The benthic foraminiferal response to late Holocene climate change over northern Europe

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ABSTRACT

Calcareous benthic foraminifera from four cores from the southern flank of the Skagerrak (NE North Sea) were investigated in order to estimate the response of this fossil group to climate fluctuations during the upper part of the Holocene. Q-mode factor analyses were carried out for the most abundant taxa.

The results reveal *C. laevigata*, *H. balthica*, *M. barleeanus*, *G. turgida*, *B. marginata*, and *U. peregrina* as most common/important taxa. In the upper part of all cores *B. skagerrakensis* shows a significant increase and dominates the foraminifer fauna in cores from greater water depth. The data suggest no direct relation between the fluctuations of foraminifer assemblages and climate change. However, climate forced fluctuations in the strength of the water-circulation caused considerable changes in the foraminifer assemblages. Three major assemblages were used for environmental analysis: *H. balthica* dominated assemblages were identified as indicators for stagnant conditions. They characterize the oldest core sections, most probably the Holocene climate optimum. *Cassidulina laevigata* assemblages seem to indicate increasing current strength, a process that is often associated with deteriorating climatic conditions. *Brizalina skagerrakensis* appears to have a certain relation to unstable water masses, and probably a tolerance for increasing polution of the North Sea since the advent of modern industrialization.

INTRODUCTION

There is currently considerable debate about the present and future development of the earth's climate. While most climate modelers agree in that there will be a remarkable warming in the near future, the regional effect of global warming still is a major issue of discussion.

During the later part of the Holocene at least Northern Europe witnessed various minor climatic changes known as the Little Ice Age or the Medieval Warm Period which had tremendous effect on ecology and human society (Lamb, 1995; Schönwiese, 1994). Understanding of the consequences of such climate fluctuations is of highest importance since they mirror conditions which we are about to face in forthcoming years. A great number of investigations, including ice-core and tree-ring analyses in the first place, are presently concerned with late Holocene climate variations. The marine record, however, often suffers from bad resolution yet it is not obvious whether the benthos is reacting to minor climate change at all.

The Skagerrak is well known as the sink for suspended matter from the North Sea (Van Weering *et al.*, 1993). Major currents keep fine material in suspension until it is deposited where currents decelerate in the Skagerrak (Van Weering, 1981). In addition, great amounts of bedload sediment enter the Skagerrak area every year. The total amount of sediment being transported annually into the Skagerrak was estimated at 28.4 Mt (Van Weering *et al.*, 1987). Due to this high sediment accumulation some areas in the Skagerrak bear virtually complete geological records for the Holocene at very high resolution (e.g. Hass, 1996; Conradsen & Heier-Nielsen, 1995; Stabell &

Thiede, 1985; Jørgensen *et al*, 1981). Sediment cores chosen for the present study provide undisturbed records of the past 1-4 millennia with sedimentation rates ranging between 0.4 and 54 mm/yr which are well suited for high resolution paleoclimate studies of the late Holocene.

Previous investigations of these cores (granulometry, $\delta^{18}O$; Hass, 1993, 1996) revealed a distinct climate signal through a coupled atmospheric-hydrographic system, in which changing mean wind speed and direction are most likely to strengthen or weaken the water-mass circulation in the Skagerrak. The present study investigates the response of the calcareous benthic foraminifera to climate fluctuations basically through the past ca. 2,000 years. Although not much is known about the ecologic preferences of benthic foraminifera they are among the most powerful tools in stratigraphy. Recent studies (e.g. Alve & Murray, 1995; Altenbach, 1992; Murray, 1991) once more point out the close relationship between benthic foraminifer assemblages and the conditions of the surrounding water masses. The North Sea in general and the Skagerrak in particular appear to be well suited to study benthic foraminifer ecology as there are narrow zones of changing conditions due to the influence of changing water masses (see e.g. Alve & Murray, 1995; Conradsen *et al*., 1994; Seidenkrantz, 1993; Corliss & Van Weering, 1993; Qvale & Van Weering, 1985; Nagy & Qvale, 1985; Van Weering & Qvale, 1983; Jørgensen *et al*., 1981; Thiede *et al*., 1981; Kihle, 1971; Lange, 1956). Thus, many different environments can be sampled in a very small area.

THE SKAGERRAK

The Skagerrak is a deep glacio-erosive sedimentary basin (>700 m water depth) between the epicontinental North and Baltic Seas bordering SW Sweden, S Norway, and N Denmark (Fig. 1). As a result of the Pleistocene glacier's general SW flow direction, the cross-section through the basin is asymmetrical, with a steep northern flank and a smooth, convex southern flank (von Haugwitz & Wong, 1993). Davies (1980) attributes higher current speed over the S flank and lower current speed over the N flank, as measured during JONSDAP '76, to the asymetry of the basin.

Oceanography

Water-mass exchange in the Skagerrak generally runs counter-clockwise, guided by a prominent current system (Fig. 1). It is fueled by the Jutland Currents which transport water masses from the southern North Sea, the South Trench Current that adds northern North Sea and Atlantic waters, and the Baltic Current that enters the Skagerrak
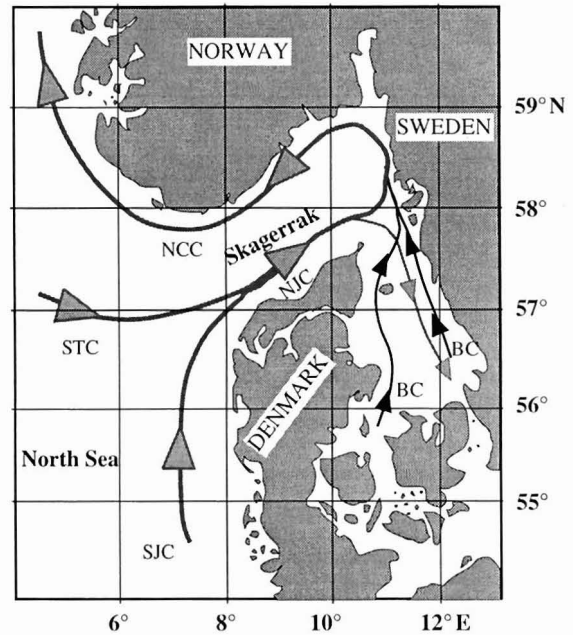
Figure 1. General circulation pattern of the Skagerrak (after Svansson, 1975 and Nordberg, 1989). SJC = South Jutland Current, NJC = North Jutland Current, STC = South Trench Current, BC = Baltic Current; NCC = Norwegian Coastal Current.

through the Kattegat, adding brackish Baltic Sea water into the westernmost part of the Skagerrak (Svansson, 1975). Furthermore, there is a deep counter current flowing through the Norwegian Trough into the deep Skagerrak. Its surface is marked by the 35 PSU isohaline (Dahl, 1978).

Surface currents change direction in the western Skagerrak and eventually leave the Skagerrak as the Norwegian Coastal Current which follows the southern Norwegian coast line. The bottom currents generally follow this cyclonic circulation pattern. Thus, inflowing water is generally constrained to the southern flank of the Skagerrak, whereas the outflow takes place over the northern flank (Larsson & Rodhe, 1979; Svansson, 1975; Figs. 1 and 2).

Ljøen (1981) differentiated 3 different water masses involved in the Skagerrak water-mass circulation: North Sea water (salinity 34-34.95 PSU), Atlantic water (salinity >34.95 PSU) and Skagerrak water (salinity <34 PSU). According to Rodhe (1987) salinity changes can be neglected below 250 m water depth (σ<0.1 PSU). Likewise, temperatures are more or less stable between 5 and 7° C below 250 m (Fonselius, 1989).

Sedimentation and climate development

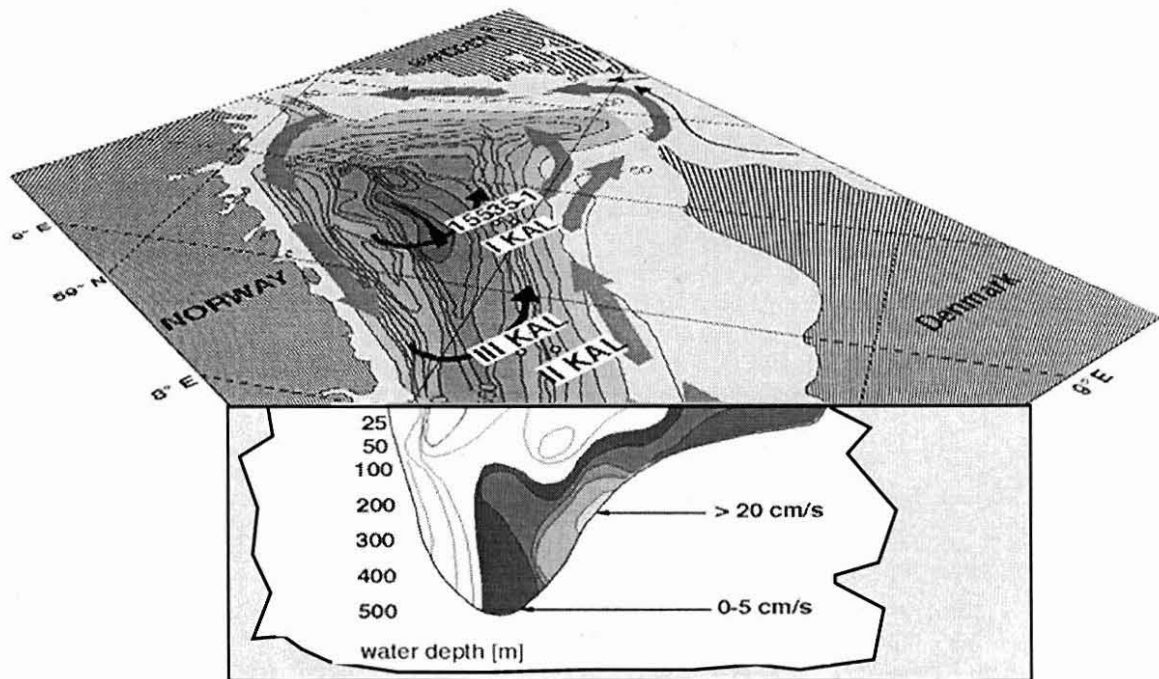There are few areas in the Skagerrak where erosion

Figure 2. Perspective map of the Skagerrak including directions of surface-currents, core locations (I, II, III KAL and 15535-1), and a current-speed profile (Hanstholm-Kristiansand, winter situation 1977, redrawn after Rodhe, 1979).

outweighs accumulation. These areas are situated on the southern flank under the influence of the Jutland Current. In these areas Quaternary tills and even Mesozoic strata crop out, blown free of sediment by intensive bottom current action (Salge & Wong, 1988; Van Weering, 1981; Sellevoll & Aalstad, 1971).

In places where sedimentation takes place (which includes most of the Skagerrak) sedimentation rates are generally high (Hass, 1996; Van Weering, 1987; Erlenkeuser & Pederstad, 1984). Extremely high sedimentation rates, especially in the eastern Skagerrak, are due to strong current activity, which transports high quantities of suspension load over the southern flank of the Skagerrak. Great amounts of bedload and suspended sediment carried by strong currents are deposited in the eastern and inner Skagerrak, where currents decelerate and dump large quantities of sediment. Sedimentation rates over the northern flank are significantly lower because of the generally lower current speed.

The Skagerrak is situated in the climate sensitive, boreal area well under the influence of the northern hemisphere main westerly wind stream. A close relation between the atmospheric and oceanic circulations has been suggested by various oceanographers (e.g. Fonselius, 1989; Rodhe, 1987). Hass (1993, 1996) was able to show a relation between the effects of atmospheric forcing on the

Skagerrak water-mass circulation and the sedimentary record of the past 3,000-4,000 years (see also Hass & Kaminski, 1994). It appears that increased current speed is induced during periods of probable stormy zonal (W to E) atmospheric circulation patterns over the North Atlantic and North Sea leading to a general coarsening of the sediment, and increased sedimentation rates at least in the eastern Skagerrak. Such events were most frequent during colder periods.

Warmer phases, however, are characterized by calmer meridional to zonal atmospheric circulation patterns which are likely to cause water mass circulation to slow down. Thus, during warmer periods less sediment is transported over the southern flank. Due to the lower current speed, a proportion of the sediment is able to settle further to the West, resulting in decreased sedimentation rates in the eastern and central Skagerrak. The granulometric composition also suggests a fining of the sediments as coarser grains can no longer be transported.

During the later part of the Holocene various climate periods affected the North Atlantic-North Sea region, which likewise had a significant influence on the Skagerrak system (basically derived from granulometric and stable isotope analyses). The following climate periods are compiled after Lamb, 1995, 1977; Schönwiese, 1994, 1979; Fairbridge, 1987, and the results of previous work on the cores presently studied (Hass, 1996). The

Subboreal climate optimum (until ca. 1300-1200 BC) and the Subatlantic climate deterioration (until ca. 300 BC) appear to have left only indistinct traces in the sediments of the Skagerrak, whereas the Roman climate optimum and a colder period between ca. 400 and 700 AD are sufficiently documented. The subsequent Medieval Warm Period is characterized by generally lower sedimentation rates and finer sediments, which point to calm atmospheric conditions over the area; slightly increased water temperatures are suggested by the stable isotope record. The onset of the Little Ice Age has been set between 1300 and 1400 AD. There are three distinct intervals of the Little Ice Age, the first and last being stormy and rough, whereas the middle phase was likely to have been calm but exceptionally cold.

The magnitude of atmospheric forcing mainly from strong westerly winds has been related to the movement and position of the North Atlantic cyclone tracks (to the south during cold phases, to the north during warm phases. See e.g. Lamb, 1969). Around 1900 AD at the termination of the Little Ice Age the cyclone track zone moved back beyond the northern limits of the Skagerrak system, signalling the beginning of the Modern Climate Optimum.

MATERIAL AND METHODS

In 1991 three long cores (4.5-8 m) were taken from the southern flank of the Skagerrak during a cruise of RV „Planet" (see Tab. 1 and Figs. 1 and 2 for details). One additional core (15535-1), taken 1980 on board the RV „Poseidon", was chosen to complete the core material. At least one box core was taken from each station in order to obtain undisturbed surface samples.

The cores were opened, described, photographed and sub-sampled onboard (except for Core 15535-1). Surface samples (approximately 1 cm thick) were taken directly from the box cores. Further subsamples (0.7 cm wide; in 4 and 8 cm intervals, respectively) were taken in the laboratory later on for granulometric analyses. Once the granulometric analyses (via settling tubes) were completed the residual coarse fractions were used for further micropaleontologic analyses.

