Benthic foraminiferal evidence of environmental change in the Skagerrak over the past six decades

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High resolution analyses of fossil benthic foraminiferal assemblages have been performed on two short (<40 cm) sediment cores from the deep Skagerrak Basin, NE North Sea. ^{210}Pb-datings of replicate cores from the same two stations have made it possible to calculate accumulation rates of both sediments and benthic foraminiferal tests, and the vertical (historical) assemblage distributions are compared with sediment surface assemblages collected in 1937 and 1992/93. The core data show that the accumulation rate of agglutinated tests was relatively constant from about 1770 to 1940-1950 and that it has increased about 5-6 times since the late 1960's compared to average pre-1940 values. This increase is due mainly to increased production in the 4 agglutinated species *Haplophragmoides bradyi*, *Eggerelloides medius*, *Saccammina* spp., and *Trochamminopsis pusillus*, of which the last 2 were present only as accessory species before the 1960's. The 3 calcareous species *Pullenia osloensis*, *Nonionella iridea*, and *Cassidulina laevigata*, which dominated the dead assemblages prior to the early 1970's, all show subsequent reduced accumulation rates. Despite possible errors caused by postmortem destruction of some agglutinated components, their overall preservation seems to be good enough to reflect the real faunal conditions over the last couple of centuries. The faunal development, as reflected by the core data, is in good agreement with the conclusions based on the comparative study of surface assemblages collected in 1937 and 1992/93. That is, the benthic foraminiferal assemblages in the deep Skagerrak Basin have changed, and according to the core data, these changes have occurred primarily since the early 1970's.

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Introduction

In order to evaluate what effects various kinds of human activity (e.g., effluent discharges and physical changes) have possibly had on the marine environment, details are needed about previous environmental conditions.
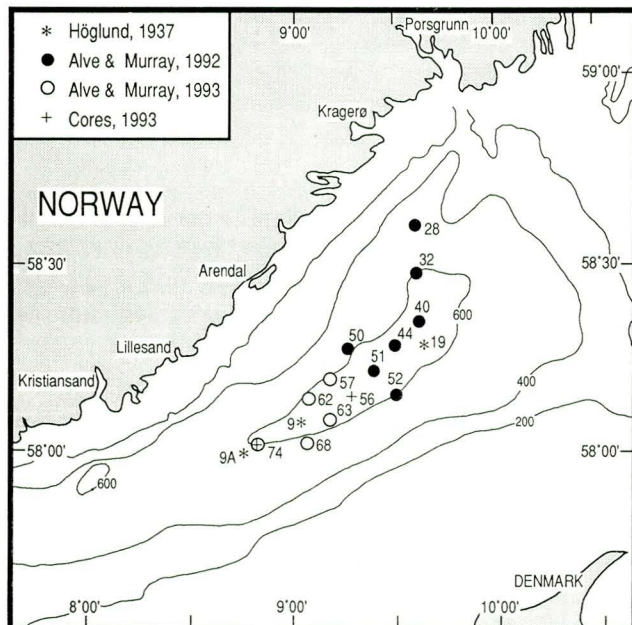

Fig. 1. Bathymetric map (contour interval 200 m) of investigation area showing the location and year of collection of the deep Skagerrak Basin surface samples and the position of the two 1993 sediment cores.

However, in most areas such information is lacking or very sparse, and the only way to gain an insight into past conditions is to interpret the record which is stored in the sediments.

A study of benthic foraminiferal distribution and abundance from surface sediments (0-2 cm) collected by Höglund in the Skagerrak in 1937 (taxonomy discussed in Höglund, 1947) compared with those collected in 1992/93 (Alve & Murray 1995) indicates that faunal changes have occurred, particularly in the deep Skagerrak Basin. These changes were interpreted as indicating environmental change. The 1937 surface sediments are now buried at a depth of 9-18 cm below the modern sediment surface. In order to test to what extent these changes are reflected by the fossil assemblages in the sedimentary record (i.e., in cores penetrating sediments deposited > 50 years ago), foraminiferal analyses have been carried out on two short (< 40 cm), ^{210}Pb-dated sediment cores from the deep Skagerrak Basin.

A summary of previous foraminiferal studies in the Skagerrak has been given by Alve & Murray (1995) and is not repeated here.

Benthic foraminiferal tests are preserved in most marine sediments but it is known that in certain cases, some calcareous tests are lost through dissolution (e.g., Scott 1975, Alve & Nagy 1986) and that some agglutinated taxa with organic or weakly mineralised cement are lost through early diagenetic destruction (e.g., Douglas et al. 1980; Mackensen et al. 1993). Consequently, studies in which changes in foraminiferal assemblages are documented both by down core variations and by compari-

sons of surface samples collected today and in the past (now equivalent to a subsurface layer in the cores) are important for evaluating the applicability of foraminiferal analysis in studies of long term environmental change.

