A comprehensive analysis of the effects of offshore oil and gas exploration and production on the benthic communities of the Norwegian continental shelf

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ABSTRACT· Multivariate statistical analyses of data on environmental variables and benthic fauna from 14 oil and gas fields obtained from 24 surveys collected between 1985 and 1993 are presented. At all fields oil-based drilling mud was used. The purpose of this study was to investigate contamination gradients, assess effects on benthic fauna both spatially and temporally and to evaluate measures such as diversity indices, indicator species and multivariate analysis techniques in assessment of pollution. Results from analyses of baseline surveys of environmental variables and fauna were characterised by a lack of distinct gradients in station placement, having a typical shot-gun pattern in PCA-, DCA- and MDS-ordination analyses. Likewise there was no consistency in which environmental variables correlated with the fauna. Contamination was assessed using all the physical and chemical data in classification and PCA-ordination analyses. Clear patterns were found using 4 categories, conveniently termed initial, moderate, severe and gross. The categories were usually apparent as rings radiating from the platform. Initial contamination of the outermost areas at most fields was shown as elevated levels of barium and total hydrocarbons (THC) and sometimes also by elevated levels of zinc, copper, cadmium and lead. Three fields were studied in particular and showed contaminated areas of over 100 km^2 (Valhall), over 15 km^2 (Gyda) and over 10 km^2 (Veslefrikk). After a period of 6 to 9 yr contamination had spread, so that nearly all of the outermost stations 2 to 6 km away from the platforms showed evidence of contamination. Thus, the existing sampling design is no longer suitable for assessment of the area contaminated. Effects on the fauna showed, as with contamination, 4 categories. Analyses linking fauna and environmental variables indicated that the effects were mainly related to THC, barium and strontium, but also to metals like zinc, copper, cadmium and lead, which are all discharged in drill-cuttings. Effects on the fauna closely followed the patterns of contamination with only a few stations at each field that were contaminated not showing effects. Thus the areas showing effects were only slightly less than the areas contaminated. Subsequent to cessation of discharges biodegradation of oil and reduced concentrations of THC were observed. Yet there was an extension of areas where the fauna was affected several years after cessation of drill-cutting discharges. This may indicate that barite and related compounds associated with the discharges also have an environmental impact. However, preliminary results from fields using only water-based mud clearly indicate a reduction in environmental contamination and biological impact, compared to effects reported here, for oil-based drill-cuttings. Diversity indices applied to the data did not show the extent of effects and such indices alone should not be used to interpret changes. The consistent patterns that the multivariate techniques were able to detect showed that these methods were far superior. Analyses of the initial effects on the fauna showed that there were no consistent patterns in changes in species composition over fields or time, and thus the search for 'universal' sensitive indicator species does not seem to be rewarding. Yet under gross effects of pollution there were consistent patterns with the same species dominating. Finally, the initial effects of pollution included severe reductions in organisms that are key components of the benthic communities and also food for bottom-living fish, and are thus ecologically important. The new fauna which establishes in the contaminated sediments close to platforms, often with high abundance, will probably be less valuable as a food source for fish populations since it is of small size and lives sub-surface.

KEY WORDS: Macrobenthos · Multivariate analyses · Norway · Offshore · Oil drilling

INTRODUCTION

Oil and gas reserves in the North Sea have been exploited since the mid 1960s. It is of wide general interest to obtain an overview of the extent to which these activities affect marine life. Davies & Kingston (1992) and Kingston (1992) have recently given reviews of effects of oil production on the benthos of the North Sea. Kingston (1992) records that in the early days of exploration it was generally believed that the major input of oil would be in water from platform drainage and production. This was found to be incorrect and the greatest source of oil until now has been in discharged drill-cuttings, which are disposed of during drilling operations (Kingston 1992).

Originally the drill-cuttings were in aqueous solution, but later oil replaced the water as it was preferable in the drilling process. However, due to observed toxic effects of oil-based drilling muds there has been a change in recent years back to water-based muds. Although the composition of drilling muds used varies from area to area, all have a weighting agent, usually barite ($BaSO_4$), viscosity agents such as bentonitic clays, swelling controllers (potassium chloride, KCl), pH controllers (potassium hydroxide, KOH), filter loss components, dispersants, defoamers, drilling lubricants (such as fatty acids and hydrocarbons), gypsum to increase the calcium content and biocides (GESAMP 1993). Of these chemicals barite is used in large quantities, a typical figure being 1500 t per well, and around 90 % of this is typically discharged after use. The barite contains impurities such as heavy metals and the concentration of such metals discharged depends on the quality of the barite. Since barite is insoluble and has high density it settles at the seabed and thus is often a good tracer for the dispersion of drill-cuttings. The effects of drill-cuttings are therefore likely to be on sediment-living benthos. As a consequence monitoring has focused on identifying changes in sediment contamination and effects of this contamination on the structure of communities living in the sediment. From the foregoing it is clear that drill-cuttings will cause a variety of effects through smothering, toxic chemicals such as heavy metals and hydrocarbons and organic enrichment. The relative importance of the different components will vary from field to field.

All countries producing oil require that monitoring be done to assess the effects on the marine environment. From published information Davies et al. (1981) showed for the UK sector of the North Sea that 'significant contamination was found only in the sediments close to some platforms'. For example Davies & Kingston (1992) showed that for the Shetland Basin, North Sea, total oil concentrations at distances between 5000 and 10000 m from platforms had risen from 3–90 ppm

in 1979 to 80–900 ppm in 1988. Kingston (1992) reported that for the North Sea typical patterns were concentrations of hydrocarbons between 1000 and 10000 times background close to platforms, with a steep downward gradient between 500 and 1000 m. GESAMP (1993), reporting data from Davies et al. (1989) and unpublished Norwegian data, showed that hydrocarbons were present in elevated concentrations in ellipses of 4000 × 8000 m in the UK sector and 5000 × 10–12000 m in the Norwegian sector. The contamination mentioned above was based on only 1 variable, usually hydrocarbon content of sediments, or at most a few of the wide range of environmental variables regularly monitored. In this paper we apply multivariate analyses to a range of environmental data in order to assess the totality of contamination rather than using merely 1 variable.

Effects of contamination by drill-cuttings were listed by GESAMP (1993) as major to a radius of 500 m from production platforms in the UK sector and to a 1000 m radius in the Norwegian sector, with subtle biological effects reaching to a 2000 × 1000 m ellipse in the UK sector and a 3000 to 5000 m radius in the Norwegian sector. Major effects are usually recorded as changes in diversity indices (Addy et al. 1984, Davies et al. 1984, 1989, Dicks et al. 1987, Mair et al. 1987, Kingston 1992). Yet Kingston (1992) showed that although reductions in diversity were found between 750 and 1500 m, using indicator species effects of contaminants can be found between 1500 and 3000 m. In applying multivariate analyses to benthic data from Ekofisk in 1987, Gray et al. (1990) were able to show clear effects out to a radius of 3000 m from the Ekofisk centre. Kingston (1992) claimed that 'the full potential of such approaches is not exploited'. The present paper addresses this issue.

Apart from the above there are surprisingly few findings published in the open scientific literature on the effects of oil from platform operations. Most of the data on effects remain confidential to the respective country's environmental authorities. Fortunately, Norway has an open policy and all data reported to the Norwegian State Pollution Control Authority (Statens Forurensningstilsyn, SFT) are open to public scrutiny. Monitoring in the Norwegian sector began in 1973 at Ekofisk and a thorough analysis of the Ekofisk and Eldfisk fields was done by Gray et al. (1990). Exploration has been moving gradually northwards with the result that the oldest fields are found in the south (Ekofisk) and the newest production fields are to be found just outside the Arctic Circle (Heidrun). At present trial drilling is taking place within the Barents Sea.

All companies involved with oil and gas exploration on the Norwegian shelf are required to monitor the

chemistry of the field annually and do biological surveys every 3 yr for fields with oil production and every 6 yr for fields with gas production. Table 1 shows the monitoring programme initiated in Norway up to 1991. We also have access to more recent surveys and have used some of these in our study as well.

Although the drilling activity has remained fairly high, and has in fact increased in recent years, the amounts of oil and oil-based drill-cuttings discharged have decreased markedly, having peaked in 1985 (Fig. 1) (Anon 1994). This is mainly due to legislation imposed by the Norwegian State Pollution Control Authority in response to findings of reduced faunal diversity 5 km away from the Statfjord C platform (Reiersen et al. 1989), and effects out to 3 km at Ekofisk and other fields (Gray et al. 1990). In 1987 the amount of oil in cuttings allowed to be discharged was reduced to a maximum of 6%, and from 1 January 1993 all discharge of oil-based mud cuttings in the Norwegian sector was banned. Water-based mud is at present the dominant drilling-fluid, and this will often lead to a 5- to 10-fold increase in the amount of barite used compared to that used with oil-based mud. Water-based cuttings are more fine grained and can be expected to lead to a wider dispersion of the barite.

We have analysed all the data sets on sediment variables and benthic communities from the Norwegian continental shelf available up to 1990 and some sets from 1990 to 1993. In this paper we describe analyses

Fig. 1 (a) Number of wells drilled on the Norwegian continental shelf (Anon 1994) and (b) discharges of oil and oil-based drilling-cuttings to the Norwegian continental shelf (Bakke et al. 1993)

Table 1. Oil monitoring on the Norwegian Shelf, 1973 to 1991. C: chemical monitoring; B: biological monitoring; F: fish monitoring; –: no monitoring

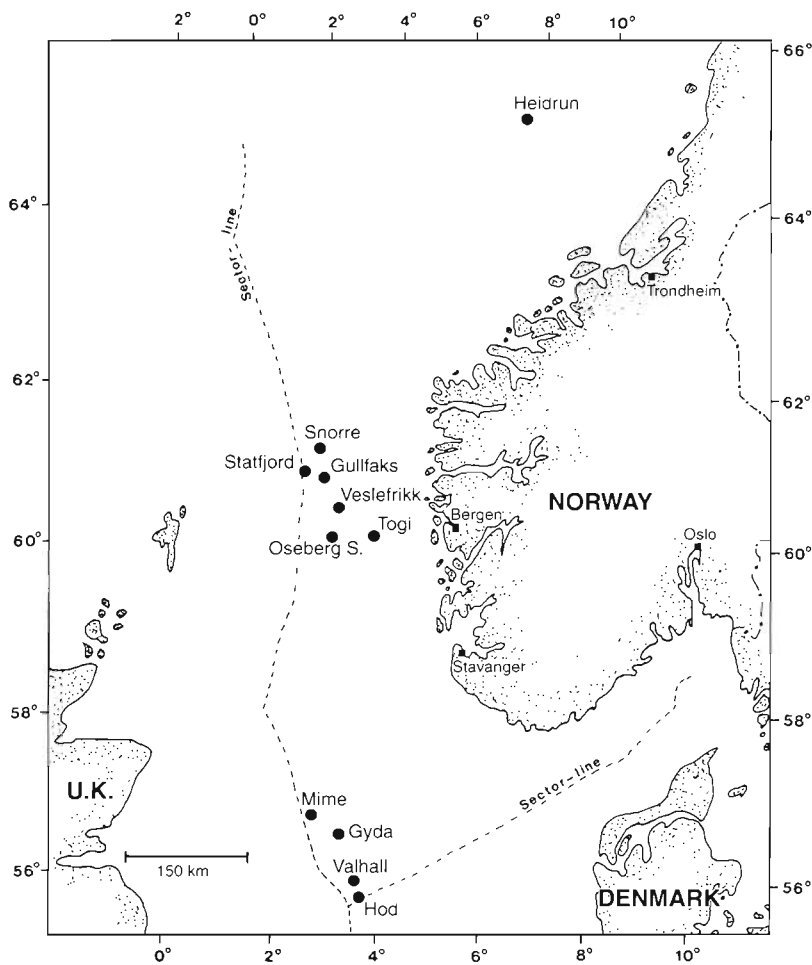| Field	1973–77	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991
Ekofisk	CB	CB	CB	B	CB	CB	C	CB	CF	–	CB	–	–	CBF	CB
Statfjord		C	C	CBF	C	CB	F	CB	C	CBF	C	CB	C	CB	CB
Frigg			C	C	–	–	C	–	–	–	CBF	–	–	–	CB
Valhall				C	C	C	C	C	CBF	CF	C	CB	C	C	CB
Hod						C	C	C	C	C	C	CB	–	–	CB
Træna Bank						CB	–	CB	–	–	–	–	–	–	–
Oseberg							CB	–	–	CBF	C	C	CB	C	C
Odin							C	C	CBF	–	–	–	–	–	CB
Ula								CB	–	–	C	C	CBF	C	CB
Heimdal									C	–	CBF	–	–	–	–
Halten Bank									CB	–	–	–	–	–	–
Gullfaks									CB	CB	C	CB	CB	CB	C
Veslefrikk											CB	C	C	CB	C
Gyda											CB	C	–	CB	CB
Tommeliten											CB	–	CB	–	–
Heidrun												CB	–	–	–
Snorre													CB	–	CB
Troll Vest I													CB	C	–
TOGI													CB	C	–
Troll Vest II														CB	CB
Mime														CB	CB
Brage														CB	–
Well 2/7-22														CB	C

Fig. 2. Location of oil and gas fields sampled

of selected fields between 1985 and 1993. The fields have been selected in part to cover the main areas of activities, in part where data for time series analysis were available and in part because of high quality of both chemical and biological data. Prior to the study the data was rigorously quality controlled and a data base prepared (see 'Materials and methods'). The geographical location of the fields selected are shown in Fig. 2.

The main purpose of this paper is to illustrate contaminant gradients using chemical data alone, to assess how contamination affects benthic fauna both spatially and temporally, and to evaluate commonly used measures of effects such as diversity indices and indicator species compared with multivariate analyses.

MATERIALS AND METHODS

Surveys are conducted in a similar manner following directives prepared by the Norwegian State Pollution Control Authority (Anon 1989), with a subsequent more detailed revision (Anon 1990). Surveys done before 1988 may have a slightly different design, but this should not influence the results.

The basic design is a cross which intersects at the centre of the field with sampling stations placed at geometrically increasing distances from the centre (viz. 250, 500, 1000, 2000, 4000 m). One axis is located along the dominant residual current direction and often samples are taken to increased distances along this axis. A reference point should be sited at 10 km distance, usually located upstream of the predominant current direction. Stations are located using either a Decca navigator system or more recently GPS systems with an accuracy of ±30 m. Fig. 3 shows a typical design (Valhall 1991). Older fields monitored before the sampling manuals were implemented may have a different design (e.g. Ekofisk; Gray et al. 1990).

At each station samples were taken with a Van Veen grab (0.1 m^2) with 5 replicates for analyses of benthic macrofauna and 3 replicates for analyses of sediment variables. The biological samples were extracted using 1 mm mesh sieves and the material fixed in formalin and analysed in the laboratory. For physical and chemical analyses subsamples were taken from the top of the grab, using the upper 5 cm for physical analyses and upper 1 cm for chemical analyses. The depth of each sampling station, sediment colour, water content, grain size distribution and sorting, skewness and kurtosis and total organic carbon (TOC) were reported for all fields. Samples for metal analyses were placed directly in PVC containers and frozen at −20°C. The following heavy metals were routinely determined: Fe, Cu, Zn, Pb, Ba, Sr, Cd, Cr and Hg. Dried samples were digested with 7 N HNO_3 (Norwegian Standard, NS 4770). Samples for hydrocarbons were wrapped in aluminium foil and frozen at −20°C for subsequent analyses of total hydrocarbon content (THC), aromatic hydrocarbons (NPD and C_1 to C_3 homologues), bicyclanes (C_5 to C_8 decalines) and the pristane/phytane ratio (see the manual of recommended monitoring methods; Anon 1990).