A total of 322 samples were micropaleontologically analyzed. The coarse fractions were dry-sieved into 4 fractions (ϕ 4-1) using a sonic sifter. Each of the fractions 125-250 μm (ϕ 3-2), 250-500 μm (ϕ 2-1), and >500 μm (<ϕ 1) were split to an appropriate size using a micro-splitter and then separately analyzed. In each of the fractions an average of 250 to 300 specimens of benthic foraminifera were identified and counted. If there were fewer than 250 specimens, the entire fraction was analyzed. The data from single fractions of each sample were then recombined for further analyses. Percentages given in the following refer to percent of the total foraminiferal fauna (fraction >125μm).

Q-mode factor analyses were carried out using the program MacCabfac (Imbrie & Kipp, 1971; Klovan & Imbrie, 1971). Two different types of analysis were run: (A) an overall analysis with all cores stacked to one data set, and (B) separate analyses of each individual core (however, not including the corresponding box cores). Run (A) provides basic information for a comparison of the benthic foraminifer assemblages from all cores. The large data set, however, blurs individual differences between assemblages in individual cores. In order to elucidate these core-specific differences and to control run (A), run (B) was carried out. For the factor analysis, frequency percentages of the most common 25 foraminiferal taxa (run (A)) and the most common taxa in the individual cores (run(B)) were used. Run (A) factors will be referred to as „O-factors" (overall factors), run (B) factors as „I-factors" (individual factors). For run (A) the program was configured to 6 factors; for run (B) it was set to 4 factors.

AGE DETERMINATIONS

Age determinations for the past 3,000-4,000 years were carried out using the advanced ^{210}Pb method described by Erlenkeuser & Pederstad (1984), Erlenkeuser (1985), and Hass (1996). The results of the age dating procedure are thoroughly described by Hass (1996). Fig. 3a and 3b depict simplified age/depth relations for the cores studied. They

Table 1. Background information on the cores used for this study.

Core (RV)	Position	Water depth [m]	Core length [cm]	Corer
15535-1 (Po)	58°04.90'N 9°37.00'E	428	800	KL
15535-2 (Po)	58°04.90'N 9°37.00'E	427	70	RL
V GKG (Pl)	58°04.55'N 9°37.21'E	422	34	GKG
I KAL (Pl)	58°02.03'N 9°37.15'E	320	507	KAL
I GKG (Pl)	58°02.3'N 9°37.15'E	320	46	GKG
II KAL (Pl)	57°46.4'N 8°42.7'E	245	539	KAL
II GKG (Pl)	57°46.4'N 8°42.7'E	245	28	GKG
III KAL (Pl)	57°50.3'N 8°42.4'E	450	485	KAL
III GKG (Pl)	57°50.3'N 8°42.4'E	450	40	GKG
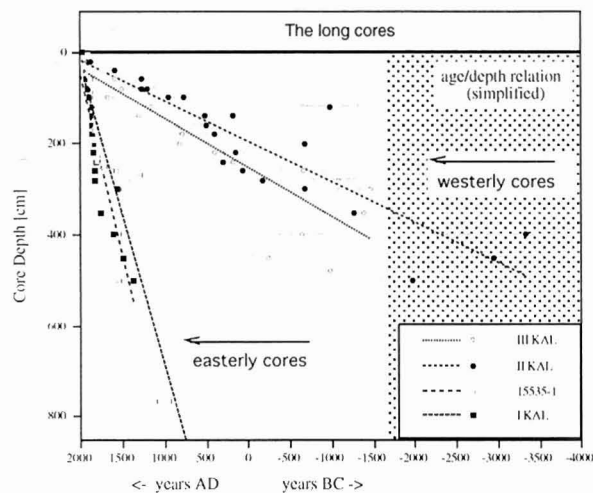
Figure 3a. Simplified age/depth relation for the long easterly (15535-1, I KAL) and the westerly (II, III KAL) cores. For more details see Hass (in press). Shaded area marks dating limit. Note strong differences in general sediment accumulation between easterly and westerly cores. (^{210}Pb-measurements: C14 Laboratory, Kiel).
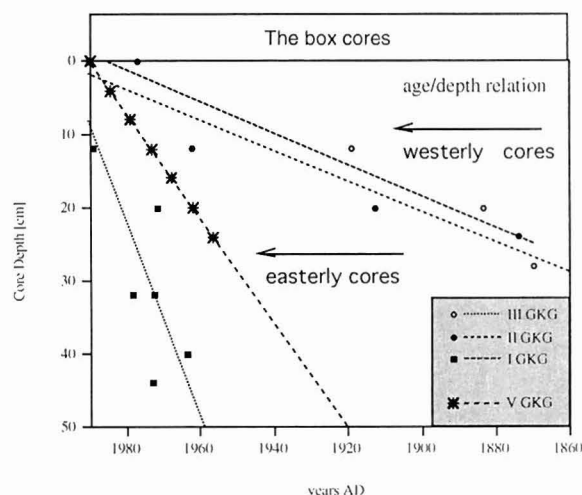
Figure 3b. Simplified age/depth relation for the long easterly (15535-1, I KAL) and the westerly (II, III KAL) cores. For more details see Hass (in press). Shaded area marks dating limit. Note strong differences in general sediment accumulation between easterly and westerly cores. (^{210}Pb-measurements: C14 Laboratory, Kiel).

show the remarkable difference in sediment accumulation between the easterly (high) and the westerly (low) stations.

TAXONOMY

For this study ca. 50 taxa of more than 130 taxa

Table 2. The most important foraminifer species, including references used for identification

Brizalina skagerrakensis **(Qvale & Nigam, 1985)**
as *Bolivina skagerrakensis* in Qvale & Nigam (1985)
Pl. 1, Fig. 1-11, Pl. 2, Fig. 1-10 in Qvale & Nigam (1985).
Pl. 7, Fig. 17 in Feyling-Hanssen *et al.* (1971) (as *Bolivina* cf. *Bolivina robusta* Brady).

Bulimina marginata **d'Orbigny, 1826**
Pl. 6, Fig. 17-20 in Feyling-Hanssen *et al.* (1971).
Pl. 14, Fig. 12 in Gabel (1971).

Cassidulina laevigata **d'Orbigny, 1826**
Pl. 7, Fig. 20-21 in Feyling-Hanssen *et al.* (1971).
Pl. 17, Fig. 7-9 in Gabel (1971).

Cassidulina reniforme **Nørvang, 1945**
Pl. 1, Fig. 7 in Hald & Vorren (1987).

Cassidulina spp. group: see text.

Cibicides lobatulus **(Walker & Jacob, 1798)**
Pl. 9, Fig. 9-14 in Feyling-Hanssen *et al.* (1971).
Pl. 18, Fig. 32-34 in Gabel, (1971).

Elphidium excavatum **Terquem, 1875**
Pl. 11, Fig. 10-13 (as *E.clavatum* Cushman) in Feyling-Hanssen *et al.* (1971).
Pl. 13, Fig. 10-11 (as *Cribrononion excavatum* Terquem) in Gabel (1971).

Elphidium spp. group: see text.

Fissurina spp.: *Lagena*spp.-*Fissurina* spp.-*Parafissurina* spp. group, see text)

Globobulimina turgida **(Bailey, 1851)**
Pl. 6, Fig. 23 in Feyling-Hanssen *et al.* (1971).
Pl. 14, Fig. 21 in Gabel (1971).

Hyalinea balthica **(Schroeter, 1783)**
Pl. 9, Fig. 7-8 in Feyling-Hanssen *et al.* (1971).
Pl. 18, Fig. 22-23 in Gabel (1971).
Pl. 18, Fig. 24-29 (as „*H. aberrante* Mutationen") in Gabel (1971).

Islandiella helenae **Feyling-Hanssen & Buzas, 1976**
Fig. 1-4 in Feyling-Hanssen & Buzas (1976).
Pl. 17, Fig. 25-26 in Gabel (1971) (as *Cassidulina teretis* Tappan).

Lagena spp.: *Lagena* spp.-*Fissurina* spp.-*Parafissurina* spp. group, see text.

Melonis barleeanum **(Wiliamson, 1858)**
as *Melonis barleeanus* in Seidenkrantz & Knudsen (1993)
Pl. 4, Fig. 6 in Struck (1992)
Pl. 9, Fig. 15-18 (as *Nonion barleeanum* Williamson) in Feyling-Hanssen *et al.* (1971).

Nonion labradoricum **(Dawson, 1860)**
Pl. 10, Fig. 1-2 in Feyling-Hanssen *et al.* (1971).

Parafissurina spp.: *Lagena* spp.-*Fissurina* spp.-*Parafissurina* spp. group, see text.

Planorbulina mediterranensis **d'Orbigny, 1826**
Pl. 4, Fig. 1 in Schiebel (1991).
Pl. 19, Fig. 18-20 in Gabel (1971).

Pullenia bulloides **(d'Orbigny, 1826)**
Pl. 10, Fig. 13-14 in Feyling-Hanssen *et al.* (1971).
Pl. 17, Fig. 39-40 in Gabel (1971).

Pullenia subcarinata **(d'Orbigny, 1839)**
Pl. 18, Fig. 7-8 in Feyling-Hanssen *et al.* (1964).
Pl. 17, Fig. 37-38 in Gabel (1971).

Quinqueloculina spp.

Rosalina williamsoni **d'Orbigny, 1826**
Pl. 16, Fig. 12-14 in Gabel (1971).

Stainforthia fusiformis **(Williamson, 1858)**
Pl. 14, Fig. 15-18 (as*Virgulina fusiformis* Williamson) in Feyling-Hanssen (1964).

Trifarina fluens **(Todd, 1947)**
Pl. 7, Fig. 12-15 in Feyling-Hanssen *et al.* (1971).
Pl. 15, Fig. 17-18 in Gabel (1971).

Triloculina spp.

Uvigerina peregrina **Cushman, 1923**
Pl. 7, Fig. 9-11 in Feyling-Hanssen *et al.* (1971)
Pl. 15, Fig. 27-29 in Feyling-Hanssen (1964).

Qvale & van Weering (1983) identified in samples from all over the Skagerrak were identified. The following list comprises the most important species, including references used for identification.

Specimens of *Stainforthia fusiformis* were often found to be sticking together in chains and clusters of different number and size glued by organic material. It was often impossible to separate them, thus counts of *Stainforthia fusiformis* may be partly incorrect or incomplete.

According to previous studies (e.g. Nagy & Qvale, 1985; Van Weering 1982; Lange, 1956; Alve & Nagy, 1990; Jørgensen *et al.*, 1981) many taxa are not relevant for paleoclimatic investigations. Furthermore, low percentage values of single rare taxa (close to 0, or even 0 in various samples) are likely to distort the results of the factor analysis. It was, therefore, attempted to group some of the taxa in order to prepare suitable data matrices. Although they mostly do, the taxa within these groups do not necessarily have ecologic or taxonomic connection. The following groups were formed:

The *Islandiella helenae - Cassidulina* spp. group
This cassidulinid-group is composed of *Cassidulina laevigata*, which dominates the group with an average percentage of 98%. *Islandiella helenae* (=*Cassidulina teretis* before 1976), *C. crassa*, and *C. reniforme* are present in insignificant numbers, thus, they were combined into the *Islandiella helenae - Cassidulina* spp. group. Studies of Nagy & Qvale (1985), Van Weering (1982), and others suggest that within the time period studied in this paper the Arctic species *Islandiella helenae*, *C. crassa*, and *C. reniforme* are very rare to absent in sediments of the Skagerrak.

The *Elphidium* spp. group
The *Elphidium* spp. group is dominated by *Elphidium excavatum*. Other *Elphidium* species occur sporadically, but do not represent a significant portion of this group.

The planktic foraminifer group
Due to their very small numbers, planktic foraminifera were not further determined.

The agglutinated foraminifer group
Agglutinated foraminifera were only poorly preserved, thus, the remains were partly indeterminable (see also Hass, *this volume*).

The *Lagena* spp.-*Fissurina* spp.-*Parafissurina* spp. group
This group was actually composed of 3 groups (*Lagena* spp., *Fissurina* spp., and *Parafissurina* spp.)

which all showed very low percentages. The species were not further determined.

The *Triloculina-Quinqueloculina* group
Only in very few samples of the entire data set *Triloculina* spp. and *Quinqueloculina* spp. together made up slightly more than 2%. Since both genera mostly occurred together, the *Triloculina-Quinqueloculina* group was established.

RESULTS
Benthic foraminifera form the major part of benthic life in the Skagerrak. Only the most important foraminiferal taxa will be discussed here. These make up between 100% (maximum) and 94% (minimum) of the total benthic foraminifer fauna. In the following the characterizing species or group is underlined.

After convention the statistical level of confidence for correlation analyses is at 0.5 (correlation coefficient) (Backhaus *et al.* 1990). In order to obtain a clearer overview this value was raised by 0.2, thus the following figures (4 and 5) only show factor loadings >0.7. The results of the O-factor analysis are compared to the results of the I-factor analyses vs. core depth for each of the cores.
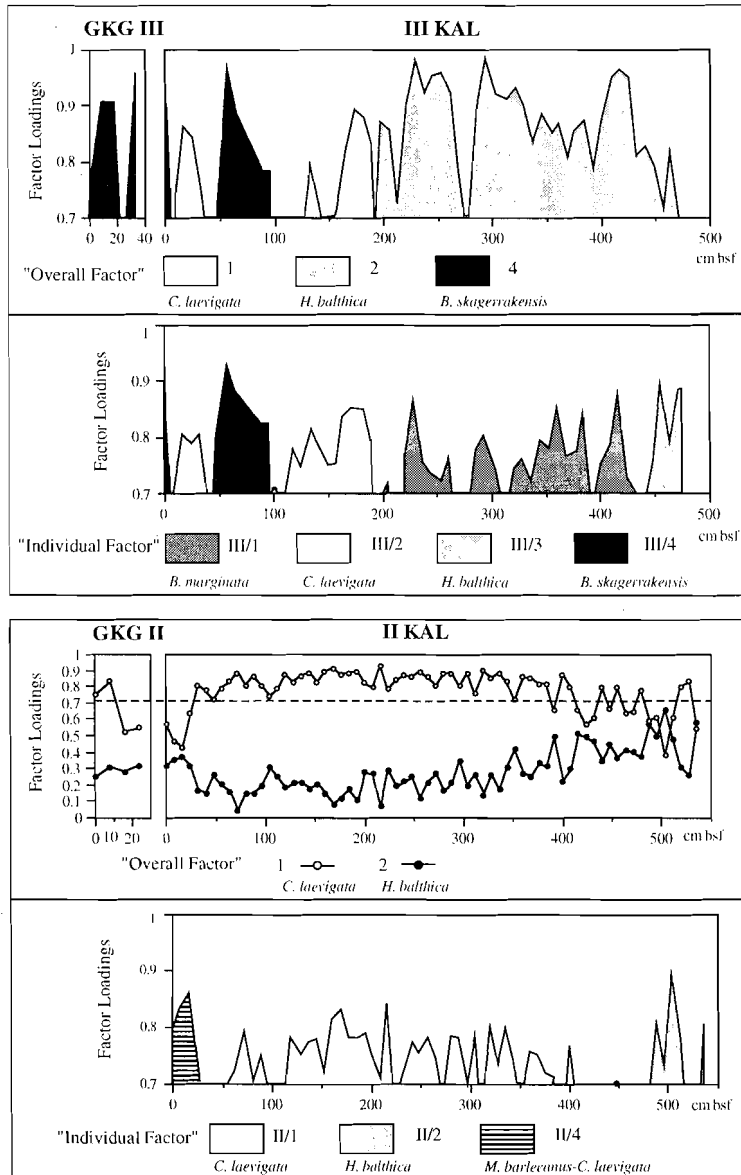
Overall factor analysis (run A)
Six factors were calculated which together account for 96% of the total variance (Figs. 4 and 5). Nine taxa clearly show increased factor values and determine the factors that can here be regarded as foraminiferal assemblages. As they are not „Assemblage Zones" according to the biostratigraphic definition, they are herein called „Foraminiferal Factor Units" following Alve (1991).