Material and Methods

Field and laboratory procedures

The sediment cores were collected from the Skagerrak at 652 m (station 56) and at 595 m (station 74) water depth (Fig. 1) in July 1993 (University of Bergen cruise no. 9307) by means of a Niemistöe gravity corer (inner diameter 50 mm). Immediately after collection, most of the water overlying the sediment in the core liner was carefully siphoned off slowly. The sediment was then gently pushed up through the core liner and the last few millimetres of water was carefully removed with a pipette and transferred to the surface sample (0.0-0.5 cm) container. The surface 1 cm was sectioned into two 0.5 cm slices, and the 2-6 cm and 6-20 cm intervals were sectioned in 1 cm and 2 cm slices, respectively. Finally, the rest of the 2 cores were sectioned in 4 cm (core 56) and 5 cm (core 74) slices, respectively. The 7 samples from the upper 6 cm of core 74 were gently mixed with 70% ethanol, whereas those from core 56 were kept at ambient temperature (6-8°C) until they were wet-sieved (63 μm sieve) in ambient temperature sea water within 3 days of collection. Fifty individuals from each sample were picked for ATP (adenosine triphosphate) extraction (Alve 1995) and the remaining parts of these 7 samples were preserved in 70% ethanol.

Samples from the deeper core levels were kept refrigerated on the ship and frozen immediately after return to the on-shore laboratory. All ethanol-preserved samples were processed by washing them on a 63μm sieve and staining the residues with rose Bengal for about one hour before they were washed again on the same sieve and dried at 50°C. The frozen samples from 6-20 cm core depths were thawed in ethanol and processed as described above. As living individuals were not expected to be present below 20 cm, the deeper samples were not stained but were otherwise processed in the same way.

At least 250 dead individuals were picked and identified from each sample. Fragments of tubular and branching forms were treated as a separate category and have not been included in the calculations (for discussion, see Murray & Alve 1994).

Datings and calculation of foraminiferal test accumulation rates

Various methods have been used to determine the rate of sediment accumulation in modern sediments (see review by van Weering et al. 1993). The most reliable are those based on ^{210}Pb and in the present study, replicate cores from both stations have been dated by Helmar Kunzendorf using the ^{210}Pb-method. The dating was carried out on 1 cm thick slices throughout both cores. From the results, the calculated sediment accumulation rates are 0.23 and 0.15 cm/yr for cores 56 and 74, respectively. Previously published rates for the study area range from 0.08 to 0.22 cm/yr (van Weering et al. 1987, 1993). Consequently, the values for the two newly investigated

Table 1. Accumulation rates and relative abundance of important species (see text), and calculated faunal parameters of dead assemblages in core 56. * = Ages are given as whole years and represent the middle of each depth interval.

Core 56, dead assemblages

Depth (cm)	0-0.5	0.5-1	1-2	2-3	3-4	4-5	5-6	6-8	8-10	10-12	12-14	14-16	16-18	18-20	20-24	24-28	28-32	32-37
Year*	1992	1991	1988	1984	1980	1976	1973	1969	1963	1956	1949	1945	1940	1931	1917	1902	1888	1871
No./10 cm²/yr																		
Earlandammina sp.	6	8	17	10	13	28	16	4	7	4	9	24	5	4	12	5	2	4
E. medius	12	17	16	25	21	27	22	15	15	17	7	9	3	7	11	1	3	5
H. bradyi	71	64	44	47	58	39	38	29	19	15	15	32	20	17	24	10	6	8
Saccammina spp.	112	58	27	40	48	28	18	2	3	2	0	2	1	0	0	0	0	0
T. pusillus	49	27	29	32	52	28	12	13	17	1	0	4	4	2	4	2	1	4
C. laevigata	5	3	2	9	10	13	16	46	12	16	29	28	30	21	33	9	34	26
N. iridea	25	5	5	15	42	64	35	80	88	72	82	84	60	52	83	60	36	54
P. osloencis	31	19	7	28	22	39	22	51	40	64	113	145	57	78	62	66	59	42
S. fusiformis	2	1	2	2	6	7	7	16	20	14	16	50	26	20	21	13	16	27
% values																		
Earlandammina sp.	1	3	9	4	4	7	5	1	2	1	2	4	2	1	3	2	1	2
E. medius	3	6	8	9	6	7	6	3	4	5	1	2	1	2	3	0	1	2
H. bradyi	17	23	21	16	16	9	11	6	5	4	3	6	6	6	6	4	2	3
Saccammina spp.	26	21	13	14	13	7	5	0	1	1	0	0	0	0	0	0	0	0
T. pusillus	12	9	14	11	14	7	4	3	5	0	0	1	1	1	1	1	0	2
C. laevigata	1	1	1	3	3	3	5	10	3	5	6	5	9	7	9	3	13	9
N. iridea	6	2	2	5	11	16	11	17	25	21	17	16	18	18	22	22	14	19
P. osloensis	7	7	3	9	6	9	6	11	11	19	23	27	18	27	16	24	23	15
S. fusiformis	0	0	1	1	2	2	2	4	6	4	3	9	8	7	5	5	6	10
No. counted	278	243	270	253	250	274	247	256	261	275	268	250	250	284	311	257	282	260
Tests/cm³	128	84	76	120	154	143	83	126	122	132	117	105	121	136	160	98	97	140
% agglutinated	74	76	82	64	61	51	52	29	26	19	17	20	22	18	19	11	10	14
Tests/10cm²/yr	426	282	204	292	375	407	334	466	349	343	489	540	327	290	386	274	260	281
Aggl./10cm²/yr	314	214	167	185	229	206	173	133	90	64	84	108	72	51	75	30	26	40

Table 2. Accumulation rates and relative abundance of important species (see text), and calculated faunal parameters of dead assemblages in core 74. * = Ages are given as whole years and represent the middle of each depth interval.