Since the present paper is primarily biological the details of the methods used for chemical analyses are
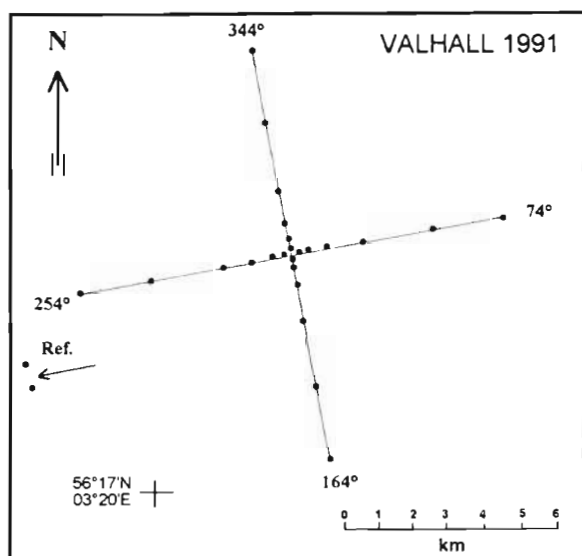
Fig. 3. A typical sampling design (Valhall 1991) with stations in a cross centred at the platform and reference station(s) 10 to 15 km distant against the predominant current direction

not described, but can be found in Anon (1989, 1990). Quality assurance procedures were mandatory for all chemical analyses.

Species identification was undertaken by a series of consultants and institutions. A database containing chemical and biological data was established. Only species that had been approved by the Riksmuseum Stockholm were added to the faunal list, thus synonyms and obvious misidentifications were excluded [see Støvring (1994) for a complete list of the species found]. Minor taxonomic groups, however, receive variable attention and faunal groups not properly sampled by the methods used, such as meiofaunal nematodes, Foraminifera, inhabitants of hard substrata such as Porifera, Bryozoa and Cirripedia, were not included. Similarly juveniles were excluded and unidentified species were included only if another species had been identified within the same genus.

Statistical treatment. *Environmental variables:* Variables analysed were depth, median grain size (Mdφ), sediment sorting (inclusive standard deviation, SD), sediment skewness and kurtosis, sediment % silt-clay (<63 µm), TOC, and concentrations of barium (Ba), strontium (Sr), lead (Pb), iron (Fe), copper (Cu), cadmium (Cd), chromium (Cr), zinc (Zn) and THC. Plots of the environmental variables using the quantile method in SYSTAT 5.0 (Systat, Inc., Evanston, IL, USA) clearly indicated that a log_{10} transformation was best prior to multivariate analyses and therefore a log_{10} transformation was used. Due to different scales each environmental variable was also normalised (by subtracting mean across stations and dividing by SD). The

data were subjected to hierarchical, agglomerative classification employing group-average linking (Lance & Williams 1967) with Euclidean distance as the distance measure. Classification analyses were performed using the CLUSTER program in the PRIMER (Plymouth Routines In Multivariate Ecological Research) package.

Non-normalised environmental variables were further subjected to Principal Component Analysis (PCA) performed on a correlation matrix (a 'species'-centred and standardised PCA) using the CANOCO package (ter Braak 1988, 1990). In a standardised PCA, a normalisation of the data, as above, is implicit. The resulting groups from the classification analysis were superimposed on the PCA plots. Correlation plots of environmental variables were also constructed in order to illustrate the strength of correlations of variables with the putative gradient of the PCA axes. PCA ordination and correlation plots were constructed with the drawing program CANODRAW (Smilauer 1992).

Faunal analyses: In order to obtain the most ecologically meaningful results the species data matrices, containing pooled data from the replicates from each station, were analysed with either no transformation or using single or double square root transformation depending on the numerical dominance in each separate matrix. The CLUSTER program in PRIMER was used to compute similarity matrices based on the Bray-Curtis similarity coefficient (Bray & Curtis 1957) and the similarity matrices were then subjected to hierarchical, agglomerative classification employing group-average sorting (Lance & Williams 1967) to classify the stations based on faunal groupings. Non-metric Multidimensional Scaling analyses (MDS ordination; Shepard 1962, Kruskal 1964a, b) were done using PRIMER on the similarity matrices obtained using the Bray-Curtis coefficient. Goodness-of-fit in the MDS ordination plots was measured as stress with Kruskal's stress formula I (Kruskal & Wish 1978). Detrended Correspondence Analysis (DCA ordination; Hill 1979, Hill & Gauch 1980) was done using the CANOCO package. The implied distance measure is chi-square distance on the original data matrices. Classification and 2 different ordination methods were used to ensure that the underlying community structure is well defined. The choice of ordination technique that best summarises the 'true' pattern in the field data is most desirable. However, one cannot know *a priori* which method is likely to reveal the optimal result (Minchin 1987), and the results from a number of analyses methods must therefore be compared (Jackson 1993). If similar patterns are found using several methods, then the result should be representative (Green 1979). For the ordinations we have made comparisons between MDS and DCA plots, but the results were seldom different indi-

cating congruent solutions and thus only one of the results, usually the MDS plot, is illustrated as an example.

Following the division into station groups from the classification and ordination results, the species having the greatest contribution to this division were determined using the similarity percentages program SIMPER (Clarke 1993), available in the PRIMER package. *Linking of environmental variables and fauna:* In order to demonstrate the most important environmental variables related to faunal patterns 2 entirely different methods were employed: forward selection in a hybrid CA/CCA ordination in the CANOCO package and rank correlations between PCA and MDS ordinations with the program BIOENV (Clarke & Ainsworth 1993) in the PRIMER package. We believe in applying different techniques in order to check the validity of the extracted explanatory variables. However, here the 2 methods mainly gave consistent results, but some important differences were also apparent.

Firstly, a forward selection of all the environmental variables was performed in a hybrid CA/CCA ordination. This method is named hybrid because it combines an unconstrained ordination (CA) with a constrained canonical ordination (CCA) in a single analysis. The proportion of the total faunal variance (= sum of all eigenvalues, called total inertia in CANOCO) which can be accounted for by the environmental variables can be estimated as the ratio of eigenvalues of constrained versus unconstrained axes. From this ratio, the percentage value which indicates the percentage explanation of each separate environmental variable to the total faunal variance was calculated. Constrained axes are constructed to maximise the fit with linear combinations of environmental variables, and remaining, unconstrained axes represent a residual variation in data after extracting the constrained axes. Whether the environmental variables were significantly correlated to the faunal ordinations was tested with unrestricted Monte Carlo permutation tests (99 permutations) for all the environmental variables in each dataset (ter Braak 1990).

BIOENV was the second method used for extracting important explanatory variables. This harmonic analysis uses a weighted Spearman's rank correlation between the resulting ranked similarity matrices which underlie the MDS ordinations of fauna and correlation-based PCA ordinations of the environmental variables. Use of a correlation-based PCA implies that a normalisation of environmental data is not necessary prior to this analysis. From each survey the 8 most important environmental variables, obtained from forward selection in the CA/CCA analyses, were used as input variables in the BIOENV program. The variable or combinations of variables which give the highest correlation coefficient is assumed to be the most important explanatory variable(s). In addition for some of the fields (baseline surveys) the relationships between community structure and environmental variables were illustrated by correlating the obtained axes in DCA ordinations with the environmental variables resulting in a biplot, using the CANOCO package and the CANODRAW program.

RESULTS

Biological data and environmental variables from 14 fields comprising 24 different surveys have been analysed. A summary of basic biological and environmental data is shown in Table 2. The study contains data collected between 1985 and 1993 at depths between 63 and 380 m.

Baseline studies

Four examples of results from baseline studies (Heidrun 1988, Snorre 1989, Togi 1989, Mime 1990) are shown. Fig. 4 shows the biplots of the DCA faunal ordinations of stations and the measured environmental variables. In this analysis the DCA ordinations are run separately followed by a correlation between the environmental variables and the obtained axes. The environmental variables are illustrated by arrows for each variable, whose direction indicates maximum correlation with stations along the same axis. The faunal ordinations showed typical 'shotgun' plots with a concentration of stations and no clear patterns at Heidrun and Togi. By contrast, at Snorre there was a clear correlation between depth (and co-related variables) and the fauna; the stations were divided into 2 groups, deeper (right) and shallower (left) than 320 m. At the Mime field the most important environmental variable was the TOC of the sediment.

Results of the MDS ordinations, together with plots of the classification analyses (dendrograms) and plots of the classification groupings on the original sampling stations for the fauna, are shown in Fig. 5. No clear patterns were found, except for the effect of the depth change across the Snorre field where the fauna was separated into 2 main depth groups, <320 m, group a and >320 m, groups b to g (compare with Fig. 4). Another indication of the lack of clear faunal gradients in these baseline surveys is also shown by the relatively high stress values obtained in the MDS ordinations, except for Mime which had few stations and as a consequence a low stress value is expected.

Table 3 shows data for the relations between environmental data and the fauna and shows that there was no

Table 2. Summary showing fields and some basic data, with ranges where applicable. Total S: total number of species found at the field; S: number of species per station; N: number of individuals per station; H': Shannon-Wiener diversity index; Ba: barium; THC: total hydrocarbons; Zn: zinc; Pb: lead. Concentrations as mg kg^{-1} dry weight. –: not measured

Field	Year	No. of stations	Depth (m)	Total S	S (0.5 m^2)	N (0.5 m^2)	H' (0.5 m^2)	Ba (mg kg^{-1})	THC (mg kg^{-1})	Zn (mg kg^{-1})	Pb (mg kg^{-1})
Heidrun	1988	25	320–380	192	46–81	141–448	3.69–5.46	65–543	1.4–5.5	32–56	11–26
Snorre	1989	20	288–340	319	59–114	162–525	4.73–5.81	94–2007	1.0–6.2	17–30	4.6–16.6
Togi	1989	21	299–303	111	24–43	83–166	3.74–4.39	129–355	4.3–9.2	59–74	30–42
Mime	1990	11	80	162	51–99	319–528	4.22–5.54	38–197	1.6–5.1	7–13	6.9–10.7
Oseberg S	1989	23	105–115	207	26–62	151–1240	2.21–5.30	34–5520	1.2–7770.7	4–52	2.3–58.3
Gullfaks A	1989	16	131–140	248	42–109	264–1054	3.74–5.36	99–5000	1.3–519.3	10–62	5.3–15
Hod	1991	24	63–70	144	32–56	169–650	3.20–4.60	15–2393	3.2–1201	4–19	4.6–23
Valhall	1985	13	65–68	73	4–34	74–502	0.57–3.94	280–96000	5.4–72000	12–180	80–375
Valhall	1988	20	65–69	96	21–47	201–1868	0.71–4.47	97–8433	9.9–5493.3	9.4–31	5.3–15.8
Valhall	1991	16	65–69	156	9–66	261–3583	0.04–4.77	55–6670	4.3–13065	6.6–55.6	6.5–55.6
Gyda	1987	18	65	106	26–43	102–209	3.94–4.68	241–591	2.5–4.0	8–13	9–14
Gyda	1990	17	65	139	14–70	136–1600	0.49–4.98	270–3297	2.1–1133.3	10.3–33.3	9.7–27.7
Gyda	1993	20	65	156	29–67	255–2270	1.00–4.83	55–3078	0.3–49.2	5.9–17.3	4–6.8
Veslefrikk	1987	10	171–181	127	43–62	115–240	4.38–5.17	90–355	7.2–15.7	8.6–31	1–11
Veslefrikk	1990	16	171–186	238	71–104	231–3290	3.40–5.79	214–6033	3.7–5596.7	6.2–29.4	–
Veslefrikk	1993	14	171–186	267	61–122	507–11600	2.09–5.62	357–6350	5.8–153	7.6–148	5.3–153
Gullfaks B	1990	12	134–193	160	22–67	49–548	2.65–5.38	37–6967	0.5–4077	8.3–42.0	6.4–34.8
Gullfaks B	1993	13	133–196	248	58–116	441–2680	2.08–5.15	49–5340	1.2–234	7.3–116	4.4–62.2
Statfjord A	1990	10	141–149	198	29–82	491–1780	2.47–5.32	460–7203	6.4–6696.7	15.9–1430	5.5–133
Statfjord A	1993	11	140–144	225	50–101	464–9410	2.09–5.60	1040–7330	21.1–736	16.5–701	7.9–311
Statfjord B	1990	9	140–145	199	57–98	448–1200	3.46–5.25	513–7870	6.4–2516.7	12.4–331	4.7–57.6
Statfjord B	1993	11	140–145	235	62–113	457–3210	1.93–5.67	376–6020	9.5–165	14.5–259	7.9–200
Statfjord C	1990	10	136–143	165	9–84	248–1350	1.30–5.15	234–7330	6.1–38333	10.0–399.7	5.1–173.7
Statfjord C	1993	13	136–143	249	39–114	167–8570	1.92–5.48	201–6630	7.3–5860	11.9–341	5.8–156

consistent pattern of variables that influenced the fauna and that the most important (highest ranked) variables varied from one field to another. Weightings (Table 3a) were low (with 1 exception ≤12.1 %), and the correlation coefficients (Table 3b) were also, with few exceptions, low. Although the correlations between faunal compo-

Table 3. Relationship between environmental variables and fauna using forward selection in CANOCO (a) and BIOENV in PRIMER (b) for baseline surveys. The 5 environmental variables best explaining the faunal patterns are given. In forward selection, the percentage explanation of each environmental variable to the total faunal variance is given together with the level of significance (**p < 0.01; *p < 0.05; ^{ns} not significant). The correlation coefficient (r_s) for a weighted Spearman rank correlation is given in (b)

