Physico-chemical and biological features of a drilling site in the North Sea, 1 year after discharges of oil-contaminated drill cuttings

R. Daan[1], H. van het Groenewoud[2], S. A. de Jong[3], M. Mulder[1]

[1] Netherlands Institute for Sea Research, PO Box 59, 1790 AB, Texel, The Netherlands
[2] TNO Laboratory for Applied Marine Research, PO Box 57, 1780 AB, Den Helder, The Netherlands
[3] Dutch Ministry of Transport and Public Works, North Sea Directorate, PO Box 5807, 2280 HV Rijswijk, The Netherlands

ABSTRACT: In the framework of the Paris Convention for the prevention of marine pollution, the Dutch government initiated a research programme on environmental effects of discharges of contaminated drill cuttings from platforms in the North Sea. The programme has run since 1985 and includes field surveys at drilling sites in different parts of the Dutch sector. One of the locations investigated is the former drilling site F18.9, situated on the Oyster grounds. The (abandoned) location was visited in 1988, 1 y after the exploratory drilling ended. This paper gives a brief overview of the 1988 study at this discharge site, which was investigated again in 1990 as part of the Bremerhaven Workshop. Chemical analyses of the sediment over a transect in the residual current direction revealed a clear gradient in contamination levels, with oil concentrations ranging from 250 to 450 mg kg^{-1} dry sediment within 250 m and gradually decreasing to < 20 mg kg^{-1} beyond 750 m. Barium concentrations showed a similar pattern. Subtle biological effects, indicated by the absence of a very sensitive species (*Montacuta ferruginosa*), were found as far as 2 km from the discharge site. Abundance patterns of 2 other sensitive species (*Harpinia antennaria* and *Callianassa subterranea*) suggested environmental stress to occur up to 1 or 2 km. Within 750 m from the discharge site an increasing number of species, including the dominant *Amphiura filiformis*, appeared to decrease in abundance, successively resulting in a reduced total macrofauna abundance and species richness. Typical opportunistic species were observed more frequently only within a radius of 250 m. An alternative measure of diversity ('relative macrofauna abundance') was introduced and its merits are discussed. It is suggested that a combination should be used of community-based parameters (e.g. species richness, relative abundance) and species-based parameters (e.g. presence of opportunistic species, absence of susceptible species) to describe the impact of pollution. In this way 7 accumulating effects were distinguished. At contamination levels > 100 mg oil kg^{-1} dry sediment all defined effects occurred, whereas below 20 mg kg^{-1} the number of effects rapidly decreased.

INTRODUCTION

One of the locations investigated during the Bremerhaven Workshop was the former drilling site F18.9, situated in the Oyster grounds, in the Dutch sector of the Continental Shelf (54°06'09" N, 04°45'25" E). Location F18.9 was drilled in May 1987 and during the drilling activities large amounts of cuttings, contaminated with adhering drilling muds, were discharged to the seabed (Table 1). Among the muds used, a considerable part consisted of 'Oil Based Muds' (OBM). Hence, the discharges included the disposal of a few

hundred tonnes of oil and were therefore a significant point source of sediment pollution.

One reason for choosing the location F18.9 from numerous other drilling sites in the southern North Sea was that the location had already been investigated. In June 1988 (1 yr after the drilling activities had ceased and the platform was removed), a field survey was carried out at the location to detect the spatial distribution of contaminants around the discharge point and to assess their impact on the macrobenthic infauna. This study was performed in the framework of a research programme initiated by the Dutch Ministry of

Table 1. Amounts of mud and cuttings (tonnes dry weight) discharged during drilling of well F18.9. From a total of 5 sections, the first 2 were drilled with water based muds; the next 2 were drilled using a low toxicity base oil ($17\frac{1}{2}$" and $8\frac{3}{8}$" holes), the last section ($5\frac{7}{8}$") being a water-based mud again. Data provided by the company concerned

Substance	Amount
Minerals:	
Lime	8.5
Baryte	275
Bentonite	525
Polymers:	
Carboxymethylcellulose	25
Others	0.9
Salts:	
KCl	40
NaCl	4.5
CaCl$_2$	4.5
KI	
Base oil:	
Low toxic[a]	300
Emulsifier:	
Fatty acids based	6
Polyamide based	10
Viscosifier:	
Amine treated bentonite	8.5
Cuttings:	
Natural rock	2000
[a] Amount includes also oil in emulsifier	