Core 74, dead assemblages

Depth (cm)	0-0.5	0.5-1	1-2	2-3	3-4	4-5	5-6	6-8	8-10	10-12	14-16	18-20	20-25	25-30	30-35
Year*	1991	1988	1983	1977	1972	1967	1961	1952	1939	1924	1897	1869	1845	1810	1777
No./10 cm²/yr															
E. medius	15	11	13	34	37	23	19	7	8	4	3	5	2	3	6
H. bradyi	40	45	29	48	28	17	13	6	4	4	14	7	6	8	7
Saccammina spp.	45	29	9	15	3	1	0	0	0	0	0	0	0	0	1
T. pusillus	30	18	10	20	19	15	6	5	3	0	0	0	0	0	0
B. skagerrakensis	10	33	29	59	68	56	60	21	16	10	46	33	6	5	7
C. laevigata	3	2	3	7	21	19	29	34	36	27	26	18	27	23	12
N. iridea	8	4	4	29	45	44	40	42	74	60	90	27	27	27	34
P. osloensis	21	25	19	35	63	52	54	37	78	49	68	59	39	23	45
S. fusiformis	9	9	5	8	6	8	4	11	16	9	13	10	7	9	10
% values															
E. medius	6	5	8	10	10	7	6	3	2	2	1	2	1	2	3
H. bradyi	15	18	18	14	7	5	4	3	1	2	4	3	3	5	4
Saccammina spp.	17	12	6	4	1	0	0	0	0	0	0	0	0	0	0
T. pusillus	11	7	6	6	5	4	2	2	1	0	0	0	0	0	0
B. skagerrakensis	4	14	18	17	17	16	20	9	5	4	13	13	3	3	4
C. laevigata	1	1	2	2	5	5	10	15	11	11	8	7	15	15	7
N. iridea	3	2	2	8	11	13	13	18	22	24	27	11	15	17	20
P. osloensis	8	10	12	10	16	15	18	16	23	20	20	24	22	15	26
S. fusiformis	3	4	3	2	2	2	1	5	5	3	4	4	4	6	6
No. counted	247	234	252	248	263	255	257	252	265	288	260	317	269	277	258
Tests/cm³	179	164	106	177	192	197	189	137	254	171	246	167	126	106	120
% agglutinated	65	59	54	45	33	28	17	17	7	8	10	8	16	15	15
Tests/10cm²/yr	267	244	163	348	392	340	300	231	344	250	340	248	180	157	173
Aggl./10cm²/yr	174	143	88	157	130	93	51	39	25	19	34	20	29	24	26

cores are in good agreement with these previous findings. The values reflect the high variability in the sediment accumulation rates in the area and, as a consequence, core 56 penetrated sediments deposited since about 1870, whereas core 74 penetrated back to about 1770 even though the cores were of comparable length.

The accumulation rates of dead, benthic foraminifera (defined as the number of tests per 10 cm² per year) were calculated as follows. For each sample, the total number of dead foraminiferal tests was divided by the core area (in cm²), multiplied by 10, and finally divided by the number of years of sedimentation represented by that sample. This gave the number of dead tests added to the sediment per 10 cm² per year. The accumulation rates of individual species and of dead agglutinated tests were calculated in the same way.

Results

The faunal data, relevant for the present discussion, are presented in Tables 1 and 2. According to the ^{210}Pb-dating, the actual 1937 sea-bed surface now lies at a depth of 17-18 cm (core 56) and 9-10 cm (core 74) below the current sea floor. In sediments deposited before about 1910 (Fig. 2), that is below 24 cm in core 56 and below 14 cm in core 74, the accumulation rates of agglutinated tests are fairly constant (20-40 tests/10 cm²/yr). At levels corresponding to the late 1960's, the rates have increased to about 100-130 tests/10 cm²/yr. Subsurface local minima are succeeded, in both cores, by maximum
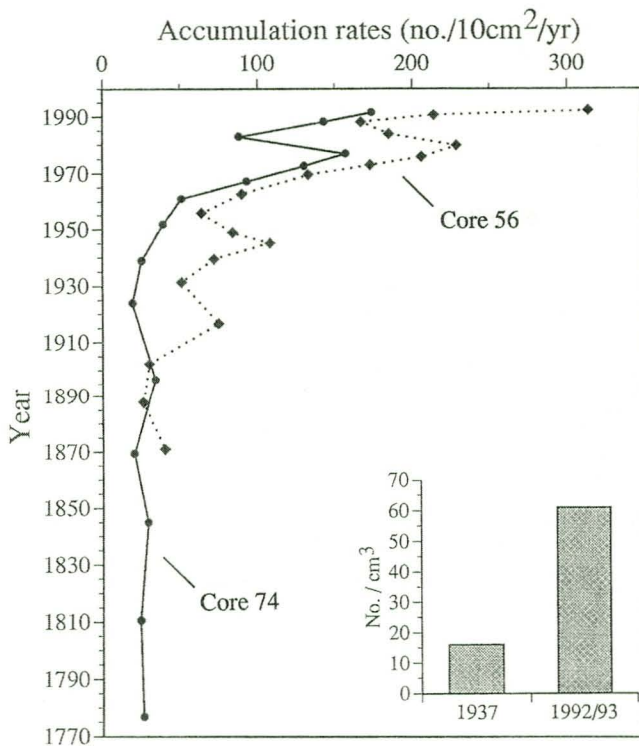

Fig. 2. Accumulation rates of dead agglutinated tests in cores 56 and 74. Histograms show the average concentration of agglutinated tests in deep Skagerrak Basin surface samples collected in 1937 and 1992/93 (surface data from Alve & Murray 1995).

