89/03). The data have been filtered with a 12-month moving average to remove seasonal variations. Also shown is the long-term trend (bold solid line).

Discussion

All the 11 foraminiferal species found in the samples are known to tolerate a wide range of environmental conditions such as salinity, temperature, bottom substrate, water-depth and oxygen content. Most of them are also commonly used as indicators of reduced (less than normal-marine) salinity and/or extreme conditions in cool, shallow water (Lutze 1965, Murray 1971, Olsson 1976, Alve & Nagy 1986, Alve 1990). Some, including the most abundant species *Eggerelloides scabrus*, are also known to tolerate various kinds of pollution (Alve & Nagy 1986, Alve 1990). Thus, considering the high tolerance of both the calcareous and the agglutinated species, there is no single obvious explanation for the faunistic change at the zonal boundary.

Faunal assemblages containing all or most of the 11 foraminiferal species have been found in the Baltic Sea (Lutze 1965) and also in estuaries in the Kattegat/Skagerrak area by, among others, Alve (1990). The faunal assemblages of Zone II are thus what could be expected, given the physical parameters. However, we raise the question as to why are there so few calcareous specimens in Zone I? One possibility is post-mortem dissolution of the calcareous tests, and the presence of free organic linings in Zone I indicates that some dissolution has indeed taken place. All the linings are from the species *Ammonia batava*, so apparently none of the *Elphidium* species produced preservable free organic linings.

According to Boltovskoy & Wright (1976), dissolution of calcareous tests takes place at pH < 7.8. The present pH-values are about 7.8 throughout the entire analysed sequence, but could have been lower during, or shortly after, the deposition of Zone I.

A constant calcareous content throughout the analysed core would create a major change in flux at the zonal boundary (Fig. 5b), but assuming that the *Ammonia/Elphidium* ratio was the same in Zone I as in Zone II, i.e. about 1:10, the number of calcareous specimens in Zone I may have been some 10-15 % higher than actually preserved. This assumption is not unreasonable, and the resulting increase in the flux is not high enough to demand an explanation; but the percentage of calcareous specimens would still be much lower in Zone I than above. It can therefore be concluded that the calcareous species apparently did not thrive during the deposition of Zone I.

One reason for this may involve the low Ca content in the sediment of Zone I, as compared with that in Zone II. Only a minor percentage of the chalk in the sediment was bound in the foraminiferal tests, but it may still have been difficult for the calcareous species to find enough accessible calcite. A second possible explanation may relate to the high tolerance for polluted environments by the strongly dominating *Eggerelloides scabrus*. The higher contents of Ba and Zr in Zone I may suggest a different kind of pollution before the 1970'ies.

A third explanation could be a change in the general hydrographic environment. In spite of the high tolerance of all the species, the palaeoenvironment of Zone I may be specifically suited for *Eggerelloides scabrus*, thus enabling this species almost completely to out-compete the other species; until a slight change, perhaps a different or stronger bottom current or a movement/weakening of the pycnocline, altered the situation in favour of the calcareous species. Such a change may be very slight, and need not show in the measured physical parameters.

The present interpretations of down-core changes in element distributions may be impeded by bioturbation effects. However, cores in which such effects could be seen were not considered here. Further, the study area is frequently struck by oxygen deficits, which places a limit on biological activity. Additionally, the abrupt down-core changes in Ca content (Fig. 3) are taken as indicating very limited bioturbation effects on our cores.

Most of the changes in the concentrations of elements which occurred at the beginning of the 1970'ies may be explained by advection. Bernard & Van Grieken (1989) showed that the North Sea acted as a source for Ca in suspended matter in the Kattegat and the Baltic. Christiansen et al. (1993) found a north to south decreasing gradient in bottom sediment Ca concentrations in the Kattegat. In a study from Århus Bay, Christiansen et al. (1994) reported high concentrations of carbonate-C in trapped sediments associated with the presence of highly saline water in the bay. Thus, the upward increase in Ca in our core suggests a stronger influence in the study area of water from the Skagerrak. The slight increase in Ti in sediments may also indicate a stronger influence of Skagerrak water. There are no local sources for this element but Schrader et al. (1994) have reported increased concentrations of Ti in the Skagerrak since about 1900. Ingri et al. (1990) observed a rise in the content of Ba in suspended matter in a profile from the Baltic Sea to the Danish Belt area. Consequently, the decrease in Ba at the beginning of the 1970'ies indirectly suggests a relatively greater inflow from the Skagerrak than outflow from the Baltic.

There has been a rising trend in salinity in the southern Kattegat since 1950, with fewer year to year fluctuations since the 1970'ies. The salinity measurements were carried out in the top 0-5 m of the water column. The rising trend could therefore indicate a reduced outflow of Baltic water. However, there is no such long-term trend present in the outflow of Baltic water through the Danish straits. The rising trend in surface-water salinity may also reflect more wind-induced entrainment of bottom waters into surface waters. However, the Middelfart site is situated in the northern part of the Lillebelt, where the water column usually is vertically homogeneous due to strong current-induced mixing. We therefore suggest that the observed rise in salinity is due to a general increase in advection. In the deeper parts of the study area, below the pycnocline, e.g. at station 7082, this means that bottom-water salinity must have increased. Such an interpretation is supported by the observed rise in the frequency of strong winds with a westerly component, as such wind directions favour inflow from the Skagerrak (Lund-Hansen et al. 1994).

The results of the present study therefore suggest that the observed sedimentological and biological changes in the southwestern Kattegat which mainly occurred at the beginning of the 1970'ies were possibly caused by a change in the advection system resulting from a general change to more frequent, strong westerly winds. In a recent study in the Skagerrak, Alve (1994) also reported on environmental changes taking place during the 1970'ies. Furthermore, Schrader et al. (1994) observed that, since 1900, chemical elements characteristic for the North Sea sedimentary system have been displaced in two steps from the southwestern Skagerrak towards the north and east. Also, Neuman et al. (1995) observed, in the sedimentary record, an increasing frequency of inflows to the Baltic Sea. Inflows at the beginning of the 1970'ies were strongly reflected in geochemical changes. To decide whether the 1970 changes discussed here were local, or whether they resulted from a single, more regional, environmental change, requires additional studies.

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