Transport and Public Works (North Sea Directorate). The aim of this programme is to detect to what extent discharges of contaminated drill cuttings affect the composition and functioning of the natural benthic fauna, and how long such effects can be observed after termination of the drilling activities. The development and standardisation of suitable monitoring techniques was also part of the study. The results of the 1988 study on short-term effects at F18.9 are described in detail in reports on the chemistry by Groenewoud (1991) and on
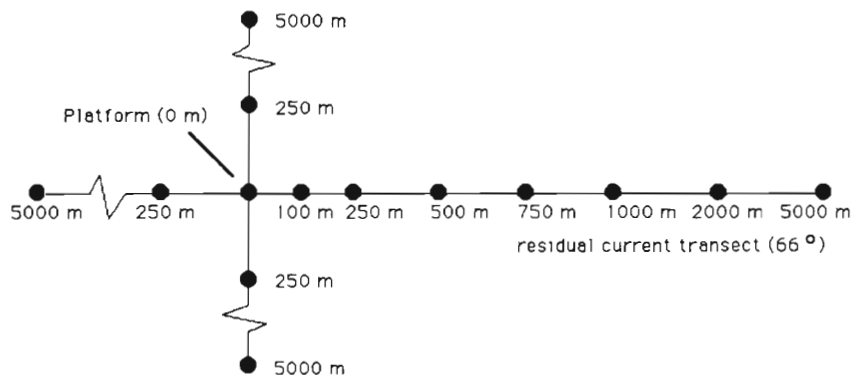
the biological effects by Daan et al. (1990). The present paper gives a brief overview of the 1988 study at F18.9.

METHODS

Positioning. Location F18.9 was abandoned after the explorative drillings were terminated in 1987 and the rig was not replaced by a production platform, so the discharge site had to be established using Decca positioning. As the RV 'Holland' is not equipped with a dynamic positioning system, the ship was anchored at each station before sampling started. Consequently the accuracy of position fixing was to within 50 to 200 m of the exact station positions. Because of this lack of precision in position finding the sampling stations may be considered as points along a continuum rather than as strictly defined sites.

Sampling. Around the discharge site a cross-shaped transect was sampled including four 250 m and four 5000 m stations. In the residual current direction ($\pm 66°$) another 6 stations were sampled (Fig. 1).

Eight 0.2 m^2 Van Veen grabs were taken at each sampling station. From each grab sample 2 small cores (28 mm, depth 10 cm) were taken for grain-size, oil and barium analyses. These samples were pooled and immediately frozen at -20 °C for later analysis. After subsampling for chemical analyses, the remaining sediment was sieved (mesh size 1 mm) and the residual macrofauna was preserved in a 6 % neutral formaldehyde solution.

Laboratory analyses. Oil analyses were performed using the gas chromatograph mass spectrometer technique. Concentrations of the fractions of alkanes (C$_9$ to C$_{30}$), unidentified complex matter (UCM) and 'other components' were quantified. The sum of these fractions is defined as the total oil concentration. Barium concentrations were determined by means of inductive coupled plasma-atomic-emission spectrometry. Methods are described in detail by Groenewoud (1991). Data on oil and barium concentrations are only available for 7 stations at the residual current transect.

The macrofauna samples were stained with Rose Bengal and sorted under a stereo microscope. Then, molluscs, crustaceans, polychaetes and echinoderms were identified and counted to species level. Remaining taxa were not further identified and only recorded at higher taxonomic levels.

Statistical procedures. Logit regression was used to detect significant gradients in the frequency of

Fig. 1. Positions of the sampled stations (distance to platform in m)

occurrence of individual species (see Jongman et al. 1987). The method is based on presence-absence data for species in individual samples. The analysis was done only for identified species for which at least 20 specimens were found.

A second statistical procedure was performed to determine the distance over which effects of pollution could be detected on the whole macrobenthic community. The method is based on the mean 'relative abundance' of all identified species at each station. Computation of the relative abundance is based on a ranking procedure. For each species the mean density is considered at each of the (n) analysed stations. A rank is attributed to each species for each station, i.e. the rank is 1 for the station with the lowest density and n for the station with the highest density. If any densities are equal, they are given the average of the tied ranks. When this procedure was completed for all species a mean rank was computed for each station. Differences in mean ranks were then tested for significance by analysis of variance.