accumulation rates of 314 (core 56) and 174 (core 74) agglutinated tests/10 cm²/yr in the most recently deposited 0.5 cm of sediment.
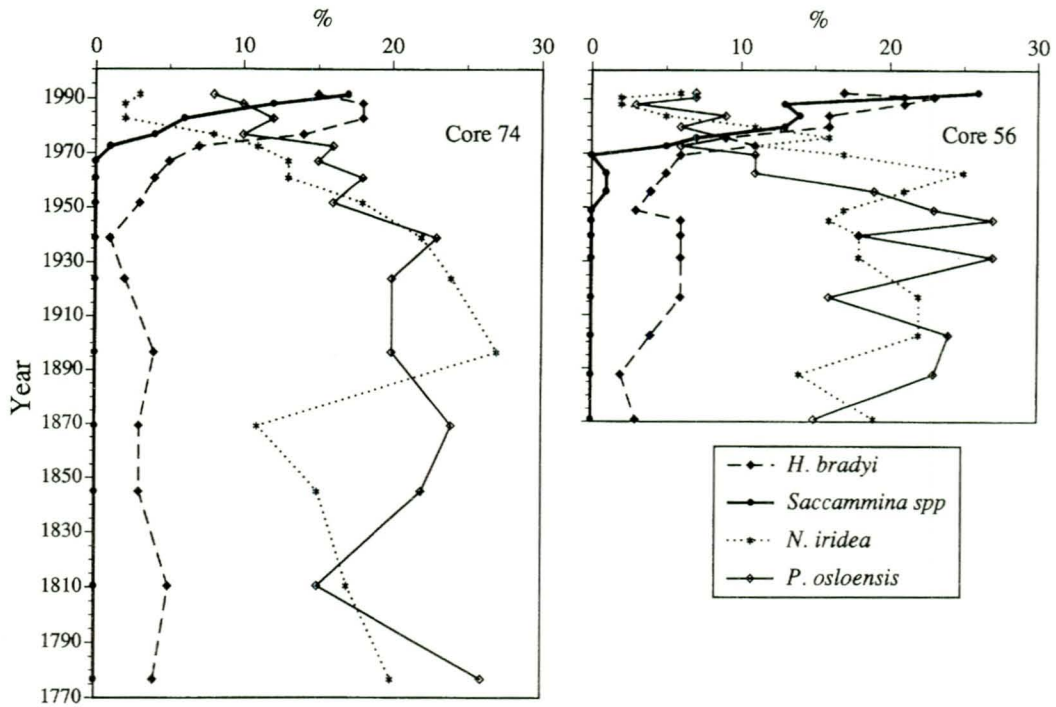
Fig. 3. Relative abundance of the 4 most frequently occurring species throughout cores 56 and 74.

Nine species make up ≥5% of the total dead assemblage in at least two samples within each core. Eight of these are the same in both cores and the relative abundances of the 4 most common species (i.e., dominant in at least one sample), except *Brizalina skagerrakensis* (Qvale & Nigam), are shown in Fig. 3. The reason for omitting this species from the diagram is discussed below. The deeper parts of the cores (>4 cm in core 56; > 6 cm in core 74) are dominated by one or the other of *Nonionella iridea* Heron-Allen & Earland and *Pullenia osloensis* Feyling-Hanssen. In core 56, *Haplophragmoides bradyi* (Robertson) dominates the core interval 0.5-4.0 cm with frequent *Saccammina* spp. and *Trochamminopsis pusillus* (Höglund), whereas *Saccammina* spp. dominate the surface 0.0-0.5 cm with the other two as frequent components. In core 74, *B. skagerrakensis* dominates the core interval 2-6 cm with frequent *P. osloensis*, *N. iridea*, *H. bradyi*, and *Eggerelloides medius* (Höglund). The surface 2 cm are generally dominated by *H. bradyi* with frequent *Saccammina* spp., *B. skagerrakensis*, *P. osloensis*, and *T. pusillus*.

The comparative study of surface assemblages from 1937 and 1992/93 (Alve & Murray 1995) indicated that the greatest changes had occurred in 4 agglutinated and 3 calcareous taxa. The calculated accumulation rates of the 4 agglutinated taxa *Saccammina* spp., *T. pusillus*, *E. medius*, and *H. bradyi*, are relatively low in both cores in sediments deposited before about 1950 with ≤1, ≤5, 1-11, and generally 4-20 tests/10 cm²/yr, respectively (Fig. 4). While *E. medius* shows maximum values (27-37 tests/10

cm²/yr) in both cores at core depths corresponding to the 1970's, the other 3 generally show maximum values in the upper 1-2 cm: *Saccammina* spp. 45-112; *T. pusillus* 30-49; *H. bradyi* 45-71 tests/10 cm²/yr .

Of the 3 calcareous taxa, *Cassidulina laevigata* d'Orbigny generally has accumulation rates between 15 and 35 tests/10 cm²/yr in pre 1970 core levels, whereas the values for *P. osloensis* and *N. iridea* generally lie in the range 30 to 90 tests/10 cm²/yr. Minimum values for all 3 species occur in the upper 1-2 cm: *C. laevigata* 2; *P. osloensis* 7-19; *N. iridea* 4-5 tests/10 cm²/yr.