| Heidrun 1988		Snorre 1989		Togi 1989		Mime 1990	
(a) Forward selection							
Cd	7.1 %*	Depth	10.4 %**	Mdφ	7.0 %^{ns}	TOC	24.1 %*
Depth	6.4 %^{ns}	Zn	8.1 %**	Fe	6.1 %^{ns}	Sorting	12.1 %^{ns}
<63 μm	6.4 %^{ns}	TOC	7.0 %**	Zn	6.1 %^{ns}	Pb	12.1 %^{ns}
Sorting	5.7 %^{ns}	Pb	7.0 %**	<63 μm	5.0 %^{ns}	Skewness	12.1 %^{ns}
Cr	5.0 %^{ns}	Sorting	6.4 %**	Ba	5.0 %^{ns}	Cd	12.1 %^{ns}
(b) BIOENV							
Cd	r = 0.256	Depth	r = 0.448	Ba	r = –0.041	TOC	r = 0.353
Depth	r = 0.219	Zn	r = 0.302	Fe	r = –0.044	<63 μm	r = 0.075
Zn	r = 0.207	Cu	r = 0.194	<63 μm	r = –0.067	Mdφ	r = 0.046
Mdφ	r = 0.203	<63 μm	r = 0.177	Mdφ	r = –0.069	Cd	r = –0.058
<63 μm	r = 0.123	Sorting	r = 0.163	Pb	r = –0.076	Skewness	r = –0.064
Max. corr.:		Max. corr.:		Max. corr.:		Max. corr.:	
Cd, Depth, Zn, <63 μm,		Depth, Zn		Ba, Fe, <63 μm		TOC	
Sorting, Skewness		r_s = 0.462		r_s = 0.025		r_s = 0.353	
r_s = 0.414							
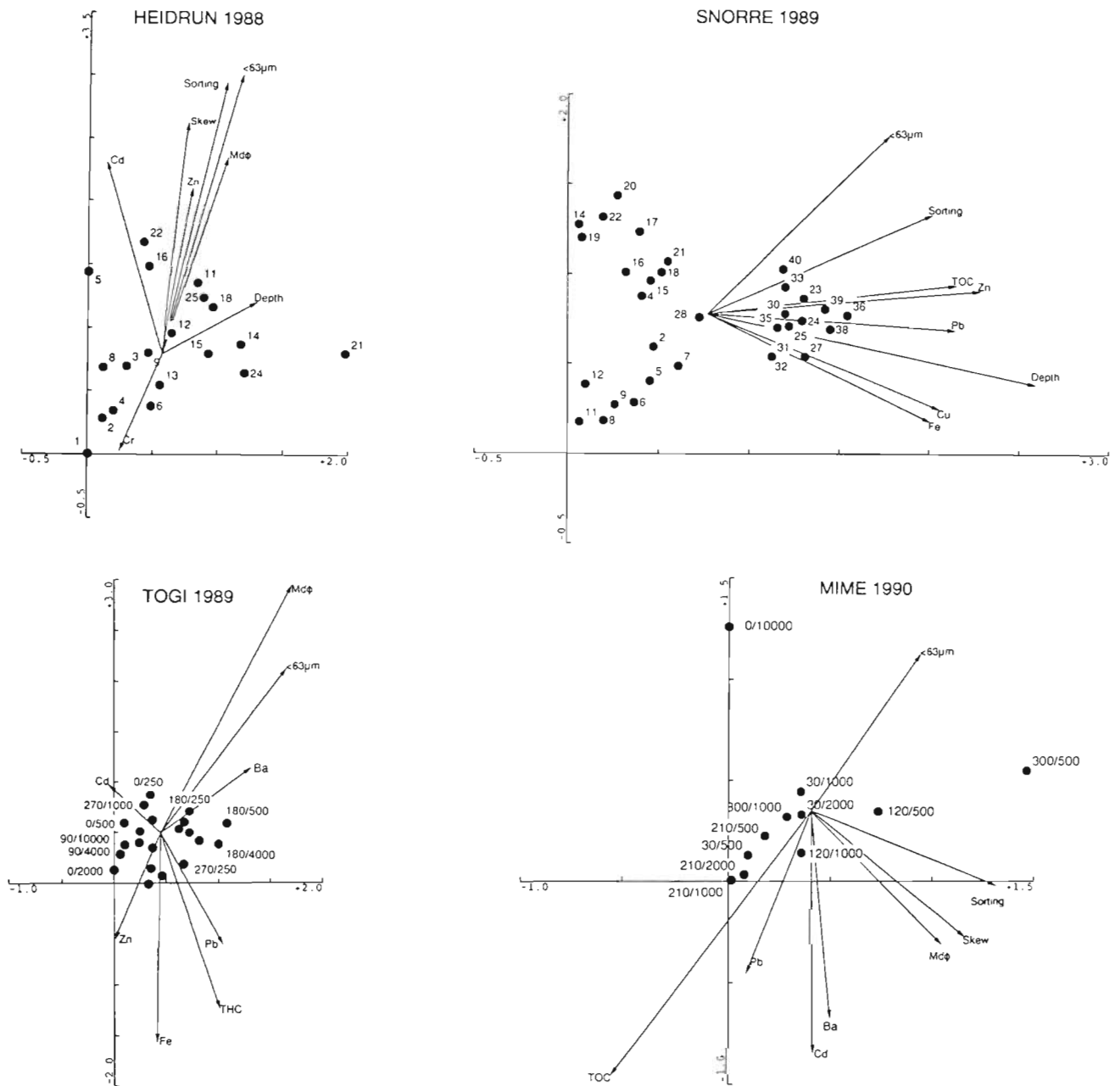
Fig. 4. Biplot of DCA faunal ordinations and the 8 most important environmental variables within each field (based on forward selection in CANOCO). For Heidrun and Snorre fields the stations are given as numbers, while for Togi and Mime fields the stations are given as bearing and direction from the platform (e.g. 180/500 is the station along the 180° bearing 500 m away from the platform). Not all stations are plotted to avoid overcrowded figures. All stations are given in the corresponding MDS plots in Fig. 5

sition and the environmental variables were in most cases weak, there was a high degree of consistency in the 2 methods applied, in both weight and rank within fields. At the Snorre field depth and related variables played an important role, despite the fact that the variation in depth was relatively small (288 to 340 m). At the Mime field the TOC content was the principal environmental variable, whereas the other variables showed a more random rank order in the 2 methods due to similarly low values.

Development of contamination

Contamination is usually regarded as a significant increase in concentration of a chemical over a back-
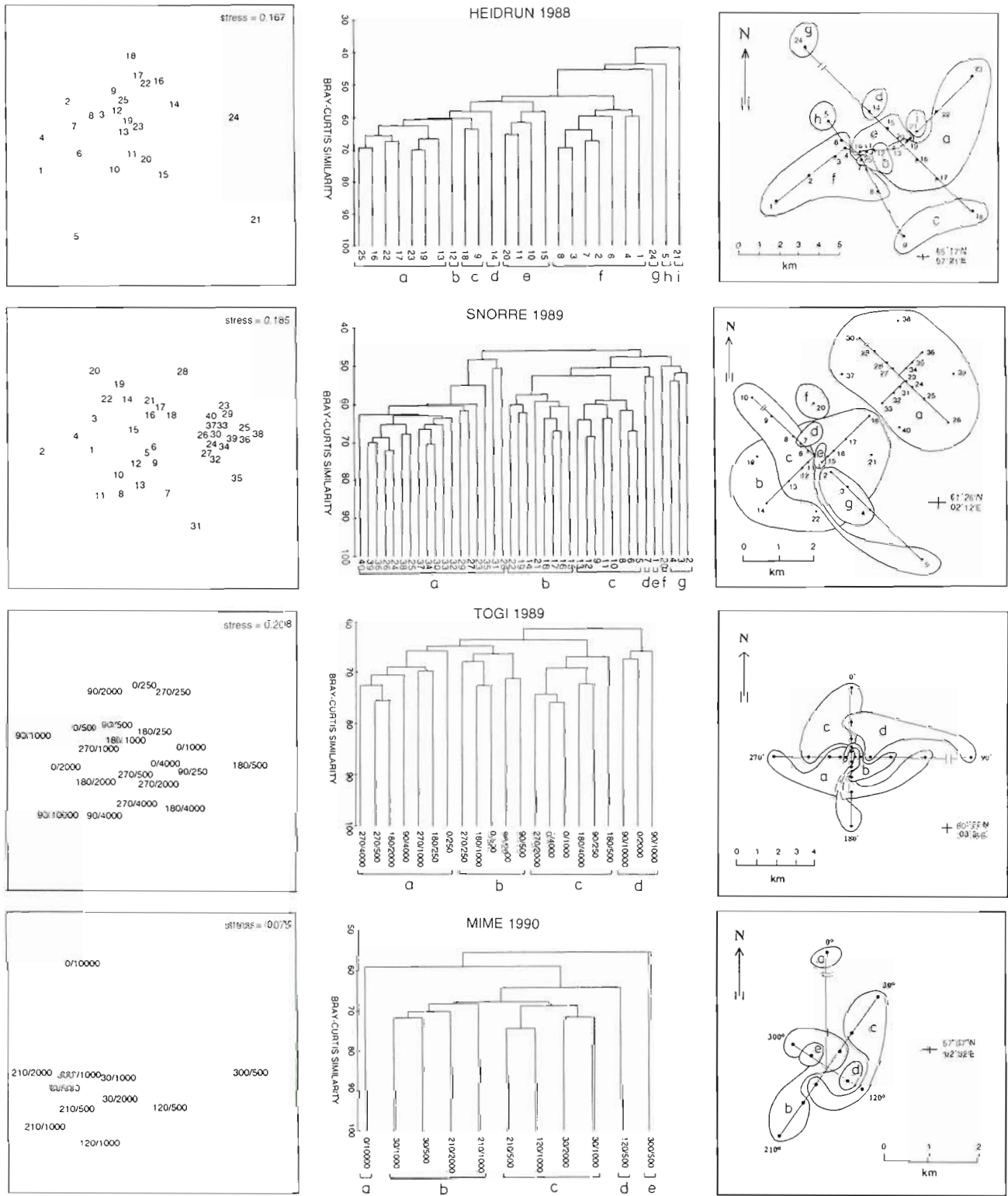
Fig. 5. MDS ordination plots of the stations at the Heidrun, Snorre, Togi and Mime fields according to faunal composition; MDS ordination (left), classification (centre) and plots of the classification groupings on the original sampling stations (right)

Table 4. Concentrations (mg kg^{-1} dry weight) of barium (Ba), lead (Pb), zinc (Zn) and total hydrocarbons (THC) in the sediment (upper 1 cm) at the Valhall, Gyda and Veslefrikk fields. Station groups determined from classification and PCA ordination of all the environmental variables (see Figs. 6 to 8). n: number of stations within each group. Concentrations as mean ± SE

Station group	n	Ba	Valhall — Pb	Zn	THC	n	Ba	Gyda — Pb	Zn	THC	n	Ba	Veslefrikk — Pb	Zn	THC
			1985					1987					1987		
a	8	501.3±93.6	87.3±3.0	14.3±0.8	14.5±2.7	12	296.7±13.1	11.8±0.4	9.8±0.4	3.1±0.1	4	164.6±17.3	5	17.9±3.8	10.1±1.3
b	1	1000	110	12	10000	2	270.5±85	10.0±1.0	9.0±0.0	3.3±0.1	2	131±5.5	8.3±2.8	13.6±5.0	9.0±1.8
c	3	11833.3±3609.4	102.7±9.0	40.7±10.5	10200±4166.9	1	271	12	11	3.0	3	130±21.9	5	14.9±4.3	12.0±1.9
d	1	96000	375	180	72000	1	241	12	13	3.1	1	354.5	9.0	31.0	9.8
e	–	–	–	–	–	1	247	12	9	2.8	–	–	–	–	–
f	–	–	–	–	–	1	591	13	12	3.3	–	–	–	–	–
			1988					1990					1990		
a	7	289.7±67.4	6.9±0.7	12.0±0.7	21.4±2.5	7	330.9±25.8	11.3±0.4	11.3±0.5	2.8±0.1	2	297.7±52.3	5.0±0.0	7.5±0.5	5.2±0.4
b	4	612.6±255.3	6.6±1.0	13.7±1.5	82.7±61.7	6	798.2±93.4	10.8±0.3	14.8±1.0	10.9±2.5	1	301.3	5.0	6.8	4.6
c	3	1203.3±152.4	8.8±1.1	16.0±1.3	160.0±88.6	4	3033.0±389.2	17.7±3.4	26.7±4.0	624.3±216.5	4	328.9±42.8	5.6±0.3	7.5±0.6	7.8±2.2
d	6	5572.2±856.7	12.4±1.7	21.7±2.4	3100.0±1203.6	–	–	–	–	–	4	514.1±141.2	5.9±0.6	10.7±0.5	8.0±1.9
e	–	–	–	–	–	–	–	–	–	–	1	512.1	5.0	6.8	4.6
f	–	–	–	–	–	–	–	–	–	–	3	4577.8±818.8	10.5±1.3	21.8±3.8	2727.8±1518.6
			1991					1993					1993		
a	2	68.5±13.5	7.6±1.1	7.4±0.4	5.1±0.8	2	65±10	5.8±0.2	7.9±1.6	0.4±0.2	1	357	4.0	9.8	6.5
b	7	184.7±21.6	8.2±0.2	7.0±0.1	5.9±0.5	5	123±20.3	5.0±0.5	7.4±0.3	0.8±0.1	5	706.0±87.4	5.1±0.5	9.0±0.5	6.8±0.7
c	6	535.8±58.6	11.1±1.4	9.3±0.9	16.9±3.0	7	424±92.9	5.8±0.3	7.7±0.5	3.4±0.9	5	2602±654.4	12.4±3.2	16.4±2.2	19.0±3.4
d	5	2114.0±456.7	11.5±0.5	12.0±1.0	158.6±30.3	1	888	5.8	8.3	8.9	2	6725±375	98±43	118.2±29.8	96.2±56.8
e	5	4942.0±802.0	22.4±4.9	28.1±6.7	1467.0±308.4	4	3376.5±1052.9	6.1±0.3	14.0±1.7	132.6±43.4	–	–	–	–	–
f	1	6670	55.6	55.6	13065	–	–	–	–	–	–	–	–	–	–

ground level. This increase may or may not lead to effects on biological systems. In this study we have used multivariate, rather than the more commonly used univariate analyses, to analyse patterns of contamination. Also depth and environmental variables that characterise the sediment composition (Mdφ, sorting, skewness, kurtosis, % silt-clay and TOC) are included in these analyses because patterns may be related both to changes in these variables and to chemical variables. Here contamination is assessed by classification analyses and PCA ordinations of the measured environmental variables which include drilling-related variables such as Ba, Sr, THC and heavy metals. It is expected that if contamination is not in evidence there will be no obvious pattern and a more or less random distribution of stations will be obtained, as in the results from the baseline surveys (Figs. 4 & 5). If contamination is present then gradients radiating from the centre of the field should occur. To illustrate this approach 3 fields have been selected where there have been clear increases in contamination over time. The fields are Valhall (1985, 1988 and 1991), Gyda (1987, 1990 and 1993) and Veslefrikk (1987, 1990 and 1993).

Figs. 6, 7 & 8 show for Valhall, Gyda and Veslefrikk, respectively, the station groups obtained from the classification analyses of the environmental variables, superimposition of these groups on the PCA plots and superimposition of the resulting groups on the sampling locations. In order to give an indication of the levels of some of the measured environmental variables, Table 4 shows the concentrations of Ba, Pb, Zn and THC in the sediment within each station group.