RESULTS

Grain-size distribution

The sediment structure appeared to be quite homogeneous in the area. The sediment is fine, the silt fraction (grain-size < 63 μm) ranging from 15 to 20 % and the total fraction < 80 μm ranging from 40 to 50 %. The two 5000 m stations at the perpendicular transect were somewhat different in the sense that the fine sand fraction (80 to 125 μm) was reduced by 10 to 15 % in favour of the course sand fraction (> 125 μm).

Chemical characteristics

A clear gradient was found in barium content of the sediment beyond 250 m in the residual current direction, and oil concentrations showed roughly a similar
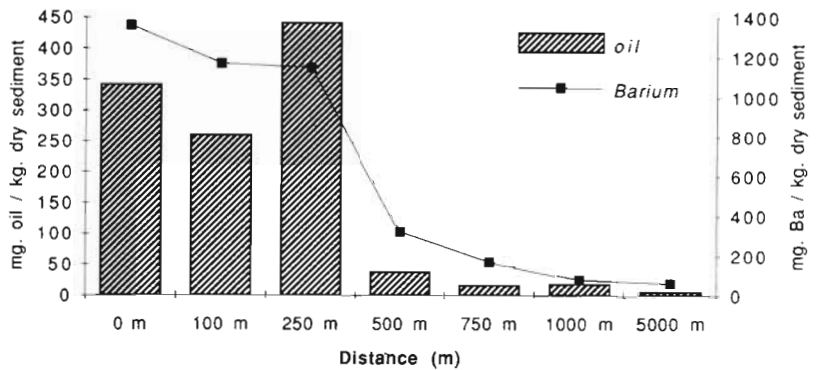

Fig. 2. Oil and barium concentrations of the sediment along the residual current transect
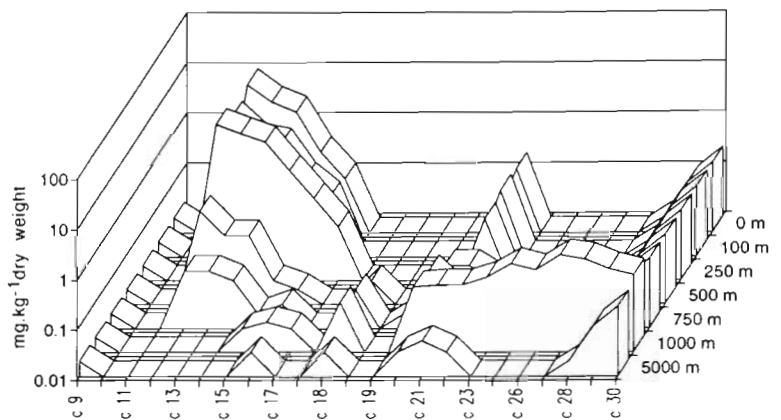

Fig. 3. Composition of alkanes (C_9 to C_{30}) of oil in the sediment along the residual current transect
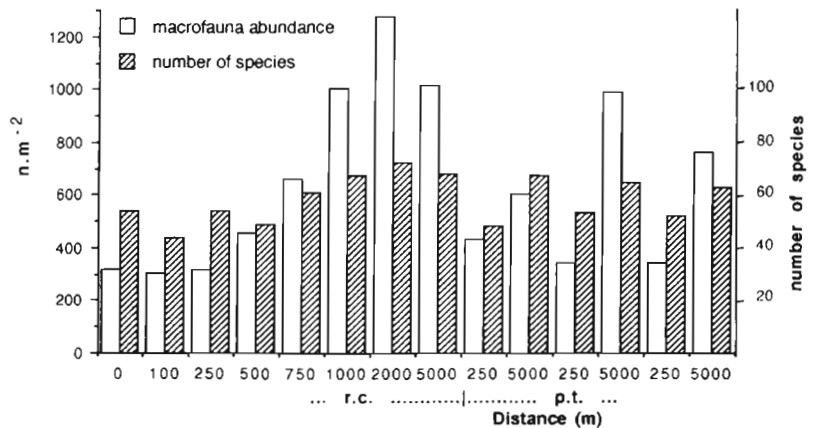