Discussion

Accumulation rates of agglutinated tests

The accumulation rates of agglutinated tests indicate reasonably stable production from the late 1700's until 1950-1960, although a minor increase is indicated in core 56 from about 1910 (Fig. 2). However, both cores show a pronounced increase from the late 1960's; by the late 1980's to early 1990's (represented by the accumulation rate in the surface 0-2 cm in core 56 and 0-1 cm in 74), the rate had increased by factors of 4.7 (core 56) and 6.3 (core 74), compared to average pre-1940 values. These values are in good agreement with the findings of Alve & Murray (1995). Their comparative study of benthic foraminiferal surface (0-2 cm) assemblages collected in the deep Skagerrak Basin in 1937 and in 1992/93 indicated that the
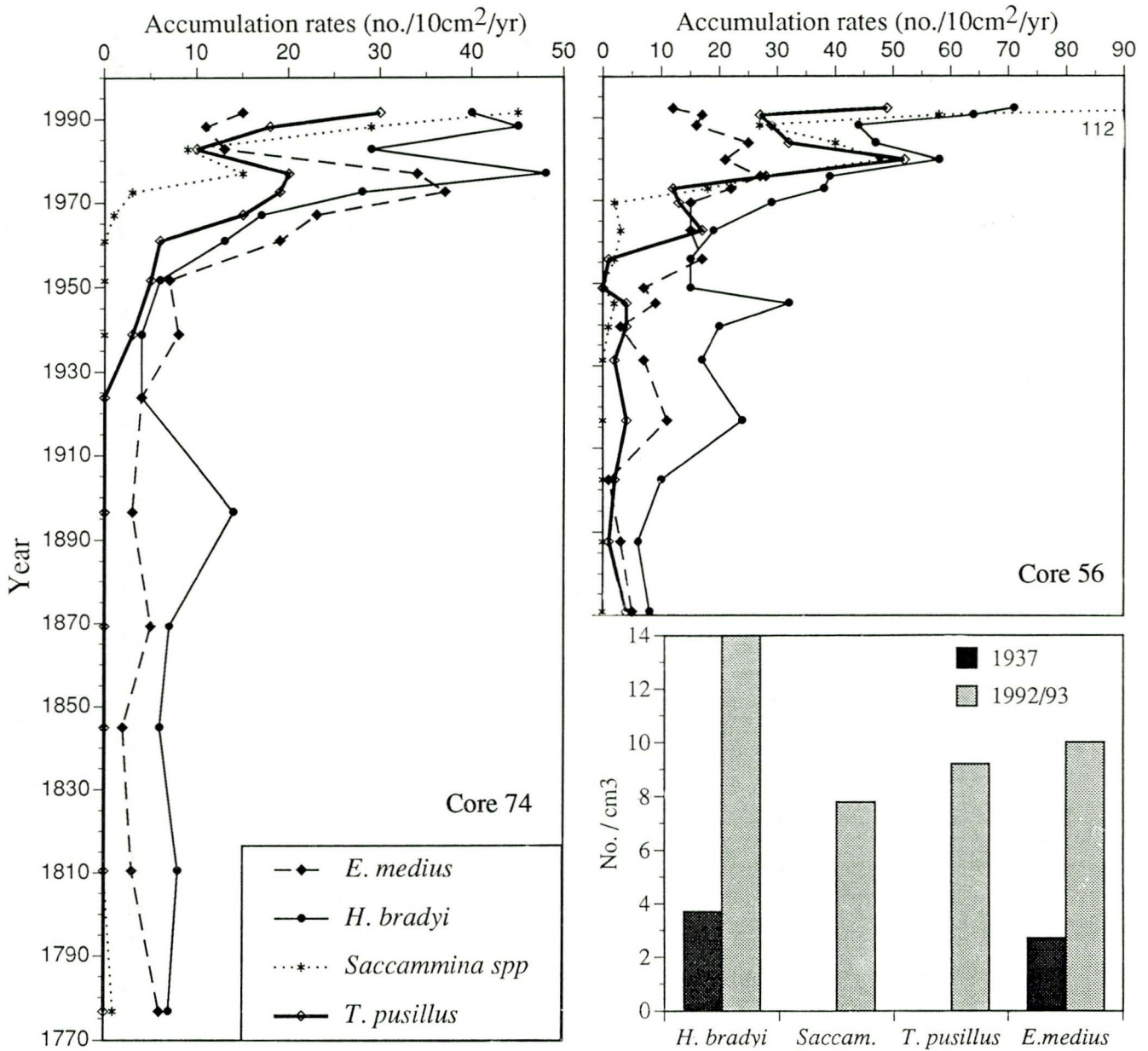
Fig. 4. Accumulation rates of 4 key agglutinated species in cores 56 and 74. Histograms show their average concentration in deep Skagerrak Basin surface samples collected in 1937 and 1992/93 (surface data from Alve & Murray 1995).

average abundance of agglutinated tests had increased by a factor of 3.8 during that time period. As this comparison was based on only 3 samples from 1937 and 12 samples from 1992/93 the factor of 3.8 should be regarded merely as an approximation. On the other hand, it can be argued that some of the agglutinated tests have been lost through early diagenetic destruction so that the agglutinated test concentration is somewhat reduced at deeper core levels compared to the time when they were deposited.