For the Valhall field, Fig. 6 shows that in 1985 the innermost stations 250 m away from the platform were grouped together, groups c and d, which were severely contaminated (high levels compared to background; see Table 4) especially with Ba, Sr and hydrocarbons. Contamination was also found out to 2000 m along the 74° axis, group b, yet most stations, group a, were not
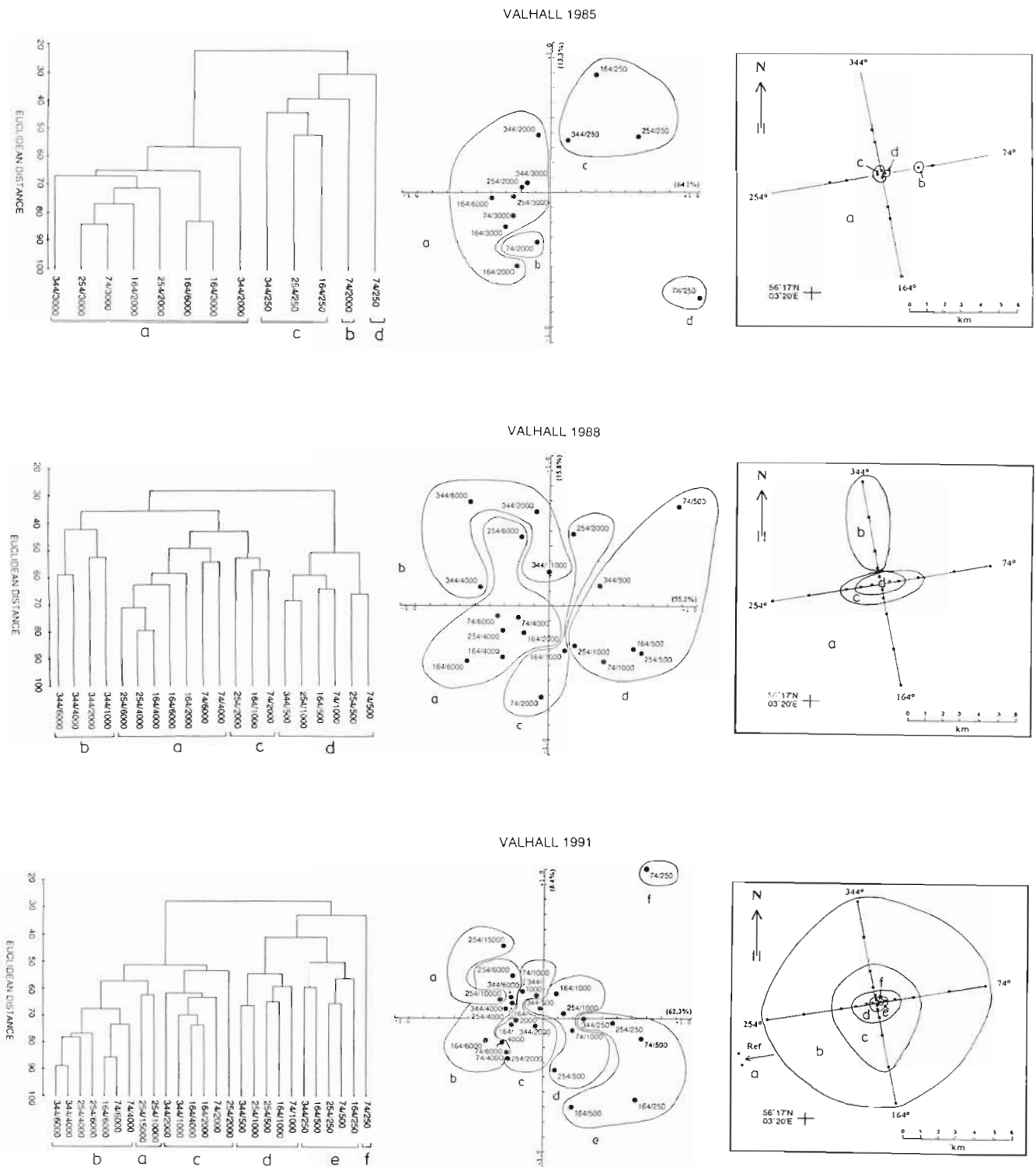
Fig. 6. Classification of stations according to environmental variables (left), superimposition of these groups on the PCA plots (centre) and the groupings on the original sampling stations at the Valhall field. In 1985 the explained variance in the PCA plot along Axis 1 was 64.2% and for Axis 2, 13.3%. The corresponding values for 1988 were 55.2% and 15.8%, and in 1991 these were 62.3% and 8.4%
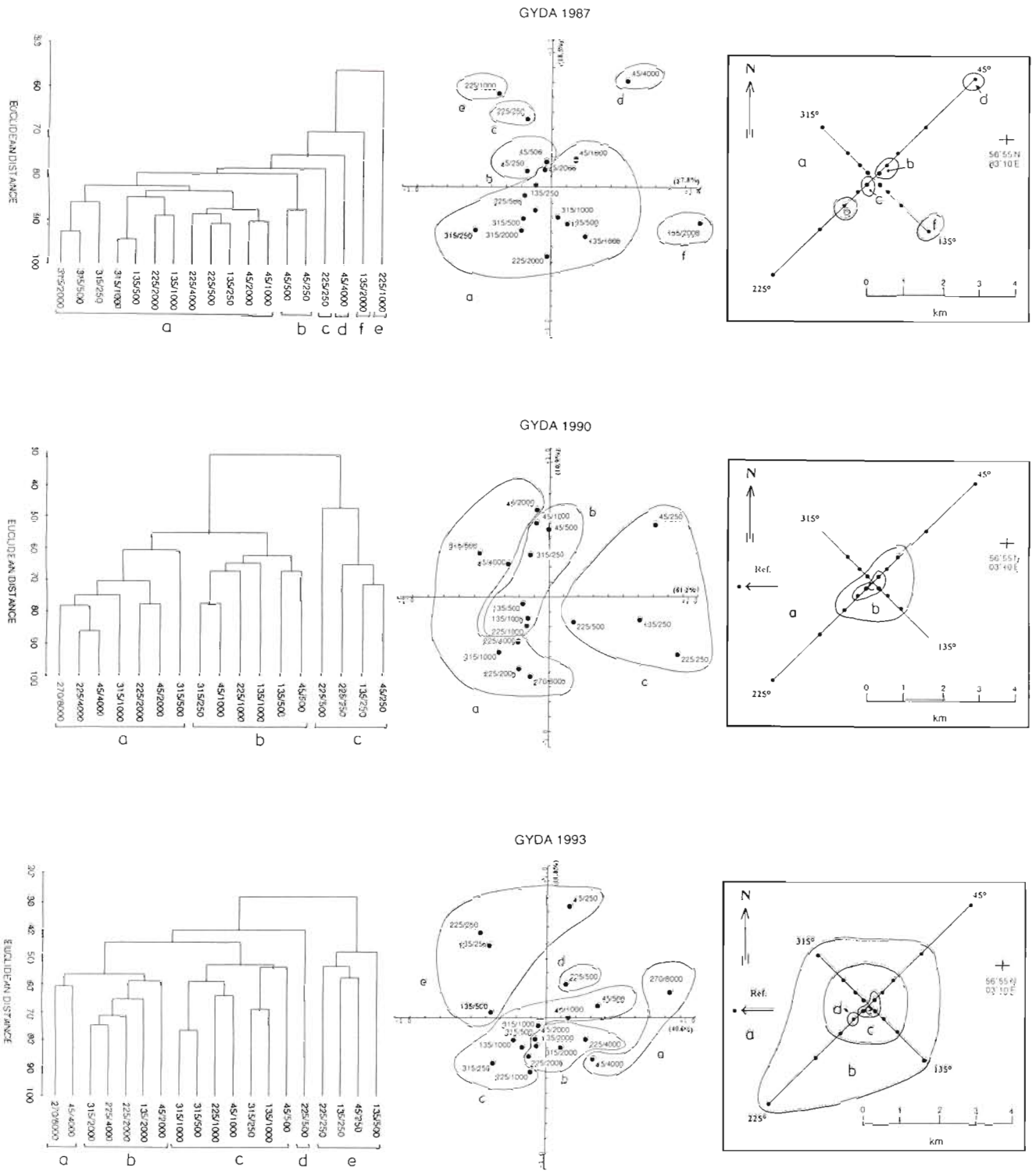
Fig. 7. As for Fig. 6, but for the Gyda field. 1987: Axis 1, 27.8 %; Axis 2, 18.5 %. 1990: Axis 1, 61.2 %; Axis 2, 10.9 %. 1993: Axis 1, 40.8 %; Axis 2, 11.8 %
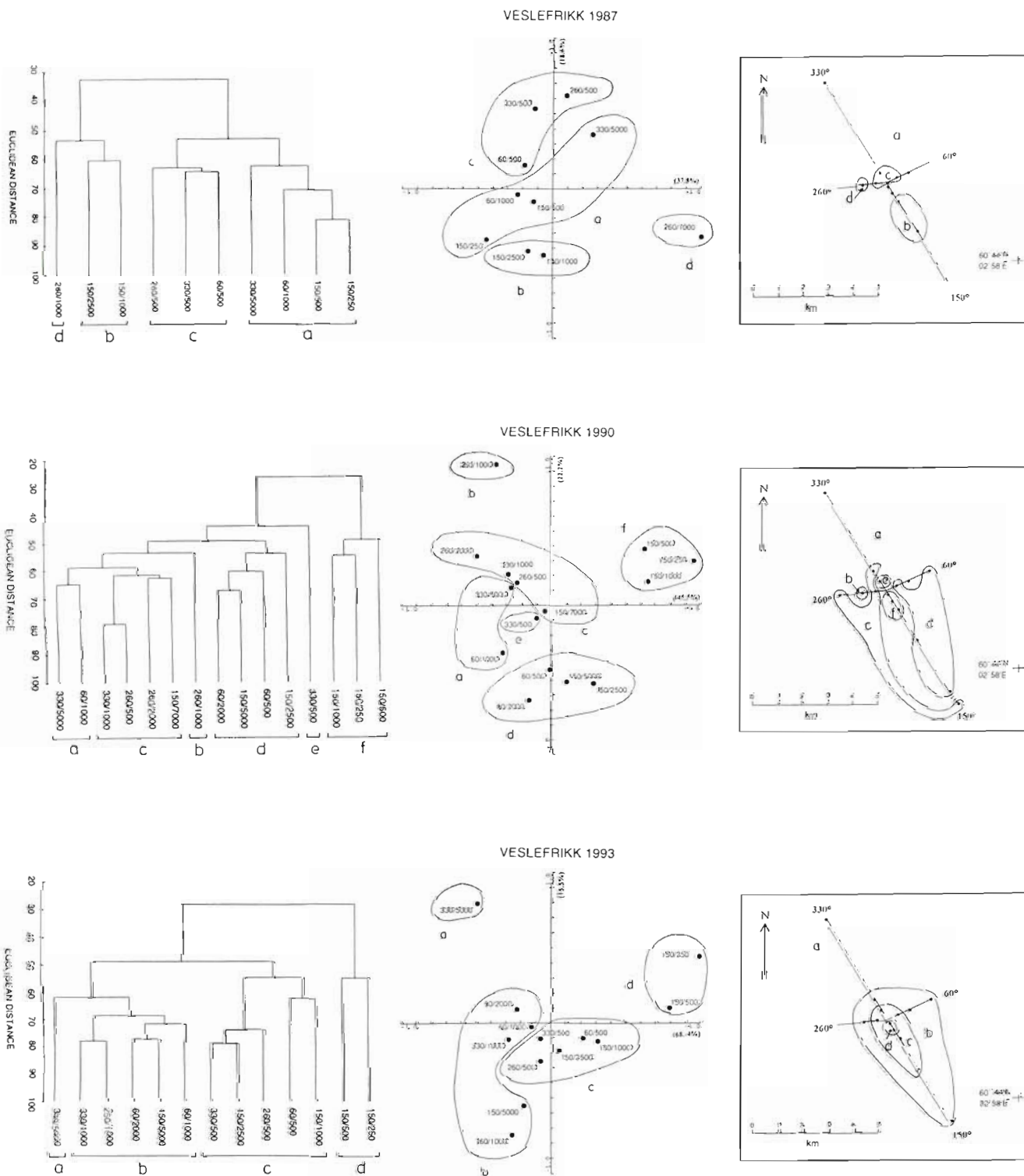
Fig. 8. As for Fig. 6, but for the Veslefrikk field. 1987: Axis 1, 37.8%; Axis 2, 18.6%. 1990: Axis 1, 45.5%; Axis 2, 22.2%. 1993: Axis 1, 68.4%; Axis 2, 15.5%

contaminated. By 1988 the area contaminated had increased and included station groups b, c and d (Fig. 6, Table 4). By 1991 all stations differed from the reference stations suggesting that the whole field was contaminated out to 6000 m on all axes.

It is of interest to find which environmental variable(s) were responsible for the observed grouping of stations, especially that leading to contamination at the outermost group b compared with the reference group a (Fig. 6). Barium is a good tracer for dispersal of drill-cuttings. In order to illustrate relations between concentrations of Ba in the sediment and the obtained

station groups (Figs. 6 to 8), values from the individual stations, each containing 3 replicates, were plotted as means with 95% confidence intervals (Fig. 9). The plots clearly show, save for Veslefrikk in 1990, a significant increase in the concentrations of Ba towards the platforms and that the outermost, uncontaminated group a have significantly lower concentrations of Ba in the sediment.

Yet it is not Ba alone that changes along the gradient. Inspection of the environmental variable data-matrix, and a superimposition of the environmental variables (not shown) on the PCA plot, showed that the variables
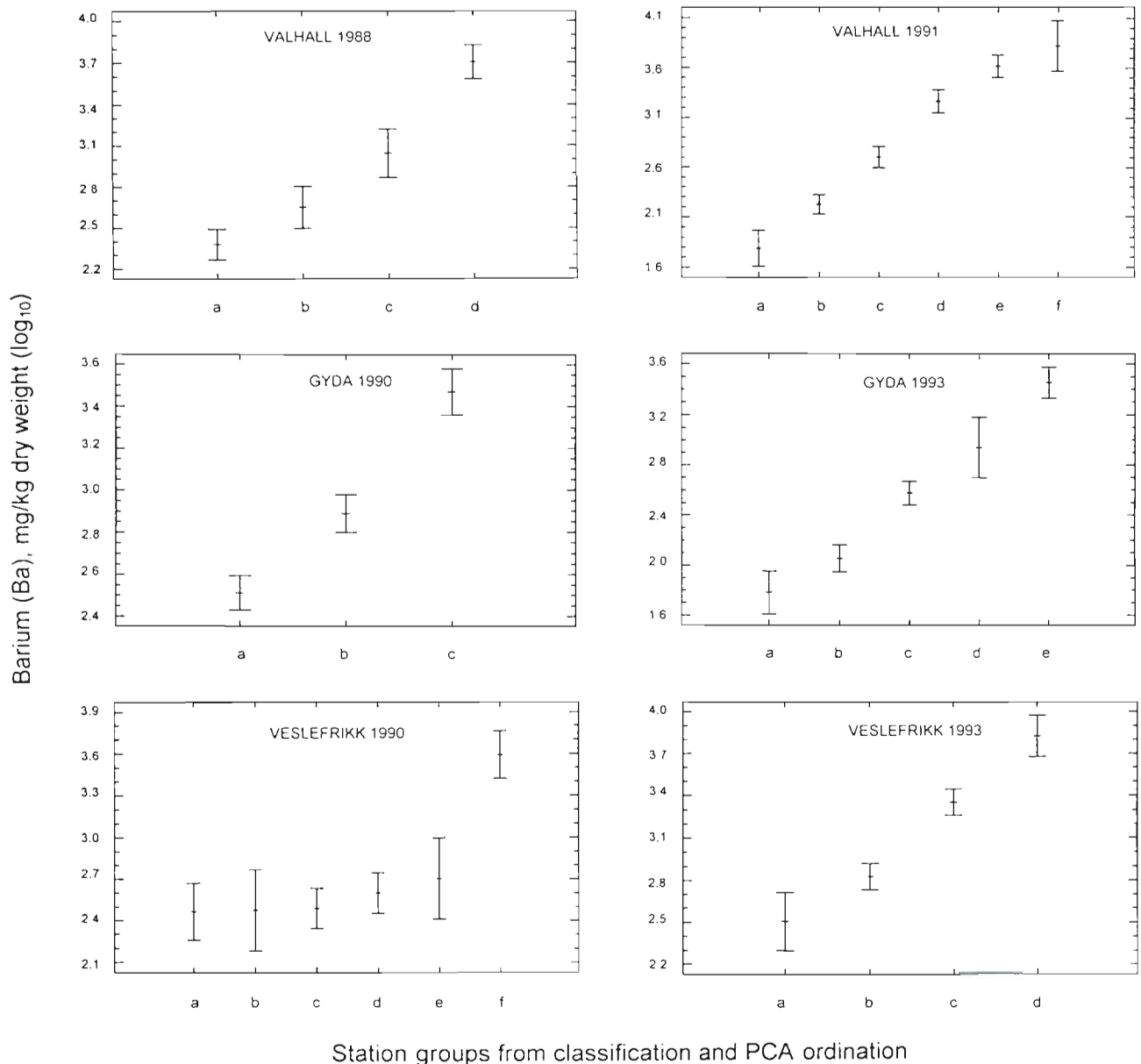
Fig. 9. Sediment concentrations of barium (Ba) within the station groups from classification and PCA ordination at the Valhall, Gyda and Veslefrikk fields. Values given as mean with 95% confidence intervals

that divided most clearly between station group a and b at the Valhall field in 1991 were Ba, Sr and Cu which all showed elevated levels within group b compared to group a. This clearly indicates that discharge from the platform was responsible for the resulting station groupings. The gradient was strong with rings of contaminant radiating from the central point. In spite of an increase in number of sampling stations from 1985 to 1988, by 1991 the sampling design was no longer appropriate as there were too few control (uncontaminated) stations against which contamination could be assessed. Only the reference stations 10 and 15 km away were different from those surrounding the platform.