Fig. 4. Total macrofauna abundance and species richness along the residual current transect (r.c.) and perpendicular transects (p.t.)

trend (Fig. 2). Within 250 m the concentrations were more or less similar. A gradient within this radius was possibly masked by inaccurate positioning. Moreover, because of the lack of precision in position finding it is not known whether the marked difference of barium and oil concentrations between 250 m and 500 m is realistic. The actual distances between the stations
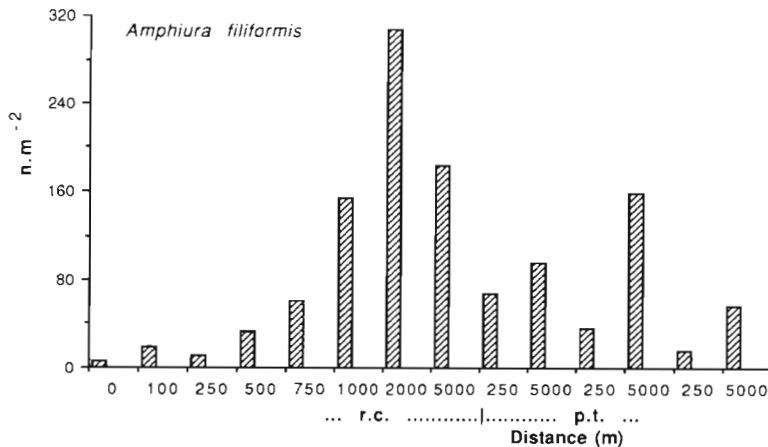
Fig. 5. *Amphiura filiformis*. Abundance pattern of the dominant species along the residual current (r.c.) and perpendicular (p.t.) transects
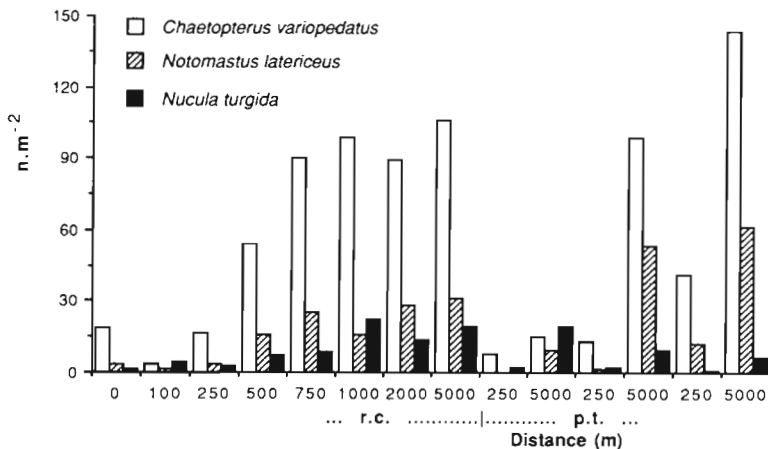

Fig. 6. Density patterns of 3 abundant species along the residual current (r.c.) and perpendicular (p.t.) transects
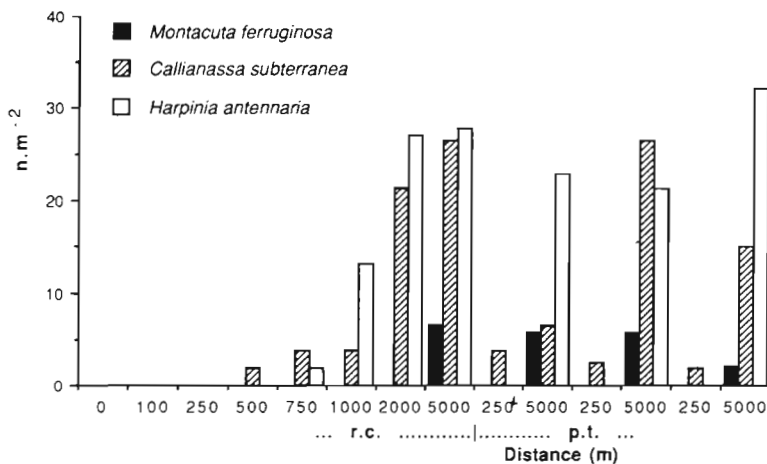

Fig. 7. Abundance patterns of 3 sensitive species along the residual current (r.c.) and perpendicular (p.t.) transects

may have been greater. The composition of the alkanes in the oil detected was quite consistent up to 750 m from the drilling site (Fig. 3). At the 1000 m station, the lack of short C-chains (C_{11} to C_{14}) and an unexpected peak of long C-chains (C_{19} to C_{30}) indicated the presence of oil not originating from the OBM discharged. Detailed data on physico-chemical features are presented by Groenewoud (1991).