Agglutinated tests which are weakly held together by organic material do not survive long after death (Murray 1991). Douglas et al. (1980) suggested that the organic matter probably is oxidised within the surface layer of the sediments, and Sidner & McKee (1976) indicated that the vertical distribution of iron-rich agglutinated taxa is con-

trolled by geochemical factors rather than ecological ones. Additionally, some agglutinated species do not survive sample processing simply because their tests are too fragile. Undoubtedly, some of the more fragile species in the deep Skagerrak Basin either rapidly disintegrated after death due to oxidation or bacterial attack of the organic material, or were destroyed during processing. Alve & Murray (1995) noted that for instance *Haplophragmoides membranaceum* Höglund, which was common in the stained assemblages in the deep basin, was rare in the companion dead assemblages, probably due to postmortem destruction. However, because this destruction seemed to happen so quickly, and because the stained assemblages generally made up <15% of the total assemblages (stained + dead in upper 0-2 cm) upon which the comparison between surface samples was
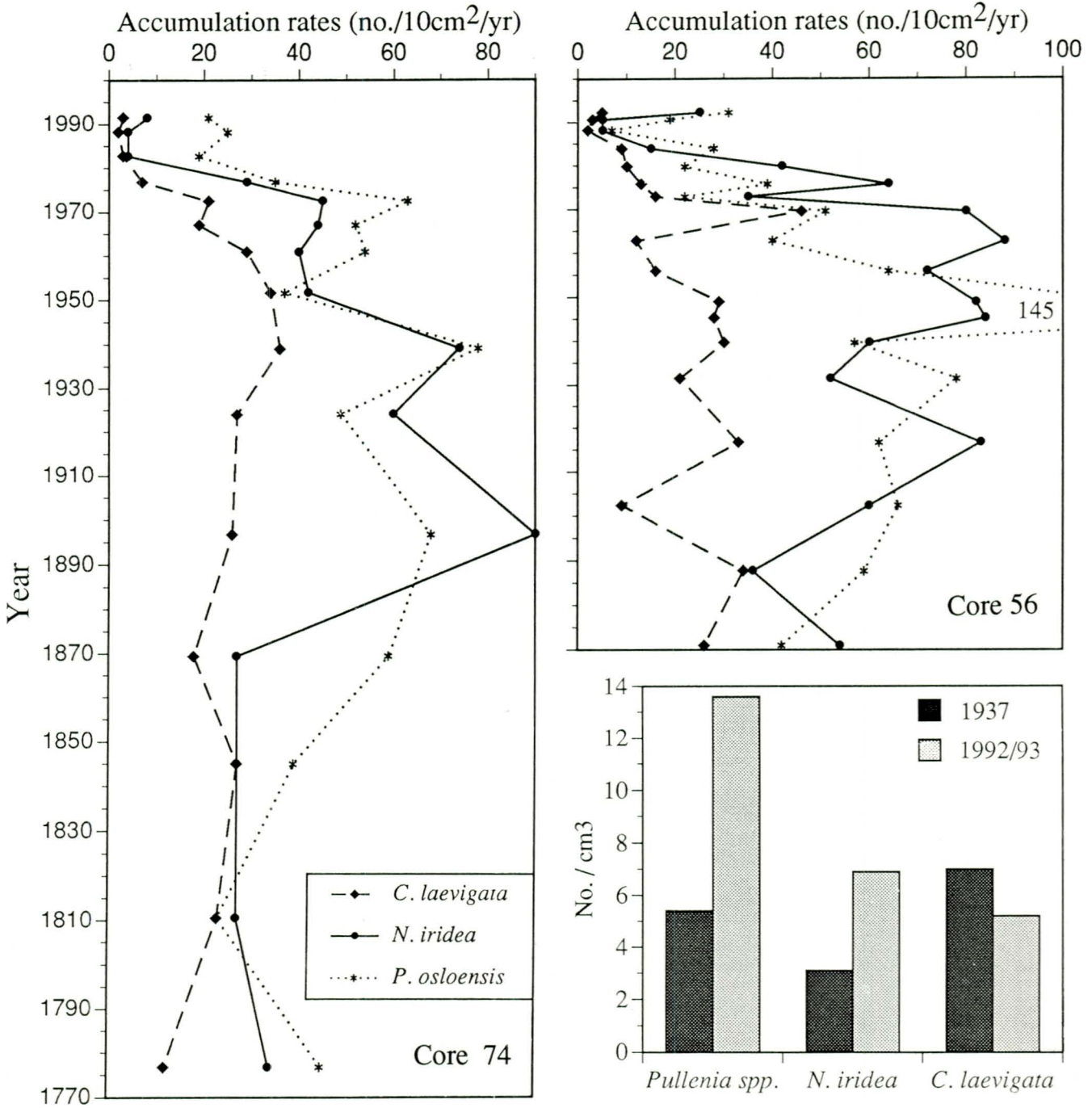
Fig. 5. Accumulation rates of 3 key calcareous species in cores 56 and 74. Histograms show their average concentration in deep Skagerrak Basin surface samples collected in 1937 and 1992/93 (surface data from Alve & Murray 1995).

based, discrepancies caused by the presence of fragile species were almost eliminated. In the down core comparisons made here, only the dead assemblages were considered. Consequently, the most fragile species had already been eliminated from the surface sediment assemblage data, before the down core comparisons were undertaken.