At the Gyda field in 1987 there was no clear pattern of station groupings (Fig. 7). This lack of pattern is typical for most baseline surveys (see above). By 1990 contamination had begun and a gradient of environmental variables emerged, shown as rings around the platform. There was an increase of contamination with increased concentrations in variables related to drill-cuttings discharges, e.g. Ba and THC (Table 4). Groups b and c, the 2 innermost station groups, had significantly higher barium concentrations compared to the outermost group a (Fig. 9). In 1993, inspection of the environmental data-matrix and superimposition of these on the PCA plot, as above, showed elevated levels of Ba, Cd and THC within station group b compared to station group a, again related to drill-cuttings discharged. By 1993 contamination was clearly evident to 2000 m along the 45°, 135° and 315° axes and to 4000 m along the 225° axis. Only station 45°/4000 m and the reference station did not show evidence of contamination. Plot of means and 95 % confidence limits of Ba (Fig. 9) clearly demonstrated a significant relation between discharges of drill-cuttings and Ba levels within the station groups. In 1993, station 45°/4000 m and the reference station were different from the remaining stations within the field suggesting that, as at Valhall, the sampling design is now unsuitable for monitoring of contamination, which has spread to the outermost stations.

At Veslefrikk in 1987 (Fig. 8) there was no pattern in the station groupings, although 1 group of stations near the platform was apparent (group c). A closer inspection of environmental data (Table 4) showed no elevated levels in station group c within variables related to discharge of drill-cuttings, e.g. Ba, Sr or THC. One exception was station 260°/1000 m (group d) which had elevated levels of Ba and Zn. The groups obtained from the 1990 survey and the values of the measured environmental variables indicated that contamination was limited to stations within 1000 m from the platform along the 150° axis, group f, and to 500 m along the 330° axis, group e (e.g. for Ba; see Fig. 9). By

1993 there was an increase in contamination along the same axes, particularly along the 150° axis, and significantly higher levels of Ba were found at all stations compared to the reference station (Table 4, Fig. 9). Again, the sampling design is inadequate to assess future trends as there are too few stations that are not contaminated in 1993. A study of the data matrix (not given) revealed that the main difference between group a and b in 1993 was associated with elevated levels of Ba and Cu within group b compared to group a. In addition, there were also differences between these 2 station groups in sediment sorting, skewness and kurtosis. This finding differs from Valhall in 1991 and Gyda in 1993, where only variables directly related to discharge of drill-cuttings were the most important for station-group differences. At Veslefrikk in 1993 differences in the physical composition of the sediment contributed to divergent station groupings in the outermost area in that the sediments were more homogeneous, less fine skewed and platycurtic at the reference station, group a, compared to the stations in group b. The main difference in environmental variables between these 2 groups was therefore a combination of contamination and differences in sediment characteristics.

Effects of contamination

In order to illustrate the effectiveness of multivariate analyses to detect effects of oil-related changes on the fauna, data from the same fields are used. That the observed patterns found in the fauna were related to contamination can be assessed by relating environmental data to faunal data.

Fig. 10 shows classification analyses of the fauna at Valhall in 1985, 1988 and 1991. The groupings obtained were superimposed on the MDS ordination plots (Fig. 10) and show clearly that there was a gradient with least affected fauna to the right and severely contaminated fauna to the left in the MDS plots. The resulting groups were superimposed on the sampling locations (Fig. 10). Fig. 11 shows similar analyses for the Gyda field and Fig. 12 for the Veslefrikk field. Low stress values were found in the MDS ordinations, save for Gyda in 1987, which was a baseline survey with no distinct faunal pattern expected. Also Veslefrikk 1987 is considered as a baseline survey, but had a low stress value consistent with the low number of stations, rather than an apparent faunal pattern. The low stress values indicate a more clear-cut faunal gradient compared with the baseline surveys (Fig. 5), as expected. Figs. 10 to 12 show that the area where the fauna was affected was largest at Valhall, less at Gyda, and smallest at Veslefrikk.
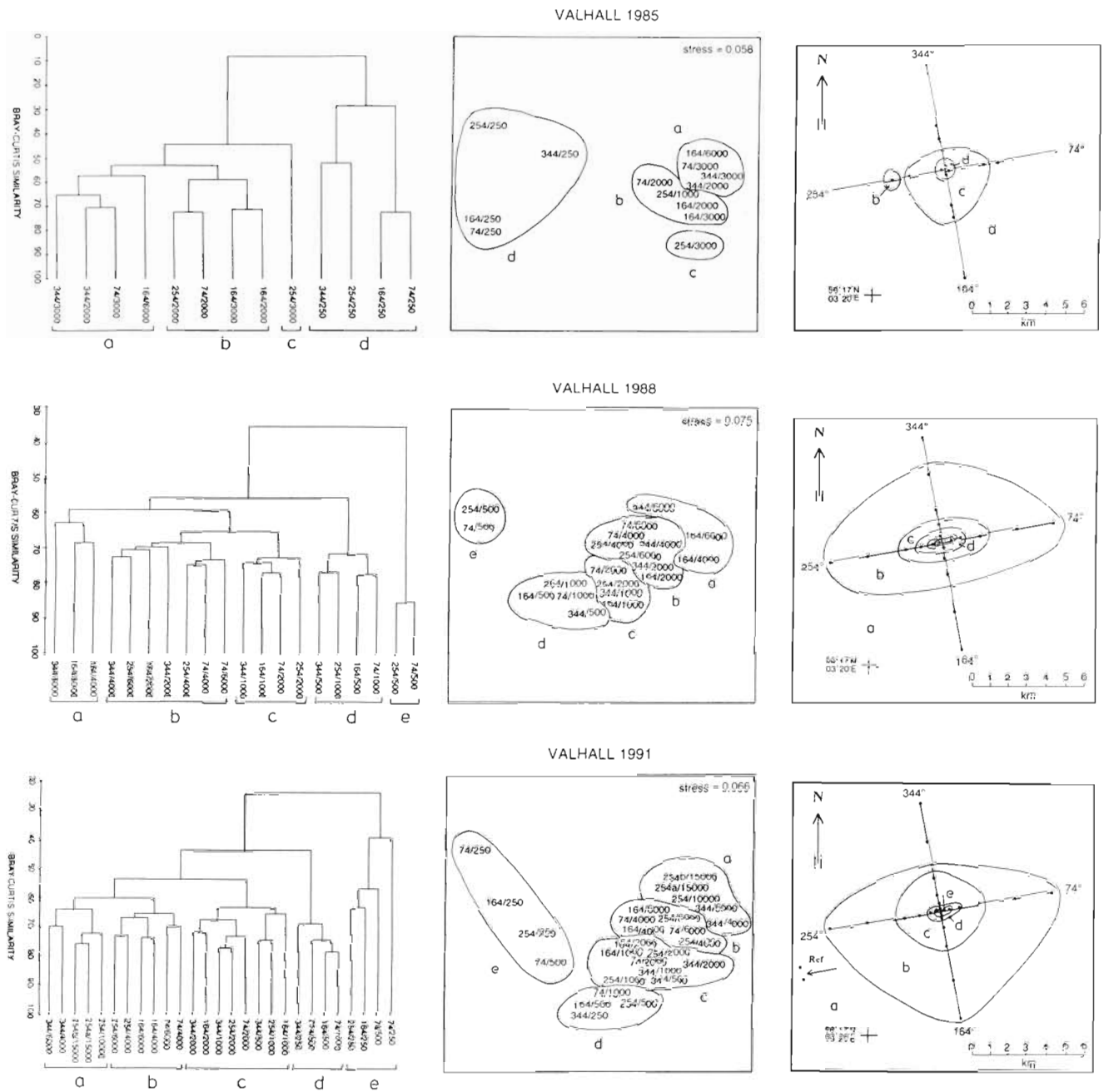
Fig. 10. Classification (left) of stations at the Valhall field according to faunal composition, MDS ordination plots (centre) with the groupings obtained from classification, and superimposition of these station groups on the original sampling stations (right) for the years 1985, 1988 and 1991

Comparison of the patterns of effects on the fauna (Figs. 10 to 12) with the patterns of contamination (Figs. 6 to 8) showed that there were remarkably few differences. In general the effects, with 4 categories, closely mimicked contamination. In terms of area, at Valhall 1991 only 2 contaminated stations had un-affected fauna (344°/4000 m and 6000 m). At Gyda in 1993 only 1 station, station 225°/4000 m, was contami-

nated but had an unaffected fauna, whereas at Vesle-frikk in 1993, 2 stations were contaminated (260°/1000 m and 330°/1000 m) and the fauna was un-affected. Effects of contamination thus closely followed contamination and the areas affected were nearly identical.

Table 5 illustrates results from forward selection of environmental variables in CANOCO and from the
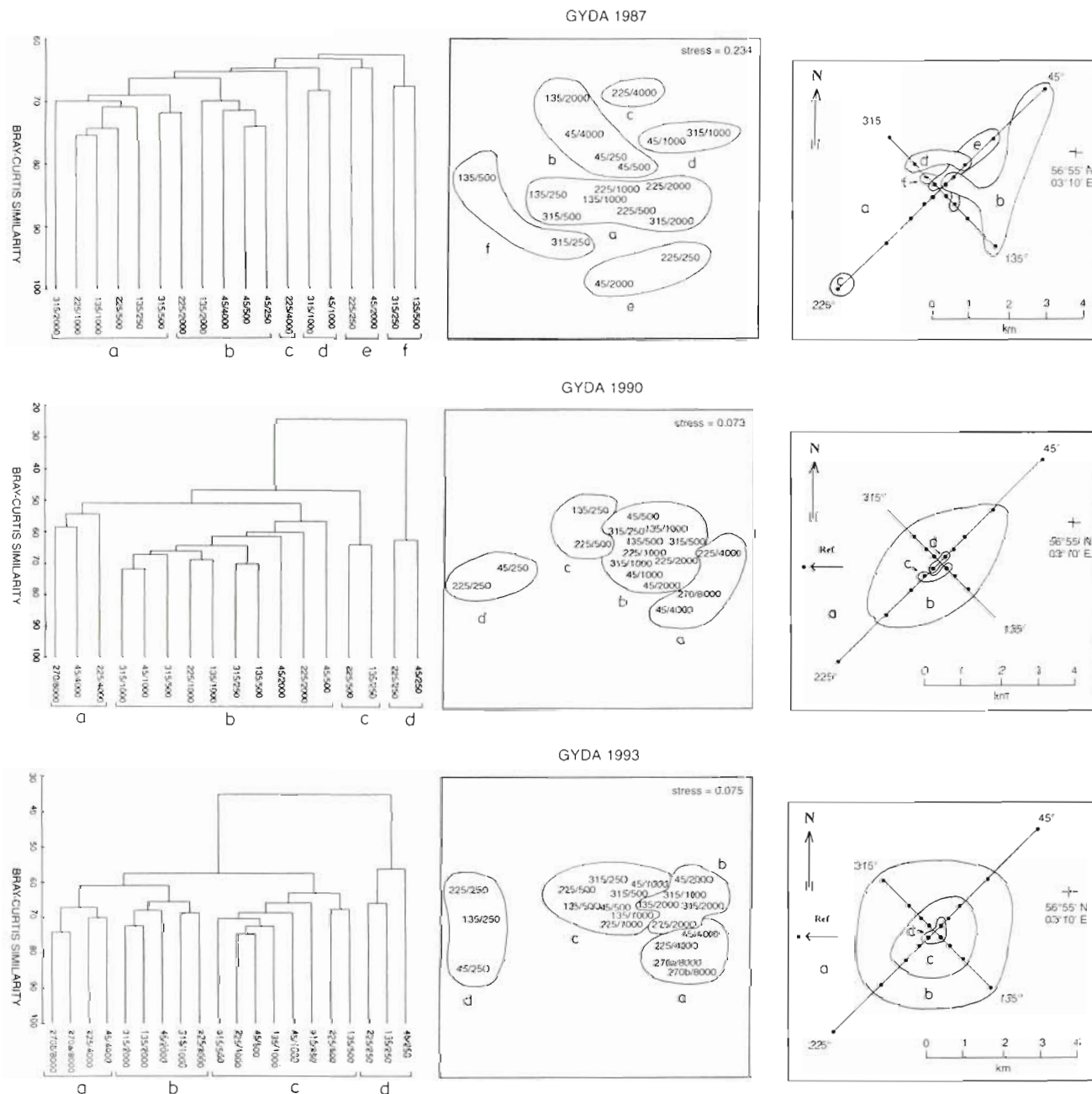
Fig. 11. As for Fig. 10, but for the Gyda field in the years 1987, 1990 and 1993

BIOENV analyses for the Valhall, Gyda and Veslefrikk fields over time. Table 5 shows clearly that whereas the fauna at Valhall was already affected by oil-related contaminants (Sr, Ba and THC) in 1985, this was not so at Gyda and Veslefrikk. At the latter 2 fields the surveys done in 1987 correspond closely to baseline surveys with low percentage values from the forward selection in CANOCO and low r_s values from BIOENV. Furthermore, the most important variables (Cu at Gyda and depth at Veslefrikk) were not those typically associated with oil-related effects such as Sr, Ba and THC, as at Valhall in 1985.

In 1990 both the Gyda and Veslefrikk fields showed clear relationships to variables associated with drill-cuttings (THC, Ba, and Zn) and both the percentage variance values from forward selection and the r_s values increased greatly from 1987 to 1990 at the 2 fields, indicating clear relationships between faunal composition and sediment contamination in 1990. In 1993 the Gyda field had variable loadings comparable to those

VESLEFRIKK 1987

VESLEFRIKK 1990
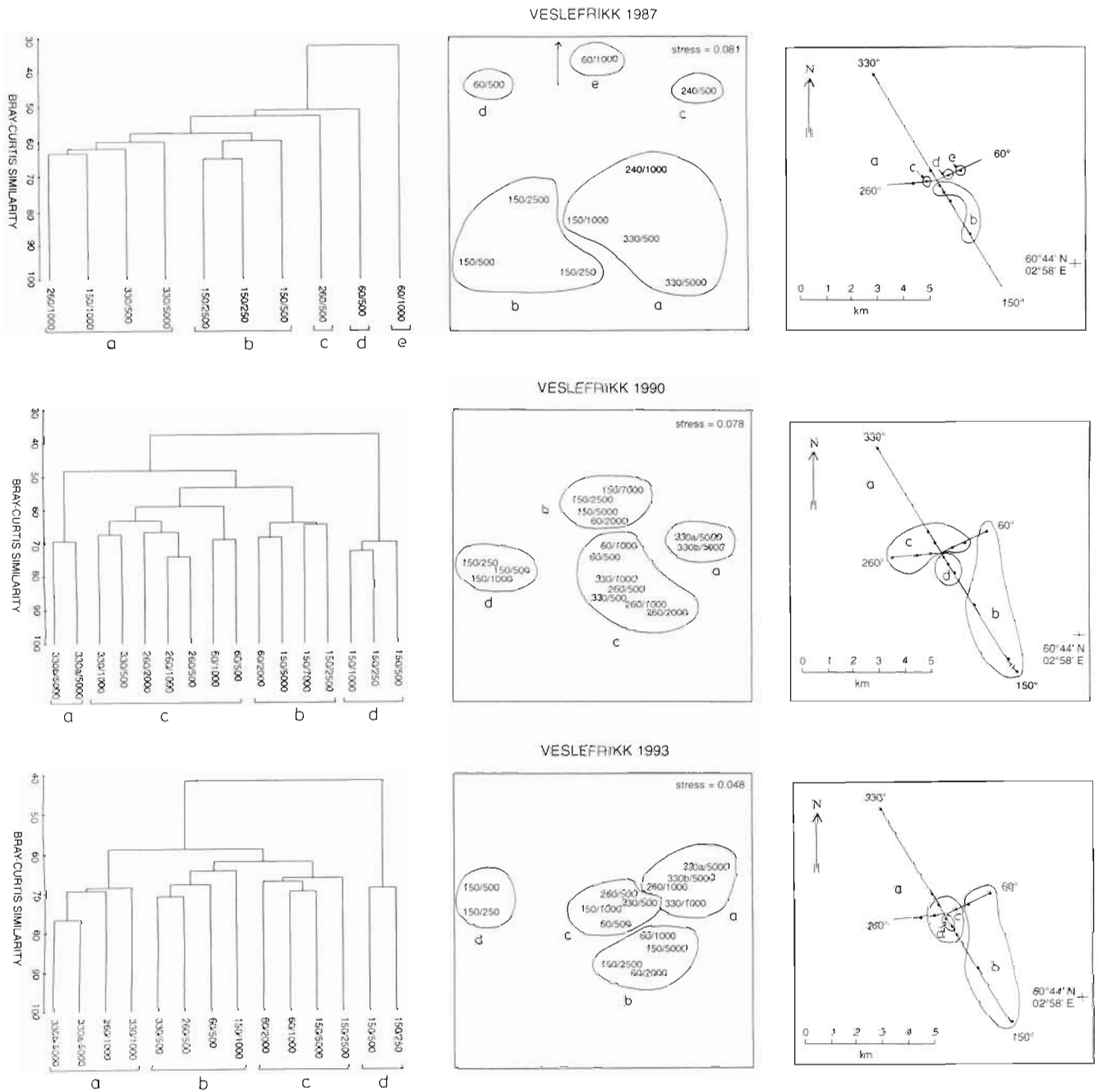

VESLEFRIKK 1993

Fig 12. As for Fig. 10, but for the Veslefrikk field in the years 1987, 1990 and 1993

of Valhall in 1988 and Veslefrikk in 1990 with THC, Ba and Sr as the most important variables in both CANOCO and BIOENV