● *O-factor 1* (38% of total variance) is characterized by the *Cassidulina* spp. group (in the following as *C. laevigata*) alone. This O-factor reveals high loadings at the westerly stations (dominating II KAL and the surface of II GKG; clear-cut sections within III KAL). Within Core I KAL O-factor 1 only explains a small amount of the samples whereas it is meaningless for Core 15535-1.

● *O-factor 2* (23% of total variance) is characterized by *H. balthica*, and further by *B. marginata* and *M. barleeanus.*, and to a lesser extend by *P. bulloides*. O-factor 2 shows clear-cut zones within cores from greater water depth (15535-1, III KAL). This factor is of significance for none of the shallower cores (with one exception all factor loadings remain <0.6).

● *O-factor 3* (15% of total variance) is clearly characterized by *G. turgida*. Subordinate species are *M. barleeanus* and the agglutinated foraminifera group. O-factor 3 is significant for a few samples of

Figure 4. Diagram of relevant factors of the westerly cores GKG III, III KAL, GKG II, and II KAL ("overall" and "individual" factor analysis). The characterizing species for each factor is indicated. For a clearer overview only significant Varimax factor loadings >0.7 vs. core depth are depicted. Due to technical reasons Varimax factor loadings of I-factors III/2 and III/3 have been multiplied by -1 (see text).

the easterly cores (I KAL, 15535-1) as well as for the surface sample of I GKG. It is meaningless for the westerly cores (II KAL, III KAL).

● *O-factor 4* explains only 11% of the total variance, however, it reveals clear-cut zones especially within the cores from greater water depth (III KAL, 15535-1). It is solely characterized by *B. skagerra-kensis*. O-factor 4 is meaningless for Core II KAL but it determines the dominant species in Cores GKG III and V.

● *O-factors* 5 (7% of total variance) and 6 (1 % of total variance) are not significant for any of the cores. They do, however, substantiate the 4-factor model used for run (B).

Individual factor analyses (run B)
Core 15535-1 (referred to as: I-factor 15/#, Fig. 5)
Factors calculated for Core 15535-1 account for 94% of the total variance.

● *I-factor 15/1* (45% of total variance) is characterized by *C. laevigata* and *H. balthica*. It is significant between 800 and 244 cm core depth.

● *I-factor 15/2* (24% of total variance) is characterized by *M. barleea-nus* and *H. balthica*. This factor only shows a clear-cut zone around 200 cm core depth. There are few single samples with increased I-factor 15/2 loadings throughout the core.

● *I-factor 15/3* (11% of total variance) contains *G. turgida* and the agglutinated foraminifera group. This factor shows dominance only around 100 cm core depth. *H. balthica* reveals slight anti-correlation.

● *I-factor 15/4* (15% of total variance) corresponds to O-factor 4 (*B. skagerrakensis*). It shows high factor loadings around 600 and <100 cm core depth.

Core I KAL (referred to as: I-factor I/#, Fig. 5)
Factors calculated for Core I KAL account for 98% of the total variance. Unless otherwise stated, the factors cannot be assigned to distinct zones or sections within the core because factor loadings show strong fluctuations from sample to sample.

● *I-factor I/1* (37% of total variance) corresponds to O-factor 1 (*C. laevigata*).

● *I-factor I/2* (24% of total variance) is characterized by *M. barleeanus, R. williamsoni, C. lobatulus*, and *Elphidium*.

● *I-factor I/3* (27% of total variance) is solely characterized by *G. turgida*.

● *I-factor I/4* (8% of total variance) contains *B. skagerrakensis* and as secondary species *H. balthica*. This factor shows high loadings within the upper 40 cm of the core.

Core II KAL (referred to as: I-factor II/#, Fig. 4)

Factors calculated for Core II KAL account for 96% of the total variance.

● *I-factor II/1* (46% of total variance) is characterized by C. laevigata and reveals slight anti-correlation to M. barleeanus. It is significant between 400 and 60 cm core depth.

● *I-factor II/2* (29% of total variance) is characterized by H. balthica, U. peregrina, and B. marginata. It shows increased factor loadings from the bottom of the core up to ca. 480 cm core depth.

● *I-factor II/3* explains less than 1% of the total variance and is thus meaningless.

● *I-factor II/4* (22% of total variance) contains M. barleeanus, and C. laevigata as characterizing species; H. balthica is weakly anti-correlated. This factor is dominant from 40 cm core depth to the core top.

Core III KAL (referred to as: I-factor III/#, Fig. 4)

Factors calculated for Core III KAL explain 97% of the total variance.

● *I-factor III/1* (37% of total variance) is dominated by B. marginata, M. barleeanus, and P. bulloides. This factor charactrizes the section between 430 and 220 cm core depth.

● *I-factor III/2* (29% of total variance) shows high negative factor scores for C. laevigata and low positive scores for B. skagerrakensis. Since all factor loadings are negative C. laevigata can be regarded as the dominant species whereas B. skagerrakensis is weakly anti-correlated. This factor is significant from 190 to 100 cm and from 40 to 8 cm core depth.

● *I-factor III/3* (17% of total variance) is dominated by H. balthica, whereas M. barleeanus is weakly anti-correlated (see I-factor III/2). This factor is significant from the core bottom to 440 cm core depth.

● *I-factor III/4* (14% of total variance) corresponds to O-factor 4 (B. skagerrakensis). It shows high loadings between 100 and 40 cm core depth and from
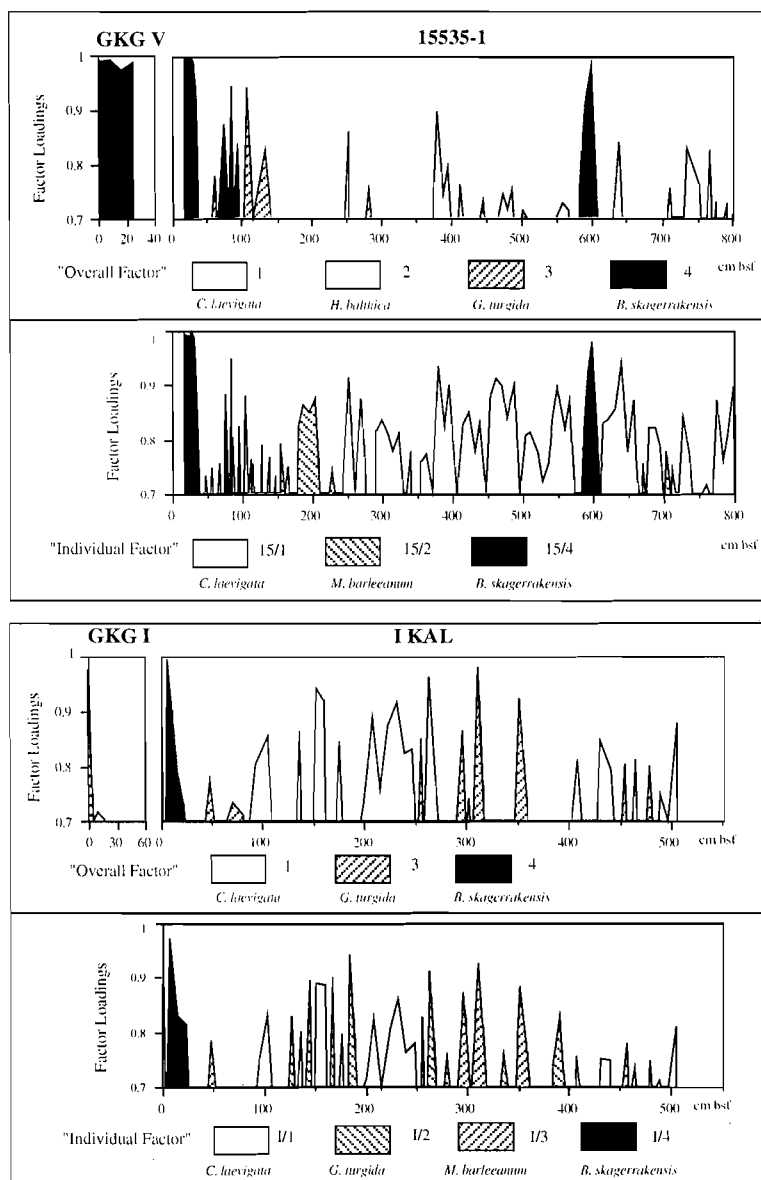
Figure 5. Diagram of relevant factors of the easterly cores GKG I, I KAL, GKG V, and 15535-1 ("overall" and "individual" factor analysis). The characterizing species for each factor is indicated. For a clearer overview only significant Varimax factor loadings >0.7 vs. core depth are depicted.

8 cm to the core top.

It appears that the sediment cores partly reveal quite different assemblages according to their location (I-factor analyses). Factor analysis of the entire data set (O-factor analysis), however, is able to discover similarities between the different cores.

Surface and near-surface samples of the GKGs reveal significantly increased amounts of agglutinated foraminifera. Quantitative down-core decreases of this group are explained by poor resistence of the tests (see also Moodley et al., 1993). This is substantiated by down-core increasing

amouts of broken tests accompanied by a down-core decrease in the size of the fragments. Thus, the GKGs were not included in the I-factor analyses.

BENTHIC FORAMINIFERA AS PALEO-ENVIRONMENTAL INDICATORS

The following sections will deal mainly with inter-pretations based on the factor analyses (Fig. 6,7). The significance of factor analyses or principal component analyses for micropaleontologic studies have been demonstrated by Imbrie & Kipp (1971) and Klovan & Imbrie (1971) in general, related to Skagerrak benthic foraminifera by e.g. Van Weering & Qvale (1983), Alve & Nagy (1990), Conradsen *et al.* (1994) and Seidenkrantz (1992, 1993).

The oldest core sections

Within the deepest sediment core, III KAL, that most probably includes the oldest deposits of this study, a factor characterized by *H. balthica* (I-factor III/3, Fig. 4) characterizes the section from its base until 450 cm core depth (Fig. 8). Stable isotopes in this zone may suggest increased temperatures and probably decreased ventilation (see also Hass, 1996). A similar *H. balthica* factor unit can be found at the base of Core II KAL (I-factor II/2, Fig. 4). These sections are not well resolved by the O-factor analysis. Both factors include increased factor scores of low oxygen conditions tolerant species like *B. marginata* (Murray, 1991; Alve, 1990; Bandy *et al.*, 1964, 1965; I-factor III/3, Fig. 4) and *U. peregrina* (Streeter & Shackleton, 1979; Schnitker, 1979, 1980; I-factors III/3, II/2, Fig. 4), and are characterized by *H. balthica* which is a boreallusitanian species which may suggest an amelioration of the climate (Nagy & Qvale, 1985). Both factors are interpreted here as indicators for increased temperatures and stagnant oxygen conditions.

Van Weering & Qvale (1983) found a *B. marginata-H. balthica* assemblage („factor 4") in Skagerrak sediments which appeared to have a relation to bottom currents. *H. balthica* was found to occur mostly at intermediate water depths. *B. marginata* occurred most frequently in relatively shallow waters, whereas *U. peregrina* seemed to prefer greater water depth, as it was found to replace deep-water assemblage of the inner Skagerrak, which was dominated by *B. skagerrakensis* (as *B.* cf. *B. robusta* in Van Weering & Qvale, 1983) where the amount of oxygen in the water decreases along the Norwegian Trench to the West and the North. Thus, at least *B. marginata* and *U. peregrina* may stand for decreased oxygen content.

Alve & Nagy (1990), working on cores from the Oslo Fjord, described a similar assemblage (*Bulimina marginata-Verneuilinoides media* assem-

blage) which is dominated by *B. marginata* (*H. balthica* ranking third); however, in this area it cha-racterizes the transitional fjord water mass between 25 and 90m water depth. The deep water mass in the Oslo Fjord is characterized by a *B. ska-gerrakensis-Nonion barleeanus* assemblage.

Investigating Eemian sediments from the Anholt III deep borehole, Seidenkrantz (1993b) explained the dominance and increasing amounts, respectively, of *H. balthica* and *B. marginata* as likely representing oxygen depletion.

Nagy & Qvale (1985) who studied benthic fo-raminifera in Core 15530-4 from the western Skagerrak (Stabell & Thiede, 1985) also found a similar assemblage. After their interpretation the *H. balthica* assemblage belongs to the Atlantic period, thus, basically indicating a climate amelio-ration.

Thus, in agreement with results and inter-pretations of cited studies and taking into account the age determinations carried out for cores II and III KAL, the sections dominated by a *H. balthica* assemblage may at least represent the later part of the Atlantic climate optimum when calm and warm atmospheric conditions prevailed.