Loss of agglutinated tests in the surface sediments have also been reported from the East Pacific Rise

(Douglas & Woodruff 1981), the southern California borderland (Douglas et al. 1980), the northwest Atlantic Ocean (Schröder 1988), the eastern Weddell Sea (Mackensen & Douglas 1989, Mackensen et al. 1990), and beneath the South Atlantic Polar Front (Mackensen et al. 1993). Schröder (1988) distinguished 3 categories of deep-sea agglutinated species according to their preservation potential and Mackensen et al. (1990, 1993) went as far as excluding from their «potential fossil assembla-

ges» all agglutinated species that they considered as non-resistant. A feature common to the samples analysed in most of these investigations is that they were collected from relatively deep-water environments (> 1000 m). On the other hand, down core investigations in more marginal marine areas have reported abundant agglutinated assemblages well below the surface few centimetres (i.e., throughout 140-170 cm cores in Drammensfjord, Norway (Alve 1991), throughout cores of up to >240 cm in Saguenay Fiord, Canada (Schafer et al. 1991), and down to 7 m below the sediment surface in Lake Melville, Labrador (Vilks & Mudie 1983). Denne & Sen Gupta (1989) concluded that «taphonomic processes are least active in areas of rapid sedimentation, where the bioturbated zone is thin, and under oxygen-deficient conditions». Consequently, it is probable that the more selective preservation of agglutinated tests in the deep-sea compared with that in marginal marine environments is, to a great extent, related to their differing sedimentation rates. Another possibility is that many typical shelf and marginal marine agglutinated species may have a higher preservation potential than that of deep-sea taxa, as a general adaption to more stressed environments.

The deep Skagerrak Basin has fairly rapid sedimentation rates (>1 mm/yr) and sediment porewater oxygen profiles in sediment cores from 27 stations in the Skagerrak, including the deep basin, showed that the oxygenated zone is thin (3-20 mm, Bakker & Helder 1993). Consequently, if a rapid sedimentation rate and a thin oxygenated zone are regarded as important criteria for the preservation of agglutinated tests, the agglutinated tests in the deep basin sediments should stand a good chance of not getting lost. Additionally, the deep Skagerrak Basin can be geomorphologically considered as a silled fjord (separated from the rest of the North Sea by a sill at about 270 m water depth), and most of the common species are also frequent components in the adjacent fjords (i.e., Qvale et al. 1984) where abundant and diverse agglutinated assemblages are preserved in the sediments (Alve 1991, unpubl. data).

To summarise, it can be concluded from the above-mentioned factors, and the fact that the core data show relatively constant accumulation rates of agglutinated tests for nearly 200 years before the recent increase, that the core data reflect the original faunal development reasonably well. Furthermore, the down core data support the conclusion drawn from the comparative study of surface assemblages of 1937 and 1992/93 that the abundance of agglutinated foraminifera has increased in the deep Skagerrak Basin during the last six decades.

Changes in the faunal composition

The comparison with Höglund's 1937 surface assemblage data indicated that a pronounced increase has occurred in 4 agglutinated species in the deep basin (see lower right-hand diagram in Fig. 4 and Alve & Murray 1995). Two of these, Saccammina spp. and Trochamminopsis

pusillus, were not recorded by Höglund in this area. However, scattered occurrences of both at pre-1940 core depths, show that they have been present there for a longer time period, but only as accessory species (Fig. 4). The two other species, Haplophragmoides bradyi and Eggerelloides scabrus, were the most frequently occurring agglutinated species in Höglund's deep basin samples. This is also in good agreement with the core data, as they are the most common agglutinated taxa at levels corresponding to sediments deposited before about 1960.

The overall most abundant taxa in Höglund's deep basin 1937 assemblages were Cassidulina laevigata, Pullenia spp. and Nonionella iridea (as his Nonion labradoricum?). Accordingly, the same species are also the most abundant in both cores in sediments deposited before about 1970. However, the surface comparison indicated an increasing trend in the abundance of Pullenia spp. and N. iridea and a minor decrease in C. laevigata (lower right-hand part of Fig. 5), whereas the core data show reduced frequencies in all (Fig. 5). This discrepancy is probably due to the fact that Höglund analysed the samples in a wet state, and probably overlooked a number of Pullenia spp. (mainly P. osloensis) and N. iridea specimens, since they are small (typically < 190 µm greatest diameter; Feyling-Hanssen 1964) and thin-shelled and relatively transparent in water. Consequently, it seems that the core data give more reliable information about the faunal changes than the comparison with Höglund's surface assemblages. On the other hand, C. laevigata, which is a bigger and thicker shelled species, shows the same decreasing trend towards today's conditions in both the comparative surface and core studies.

Alve & Murray (1995) suggested that active carbonate dissolution is taking place in the deep Skagerrak Basin today (presence of corroded tests), and the recent decreasing trend in the accumulation rates of calcareous tests in the two cores analysed seems to reinforce this observation. This topic will be further focused upon in a later paper following completion of more core analyses.

When considering the historical development of the relative abundances of the most common taxa, the core data show that, except for a dominance of Brizalina skagerrakensis between the late 1950's and 1980 in core 74 (Table 2), a pronounced faunal shift from P. osloensis and N. iridea dominated assemblages to H. bradyi and Saccammina spp. dominated assemblages occurred during the 1970's (Fig. 3; Tables 1 and 2). The subsurface dominance of B. skagerrakensis, which is only an accessory species in core 56, brings up the topic of temporal mixing of faunas due to differences in vertical habitat preferences. It is now generally accepted that certain infaunal benthic foraminiferal species may live at various depths below the current sediment surface (e.g., Corliss 1985, Gooday 1986, Mackensen & Douglas 1989, Alve & Bernhard 1995). Deep infaunal taxa live in sediments laid down decades ago. Thus, as also pointed out by Murray (1995), the final dead assemblages may consist of contemporary deep infaunal tests plus epifaunal and shallow