Macrofauna composition

A total of 107 macrobenthos species were identified from 14 stations. The number of species found at each station varied between 44 and 72 (Fig. 4). At the residual current transect the numbers were low within 500 m (44 to 54) and tended to increase beyond 750 m (63 to 72). At the 750 m station the number was intermediate (61). Numbers of species found at the perpendicular transects indicated similar gradients in species richness.

The polychaete *Lumbrineris latreilli* and juvenile specimens of the echinoderm *Amphiura filiformis* dominated the macrofauna by number. Together they accounted for 10 to 40 % of the macrofauna in the area. The latter species in particular showed obvious lower densities within 750 m on each transect when compared to the densities at the corresponding 5000 m reference sites (Fig. 5). A similar trend was found in most other relatively abundant species (≥ 10 specimens m^{-2}). More than 50 % of the species declined in densities within 750 m from the platform. Examples of density patterns of 3 abundant species are shown in Fig. 6. Logit regression, applied to 46 species for which at least 20 specimens were found, confirmed that gradients in frequency of occurrence were significant (5 % level) in 21 species (Table 2). A few species (the crustaceans *Harpinia antennaria* and *Callianassa subterranea*) seemed to increase in abundance even beyond 1000 m, and the mollusc *Montacuta ferruginosa* was found in 50 % of the

Table 2. List of species showing a significant gradient in frequency of occurrence (logit regression). Sign of the gradient (+/−) and significance level are indicated. +: Increasing frequency away from the location; −: decreasing frequency away from the location

	Sign	Signif. level (%)
Harmothoe longisetis	+	0.5
Anaitides groenlandica	−	5
Glycinde nordmanni	+	5
Lumbrineris latreilli	+	5
Lumbrineris fragilis	+	1
Spiophanes bombyx	+	0.1
Chaetopterus variopedatus	+	0.5
Chaetozone setosa	+	0.5
Notomastus latericeus	+	0.1
Heteromastus filiformis	+	0.1
Owenia fusiformis	+	5
Nucula turgida	+	0.1
Montacuta ferruginosa	+	0.1
Mysella bidentata	+	1
Abra alba	+	5
Cingula nitida	+	5
Cylichna cylindracea	+	5
Callianassa subterranea	+	0.1
Diastylis bradyi	+	5
Harpinia antennaria	+	0.1
Amphiura filiformis	+	0.1
Echinocardium cordatum	+	5

samples at all 5000 m stations (Fig. 7). One species, the polychaete *Anaitides groenlandica*, showed an opposite trend and occurred in significantly higher densities within 250 m of the discharge point (Fig. 8). The same pattern was found in the polychaete *Capitella capitata*, but was not statistically significant as the number of specimens found was too small (14).

In accordance with the abundance patterns described above for most of the individual species, total macrofauna abundance was considerably lower at stations ≤ 500 m (300 to 450 ind. m^{-2}) than at stations ≥ 1000 m (600 to 1300 ind. m^{-2}). The 750 m station was intermediate (Fig. 4). Within 250 m no further gradual decrease to the 0 m station was observed.

The relative macrofauna abundance at the 14 stations sampled clearly illustrates the lower densities of most species at all stations ≤ 500 m from the discharge point (Fig. 9). Analysis of variance and an additionally applied Least Significant Difference test (LSD-test; Sokal & Rohlf 1981) revealed that the relative abundance was significantly lower at stations within 500 m than at stations ≥ 750 m from the discharge point.