Cassidulina laevigata documents changes in water-mass circulation

Changes in foraminifer assemblages above the previously described *H. balthica* factor unit within Cores II and III KAL are likely to document drastic changes in ecologic conditions (Fig. 4). Oxygen iso-topes suggest slightly decreasing temperatures (or/and a salinity increase) (Hass, 1996; see also Figs. 8,9). Both cores show a very slight coarsening of the sediment which may be interpreted as an increase in bottom current strength (Hass, 1993; see also Figs. 8,9). Corresponding changes in the envi-ronment are mirrored by O-factor 2 within Core III KAL. Among the 3 species with high factor scores, *H. balthica* now is less significant, wheras I-factor III/1 points to *B. marginata* (Fig. 6) (which also is a component of the *H. balthica* assemblage in Core II KAL) and *M. barleeanus* as the characterizing spe-cies. O-factor 2 remains dominant within Core III KAL until the age-dated section around 700 AD (ca. 190 cm core depth).

In contrast, the changes that affected Core II KAL from 400 cm (probably intensifying current strength and coarsening of the sediment; Hass, 1996) lead to the establishment of an assemblage clearly dominated by *C. laevigata*: O-factor 1 and I-factor II/1, respectively (Figs. 6, 9). The assemblage which characterizes O-factor 1, thus, may indicate ecologic conditions under a slightly intensifying water-mass circulation.

O-factor 1 (*C. laevigata*) replaces O-factor 2 (*B.*

Figure 6. Cores II and III KAL: selected varimax factor loadings of the „overall" (OF) and „individual" (IF) factor analysis vs. years AD/BC in regard to climate periods and lithofacies (FSD; see also Figs. 8 and 9. For more detail on lithofacies refer to Hass, 1996). Climate period abbreviations (see also Figs. 7-11): AO = Atlantic Climate Optimum; SBO = Subboreal climate optimum; SAP = Subatlantic climate deterioration („pessimum"); RO = Roman climate optimum; VW = Climate Deterioration of the period of the migration of the Germanic tribes („Pessimum der Völkerwanderungszeit" after Schönwiese 1979); MWP = Medieval Warm Period; LIA = Little Ice Age.

Figure 7. Cores I and 15535-1: selected varimax factor loadings of the „overall" (OF) and „individual" (IF) factor analysis vs. years AD/BC in regard to climate periods and lithofacies (FSD; see also Figs. 8 and 9. For more detail on lithofacies refer to Hass, 1996. For abbreviations of climate periods see Fig. 6.

marginata) rapidly within Core III KAL around 700 AD. During the Period between 600 and 700 AD all investigated parameters suggest a significant environmental change: sediments abruptly begin to coarsen, whereas the oxygen isotopes decrease to Medieval Warm Period minimum values (Hass, 1996; see also Fig. 8). Core II KAL, which suggests similar changes, appears to be dominated by O-factor 1 (*C. laevigata* showing high factor loadings) already from 400 cm core depth. This factor remains dominant until the 14th century AD. I-factor II/4, however, shows that *M. barleeanus* becomes more important from 600-700 AD. At the onset of the Little Ice Age *M. barleeanus* starts to become significant at the cost of *C. laevigata* (I-factor II/4, Fig. 6).

Apparently O-factor 1 and the corresponding I-factors can be interpreted as a 'current-indicative' factor. The *Cassidulina laevigata* assemblage seems to have expanded down-slope from at least the shallow Core II KAL to the deeper Core III KAL. A slight increase in current strength appears to have led to a change from a *H. balthica* assemblage to a *B. marginata* dominated assemblage at Station III KAL (Fig. 8). Another hydrographic shift then caused the dominance of a *C. laevigata* assemblage, replacing the *H. balthica-B. marginata* assemblage subsequently around 600-700 AD. Individual percentage data show that a '*H. balthica-B. marginata-C. laevigata*' succession is also present in Core II KAL during the probable manifestation of the first increase in water-mass circulation in the Skagerrak (II KAL: core base until ca. 400 cm, Fig. 9). Although not mentioned, a similar succession can be seen in Nagy & Qvale (1985: Fig. 1).

Seidenkrantz (1993) explains a recent/subrecent change from *H. balthica* to *B. marginata* as a result of increased organic carbon content and oxygen depletion due to anthropogenic polution. This cannot be the reason for the succession during the Atlantic/Subboreal, though. More likely it is steered by a gradual change of the environment and/or competition between species. It seems, however, after studies of Alve (1994), Conradsen *et al.* (1994), and others that a succession via *C. laevigata* to either a *E. excavatum* assemblage in case of a more or less natural intensification of the water-mass circulation, or to a *S. fusiformis* assemblage in case of intensification of the circulation *and* a certain level of oxygen depletion (most probably caused by anthropogenic pollution) is possible. Since neither a fall of the sea level nor a permanent change in salinity could have triggered the change, a slight intensification of the bottom currents must have led to the establishment of conditions favorable for foraminifera of the shallower areas to dwell in deeper areas of the Skagerrak.

There seems to be no doubt that *C. laevigata* assemblages occur most frequently in turbulent or at least strongly current-influenced environments and on coarser grained substrate than is normally found in the deeper areas of the Skagerrak (see Conradsen *et al.*, 1994). This assemblage is mostly situated in the transitional zone between two water masses, thus under unstable oceanographic conditions (see Nagy & Qvale, 1985; Van Weering & Qvale, 1983). Since a change of the environment seems to have taken place from the shallower into the deeper Skagerrak as well as from the West to the East (i.e. from the higher to the lower energy zone) in order to provide conditions suitable for a *C. laevigata* assemblage a general increase in bottom current strength can be inferred. As a further point *Elphidium* spp. shows an increase in Core II KAL and a very slight increase in Core 15535-1. Two cores studied by Jørgensen *et al.* (1981) reveal a similar pattern (see Figs. 13 and 14 by Jørgensen *et al.*, 1981).

It can thus be inferred that bottom current energy was increasing at least from the later part of the Atlantic until at least the Medieval Warm Period including a phase of rapid increase around 600-700 AD. Foraminiferal data suggest that the high energy zone migrated down-slope most likely in a northwesterly direction. Hass (1996) came to a similar interpretation while studying stable isotopes and granulometry of the same cores used in the present study.

The easterly cores: alternating ecologic conditions?

Within sediment Core 15535-1 *H. balthica* and *C. laevigata* assemblages seem to be mixed (I-factor 15/1, Figs. 5,7). This is also suggested by fluctuating but generally high loadings of O-factors 1 and 2 which may be caused by alternating ecologic conditions due to fluctuating current strength. During the last phase of the Little Ice Age, which has been interpreted as a phase of strongly increased current speed (Hass, 1996; Hass & Kaminski, 1994; see also Fig. 11) all individual factors apper to have fluctuated.

Core I KAL shows small scale fluctuations within the corresponding period just like Core 15535-1 (Figs. 5,7). This is also reflected by the I-factors. Thus, rapidly changing bottom current strengths are suggested, leading to likewise rapid changes in ecologic conditions. Results show, however, that especially *C. laevigata* and *M. barleeanus* have increased in number during the phase of stronger current activity of FSD 2a (Fig. 10; see also Core II KAL, Fig. 9).

1300 AD until Present: *B. skagerrakensis* „conquers" the area

Assemblages with high abundances of *C. laevigata* or with *C. laevigata* as the dominant species (O-factor 1: indicative for intensified current strength) occur mainly where higher current speed is suggested (see Hass, 1996). High loadings of this factor are interrupted when *Brizalina skagerrakensis* (O-factor 4) appears in the sediments. *B. skagerrakensis* is principally (in very small amounts) present throughout the cores from deeper water (15535-1, III KAL, Figs. 8, 11). However, it is not before 1300-1400 AD that this species increases dramatically up to 60%, but only to decrease again until the mid-19th century AD, when another acme occurs (Core 15535-1, Figs. 7, 11). Until the end of the 19th century AD *B. skagerrakensis* again decreases but only to dominate the benthic foraminifer fauna with more than 70% from the mid-20th century AD onwards (Fig. 11).

Within Core III KAL (Fig. 8) *B. skagerrakensis* shows less variability, probably because of the lower temporal resolution. It does not exceed 50%; the first maximum appears ca. 100 years later than it occurs in Core 15535-1. Between 1700 and 1900 AD *B. skagerrakensis* decreases down to 5%. From ca. 1900 AD the corresponding O-factor increases again to high factor loadings and remains dominant until the top of the core (Fig. 6). *B. skagerrakensis* shows a strong increase in all examined cores

at the beginning of the 20th century AD except in Core II KAL, which is the shallowest core. However, even in this core the amount of *B. skagerrakensis* increases threefold but it never exceeds 7% (9% in GKG II) (Fig. 9). All cores are characterized by a strong increase of *B. skagerrakensis* although it does not dominate the foraminifer fauna in the shallow cores.

The sudden first increase of *B. skagerrakensis* can be related to the first increase in current strength during the initial phase of the Little Ice Age (FSD 2c). At least Core 15535-1 suggests the second *B. skagerrakensis* increase is related to the last phase of the Little Ice Age (FSD 2a, Fig. 7). Both phases were characterized as being strongly influenced by the atmospheric forced intensification of the Skagerrak circulation system. The younger maxima, including the successive 'conquest' cannot easily be explained. There may be a relation to increasing anthropogenic pollution of the North Sea since the advent of industrialization. Aside from possible reasons such as changing hydrographic conditions or the quality of the TOC, it seems that the trend to increase has not yet finished.

WHAT CONTROLS THE DYNAMICS OF FORAMINIFER ASSEMBLAGES IN THE SKAGERRAK?
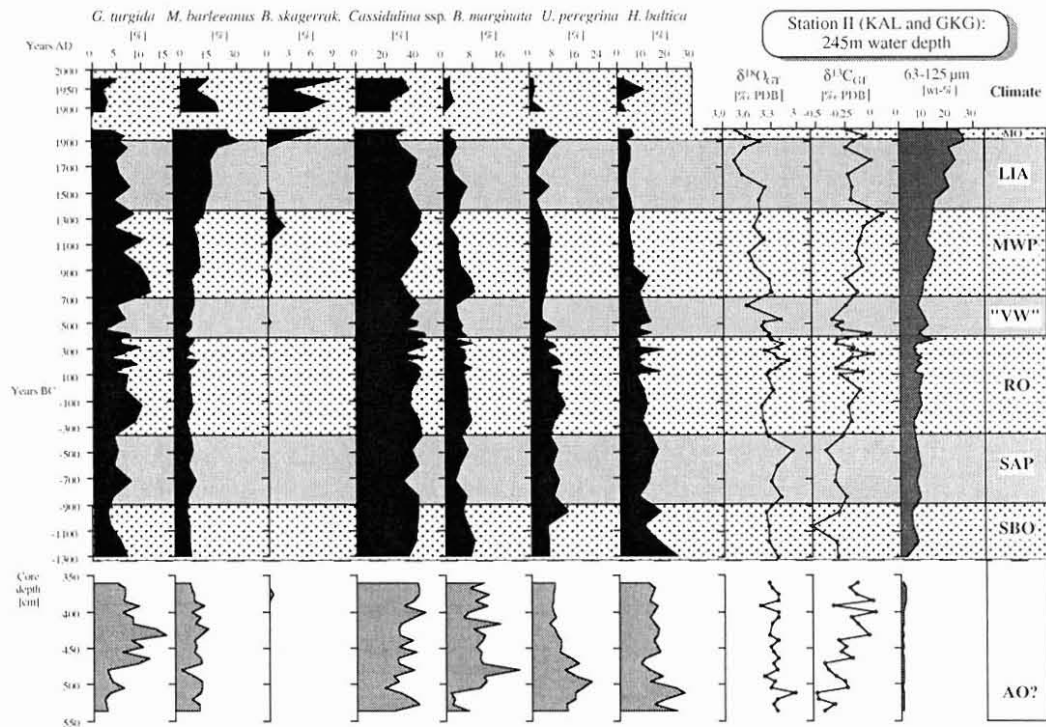
Due to the strong variability of ecologic conditions,
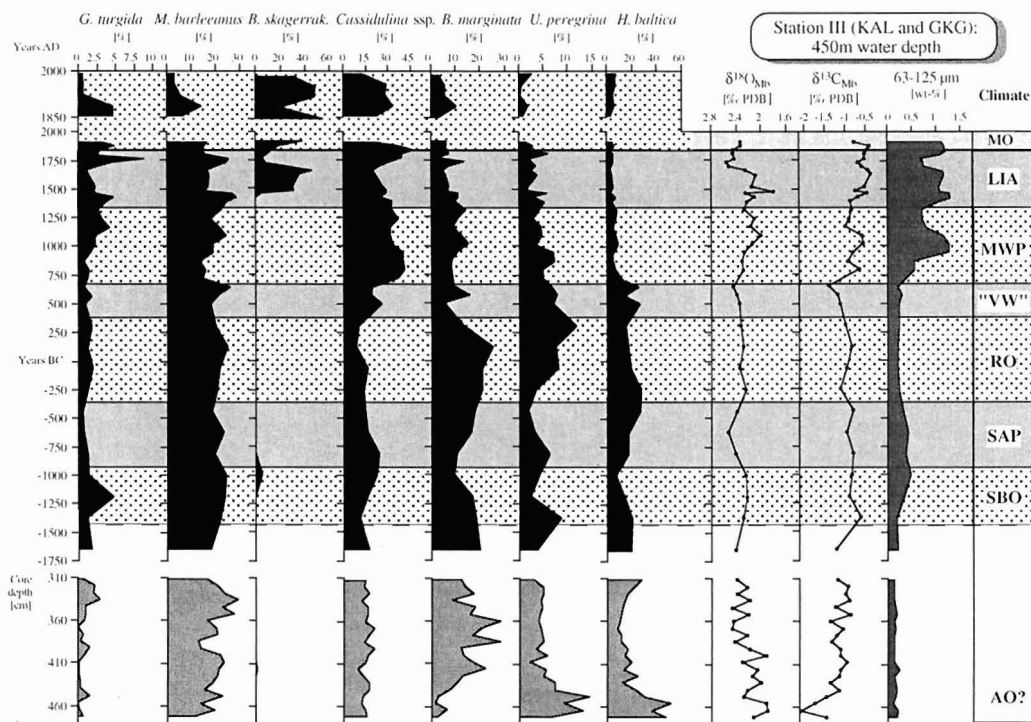
Figure 8. Selected benthic foraminifer species (Gt = *Globobulimina turgida*), $\delta^{18}O$, $\delta^{13}C$, and indicative grain-size class (see Hass & Kaminski, 1994) from Cores 15535-1 and GKG V. The uppermost part of the figure refers to the surface samples (boxcorer GKG V), the lower part refers to the long core (15535-1). ($\delta^{18}O$ and $\delta^{13}C$ measurements: C14 Laboratory, Kiel).
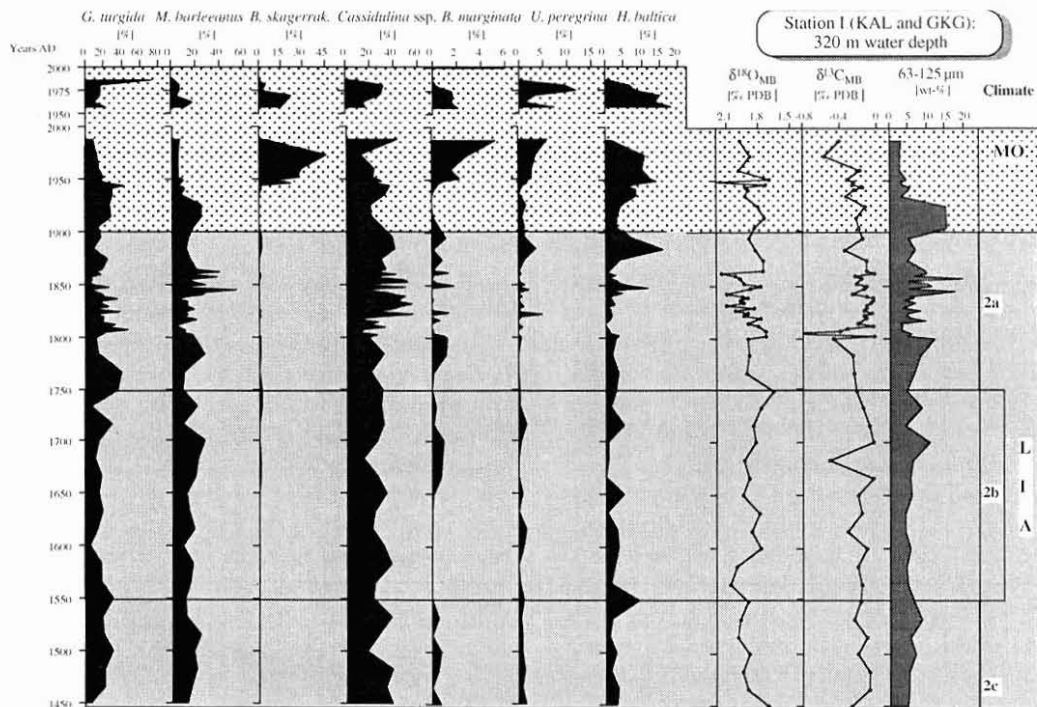
Figure 9. Selected benthic foraminifer species (Gt = *Globobulimina turgida*), δ18O, δ13C, and indicative grain-size class (see Hass & Kaminski, 1994) from Cores II KAL and GKG II. Note different vertical scales („years AD/BC" where age determination have been carried out and „cm" where no age determinations were available). The uppermost part of the figure refers to the surface samples (boxcorer GKG II), the lower part refers to the long core (II KAL). (δ18O and δ13C measurements: C14 Laboratory, Kiel).