infaunal tests which died decades ago. In core 74, abundant and nearly monospecific living *B. skagerrakensis* assemblegs were present at 8-20 cm core depths (Alve 1995). In contrast to this, *B. skagerrakensis* had its live maximum abundance in the upper 0.5 cm of the sediments in a core from the same area (621 m water depth) investigated by Corliss & van Weering (1993). Based on these findings, it is reasonable to assume that the subsurface dominance of dead *B. skagerrakensis* in core 74 does not reflect that it actually dominated the original assemblages deposited between the late 1950's and 1980. Its dominance is probably rather an effect of its temporally changing vertical position in the sediments causing it to leave its empty tests together with non-contemporary deposited assemblages. Exclusion of *B. skagerrakensis* from the dead assemblage data during calculations of the relative abundances did not alter the signals from the other dominant species concerning the timing of the faunal shift. However, environmental misinterpretations of the core interval where it dominates were avoided, due to the knowledge about its extremely changing vertical living occurrences in the sediments in this area.

Significance of the faunal changes

The faunal changes indicated by the comparative study of Alve & Murray (1995) based on surface assemblages collected in 1937 and in 1992/93 have now been confirmed by the down core investigations. The question then arises as to what these changes actually mean? There is limited information available concerning the reasons why agglutinated assemblages suddenly should increase in density. However, it is worthwhile mentioning that core studies of sediments deposited over the last 400-500 years in Frierfjord near Porsgrunn (Fig. 1), southern Norway, showed an increased abundance of agglutinated taxa during the 'saw-mill period' (1600, 1700 and initial parts of the 1800's), before they disappeared due to the development of nearly permanently anoxic conditions (Alve, unpubl. data). Furthermore, it is noteworthy that, in the same way as in the Skagerrak, *T. pusillus*, and to some degree *H. bradyi*, were among the agglutinated species which showed increased abundance, whereas at the same time *C. laevigata*, which previously had dominated the assemblages, showed a clear decrease. In Frierfjord, this faunal shift is interpreted to reflect poorly oxygenated conditions in the surface sediments due to the combined effects of infrequent deep-water renewals and increased load of organic material.

Drastic changes in the foraminiferal assemblages have also recently been noted at core levels dated to the early 1970's in the southern Kattegat, between the Skagerrak and the Baltic (Christiansen et al. 1994). It was speculated that these changes were connected to documented wind-induced higher salinities and declining bottom water oxygen concentrations. The timing of the southern Kattegat faunal changes fits surprisingly well with the timing of the changes in the deep Skagerrak Basin.

However, it would be far too speculative to suggest that these changes are linked to some overall environmental changes that would affect two such different, although not too distant, areas.

The deep Skagerrak Basin is the main depository of fine-grained particulate material in the North Sea (e.g., van Weering et al. 1987). Additionally, because of its physical properties (sill at about 270 m water depth) and general water circulation patterns which prevent efficient deep water exchange (on average, deep water renewal is every 25th month; Aure & Dahl 1994), the bottom environment is probably more sensitive to changing fluxes in nutrients and organic material than well-flushed areas. It is not clear to what extent the yearly influx of anthropogenically induced nutrients and organic matter to the North Sea has changed over the past 50-60 years but considering the general industrial and urban development in northern Europe, it is reasonable to assume that it has increased.

At the present stage, it is difficult to draw any firm conclusions about what kind of environmental changes might have caused the observed faunal changes in the deep Skagerrak Basin. However, the fact that the foraminiferal assemblages have changed, especially over the last 20-30 years, is an interesting observation in itself. Further investigations are needed in the area to try to explain what the reasons might be.

Conclusions

Detailed foraminiferal analyses of two ^{210}Pb-dated cores from the deep Skagerrak Basin which penetrate sediments deposited since about 1770 and 1870, respectively, have shown that:

(1) The accumulation rate of agglutinated foraminiferal tests was relatively stable up to about 1950-1960 and has increased about 5-6 times since the late 1960's compared to average pre-1940 values.

(2) The increased accumulation rate of agglutinated tests is primarily due to increases in *Haplophragmoides bradyi*, *Saccammina* spp., *Trochamminopsis pusillus*, and *Eggerelloides medius*. Before about 1950, *H. bradyi* and *E. medius* were the most common agglutinated taxa, whereas *Saccammina* spp. and *Trochamminopsis pusillus* occurred only as accessory species.

(3) A drastic faunal change from assemblages dominated by the calcareous *Pullenia osloensis*, *Nonionella iridea* and *Cassidulina laevigata* to the above-mentioned agglutinated species occurred during the early 1970's. Since then, reduced accumulation rates have been recorded for all 3 species.

The general trends concerning faunal development in the deep basin support the conclusions drawn from the comparative study of surface assemblages collected in 1937 and 1992/93 (Alve & Murray 1995). The discrepancies concerning the two calcareous taxa *P. osloensis* and *N. iridea* are probably due to an underestimation of their

presence in the 1937 samples. Consequently, the core data seem, in some respects, to give a more reliable impression of the real faunal changes than the surface sample comparison.

This is the first study where long-term changes in foraminiferal assemblages have been documented both by down core variations and by comparisons of surface samples collected today and >50 years ago. These findings have important implications for future investigations as they demonstrate the applicability of foraminiferal analyses in studies of long-term environmental change.

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