Dose-effect relationships

So far, the biological features around F18.9 have been described in terms of gradual changes in faunal abundance along the sampled transect. Spatial gradients in abundance patterns (on species level or community level) may be implicitly assumed to represent an effect of the contaminated material discharged. It is in general not possible, however, to quantify such effects reliably, because of the natural variability in the abundance of species within the area investigated. We are compelled, therefore, to compare contamination levels (expressed as mg oil kg^{-1} dry sediment) and biological effects in a qualitative way. Although the effects that were identified are generally not independent of each other, accumulation of effects may serve as the most suitable response variable. Fig. 10 shows that the number of measurable effects increased with oil concentrations in the sediment. At contamination levels beyond 100 mg oil kg^{-1} dry sediment, all defined effects were consistently observed. At levels between 20 and 100 mg kg^{-1} most effects were observed, but opportunist species hardly seemed to increase in abundance. In some respects the effects at these concentrations were less severe than at concentrations higher than 100 mg kg^{-1}, e.g. the reduction in densities of dominant (*Amphiura filiformis*) and abundant species was less pronounced (Figs. 5 & 6). Below 20 mg kg^{-1} the number of effects rapidly decreased. Only some species that seemed to be particularly susceptible to the kind of pollution involved occurred in reduced numbers.

DISCUSSION

Numerous studies have shown biological effects due to discharges of OBM contaminated drill cuttings on
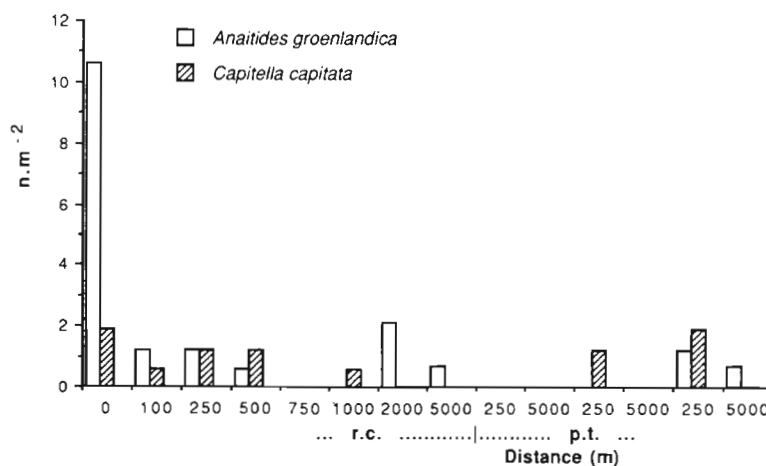

Fig. 8. Abundance patterns of 2 opportunistic species along the residual current (r.c.) and perpendicular (p.t.) transects
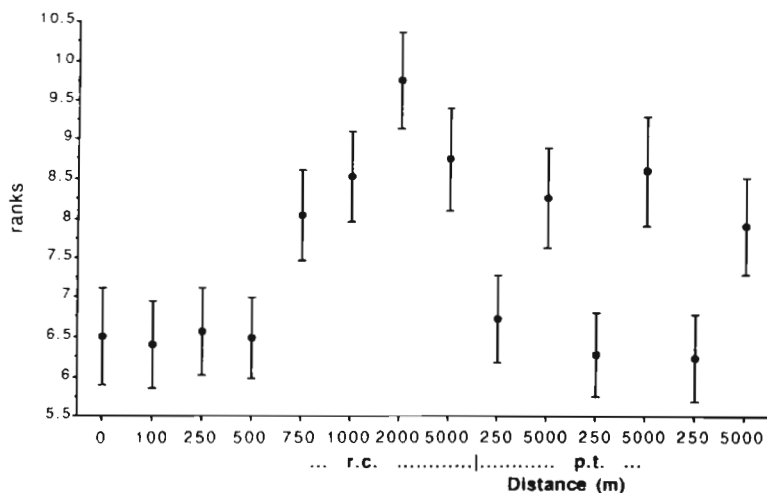
Fig. 9. Pattern of relative macrofauna abundance along the residual current (r.c.) and perpendicular (p.t.) transects. Centre points are mean ranks and vertical bars give 95 % confidence limits

the seabed. Field surveys at OBM drill sites in all sectors of the North Sea have revealed that such discharges affect the faunal composition of the sediment (e.g. Gray 1982, Addy et al. 1984, Davies et al. 1984, 1989, Matheson et al. 1986, Kingston 1987, Mulder et al. 1987, 1988, Reiersen et al. 1989, Daan et al. 1990, 1991, Gray et al. 1990).