Figure 10. Selected benthic foraminifer species (Mb = *Melonis barleeanus*), δ18O, δ13C, and indicative grain-size class (see Hass & Kaminski, 1994) from Cores I KAL and GKG I. The uppermost part of the figure refers to the surface samples (boxcorer GKG I), the lower part refers to the long core (I KAL). (δ18O and δ13C measurements: C14 Laboratory, Kiel).

Figure 11. Selected benthic foraminifer species (Mb = *Melonis barleeanus*), $\delta^{18}O$, $\delta^{13}C$, and indicative grain-size class (see Hass & Kaminski, 1994) from Cores I KAL and GKG I. The uppermost part of the figure refers to the surface samples (boxcorer GKG I), the lower part refers to the long core (I KAL). ($\delta^{18}O$ and $\delta^{13}C$ measurements: C14 Laboratory, Kiel).
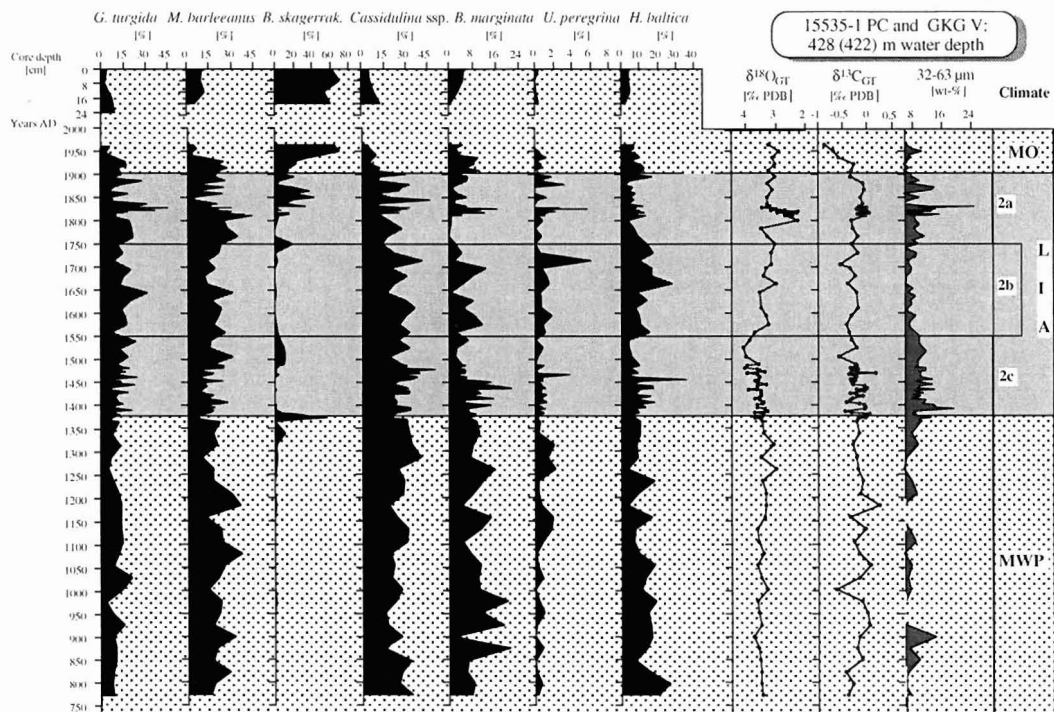
results of investigations on the continental slope and in the deep sea cannot directly be related to shallow-water foraminifer assemblages (Corliss & Van Weering, 1993; see also Qvale *et al.*, 1984). Shallow-water environments often provide extreme habitats which are not comparable to the deep sea. Direct interpretation from assemblages to the prevailing ecologic conditions are therefore difficult or impossible in shallower, current controlled environments. Corliss & Van Weering (1993) consider the differences in the habitats of benthic foraminifera from the Skagerrak and the continental slope off Nova Scotia (Corliss & Emerson, 1990) to be related to the effect of water depths and to micro-habitats affected by different grades of bioturbation.

Dynamics of the bottom currents
The dependency of foraminifer assemblages on oceanographic parameters within the Skagerrak has been outlined by e.g. Conradsen *et al.* (1994), and Van Weering & Qvale (1993). Such a dependency can be substantiated by the results of the present study. It can be concluded that despite the spacial proximity of the core locations there is a significant heterogeneity in the foraminifer assemblages, which can be attributed to the dynamics of the bottom current circulation.

It could be shown that a persistant intensifica-

tion of the bottom currents lead to the establishment of a *C. laevigata* dominated assemblage replacing a *H. balthica* assemblage in the lower part of Core II KAL. Probably synchronously, *M. barleeanus* established itself at the deeper location of Core III KAL. A similar zone was not outlined but is evident from the data of Nagy & Qvale (1985: Fig. 1, p. 108). Investigations of „Core 2" (Jørgensen *et al.*, 1981), and P78-4 (Van Weering, 1982) suggest similarities as well.

Present day observations of surface assemblages of the Skagerrak (e.g. Conradsen *et al.*, 1994; Van Weering & Qvale, 1983) cannot easily be related to fossil assemblages, as the huge abundance of *B. skagerrakensis* during the past 500-1,000 years strongly affects the percentage distribution. However, at least „Factor 3" (Van Weering & Qvale, 1983), which identifies a *C. laevigata* assemblage, shows a strong maximum on the southern flank of the Skagerrak, an area which is basically characterized by a coarser substrate. In zones where slower currents lead to a finer grained substrate, assemblages such as „Factor 4" (*B. marginata-H. balthica assemblage*) are dominant (Van Weering & Qvale, 1983). The interpretation of the *C. laevigata* assemblage as 'current indicative' as well as its expansion down slope, thereby replacing firstly *H. balthica* and later on (600-700 AD) also *B. marginata* assemblages in the course of

intensifying currents, can thus be substantiated.

Mackensen & Hald (1988) describe a weak preference by *C. laevigata* for sandy substrates in the North Sea. Further east, in the Skagerrak, Conradsen *et al.* (1994) found a *C. laevigata* assemblage on sandy to fine grained substrate and under rather high current velocities (see also Seidenkrantz, 1992). It is not evident, however, whether *C. laevigata* prefers a coarser substrate or the conditions which characterize shallower (i.e. 100-400m) water depths, such as generally higher current velocities with higher standard deviations leading then to coarser substrate. A preference of *H. balthica* for coarser substrate, as suggested by Pujos (1972, Golf de Gascogne), is not evident from the Skagerrak. However, a preference for certain sediment types is often secondary, as the prime cause for foraminifera living on a given substrate is the availability of food (Graf, 1989; Lutze *et al.*, 1983). The changes in foraminiferal assemblages within Core III KAL during the intensification of water-mass circulation, thus, are likely to mirror changes in the availability of food and probably changes in ventilation of the bottom water mass, which generally favor smaller foraminifer forms like *C. laevigata* (Perez-Cruz & Costillo, 1990).

It appears that between ca. 600 and 700 AD a general displacement of the average situation of the current core by some 100 m down-slope the southern flank of the Skagerrak has taken place. Correspondingly, the biotopes including the associated foraminifer assemblages joined that down-slope movement. Slightly increasing amounts of *E. excavatum* which forms the dominant species in the shallow-water assemblage (Van Weering & Qvale, 1983) in Cores II and III KAL (see also Jørgensen *et al.*, 1981) suggest that the shallow water assemblages may also have slightly expanded down-slope.

Brizalina skagerrakensis: indicator for stable conditions?

O-factor 4 (characterized by *B. skagerrakensis*) which loads high in all of the surface samples of the four analyzed cores, except for the shallow water Core II KAL (*B. skagerrakensis* is also increasing in this core, however, remains at low percentage), is similar to „Factor 1" (Van Weering & Qvale, 1983) and an assemblage described by Conradsen *et al.* (1994) (see also Nagy & Qvale, 1985; Qvale & Van Weering, 1985; Van Weering, 1982a; Jørgensen *et al.*, 1981; Lange, 1956). The main area of distribution of *B. skagerrakensis* is below 200 m water depth. The immigration of *B. skagerrakensis* is thought to have taken place between 2000 BP (Lange, 1956) and 1000 BP (Jørgensen *et al.*, 1981). Results of the present work,

however, suggest that this species occurred already much earlier in very small amounts. Despite this, a pronounced maximum was established not earlier than at the beginning of the Little Ice Age. The establishment of this maximum takes place during the start of a period of generally unstable conditions. The circulation energy was already increased through a „hydrographic jump" around 600-700 AD. Superimposed on this, a further atmospherically forced increase in current speed during the Little Ice Age may have finally produced conditions that were favorable for *B. skagerrakensis* to invade the southern flank of the Skagerrak. Thus, the established consensus that *B. skagerrakensis* indicated stable hydrographic conditions or at least a stable bottom water mass in the Skagerrak (Conradsen *et al.*, 1994; Nagy & Qvale, 1985; Qvale & Van Weering, 1985; Van Weering, 1985) cannot be confirmed by all means. The steady occupation even of the shallower areas of the Skagerrak (Core II KAL, 245 m), that are rather prone to stronger hydrodynamic variability appears to be contradictive to this view. The occurrence of *B. skagerrakensis* under stable conditions in the Oslo Fjord (Alve & Nagy, 1990; Thiede *et al.*, 1981; Risdal, 1964) may thus not be primarily caused by stable hydrodynamic conditions. The present study, however, is not able to elucidate the causes that have supported the extreme fluctuations of *B. skagerrakensis* during the past ca. 500 years (varying between 1 and 70%).

Most likely there is a relation between the latest increase of *B. skagerrakensis* and anthropogenic pollution since the advent of the industrialized era. Earlier spikes may be favored by current speed fluctuations, thus a preference of *B. skagerrakensis* for unstable conditions. Although a relation between the Little Ice Age climate deterioration and the distribution of *B. skagerrakensis* seems to exist, there is - as for the entire benthic foraminifer fauna of the Skagerrak - no striking evidence for a climatic response during the latest part of the Holocene.

CONCLUSIONS: FORAMINIFER ASSEMBLAGES IN THE SKAGERRAK AND CLIMATE FLUCTUATIONS

The investigations suggest that fluctuations in benthic foraminiferal assemblages are principally caused by long-term energy changes in the water mass circulation system. These changes, however, appear to be only indirectly caused by climate change. Pronounced climate fluctuations, such as the Medieval Warm Period or the Little Ice Age, affected the system only periodically through atmospherically forced alterations of the water mass circulation strength, whereas the general circulation regime (refering e.g. to the energy increase

around AD 700) is more probably depending on large scale oceanographic processes elsewhere.

The primary effect of e.g. the Medieval Warm Period (i.e. warming) is obviously not reflected by the benthic foraminifer fauna as there seems to be no obvious correlation between the stable oxygen isotopes (as a major indicator for temperatures) and the benthic foraminifer assemblages. It was the rapid hydrographic change to a higher energy level producing conditions similar to those of earlier cooler climate phases that finally supported C. laevigata. Under normal conditions of a warm period one would have expected a H. balthica assemblage to become dominant just like what possibly happened during the Holocene Optimum. During the Little Ice Age, however, one would have expected the C. laevigata assemblage to become even stronger as strong westerly winds increased the current energy above the level that was already present. Instead, B. skagerrakensis invades the area, most likely supported by strong currents or the effects resulting therefrom. Decreased current energy during the Little Ice Age maximum may then have supported the C. laevigata assemblage again whereas B. skagerrakensis nearly completely disappeared. B. skagerrakensis occurs again in very high amounts at the end of the Little Ice Age probably supported by a combination of increased currents and increasing pollution. Thus, it can be concluded that changes in the composition of foraminifer assemblages are directly related to the dynamics of the Skagerrak circulation system.