In 1991 at Valhall (Table 5a) the CANOCO forward selection suggested TOC, Zn, Pb, THC and Sr as the most important variables related to the fauna whereas BIOENV ranked the variables: THC, Sr, Zn, Ba and TOC. Overall the same 5 variables were ranked significantly, and all showed a high degree of correlation

with the faunal composition. This shows that the differences between methods were small, and that in an area clearly affected by drill-cuttings all the variables related to the discharges were highly intercorrelated. In 1993 at Veslefrikk (Table 5c) the key variables associated with faunal changes were the heavy metals Cd, Cu, Zn, Pb and the TOC in CANOCO and Fe, Cd, Cu, Pb and Zn in BIOENV. Of the 5 most significant only TOC and Fe were not selected in both methods, again

Table 5. Relationship between environmental variables and fauna using forward selection in CANOCO (left) and BIOENV in PRIMER (right) for non-baseline surveys (except for Gyda in 1987 and Veslefrikk in 1987, which are baseline surveys). Explanation as in Table 3

(a) Valhall — CANOCO

1985		1988		1991	
Sr	43.8%**	THC	41.6%**	TOC	33.8%**
Ba	41.5%**	Ba	37.1%**	Zn	33.4%**
THC	38.8%**	Sr	37.1%**	Pb	31.7%**
Zn	38.2%**	Fe	35.4%**	THC	31.3%**
Fe	33.2%**	Pb	34.2%**	Sr	30.9%**

(a) Valhall — BIOENV

1985		1988		1991	
Sr	$r = 0.640$	Ba	$r = 0.662$	THC	$r = 0.750$
Ba	$r = 0.618$	THC	$r = 0.652$	Sr	$r = 0.753$
Zn	$r = 0.588$	Sr	$r = 0.554$	Zn	$r = 0.677$
THC	$r = 0.523$	Zn	$r = 0.463$	Ba	$r = 0.675$
Fe	$r = 0.484$	Pb	$r = 0.343$	TOC	$r = 0.655$
Max. corr.:		Max. corr.:		Max. corr.:	
Sr, Ba, THC, <63 µm		Ba, THC		THC, Ba, TOC	
$r_s = 0.727$		$r_s = 0.693$		$r_s = 0.833$	

(b) Gyda — CANOCO

1987		1990		1993	
Cu	14.7%**	Cu	38.1%**	THC	39.7%**
Sr	9.4%**	THC	37.7%**	Ba	39.2%**
Zn	8.4%**	Zn	37.2%**	Sr	39.2%**
Mdφ	7.3%ns	Sorting	34.5%**	Zn	37.5%**
TOC	6.3%ns	Ba	33.6%*	Cu	37.0%**

(b) Gyda — BIOENV

1987		1990		1993	
Cu	$r = 0.312$	Ba	$r = 0.583$	Ba	$r = 0.679$
Mdφ	$r = 0.039$	THC	$r = 0.535$	THC	$r = 0.677$
Sr	$r = 0.014$	Cu	$r = 0.531$	Sr	$r = 0.599$
Sorting	$r = -0.075$	Zn	$r = 0.395$	Kurtosis	$r = 0.485$
Pb	$r = -0.011$	Sorting	$r = 0.341$	Cu	$r = 0.443$
Max. corr.:		Max. corr.:		Max. corr.:	
Cu		Ba, Cu		Ba, THC, Kurtosis	
$r_s = 0.312$		$r_s = 0.687$		$r_s = 0.773$	

(c) Veslefrikk — CANOCO

1987		1990		1993	
Depth	19.4%**	THC	38.0%**	C	40.2%**
<63 µm	18.6%**	Ba	37.4%**	Cu	40.2%**
Mdφ	16.3%ns	Zn	35.6%**	Zn	40.2%**
Sorting	15.5%ns	Cr	35.0%**	TOC	39.0%**
THC	11.6%ns	Fe	33.1%**	Pb	39.0%**

(c) Veslefrikk — BIOENV

1987		1990		1993	
Depth	$r = 0.371$	Zn	$r = 0.623$	Fe	$r = 0.710$
<63 µm	$r = 0.018$	Cr	$r = 0.587$	C	$r = 0.697$
Mdφ	$r = -0.015$	Ba	$r = 0.549$	Cu	$r = 0.608$
Sorting	$r = -0.056$	Cu	$r = 0.436$	Pb	$r = 0.556$
TOC	$r = -0.065$	Fe	$r = 0.431$	Zn	$r = 0.549$
Max. corr.:		Max. corr.:		Max. corr.:	
Depth		Ba, Fe, THC		Fe, TOC	
$r_s = 0.371$		$r_s = 0.733$		$r_s = 0.765$	

indicating consistency in the results. The percentage values in CANOCO and correlation coefficients in BIOENV were also high, both indicating clear impact from cuttings discharges. Due to small differences and high degree of intercorrelation between the measured environmental variables the rank orders in 1993 varied randomly. The results in Table 5c also suggest that at Veslefrikk over time (1990 to 1993) there was a change in indicators of effect from initially Ba and THC to heavy metals presumably because the oil was degraded but the barite continued to spread.

To illustrate that the trends found at the Valhall, Gyda and Veslefrikk fields after several years of discharges of oil-based drill-cuttings are general ones the results from similar analyses of data from Oseberg South 1989, Gullfaks A 1989 and Hod 1991 are shown in Table 6. Development drilling began at Oseberg S and Gullfaks A in 1985 and at Hod in 1982. Table 6 shows clearly that the 'best' explanatory variables also

at these fields were THC, Ba and Sr, all related to cuttings discharges from the platforms.

Fig. 13 shows results from correlation-based PCA analyses of the environmental variables at the Veslefrikk field in 1987, 1990 and 1993. In 1987, with no contamination, there was little positive correlation between the environmental variables (arrows representing the individual environmental variables do not point in the same direction) except for the sediment parameters median grain size (Mdφ), sorting and silt-clay content (<63 µm) and Sr and Cr. After 3 yr of discharge, the measured variables tend to be more positively correlated over time. By 1993 the heavy metals are strongly intercorrelated with each other and with the content of THC, shown by these arrows having a uniform direction.

Despite the fact that many of the results presented are based on biological data, so far there has been little mention of the faunal characteristics. One question

Table 6. Relationships between environmental variables and fauna for 3 non-baseline surveys using forward selection in CANOCO (left) and BIOENV in PRIMER (right). Explanation as in Table 3

Oseberg S 1989		Gullfaks A 1989		Hod 1991		Oseberg S 1989		Gullfaks A 1989		Hod 1991	
Ba	15.7%**	THC	29.9%**	THC	16.8%**	Ba	r = 0.340	THC	r = 0.501	Ba	r = 0.415
THC	14.5%**	Ba	25.9%**	Ba	16.0%**	THC	r = 0.338	Ba	r = 0.492	Sr	r = 0.373
Sr	12.2%**	Cu	24.2%**	Sr	15.2%**	Sr	r = 0.191	Cu	r = 0.389	THC	r = 0.322
Depth	6.5%^{ns}	Zn	22.5%**	Pb	14.4%**	Depth	r = 0.073	Fe	r = 0.292	Cd	r = 0.321
<63 μm	6.1%^{ns}	Pb	22.5%**	Cd	12.0%**	Zn	r = 0.039	Zn	r = 0.292	Pb	r = 0.291
						Max. corr.: Ba, THC, Depth r_s = 0.373		Max. corr.: THC, Ba, TOC r_s = 0.571		Max. corr.: Ba, Sr, THC, Cd, Zn, Mdφ r_s = 0.552	

VESLEFRIKK 1987

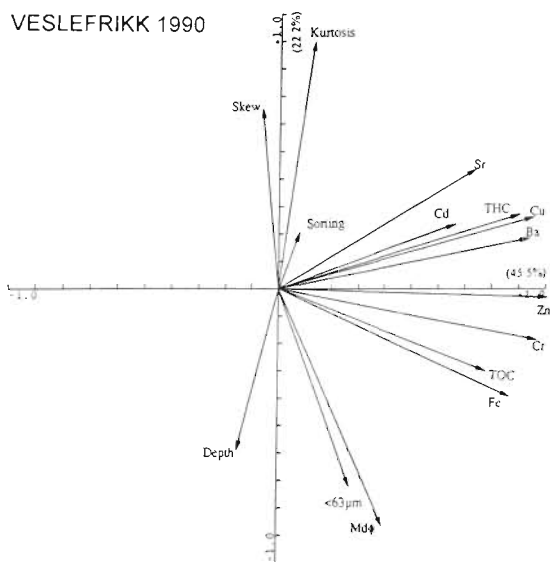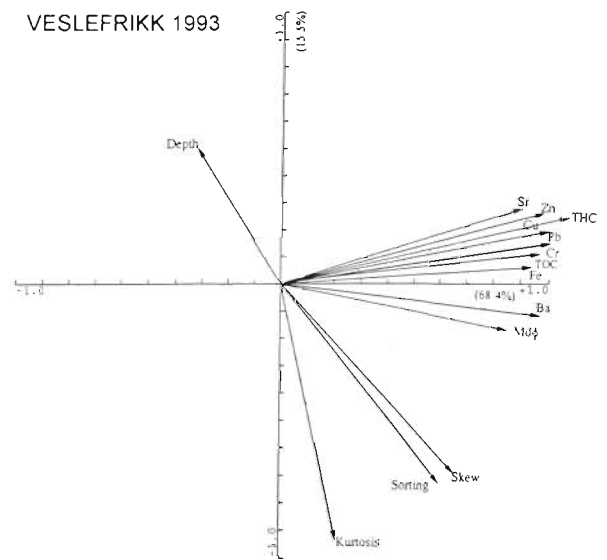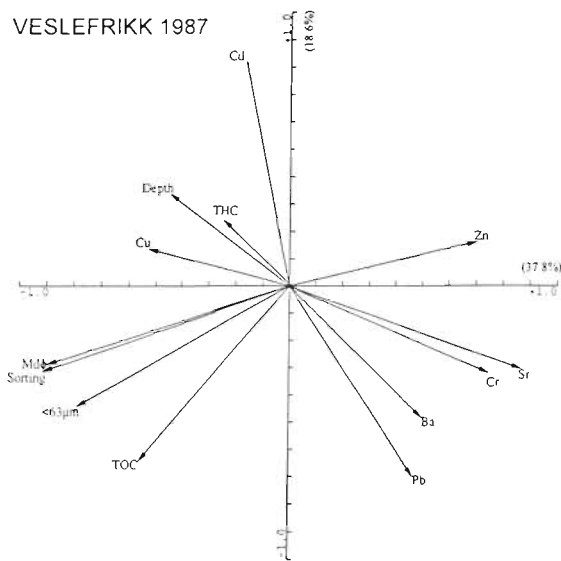VESLEFRIKK 1993

VESLEFRIKK 1990

Fig. 13. Correlation between environmental variables, as shown by a PCA ordination plot of the environmental variables measured at the Veslefrikk field in 1987, 1990 and 1993. Arrows that point in the same direction indicate positively correlated variables, perpendicular arrows indicate lack of correlation and arrows pointing in the opposite direction indicate negatively correlated variables. In 1987 the explained variance along Axis 1 and 2 was 37.8% and 18.6%, respectively. The corresponding values in 1990 were 45.5% and 22.2%, and in 1993, 68.4% and 15.5%, respectively

that is often raised is are there species that characterise the initial stages of effects of pollution, and are these species similar over large geographical scales, i.e. universal indicators of initial disturbance? Using the SIMPER program in PRIMER the species that characterise the difference between the unaffected group a and the just-affected group b were determined. Table 7 shows just the 3 species highest ranked in SIMPER that show highest reduction in abundance from the uncontaminated to the just-contaminated groups of stations (although there are in fact many more than 3 species

Table 7. Most sensitive species, extracted from the SIMPER analyses as the 3 top ranked species from each survey showing highest reduction in abundance (m^{-2}) from group a to group b, i.e. number individuals in group a / number individuals in group b. 1: Valhall, 1988; 2: Valhall, 1991; 3: Gyda, 1990; 4: Gyda, 1993; 5: Veslefrikk, 1990; 6: Veslefrikk, 1993; 7: Oseberg South, 1989; 8: Gullfaks A, 1989; 9: Hod, 1991; 10: Gullfaks B, 1990; 11: Gullfaks B, 1993; 12: Statfjord A, 1990; 13: Statfjord A, 1993; 14: Statfjord B, 1990; 15: Statfjord B, 1993; 16: Statfjord C, 1990; 17: Statfjord C, 1993

Species	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Anthozoa																	
Edwardsia sp.									32/8								
Polychaeta																	
Sthenelais limicola	8/4																
Nephtys longosetosa									20/0								
Aricidea wassi					10/5												
Scoloplos armiger						14/1											
Aonides paucibranchiata										3/1			23/1		22/1	15/0	141/4
Spiophanes bombyx			24/2				104/36										
Malacoceros fuliginosus											23/3						
Myriochele oculata						476/3								27/4	29/2		
Owenia fusiformis						145/4								60/10			
Eclysippe vanelli								107/73				52/11					
Amythasides macroglossum												145/27					
Pista cristata								6/4					37/9		37/2		41/0
Polycirrus spp.													12/2				
Sipuncula																	
Phascolion strombi											5/1						
Golfingia vulgaris											8/2						
Crustacea																	
Harpinia antennaria				38/2													
Tmetonyx cicada														11/2			
Podoceropsis nitida					5/0												
Unciola planipes										5/1							
Gastropoda																	
Spiratella retroversa									50/14								
Bivalvia																	
Portlandia phillippiana					10/3												
Limatula subauriculata												61/20				20/1	384/26
Mysella bidentata		24/0	16/2														
Montacuta substriata				5/0													
Spisula elliptica										7/4							
Abra prismatica							36/3	6/1									
Brachiopoda																	
Macandrevia cranium																140/26	
Echinodermata																	
Echinocardium flavescens		8/2															
Echinocyamus pusillus																	
Ophiura affinis	20/10																
Amphiura filiformis	26/13	114/40	80/18	162/32			106/11										

Table 8. Most tolerant species, extracted from the SIMPER analyses as the 3 top ranked species from each survey showing highest increase in abundance (m⁻²) at the innermost group compared to the outermost group (group a), i.e. number individuals in the innermost group/number individuals in the outermost group a. Fields as in Table 7

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Nemertini																	
Nemertini spp.			19/2	82/0					60/12								
Polychaeta																	
Paramphinome jeffreysii					486/2			142/0									
Ophryotrocha spp.										90/0				302/0		332/0	
Rhaphidrius spp.																374/0	
Raricirrus berylii									7/2		1584/4		875/0		66/0		2236/2
Cirratulus cirratus	42/2	32/5				2088/7	282/10					640/2	2726/0				314/0
Chaetozone setosa	3358/2	2934/0	2368/1			12964/186	539/0	126/0	109/37	224/2	2600/80	693/44	8247/0	112/0	4128/0	1060/0	670/0
Capitella capitata								112/0		243/0	230/0						
Gastropoda																	
Lunatia montagui	21/1	16/1	16/10	10/1													
Bivalvia																	
Thyasira sarsii					431/0	1633/8	136/0					157/2		142/0	242/0		

that characterise the difference between these 2 groups). The table shows that there were few species that were consistently important as indicators of initial effects within the southern Norwegian continental shelf. The analyses also rank species showing increased abundances from group a to b, but similarly showed no consistent pattern.