The criteria used to decide whether biological effects of sediment pollution are demonstrable are numerous, varying from community-based parameters (e.g. species richness, diversity or equitability) to species-based

parameters (e.g. dominance of opportunistic species, absence of susceptible species). It is not only the use of different criteria, but also the differences in interpretation of data, that causes controversy concerning the extent of impact zones around drilling sites. For example, in the heavily polluted area around the Statfjord oil field (Norwegian sector), the maximal range of effects on the macrofauna was estimated as 500 to 1000 m in 1984 (Davies et al. 1984, Matheson et al. 1986, Kingston 1987), but in 1986 Reiersen et al. (1989) found a change in macrofauna out to 5000 m. Although additional discharges in the intervening years may have increased the area of environmental perturbation, this cannot explain completely the discrepancy between the 2 estimates. Differences of opinion about the interpretation of field data seem to play a major role.

It seems plausible that the intensity of effects will decrease with decreasing intensity of the stressor. This implies that the detection of effects will become more difficult and less reliably quantifiable as the distance to the point source of pollution increases. Therefore, it is advisable to use a combination of criteria to qualitatively assess the impact of pollution. Gray et al. (1990), who clearly demonstrated effects in terms of changed fauna composition up to 2000–3000 m from the Ekofisk
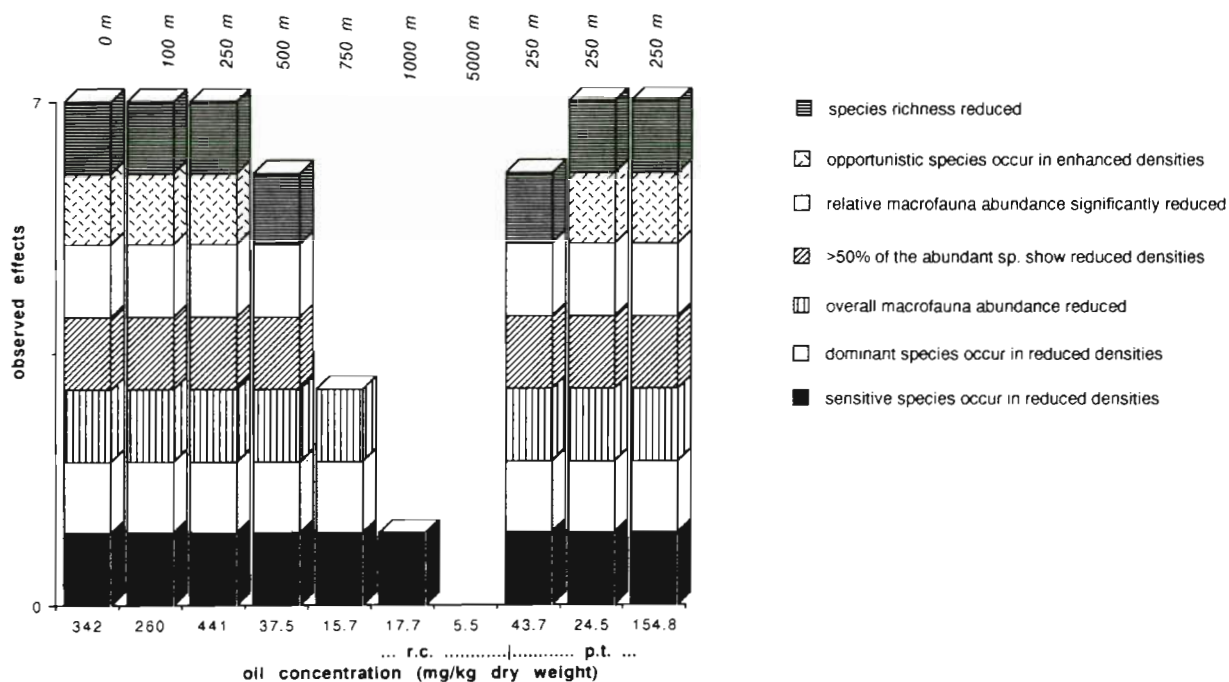