Although the mentioned climate phases were the result of substantial changes in the atmospheric circulation (e.g. Lamb, 1979, 1969), that resulted in significant fluctuations of the climate aspects, they did not lead to significant changes in the benthic foraminifer fauna other than as a reaction to the displacement of the average position of the current core over the southern flank of the Skagerrak. Thus, strong fluctuations in the amount of B. skagerrakensis are most likely caused by fluctuations of the Jutland Current and its bottom current counterpart, respectively. Part of the dynamics within the foraminiferal assemblages from the beginning of the Little Ice Age is probably linked to „competition" between B. skagerrakensis and C. laevigata dominated assemblages (see also Van Weering & Qvale, 1983), suggesting limiting ecologic conditions for either of them. There is, however, some evidence that current energy fluctuations also lead to fluctuations in the availability and quality of food which is one of the major aspects influencing benthic foraminifer assemblages (Altenbach, 1992). Not enough is known, though, about the food and nutrient preferences of the individual species involved.

The strong increase of B. skagerrakensis from the beginning of the 20th century AD may be supported by anthropogenic pollution of the North Sea since the advent of modern industry in the area.

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Recent and subrecent agglutinated foraminifers in four box cores from the Skagerrak (NE North Sea)

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ABSTRACT

Agglutinated foraminifers from 4 box cores spanning the past ca. 140 years (maximum) taken from the southern flank of the Skagerrak (NE North Sea) were studied. Fourtyseven species were identified, among them *Liebusella goesi, Eggerelloides* spp., *Rhabdammina discreta*, and *Haplophragmoides bradyi* are the most common. The two more westerly locations reveal significantly higher amounts of agglutinated foraminifers, which may be caused by a better supply of suitable food provided by east headed bottom currents. Extremely high sedimentation rates and a higher degree of pollution suggest environmental stress that may be one reason for lower amounts of agglutinated foraminifers at the two more easterly stations close to the Skagerrak deep. Increasing numbers of specimens within the present century suggests a combination of instability of the tests and ecological controls.

INTRODUCTION

„Agglutinated foraminifera belong to the most widely distributed and abundant groups of marine meiofaunna *in some environments* (e.g. salt marshes, deep sea)." That is how the editors of the special publication on paleoecology, biostratigraphy paleoceanography and taxonomy of agglutinated foraminifera (Hemleben *et al.*, 1990) start the preface of their book. Indeed, the restriction (here in italics, above) to only some environments promoted this foraminifer group as an unpopular one. Recent efforts, however, namely through the IWAF (International Workshop on Agglutinated Foraminifera) meetings and proceedings, however, succeeded in establishing a forum, that exclusively deals with agglutinated foraminifers.

Numerous investigations of benthic foraminifers from the Skagerrak have been carried out through the past 50 years (e.g. Knudsen *et al.*, 1996 a, b; Alve & Murray, 1995, Conradsen *et al.*, 1994; Seidenkrantz, 1993; Alve & Nagy, 1986; Nagy & Qvale, 1985; Van Weering & Qvale, 1983; Jørgensen *et al.*, 1981; Höglund, 1947; see also Hass, *this volume*), however, mostly, the agglutinated foraminifers have not enjoyed a great deal of attention as sometimes the poor resistability of their tests results in disintegration in a short time period in some environments. This study exclusively investi-

gates the agglutinated foraminifer fauna of four box cores from the Skagerrak with regard to the physical environment, and with regard to the apparent strong increase of agglutinated foraminifers during the present century.

OCEANOGRAPHY AND SEDIMENTS

The Skagerrak forms the deepest part of the Norwegian Trough that stretches in a northerly direction along the Norwegian coastline. It consists of a number of different sedimentary environments, characterized by current-energy related grain-size distributions and assemblage zones of calcareous benthic foraminifers (see references above).

Generally, the water mass circulation is counterclockwise (Svansson, 1975) (Fig.1). The southern flank of the Skagerrak is affected by the Jutland Current that transports North Sea water masses into the Skagerrak. According to the dominant wind conditions the Jutland Current largely varies in flow energy (Hass, 1996; Fonselius, 1989; Rodhe, 1987; Davies, 1980). Bottom current speed may vary between 0 and 15-20 cm/s on average (Rodhe, 1987). In the inner Skagerrak water masses turn around and eventually leave the Skagerrak as the Norwegian Coastal Current. A deep counter current to the Norwegian Coastal Current injects sa-
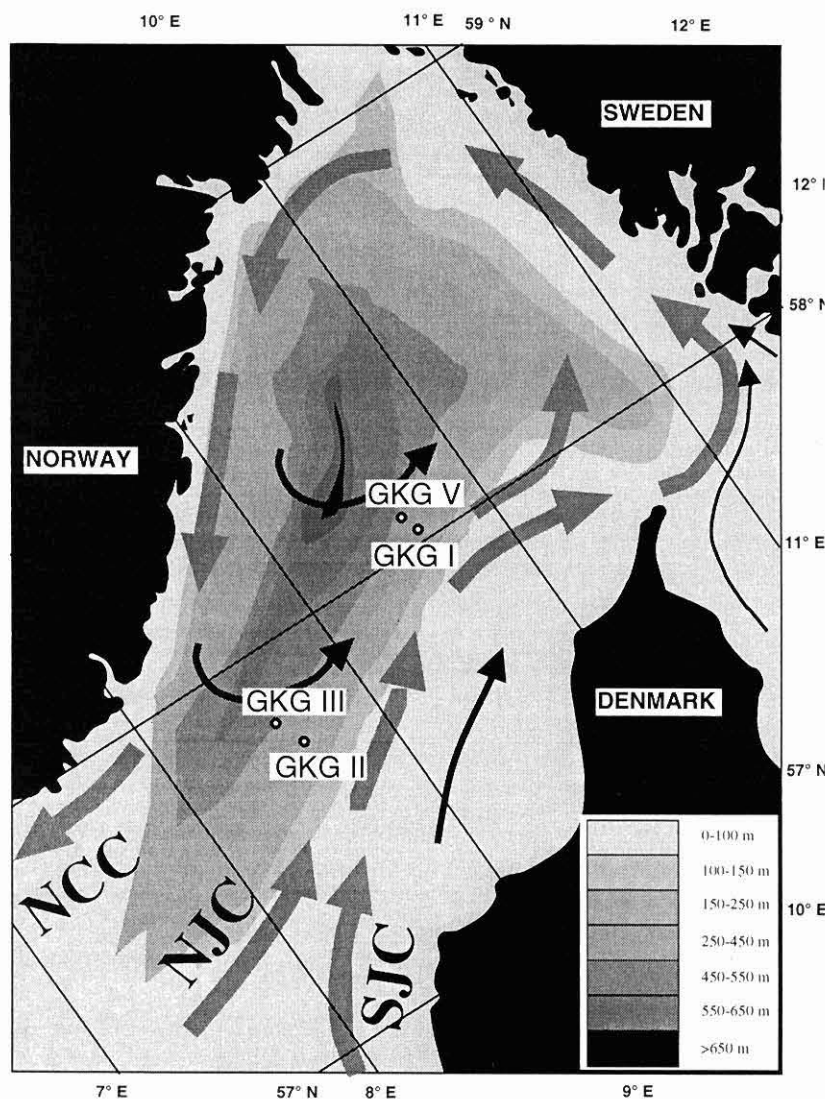
Figure 1. Bathymetry (continents in black, water depths in shades of gray), general surface circulation pattern (after Svansson, 1975) and core locations (GKG I, II, III, V). SJC = South Jutland Current; NJC = North Jutland Current; NCC = Norwegian Coastal Current (after Nordberg, 1989).

450 m) to to silty sand with about 26 weight% of sand at the shallowest location (GKG II, 245 m). Equally different appear the sedimentation rates, that vary between 2 and 10 mm/yr (Hass, 1994).

The Skagerrak basin is affected by environmental pollution that began with the onset of modern industrialization during the last century. Especially heavy metals (Cr, Pb, Cu, Co, Mn) show a clear increase (Müller & Irion, 1984; Erlenkeuser & Pederstad, 1984).

MATERIAL AND METHODS
In November 1991 four box cores were taken from the southern flank of the Skagerrak during a cruise of RV „Planet" (GKG I, II, III, V; see Tab. 1). In the following, Cores GKG II and III will be addressed as the „westerly cores", Cores GKG I and V are termed the „easterly cores".

Bulk density measurements (4cm intervals) were carried out using syringe samples that were taken aboard the research vessel during the cruise. The cores were subsampled using 50 cm plastic liners which were

line Atlantic water into the Skagerrak deep (Dahl, 1978).

At the depths that are of interest for this study, seasonal influences are minor (Corliss & Van Weering, 1993). Temperatures may vary between 4 and 7°C (Larsson & Rodhe, 1979; Fonselius, 1989), but remain usually around 6°C. Salinities show little variation around 35 PSU (Lee, 1980). TOC values range between 1.3 and 3% (Hass, 1994); oxygen saturation is good throughout (Svansson, 1975). The sediments suggest a series of environments characterized by different current strengths. Sediments range from silty clay with about 57 weight% of clay at the deepest location (GKG III,

Table 1. Background information on the cores used for this study.

Core (RV)	Position	Water depth [m]	Recovery [cm]	Corer
V GKG (Pl)	58°04.55′N 9°37.21′E	422	34	GKG
V GKG (Pl)	58°02. 3′N 9°37.15′E	320	46	GKG
V GKG (Pl)	57°46.4′N 8°42.7′E	245	28	GKG
V GKG (Pl)	57°50.3′N 8°42.4′E	450	40	GKG

GKG = Large Box Core (30 x 30 x 50 cm)
(Pl) = RV "Planet"

then sliced into 0.7 cm slabs every 4 cm (Core GKG I: 8 cm intervals). After freeze-drying the samples were washed through a 63 μm standard sieve. Then the dried coarse fraction was further fractionated into the usual fractions 63-125 μm, 125-250 μm, 250-500 μm, and >500 μm using a sonic-sifter. Agglutinated foraminifers were picked and counted in 3 fractions: 125-250 μm, 250-500 μm, and >500 μm. Where possible, at least 300 specimens in each sample were counted. If there were less than 300 individuals, the entire sample was counted. Fragments of agglutinated foraminifers were counted whenever the fragment was unequivocally the larger part of an agglutinated test. Very small fragments were generally not counted. In the following quantitative data are always rounded to the nearest integer value.

Age determinations were carried out by means of the excess ^{210}Pb method (for sample preparation and chemical treatments see Erlenkeuser & Pederstad, 1984). All measurements were taken by and at the C14-Laboratory of the Institute for Pure and Applied Nuclear Physics, Kiel University. There are no age determinations for Core GKG V. It was assumed that sedimentation rates have not significantly changed during the past 30-40 years, thus sedimentation rates for the upper part of a long core from the same location were applied, and age data calculated (Core 15535-1: see Hass, 1996).

Individual accumulation rates (INDAR) were calculated by multiplying dry bulk density data, linear sedimentation rate, and quantitative foraminifer data according to Ehrmann & Thiede (1985) and Struck (1992; see also Nees, *this volume*; Hass, *this volume*).

Various further analyses (stable isotopes, calcareous foraminifers, CaCO$_3$, TOC) were carried out using sediments from the same cores used for this study (Hass, 1994, 1996, *this volume*).

RESULTS

### Total abundance of agglutinated foraminifers

Highest abundances of agglutinated foraminifers were found throughout the cores in the topmost samples. The westerly stations reveal between 3 and 5 times as many individuals within the topmost samples than the easterly stations (Fig. 2).
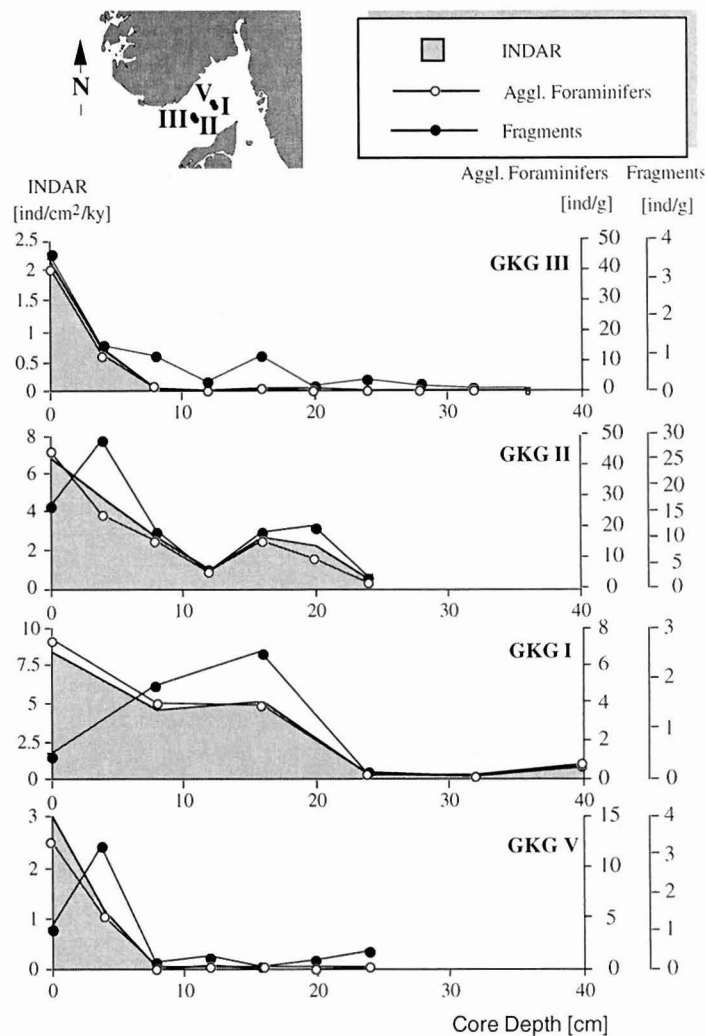
Figure 2. Agglutinated foraminifers per cm^2 and per year (INDAR), agglutinated foraminifers per gram dry sediment (ind/g) and counted fragments versus core depth.

Westerly Core GKG III shows about 41 individuals per gram dry sediment (Ind/g), whereas Core GKG II shows up to 45 Ind/g. Easterly Core GKG V reveals about 12.5 Ind/g; Core I GKG shows even less (7.5 Ind/g).