Table 8 shows data obtained from SIMPER analyses showing species that characterise the differences between the highly polluted group close to the platforms and the unpolluted, outermost group a. Here there were many species that showed consistent patterns indicating that the pollutant tolerant species were more ubiquitous within this part of the North Sea.

DISCUSSION

In relation to chemical discharges often no distinction is made between contamination (raised levels of the chemical compared with natural background levels) and the effects of this contamination; both are called pollution. The UN Group of Experts on Scientific Aspects of Marine Environmental Protection (GESAMP) distinguishes between raised concentrations of chemicals, called contamination, and the effects of that contamination on biota, called pollution. Here we examine first contamination and then pollution from oil-related discharges.

The primary source of environmental disturbance around oil and gas platforms in the Norwegian sector has been the discharge of drill-cuttings containing oil. However, the amounts of oil and oil-based cuttings discharged have decreased in recent years (Fig. 1). At the 3 main fields analysed here, discharges of oil-based drill-cuttings show that the Valhall and Gyda fields received far more cuttings than at Veslefrikk (Table 9). In addition, of the 3 fields, the Valhall field has a longer history of oil activities. Thus one might expect that effects were more severe at Valhall than Gyda and Veslefrikk.

Little use has been made in previous studies of both physical and chemical data in the analysis of the patterns ensuing from oil-related activities. Here we have used several multivariate techniques applied to physical and chemical data. Baseline data show no clear patterns with a 'shotgun' type scatter of stations (Figs. 4 & 5) and no clear correlation between any of the environmental variables and the fauna (Table 3), save for Snorre where depth was important, and Mime where TOC was correlated with the pattern of stations.

The patterns of development of contamination were clearly shown at all 3 fields studied, Valhall (Fig. 6), Gyda (Fig. 7) and Veslefrikk (Fig. 8). Plots of mean values of Ba and 95% confidence intervals (Fig. 9) clearly

demonstrated the relation between drill-cuttings discharges and station groupings. Significantly higher Ba values were found between the just-contaminated station groups (group b) compared to levels at a few of the outermost stations and the reference stations (group a). Inspection of the environmental data-matrices also revealed that other compounds related to cuttings discharges, such as Sr, Cu, Cd and THC, often showed elevated concentrations in the group b stations compared to group a.

Table 9. Discharges of oil-based drill-cuttings (t) at the Valhall, Gyda and Veslefrikk fields. (Data from Anon 1993, Bakke et al. 1993)

Valhall (Production start 1982)		Gyda (Production start 1990)		Veslefrikk (Production start 1989)	
1983–1987	15389	1987–1989	17750	1987–1989	1863
1990–1991	269	1990–1991	2177	1990–1991	2986
1992	6	1992	0	1992	392

It might be argued that since only the reference stations were different from the just-affected group b, one can only say that this group of stations differed from the reference and this may not be due to increased contamination. However, Figs. 6 to 8 show a gradual increase in the area of contamination, displayed as rings around the platforms, consistent with the argument that only the reference stations were uncontaminated after 6 to 9 yr of discharge. Fig. 9 shows that the group a stations at Valhall and Gyda in 1990 and 1993 and Veslefrikk in 1993 had significantly lower levels of Ba than the remaining station groups. If one accepts contamination has been shown out to a 6000 m radius at Valhall this gives an area of at least 100 km^2 contaminated. For the Gyda field in 1993 there were samples taken only out to 2000 m on 2 axes (135° and 315°) and the contamination extends to >2000 m along these axes and >4000 m on the 225° axis. Thus the area contaminated is probably in excess of 15 km^2. At Veslefrikk in 1993 the contamination was ellipsoidal stretching along the main current direction out to the furthest point measured (5 km along the 150° axis), and affected an area of at least 10 km^2. These findings substantiate the unpublished data referred to in the GESAMP report (1993) that contamination covers large areas of sea-bed.

Davies et al. (1984) have suggested that there is a gradual movement of cuttings away from the platforms and that during this movement biodegradation of THC takes place. This was also shown at the Gyda, Valhall and Veslefrikk fields. After cessation, or almost cessation, of drill-cuttings discharges reduced THC concentrations were found in the outer areas. Also Ba and many of the associated metals in the sediments showed a decrease in concentration subsequent to cessation of discharges. The observed decrease in concentrations of Ba and associated heavy metals in the outermost areas at Valhall in 1991 and Gyda in 1993 may indicate resuspension and a continuous and wide dispersal of these elements. Despite reductions in concentrations of both THC and metals following cessation of cuttings an obvious enlargement of the total area of biological

impact was observed. This indicates that there are other compounds in the discharges, that were not measured, that have a negative ecological impact.

Some workers have suggested that once discharge of drill-cuttings has stopped, improvement of environmental conditions will occur almost immediately (e.g. Levell 1987). Davies et al. (1989) argue that recovery and recolonization of the transition zone begins within 1 to 2 yr. They suggest that following a degradation of the oil hydrocarbons, the biological transition zone begins to move inwards, despite some outward redistribution of drill-cuttings. Our data show that this is not the case; there is a continuous increase in the total area affected even several years after cessation of cuttings discharges; see Table 9 and Figs. 10 to 12 for the Valhall, Gyda and Veslefrikk fields.

Our data from these 3 fields clearly illustrate that the sampling design is now inadequate to assess the degree of contamination as there are too few reference stations in the unaffected area. There is thus a need for a revision of the sampling strategy, especially since the present design does not take neighbouring fields into account. Now that contamination can be demonstrated to cover 100 km^2 around 1 field it is likely that many adjacent fields show overlapping contamination.

The development of patterns showing effects on the fauna were consistent within fields. Baseline surveys show that there was no consistent pattern between the measured environmental variables and the fauna, as assessed by 2 different methods, forward selection in CANOCO and the BIOENV program in PRIMER (Table 3). At the Snorre field, depth was a significant factor in both methods and at Mime, sediment content of TOC, whereas at the other fields different variables correlated with the fauna (Table 3). The development of contamination and its correlation with effects on the fauna showed that the effects were associated predominantly with THC, Ba and Sr (Table 5).

When/where pollution was severe, e.g. at Valhall in 1991 and Gyda in 1993, it was THC, Ba, Sr and heavy metals associated with the barite component of the drill-cuttings which showed the clearest correlation with the patterns in the fauna (Table 5). As contamination developed, the measured environmental variables became more intercorrelated (Fig. 13, right hand side).

However, correlations between effects on the fauna and physical and chemical variables do not necessarily show cause and effect relationships. Furthermore, one cannot be sure that an apparently explanatory variable was not a proxy for an unmeasured variable that really was causal.

As Dixon (1987) has pointed out, long-term comparative studies using experimental systems such as mesocosms are needed to determine cause and effect relationships. Whilst we agree with this, at the same time the recent change to water-based drilling muds on the Norwegian continental shelf is in itself a field-experiment. A comparison of contamination and biological effects between areas where oil-based mud and areas where only water-based mud have been used should give indications of which components result in adverse effects. Preliminary results (unpubl.) from monitoring surveys at fields where only water-based mud were employed clearly indicate less contamination and biological impact, compared to the results reported here. This suggests that the main adverse effects were related to the oil-components in the mud, but further investigations are necessary to establish the relationships. Yet the fact that more barite is now being used, and that the barite contains high quantities of heavy metal impurities, suggests the need of further studies.

Acute toxicity studies, however, suggest that barite is not particularly toxic (e.g. Cabrera 1971, George 1975). Starczak et al. (1992) showed that in laboratory tests there were no deleterious effects on faecal pellet production, growth and tube production in the polychaete *Mediomastus ambiseta* at realistic sediment concentrations of barite. However, in laboratory studies on development of an estuarine community Tagatz & Tobia (1978) found that significantly fewer individuals and species colonised sand covered by barite compared with controls. Polychaetes were particularly affected. The study of Tagatz & Tobia was on a community comprising 59 species rather than on a single species as in the acute tests and *M. ambiseta* study. It is likely that the application of multivariate techniques to complex community data, as done here with usually over 150 species per field studied (see Table 2), will reveal far more subtle effects than toxicity studies.

Another important finding was that the degree of contamination, as defined by multivariate analyses of physical and chemical data, and the degree of effects were closely similar and patterns were repeated at the different fields (comparison of Figs. 6 to 8 and 10 to 12). The spatial extent of effects was only slightly less than that of contamination. This illustrates that (1) the methods used are highly sensitive and (2) the effects are traceable to a larger area than has been assessed previously.

The most obvious question to ask is do the effects found relate to the amount of drill-cuttings discharged? The distance to which the fauna was affected along the major axis was plotted against the amount of drill-cuttings discharged (Fig. 14). There was no correlation ($r = 0.328$, $n = 10$, $p > 0.05$) between input of drill-cuttings and the border of affected fauna. For example, Statfjord C in 1990 did not show the largest extent of affected fauna despite having the largest amount of cuttings discharged. Other factors than mere amounts of drill-cuttings are clearly important, such as the type of mud used, the particle size of the cuttings, hydrographic conditions, depth, etc., all of which varied between fields. In addition, multivariate analyses are better able to detect effects of contamination in areas where environmental variables (e.g. depth and sediment characteristics) and faunal distribution are homogeneous. This is the probable explanation for the fact that there were clear patterns at Valhall and Gyda, but less clear patterns at Statfjord C which has been subjected to higher loads of drill-cuttings, but has a more heterogeneous sediment and probably stronger bottom currents.

One can obtain a scaling of pollution using the effects on the fauna. Table 10 shows the data where the criterion used was the reduction in number of species from the background (uncontaminated) stations compared with the 500 m stations along the main current direction. In this analysis, Statfjord C in 1990 was the most affected field, followed by Valhall 1991. Interestingly, in 1993 Statfjord C was less affected with a higher number of species at the 500 m station than in 1990. This was also the case for Statfjord A and B and Gullfaks B which were all less affected in 1993 compared with 1990. This suggests that there has been an improvement due to abatement of discharges at these fields in recent years, measured as an increased num-
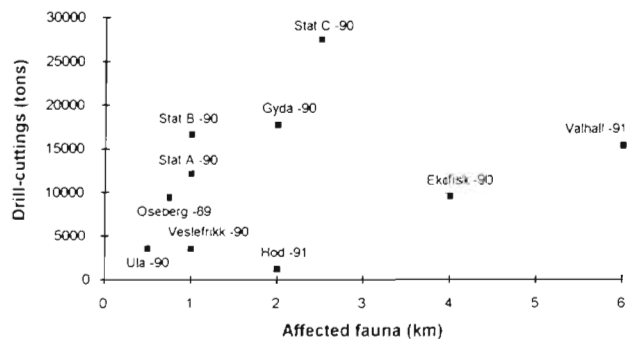

Fig. 14. Relationships between maximum distance from the platforms of measured faunal effects and the amount of oil-based drill cuttings discharged. Data from separate investigations at the Ula and the Ekofisk field, both in 1990, are also included

ber of species compared to back-
ground values.

Here, using multivariate techniques
the areas of effects were far larger than
could be found using diversity indices.
Fig. 15 shows values for Shannon-
Wiener diversity (H') plotted against
sediment content of Ba (Fig. 15a) and
THC (Fig. 15b) as indicators of contam-
ination, at the 500 m stations along the
primary current direction axis. Values
of diversity, Ba and THC are given as
ratios of the observed value divided by
the background value, which allows
comparisons to be made taking into ac-
count the natural differences in diver-
sity (cf. Heip et al. 1992) and levels of
Ba and THC within the areas studied
and any slight differences in method-
ology. The Shannon-Wiener diversity
indices showed wide scatter and no
clear gradient of effects whereas an
even simpler measure, number of spe-
cies (Fig. 15c, d), showed a significant
decrease with increased levels of cont-

Table 10. Ranking of non-baseline fields according to reduction in number of
species (N) at the 500 m station along the prevailing current direction compared
to control(s) and/or unaffected stations (N 500 m station/mean N control and/or
unaffected stations). –: increase

Field	N at 500 m station	Mean N at control and/or unaffected station(s)	N 500 m/mean N control and/or unaffected station(s)	% reduction in N
Statfjord C, 1990	25	84	0.30	70
Valhall, 1991	24	56	0.42	58
Statfjord C, 1993	49	112	0.44	56
Valhall, 1988	21	39	0.54	46
Gyda, 1990	42	66	0.63	37
Veslefrikk, 1993	61	86	0.71	29
Gyda, 1993	43	59	0.72	28
Valhall, 1985	24	33	0.72	28
Gullfaks A, 1989	53	79	0.73	27
Statfjord A, 1990	62	76	0.82	18
Statfjord B, 1990	60	72	0.83	17
Gullfaks B, 1990	39	46	0.85	15
Oseberg S, 1989	34	40	0.85	15
Hod, 1991	50	58	0.86	14
Statfjord A, 1993	77	87	0.89	11
Veslefrikk, 1990	80	89	0.90	10
Statfjord B, 1993	84	86	0.98	2
Gullfaks B, 1993	85	77	1.10	–
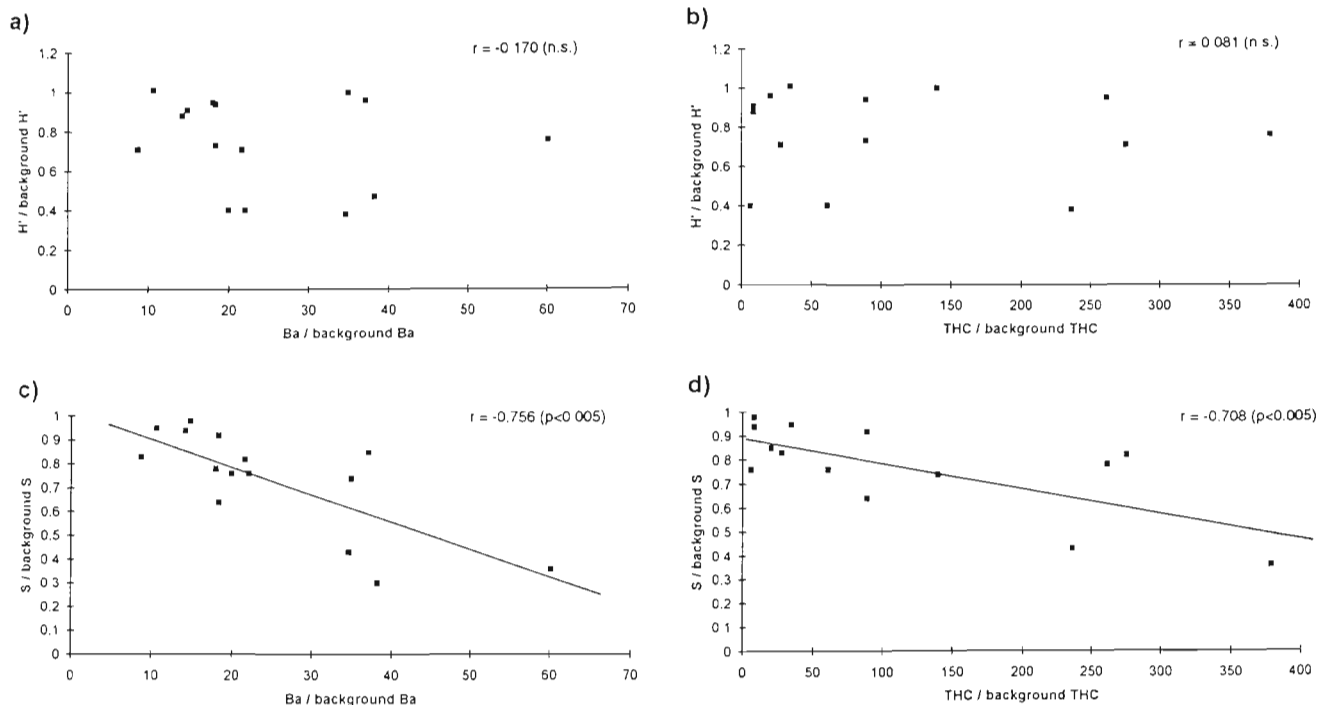
Fig. 15. Relationships between relative diversity (see text) against (a) relative values of barium, Ba and (b) relative values of total
hydrocarbons, THC; and relationship between relative number of species and relative values of (c) Ba and (d) THC. The result-
ing correlation coefficients (r) from linear regression analysis are also given, with level of significance. Only the regressions in (c)
and (d) were statistically significant (p < 0.05) and hence the regression lines (solid) are given for these 2 plots

amination. This is in agreement with Olsgard (1993) that changes in species richness are often a simpler and better parameter than e.g. Shannon-Wiener diversity index in assessing disturbance in benthic communities.