INDAR („individuals per square centimeter and per year" in the following as ind·cm^{-2}·y^{-1}), however, show more balanced values. These are likely to depend more on water depth (Fig. 2): GKG II (245 m) shows highest values at 6.8 ind·cm^{-2}·y^{-1}, GKG I (320 m) records 8.4 ind·cm^{-2}·y^{-1}, GKG V (427 m) shows 2.9 ind·cm^{-2}·y^{-1}, and GKG III (460 m) reaches only 2.1 ind·cm^{-2}·y^{-1}. INDARs strongly depend on the calculated linear sedimentation rates (LSR, Fig. 3) which may be biased by different degrees of compaction, as the sediments dealt with in this study are very young. Because of different hydrographic regimes and likewise diffe-
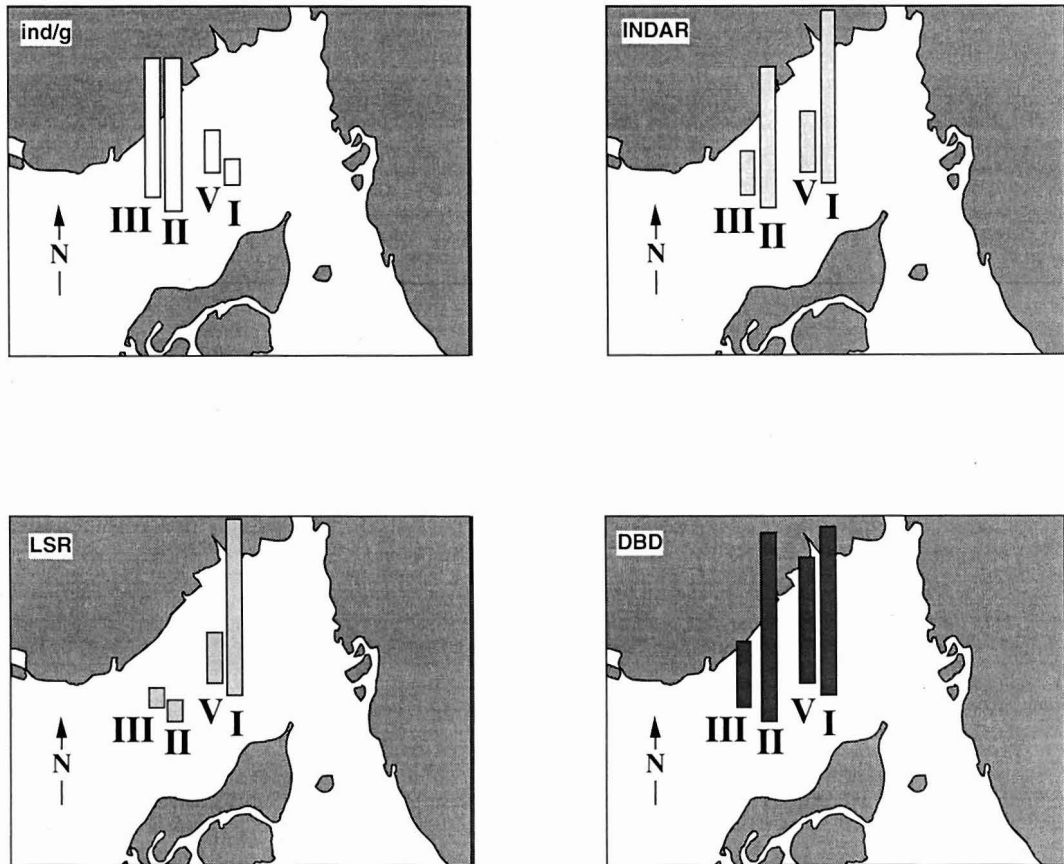
Figure 3. Measured and calculated data from surface sample of the four cores: agglutinated foraminifers per gram dry sediment (ind/g); agglutinated foraminifers per cm² and year (INDAR); linear sedimentation rate (LSR); dry bulk density (DBD).

rent grain size distributions, the dry bulk density data is different in all four cores as well (Fig. 3). All of these variables may have a considerable influence on the INDARs. Thus, in the following discussion, the main emphasis will be placed on the parameter „Ind/g" that appears to be less biased by the physical properties of the sediment (although strongly influenced by the sedimentation rate).

All four cores show a marked downcore trend towards a decreasing abundance of agglutinated foraminifers. Figure 2 depicts INDAR and „Ind/g" values of the bulk agglutinated foraminifer fauna for the four box cores. Westerly Core GKG II carries the maximum number of agglutinated foraminifers of all cores with approximately 2.5 Ind/g within the lowermost sample (24 cm core depth). The remaining cores show values below 0.02 Ind/g. These trends are paralleled by INDAR values. Compared to the calcareous benthic foraminifer fauna (% agglutinated foraminifers of the bulk benthic foraminifer fauna), percentages are hetero-

genous: Core GKG III starts at about 34% and decreases downcore to 0.008%; Core GKG II starts at 3.2% and finishes with 0.2% at the bottom of the core. The easterly cores show more similarities: Core GKG V starts at 11% and decreases to 0.16%, whereas GKG I decreases from approximately 7% down to 5.8%. Only in Core GKG I the calcareous foraminifers reveal a similar downcore decreasing trend.

Species distributions: the surface samples

Fourty-seven agglutinated foraminifer species were identified (see Appendix 1). About 15 species accounted for more than 5% or totalled to more than 0.2 Ind/g (> 0.5 Ind/g in Core GKG II). Only 5 agglutinated species appeared to be characteristic for the cores investigated.

Since there is a rapid decrease in the number of individuals downcore, species distributions expressed in percent are likely to loose competence from the top to the bottom of the cores (see Fig. 4: bulk agglutinated foraminifer data is included).
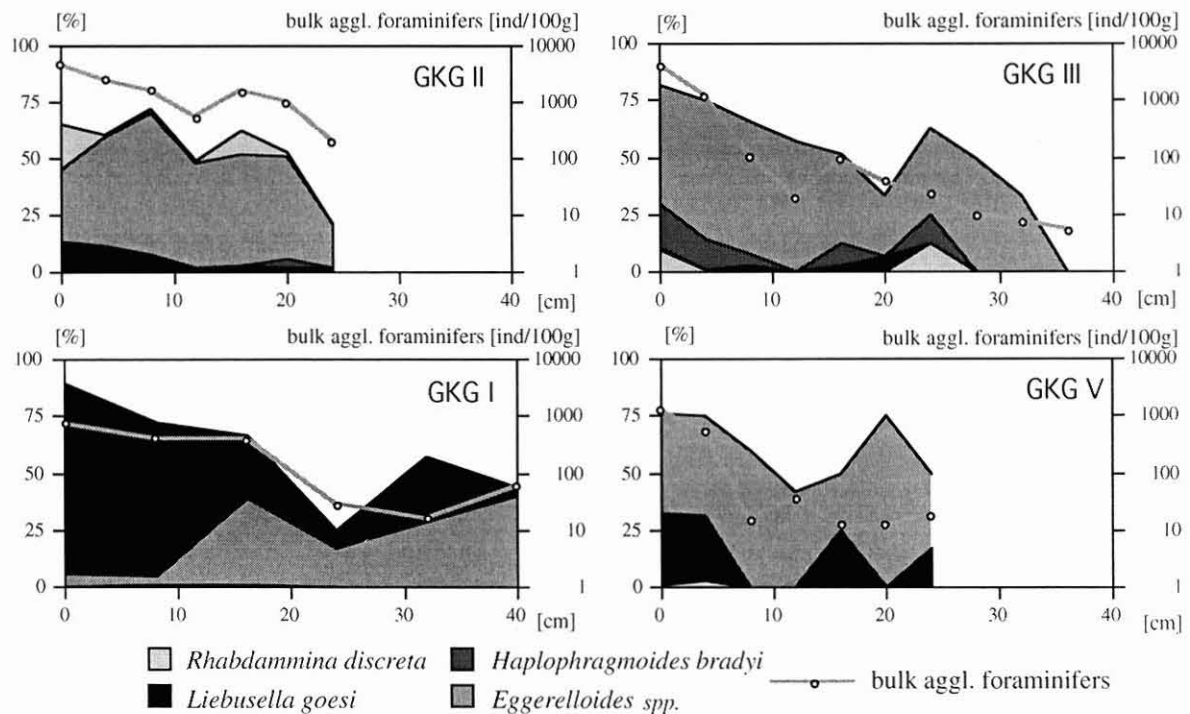
Figure 4. The most important species (in %) versus core depth, and the total amount of agglutinated foraminifers (ind/100g).

Thus, in this chapter main emphasis will be placed on the surface samples.

The characteristic, and thus most abundant species are *L. goesi*, *Eggerelloides* spp., *H. bradyi*, and *R. discreta* (Fig. 4). Core GKG I, the shallower of the easterly cores, reveals an assemblage that is strongly dominated by *L. goesi* accounting for 83% of the agglutinated foraminifer fauna (>0.6 Ind/g). In the deeper easterly core (GKG V) *Eggerelloides* spp. (44%, 5.50 Ind/g) and *L. goesi* (30%, 3.8 Ind/g) dominate the fauna. In the westerly cores *L. goesi* is of less importance. The shallower core GKG II shows only 13% (5.6 Ind/g) *L. goesi*, whereas *Eggerelloides* spp. amounts to 32% (14.4 Ind/g). *R. discreta* shows 20% (8.8 Ind/g). In the deeper westerly core GKG III, *L. goesi* remains below 1%. In this core the dominant species are *Eggerelloides* spp. (53%, 21.4 Ind/g), *H. bradyi* (20%, 7.9 Ind/g), and *R. discreta* (10%, 4.0 Ind/g).

Downcore changes in species distribution

Downcore changes in agglutinated foraminifer species are expressed in terms of quantity rather than in terms of percentages as the number of individuals rapidly decreases to values beyond a reasonable interpretation of percentages (see previous sections). Figure 4 shows the percentage distribution of the agglutinated foraminifers in comparison with the bulk number of agglutinated foraminifers as the strong decrease in quantity makes a quanti-

tative graph unreadable.

Easterly Core GKG V shows no significant change in the characteristic species core depth. Although *L. goesi* decreases to zero within the upper 8 cm of the core, no other species takes its place in a significant quantity. The decrease of *Eggerelloides* spp. parallels the decrease of the entire agglutinated foraminiferal assemblage, thus, it is present from the top to the bottom of the core. The shallower easterly Core GKG I reveals a decrease of *L. goesi* parallel to the decrease of the entire benthic foraminifer assemblage (including the agglutinated foraminifers); *Eggerelloides* spp. shows strong changes, but is present throughout the core.

The shallower westerly Core GKG II shows relatively high numbers of *Eggerelloides* spp. throughout the core, whereas *R. discreta* seems to be present in significant numbers only in the topmost sample and to a lesser extent at 16 cm core depth where the entire agglutinated foraminfer assemblage shows a short-term increase. *Liebusella goesi* steadily decreases in number from top to bottom of the core, also showing a slight increase at 16 cm core depth. The deeper westerly Core GKG III reveals the most significant decrease in the number of agglutinated foraminifers of the four cores analyzed. It drops from more than 40 to less than 0.2 Ind/g within the upper 12 cm. There is a very slight increase at 16 cm core depth mirroring Core

GKG II. *Eggerelloides* spp. parallels the decreasing trend of the entire agglutinated foraminifer fauna. *Haplophragmoides bradyi* drops from 7.9 Ind/g to 5 within the upper 8 cm of the core. *Rhabdammina discreta* is is only present at 0.06 Ind/g at 4 cm and disappears at 8 cm core depth.

ENVIRONMENTAL PROPERTIES
What controls quantitative differences between easterly and westerly stations?

According to the abundance data, the westerly stations show more than 300% more individuals of agglutinated foraminifera than the easterly stations. Both areas are also characterized by strongly different sedimentation rates (Fig. 3). According to the INDAR, both shallower cores yield more than 100% higher values than the two deeper cores.

Thus, most likely the differences between the four cores from the southern flank of the Skagerrak are not entirely the result of dilution through different sedimentation/accumulation rates.

In terms of grain sizes, Cores GKG V and III, and GKG I and II are comparable, more or less reflecting the average strengths of the bottom currents and the INDAR results. TOC, taken as an indicator for the supply of food, however, does not show any dependence on water depth: GKG I: 2.67%; GKG V: 2.48% GKG II: 2.03%; GKG III: 2.62% (surface samples). With regard to the calcareous benthic foraminifer fauna, there also appear to be similarities that are more related to water depth than to the juxtoposition of the location (e.g. strong *Brizalina skagerrakensis* assemblages in both deeper Cores GKG V and III, but differing assemblages in the shallower cores) (Hass, *this volume*). Winnowing may be a reasonable interpretation for highest abundances of foraminifers in core GKG II, however, grain size distributions do not back up this interpretation for core GKG I.

Various possibilities may account for the differences in abundance (here: „ind/g") of agglutinated foraminifers between the agglutinated foraminifer faunas of the easterly and the westerly stations: The quality of the TOC (i. e. the food supply) may vary. Anton *et al.* (1983) and Liebezeit (1988) point out that up to 89% of the TOC is refractory in nature and, thus, not suitable as food for benthic foraminifers, although they might benefit from the associated bacteria (Alve & Murray, submitted). Van Weering *et al* (1987) suggest the TOC may be of allochthonous origin; Anton *et al.* (1993) were not able to clearly determine the portions of terrestrial and marine origin of the organic material. The fraction of TOC that may serve as a potential food source for benthic foraminifers thus decreases down to 0.20-0.27%. Given the quantity of the bulk foraminifer fauna (GKG I: 101 ind/g; GKG II: 1359

ind/g; GKG III: 104 ind/g; GKG V: 94 ind/g), the TOC content of the sediments turns out to be a crucial environmental factor in the sediments investigated for this study. As most of the organic carbon is considered to be allochthonous, the portion that arrives at the easterly stations has to be transported a longer way and may be more affected by oxydization and consumption, thus reducing both quantity and quality for marine benthic life. The calcareous portion of the benthic foraminifers shows numbers of individuals per gram dry sediment (see above) in all cores except GKG II that are similar to each other, hence the calcareous foraminifers might have advantages when competing with the agglutinated foraminifers for food.