The results in Fig. 15 suggest that clear changes in diversity occur only at approximately 20 times background levels of Ba and 50 times background levels of THC. Gray et al. (1990) and Warwick & Clarke (1992) have illustrated similar findings for the lack of sensitivity of changes in pattern of diversity at the Ekofisk field. Thus reliance by monitoring programmes on interpretations based on patterns of diversity alone need to be abandoned. Furthermore, species identity is not taken into account and identity is needed for a full interpretation of the data (see below).

The fact that multivariate methods showed much more sensitive responses is shown in Fig. 16a, b where fauna group b (the initial phase of effect), when compared to the unaffected group a, was characterised by a doubling of background levels of Ba at Valhall

(Fig. 16a) and both Ba and THC at Gyda (Fig. 16b). Yet many chemical and physical variables, such as heavy metals and silt-clay fraction of the sediment, were intercorrelated with THC and Ba.

Prior to the application of multivariate analyses methods, effects of oil-related discharges from platforms were generally believed to be found only within a 1 to 1.5 km radius. This was based on application of univariate statistical analysis tools to data such as the number of species and diversity indices (e.g. Addy et al. 1984, Davies et al. 1984, 1989, Mair et al. 1987, Kingston 1992, GESAMP 1993). In a comparison between species independent univariate and species dependent multivariate methods for analysing changes in benthic community structure, Warwick & Clarke (1991) concluded that multivariate methods were much more sensitive in discriminating between stations or times.

Using multivariate analyses, Gray et al. (1990) were able to demonstrate clear effects to a radius of 3 km from the centre of the Ekofisk field in 1987. Thus the area affected was approximately 27 km^2 compared with the accepted area of only 3 km^2, which was mainly based on information from diversity indices. In this study we have shown clear contamination to areas of >100 km^2 at Valhall, >15 km^2 at Gyda and >10 km^2 at Veslefrikk with effects covering slightly smaller areas, >60 km^2, >12 km^2 and >9 km^2, respectively. Pollution effects are thus found out to significantly greater distances than the accepted 1 to 1.5 km radius, suggested by Kingston (1992) in a recent review.

Addy et al. (1978) subjectively picked out species which to a large extent showed reduced abundance within 2 to 3 km from the Ekofisk oil-field and suggested this was related to discharges of oil from the platforms and to physical disturbance of the sediments. These species were the brittle star *Amphiura filiformis* and the 2 polychaetes *Myriochele oculata* and *Owenia fusiformis*. In our objective SIMPER analyses *A. filiformis* was also extracted as a sensitive species in this part of the North Sea (Table 7), while the 2 latter species in our study were ranked as sensitive species in fields further north (Table 7). Addy et al. (1978) also applied the Shannon-Wiener diversity index, but this did not lead to identification of the existing pollution gradient. In fact, due to an increased density of *M. oculata* mov-
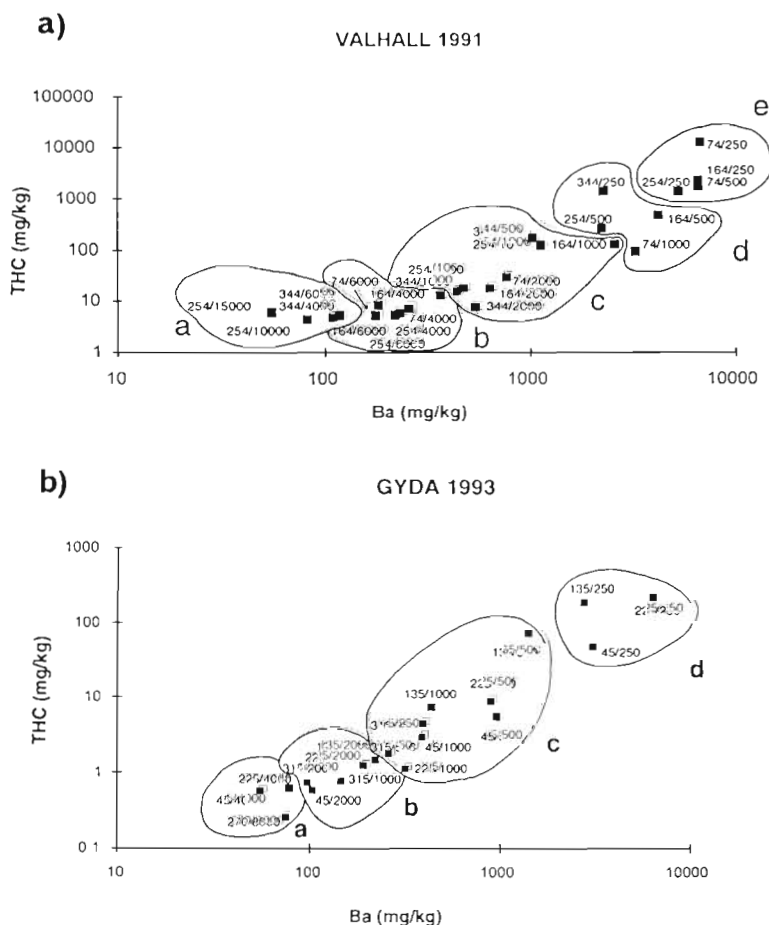

Fig. 16. Plots showing relationships between total hydrocarbons (THC) and barium (Ba) in the sediments and the obtained faunal groupings from the multivariate analyses at (a) the Valhall field in 1991 and (b) the Gyda field in 1993

ing away from the platform a clear reduction in diversity with increased distance from the platforms emerged, again illustrating the lack of appropriateness of diversity indices for the assessment of effects of pollution on benthic communities.

The species that characterise the first stages of effects of pollution (Table 7) varied greatly over time and between fields. Between years at the same field there was little consistency, save perhaps for the polychaete *Aonides paucibranchiata* at the Statfjord field and *Amphiura filiformis* which characterised initial stages of effect at 4 and 5 different surveys, respectively. Gray et al. (1990) used identical methods to survey data from the Ekofisk field in 1987. Of the 15 species listed as characterising the initial stages of impact at Ekofisk only 3 (*Myriochele oculata*, *Montacuta substriata* and *Ophiura affinis*) occurred within the list of 32 species in Table 7. This suggests that the pattern found in this study of no consistency either between years and/or fields is a general one, and that a search for 'universal' sensitive species is probably not worthwhile. This is not surprising since most of the species listed in Table 7 occurred in relatively low abundances and thus often changes in abundances recorded are small. The multivariate analyses are nevertheless sensitive to the patterns of increase and decrease of a relatively large number of species, and it is these changes that give discrimination between groups.

With severe pollution the characteristic species were more consistent between fields and times (Table 8). The typical indicators of severe effects around oil platforms were the polychaetes *Capitella capitata*, *Chaetozone setosa*, *Cirratulus cirratus*, *Raricirrus berylli* and the bivalve *Thyasira sarsii*. These species increased in abundance in the severely polluted zone at 5 surveys or more in different areas. In the Ekofisk analyses, Gray et al. (1990) found that *C. capitata* and *C. setosa* were the 2 most pollution tolerant species. *C. capitata* has been suggested as a 'universal indicator' of organic pollution (Reish 1973).

Gray (1982) suggested that what was needed were not indicators of end-points of severe pollution but rather indicators of the initial stages of pollution. The results from our study suggest that even within fairly discrete geographical areas there are no consistent patterns of sensitive 'indicator species' that can be suggested. There can be several reasons why the search for universal, sensitive indicator species is unfruitful. Firstly, there seem to be notable, natural differences in fauna composition within fairly restricted areas, probably due to minor differences in depth and sediment composition. Secondly, sensitive species are likely to be specific for 1, or maybe 2 particular types of pollution as the organisms cannot be equally sensitive to all types of pollution (e.g organics, metals, oil, pesti-cides, etc.). Thirdly, an indi-

cator species can be sensitive to one pollutant and tolerant to another. In a review of biotic indices based on tolerant and sensitive species, Washington (1984) stressed that such indices were necessarily limited to the geographical area in which the species lists are compiled. This being the case, reliance has rather to be placed on the application of statistical techniques, such as those used here to assess the patterns of change. The idea behind the use of indicators is that it might be possible to simplify assessments by concentrating only on these species in future surveys. Such a simplification does not seem realistic.

Another key question can be raised: Is it possible to distinguish between effects of physical disturbance, chemical toxicity and organic enrichment on the benthos? Gray (1982) suggested that rather than adapting to pollution by means of tolerance, many benthic species were more likely to be adapting to physical disturbance and that responses shown by species to organic enrichment were more likely to be a response to physical disturbance (sedimentation) than to tolerance of low oxygen. Olsgard & Hasle (1993) supported Gray's hypothesis, showing that the responses of species to a purely physical pollutant (mine waste) were identical to that shown to organic enrichment (Pearson & Rosenberg 1978), in that the total number of species was severely reduced, and a few opportunistic species increased greatly in abundance thereby increasing the total abundance. As a consequence of these changes, values of diversity indices decreased significantly. In contrast, where toxic effects often occur, often both the total number of species and the number of individuals decreases [e.g. response to a toxic alga (Olsgard 1993) or heavy metals (Rygg 1986)] and as a consequence the values of diversity indices did not usually decrease. These findings suggest that it may be possible to separate impact resulting from physical effects/organic enrichment from toxic effects.

As shown above, diversity indices show varying responses depending on the type of pollutant. Since pollution gradients will often be composed of a mixture of physical/organic and toxic compounds it will not usually be possible to predict how diversity indices will respond. This can be illustrated from our data in that near the oil platforms there was no relationship between the concentration of known pollutants (e.g. Ba and THC) and diversity (Fig. 15a, b). At the stations with clearly elevated levels of Ba and THC chemical effects presumably dominated whereas at others physical effects dominated, hence there is no clear relationship between diversity and contaminant load. However, where there are clear gradients of a single, non-toxic factor a relationship between diversity and the dose can be shown (e.g. physical disturbance by sedimentation; Olsgard & Hasle 1993). One must also

bear in mind that diversity indices will be affected by natural factors, for example recruitment of large numbers of individuals will reduce the values of indices, and it is well-known that diversity indices are sample-size dependent. Interpretation of changes in values of diversity indices are therefore difficult. In contrast, using multivariate analyses, which are based on a detailed comparison of the totality of responses of all the species present in field samples, it is now possible to identify pollution effects at an early stage and, in addition, by comparing number of species and abundance it should be possible to separate the effects of physical effects/organic enrichment from chemical sources of pollution. Where toxic effects dominate the major response is likely to be a reduction in both numbers of species and abundance, without a significant increase in abundance of opportunistic species. Such findings must call into question the utility of using short-term toxicity tests on robust (often opportunistic) species as a means of predicting the likely environmental impact of discharging such chemicals.

Heip et al. (1988) and Warwick (1988a, b) have suggested that identification to the species level may not be necessary, as from cases related to organic and chemical pollution they were able to show that using the same data no information was lost by analysing the results at the family level. If such findings can be applied generally and consistently then considerable improvements can be made in survey efficiency, as it will be possible to take more samples for the same effort and thereby give better spatial coverage and statistical precision to the analyses. The data sets in this paper are appropriate for assessment of the utility of analyses based on higher taxal levels than the species and will be the subject of a further paper.

There has been considerable debate on whether or not the initial effects recorded here, of changes in benthic community structure, are important (Gray 1991, 1992, Holt 1992, Milne 1992). The Norwegian authorities reacted to the 27 km^2 affected at Ekofisk (Gray et al. 1990), together with indications of similar effects at Statfjord (Reiersen et al. 1989), by saying that this was not predicted by Environmental Impact Assessments which claimed that only a 3 km^2 area would be affected. They first legislated the amount of oil *in cuttings* that could be discharged to 6% in 1987 and then instituted a total ban on discharges of oil-based drill-cuttings in January 1993. The oil-based drill-cuttings in the Norwegian sector are now occasionally re-injected down the bore hole, or brought ashore for disposal.

It is known that in the period 1984 to 1990, in the British sector of the North Sea, the amount of oil-based drill-cuttings discharged was over 8 times that discharged in the Norwegian sector (PARCOM 1992).

Thus it is likely that a large area of the sea-bed of the North Sea is contaminated and will show effects on the benthic fauna.

In the context of importance of these effects one question that is often raised is what is the wider significance of finding effects on benthos for fish or the food for fish. Our data for the Valhall and Gyda fields showed that one of the significant effects was that the densities of the brittle star *Amphiura filiformis* decreased from mean values of 80 to 160 ind. m^{-2} in the uncontaminated areas to means of 10 to 40 ind. m^{-2} in the initially affected areas and were almost absent closer than 1 to 2 km from the platforms. The ventilatory activities of this brittle star improve the oxygenation of the sediment which subsequently affects the total benthic respiration, mineralisation and distribution of other fauna (Ockelman & Muus 1978).

Amphiura filiformis is known to be eaten by Gadidae (cod, haddock and whiting) and Pleuronectidae (plaice, witch, dab and sole) in Norwegian coastal areas (Pethon 1989), the North Sea (Duineveld & Van Noort 1986), the Kattegat (Blegvad 1930, Pihl 1994) and the Irish Sea (Jones 1952). The study of Jones (1952) showed that *A. filiformis* in fact was the main food item of plaice, dab and sole in these waters, and Pihl (1994) found that this brittle star was the main prey of plaice and dab in the Kattegat. *A. filiformis* is a dominant member of the community and is a key member controlling structure and probably function of the benthic communities studied (Duineveld & Van Noort 1986). The fauna in the highly contaminated areas is dominated by small polychaetes which are subsurface living. It is unlikely that such fauna are as valuable as an undisturbed community with a wider range of both sizes of organisms and modes of life. There is therefore emerging evidence that the effects which are now found to cover large areas of sea-bed could potentially have negative effect on fish.

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