The extreme sedimentation rates at the easterly stations may produce some additional stress for the agglutinated foraminifer fauna that results in a lower number of individuals. Agglutinated foraminifers may have a general disadvantage in areas of very high sedimentation rates when compared to the calcareous foraminifers, as their tests do not posses wall pores, which may limit oxygen uptake (Murray, 1991). Thus, the infaunal forms may have to constantly move to escape the oxygen depleted zones in the sediment, these may be as shallow as 0.5 cm core depth in places (Bakker & Helder, 1993).

Geochemical investigations of Kuijpers *et al.* (1993) reveal pathways and concentrations of heavy metals over the study area, that might provide further suggestions for the differences between the easterly and the westerly core locations on the southern flank of the Skagerrak. They showed that concentrations of Hg, Cu, Zn and most likely Pb as well significantly increase from west to east. Mercury, Cu, and Zn contents of the sediment surface appear to increase by 100% from the westerly to the easterly stations. Although absolute values are not exceptionally high, it can be speculated that heavy metal pollution adds further environmental stress to the easterly stations.

Although it is not yet entirely clear which environmental factor is the dominant controlling factor, it appears that the easterly core locations are probably more affected by environmental stress than the westerly stations. This may account for significantly lower abundance of agglutinated foraminifers at these stations.

The recent abundance increase of agglutinated foraminifers

Quantitative analyses carried out for this study support the findings of Alve & Murray (1995) and Alve (in press), showing generally balanced amounts of agglutinated foraminifers during the past 200 years and a marked increase from the
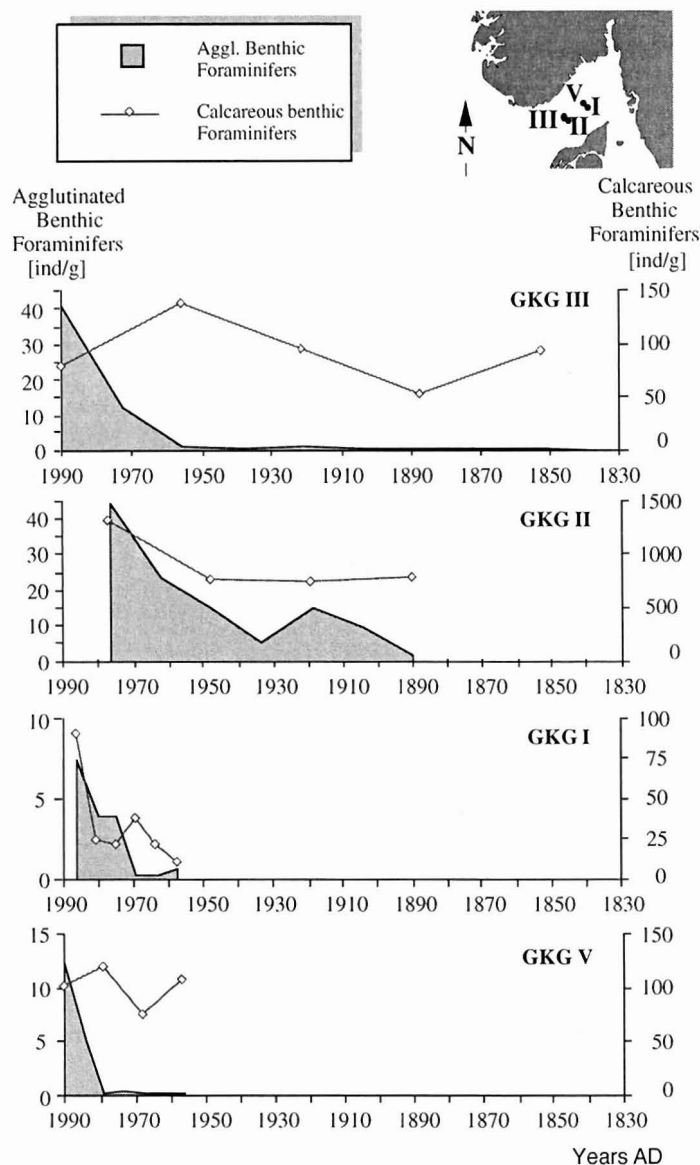
Figure 5. Agglutinated foraminifers and calcareous foraminifers (both ind/g) versus years AD.

plete tests (Fig. 2). This should be significantly different if a large portion of the agglutinated tests were broken or disintegrated in the lower part of the box cores.

A quantitative plot of the agglutinated foraminifers versus depth reveals that a prominent increase in numbers of tests starts basically at approximately 10 cm. The shallow cores GKG I and II show a significant increase at the deeper depth of approximately 24 cm. As there are similar depth-features in cores of strongly different sedimentation rates, these results suggest, that the recent increase may at least partly be controlled by burial depth rather than by external parameters.

Alve (in press), working on cores from the deep Skagerrak basin, could show that not only the quantity but also the species distribution of the agglutinated foraminifer fauna has changed over the past 20-30 years (strong increase of *T. pusillus* and *Saccammina* sp.). As stated in previous chapters, no significant change could be found in the four cores analyzed in this study, however, these are from shallower areas of the Skagerrak than those studied by Alve (op. cit.).

Species distributions
Not much is known about the ecologic preferences of agglutinated foraminifers from the study area. *Eggerelloides* and *L. goesi* dominate the assemblages of all cores. Whereas *Eggerelloides* is of minor importance in Core GKG I, *L. goesi* shows high abundance in both easterly cores. *L. goesi* is of less importance within the cores from the westerly area.

More interestingly, *R. discreta* accounts here for 10 and 20%, respectively. Alve & Murray (submitted) point out that tubular agglutinated foraminifers such as *Rhabdammina* generally suggest a higher food supply because of their relatively high biomass volume. Thus, it may be substantiated that food supply is greater towards the west than at the easterly stations, although this is not reflected by the TOC contents of the sediments.

In addition, the deeper westerly station additionally reveals *H. bradyi*, a species that is not important in any of the other cores. *H. bradyi* and *Eggerelloides* are also among the most frequent agglutinated taxa elsewhere in the deep Skagerrak (see Alve, in press); they mark the upper part of the

early 1970's (Fig. 5). It is apparant, however, that this increase is more marked than that found in the cores of the study of Alve & Murray (op. cit.). This latter effect may be due to different preparation techniques.

The recent increase in agglutinated foraminifers is not paralleled by any of the other variables measured ($\delta^{18}O$, $\delta^{13}C$, $CaCO_3$, TOC, grain size, calcareous benthic foraminifers, etc; see Hass, 1994). Thus, the increase can be inferred to be either the result of a physical or chemical change of the water masses that is not affecting the other parameters analyzed, or it may be a taphonomic effect. Counts of the fragments of the agglutinated foraminifer tests yield trends similar to the com-

stable deep water and the lower part of the transitional water layer, respectively, in the Oslo Fjord (Alve & Nagy, 1990). Thus, *H. bradyi* may account for the conditions, that characterize the Skagerrak deep water, such as more stable conditions and the increased influence of Atlantic water. Since one major difference between location III and the three other stations is lower current speed (Hass, 1996; Rodhe, 1987), *H. bradyi* may as well be indicating a weaker current circulation.

It is possible that, along with other shelf species, *E. scabrus* has been transported in from shelf areas of the Skagerrak, probably originating from the southern North Sea (Alve & Murray, submitted), as only very rarely living specimens have been found outside the shelf area of the Danish slope in the Skagerrak. *Eggerelloides medius*, however, is common, especially in the deeper Skagerrak (Alve & Murray, submitted), a fact that is reflected by the depth dependence of *Eggerelloides* in the sediments investigated for this study.

There is no hint to current strengths sufficient to transport noticable amounts of foraminifers into the deeper Skagerrak (e.g. Rodhe, 1987). Slight downslope transport (creeping) of sediment cannot be excluded, but significant transport would have affected all foraminifers, which is not the case (see also Hass, *this volume*), and terrigenous material of the appropriate equivalent grain size as well. Thus, resedimentation of benthic foraminifers is unlikely at least at the deeper two stations investigated here (GKG III, V).

SUMMARY AND CONCLUSIONS

Four box cores from the southern flank of the Skagerrak covering the past 30-150 years revealed remarkable differences in quality and quantity of the agglutinated foraminifer fauna. Of up to 47 taxa, the four most common are considered to yield information on environmental properties (*L. goesi, Eggerelloides, R. discreta* and *H. bradyi*).

Generally, the two more westerly locations yield higher ammounts („ind/g") of agglutinated foraminifers than two more easterly locations. The supply of food in combination with the hydrographic regime is the most likely control over these differences. The water mass circulation over the southern flank of the Skagerrak runs from west to east, thus the westerly locations most likely receive a greater amount of more suitable food for foraminifers than the easterly locations. This is not only reflected in the number of agglutinated foraminifers per gram sediment but also in the species distribution. *Rhabdammina discreta*, a suspension feeding tube-shaped agglutinated foraminifer, is characterized by a higher volume of biomass. This foraminifer is abundant in sediments from the

westerly locations, whereas it is rare at the easterly locations.

Downcore, the number of specimens in all cores decrease in a manner that suggests a combination of instability of the tests and ecological controls.

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APPENDIX : Taxonomy

A total of 47 species could be identified. Although it was attempted to determine the agglutinated foraminifers to the species level, some could not sufficiently be determined. Thus, in the text, references are occasionally only to the genus level.

Adercotryma glomeratum (Brady, 1878)
Plate 4, Fig. 19 in Bender (1995);
Plate 67, Figs. 1-3 in Loeblich & Tappan (1988);
Plate 3, Figs. 22-23 in Gabel 1971 (as *Adercotryma glomerata*).
Ammodiscus sp.
Ammolagena clavata (Jones & Parker, 1860)
Plate 41, Figs. 12-16 in Jones (1994);
Plate 2, Fig. 9 in Bender (1995);
Plate 36, Fig. 16 in Loeblich & Tappan (1988);
Plate 3, Figs. 16-17 in Gabel (1971)
Bathysiphon filiformis (Sars, 1872)
Plate 13, Fig. 2 in Loeblich & Tappan (1988);
Plate 26, Figs. 17-20 in Jones (1994).
Bigenerina nodosaria (d'Orbigny, 1826)
Plate 7, Fig. 1 in Bender (1995);
Plate 191, Figs. 1-2 in Loeblich & Tappan (1988);
Plate 46, Figs. 46-48 in Gabel, 1971.
Cribrostomoides kosterensis (Höglund, 1974)
Plate 4, Figs. 5-6 in Gabel (1971).
Cribrostomoides subglobosus (Cushman, 1910)
Plate 5, Fig. 2 in Bender (1995);
Plate 1, Figs. 1-4 in Jones et al. (1993) (as *Cribrostomoides subglobosus* forma *subglobosus* [Cushman, 1910]);
Plate 4, Figs. 1-2 in Gabel (1971) (as *Cribrostomoides subglobosum* [Sars]).
Cribrostomoides wiesneri Parr, 1950
Plate 3, Figs. 36-37 in Gabel (1971).
Cribrostomoides sp.
Crithionina sp.
Dorothia sp.
Eggerelloides scabrus (Williamson, 1858)
Plate 1, Figs 6-7 in Alve & Murray (1995);
Plate 47, Figs. 15-17 in Jones et al. (1995) (as *Eggerelloides scaber* [Williamson]);
Plate 189, Figs. 5-7 in Loeblich & Tappan (1988).
Eggerelloides medius (Höglund, 1947)
Plate 1, Figs 6-7 in Alve & Murray (1995).
Eratidus foliaceus (Brady, 1884)
Plate 59, Figs. 1-3 in Loeblich & Tappan (1988).
Glomospira charoides (Jones & Parker, 1860)
Plate 3, Fig. 1 in Bender (1995);
Plate 3, Figs. 13-15 in Gabel (1971).
Haplophragmoides bradyi (Robertson, 1893)
Plate 1, Figs. 10-11 in Alve & Murray (1995);
Plate 3, Figs. 30-31 in Gabel (1971).
Haplophragmoides sphaeriloculus Cushman, 1910
Plate 17, Figs. 5-7 in Schröder (1986).
Hyperammina cylindrica Parr, 1950
Plate 23, Fig. 4, 7 in Jones (1994).
Hyperammina laevigata Wright, 1891
Plate 16, Fig. 6 in Bender (1989);

Plate 23, Figs. 9-10 in Jones (1994).
Hyperammina sp.
Lagenammina sp.
Liebusella goesi Höglund, 1947
Plate 14, Figs. 4-8 in Höglund (1947);
Plate 6, Fig. 4 in Bender (1995) (as *L.? goesi*);
Plate 5, Figs. 20-21 in Gabel (1971).
Liebusella sp.
Morulaeplecta bulbosa (?)
Psammosphaera fusca Schulze, 1875
Plate 4, Figs. 9-14 in Höglund (1947);
Plate 1, Fig. 14 in Bender (1995).
Quinqueloculina agglutinans d'Orbigny, 1839
Plate 7, Fig.16 in Bender (1995).
Recurvoides sp.
Reophax difflugiformis Brady, 1879
Plate 3, Fig. 9 in Bender (1995) (as *R.* cf. *R. difflugiformis*);
Reophax fusiformis (Williamson, 1858)
Plate , Fig. 1 in Bender (1995).
Reophax micacea Earland, 1934
Plate 4, Fig. 3 in Bender (1995);
Plate 1, Figs 20-21 in Alve & Murray (1995).
Reophax regularis Björkholmen
Plate 9, Figs. 11-12 in Höglund (1947).
Reophax scorpiurus Montfort, 1808
Plate 9, Figs. 9-10 in Höglund (1947);
Plate 4, Fig. 5 in Bender (1995);
Reophax subfusiformis Earland, 1933
Plate 9, Figs. 1-4 in Höglund (1947).
Reophax sp.
Rhabdammina discreta Brady, 1884
Plate 1, Figs. 6-7 in Höglund (1947).
Rhabdammina linearis Brady, 1879
Plate 1, Figs. 1-5 in Höglund (1947);
Plate 20, Fig. 1 in Gabel (1971).
Rhabdammina sp.
Saccammina sp.
Saccammina sphaerica Brady, 1871
Plate 4, Figs. 15-17 in Höglund (1947);
Plate 3, Fig. 2 in Gabel (1971).
Spiroplectammina sp.
Textularia conica d'Orbigny, 1839
Plate 17, Fig. 17 in Bender (1989);
Textularia sp.
Tritaxis sp.
Trochamminopsis pusillus (Höglund, 1947)
Plate 1, Figs 24-25 in Alve & Murray (1995).
Trochammina sp.
Veleroninoides sp.
Verneuilina advena Cushman, 1910
Plate 13, Fig. 11 in Höglund (1947).