Fig. 10. Observed effects around F18.9 at different levels of sediment contamination

oil field, suggested that one of the initial effects of disturbance is the eradication of some 'rare' species. The authors did not explain why rare species should be more susceptible to disturbance than abundant species, but they may have assumed implicitly that rare species are generally living on the border of their ecological range and hence tolerate less additional stress. This indeed seems plausible, but it is questionable whether species that are found only a few times in samples should be considered rare in the true sense of the word. We believe that most species considered as 'rare' are only rare compared to other species, which are more or less abundant by nature. Nevertheless, our data support the idea that absence or reduced abundance of some susceptible species is the most sensitive indication of environmental stress. Up to 1000 m, at 16 mg oil kg^{-1} sediment, *Harpinia antennaria* and *Callianassa subterranea* were found in significantly reduced numbers and *Montacuta ferruginosa* was even absent out to 2000 m in the residual current direction, whereas it was found to be present at all 5000 m stations. There is, indeed, much evidence that species belonging to the genus *Montacuta* are extremely sensitive to the toxic effect of oil contamination. During 9 surveys of 4 other OBM locations in the Dutch sector *M. ferruginosa* was found to be consistently absent in the vicinity of platforms and in 4 cases the species was found exclusively or almost exclusively at ≥ 3000 m from the discharge site and furthermore in densities of ≥ 20 ind. m^{-2} (see Mulder et al. 1987, 1988, Daan et al. 1990, 1991). On the other hand, at 2 locations where only WBM (water based muds) were used, the species did not show any sign of a gradient in abundance pattern. The sensitivity of *Montacuta* is also supported by the data presented by Gray et al. (1990), who found *M. substriata* abundant at Ekofisk only outside a radius of 2 to 3 km, whereas it was absent within 500 m. At Eldfisk *M. substriata* was found only outside a radius of 1 to 2 km. If we consider oil contamination as a major stress factor affecting the distribution pattern of *Montacuta*, it is concluded that *M. ferruginosa* seems to suffer from environmental stress out to 2 km from the discharge point at F18.9 (residual current direction; Fig. 7).•

The abundance patterns of *Harpinia antennaria* and *Callianassa subterranea* too are not likely to be explained by accidental natural variation. During surveys at other drill sites in the Dutch sector, where these species occurred in densities sufficiently high to discern a pattern, *H. antennaria* decreased in density towards the platform at 5 OBM locations and exhibited no gradient at 2 WBM locations. *C. subterranea* showed decreasing densities towards the platform at 5 OBM locations and exhibited no gradient at 1 OBM and 1 WBM location (see Mulder et al. 1987, 1988, Daan et al. 1990,

1991). Hence, both species may be considered susceptible to oil contamination and, at F18.9, suffering from environmental stress up to 1 to 2 km from the discharge point (residual current direction; Fig. 7).

At the stations 750 m and 500 m from the drilling site an increasing number of species appeared to decline in abundance, including some species that were abundant (≥ 10 ind. m^{-2}) or even dominant by nature (*Amphiura filiformis*). As a result a gradual reduction could be observed in the total macrofauna abundance, relative abundance and species richness. No species were found that increased in density at the moderate contamination levels found in this zone. This was in contrast to the scenario outlined by Gray et al. (1990), who suggested that (moderate) disturbance could confer an advantage on some species, which can exploit the resource with reduced competition from less tolerant species and consequently increase in abundance. Indeed, their data show a dramatic increase in abundance of several species in the polluted area, e.g. the polychaete *Chaetozone setosa*. At F18.9 we found no such increase, but a decrease in abundance of this species. A possible explanation for these conflicting results may be that their data originate from locations where platforms are present. The presence of platforms keeps fisheries activities at a distance, which have adverse effects on some benthic species, and are thus beneficial to the local abundance of those species, when they are not extremely sensitive to OBM contamination. The observations of Levell et al. (1989) in the Thistle oil field (UK sector) and of Davies et al. (1984) in the Beatrice oil field (also UK sector) support this idea. Within 1000 m they found a dramatic increase of *C. setosa*, followed by a steep decline in the very close vicinity of the platform. At location K12a in the Dutch sector, where a platform is present, we found a similar abundance pattern of *C. setosa* during annual surveys between 1985 and 1988 (Mulder et al. 1987, 1988, Daan et al. 1990). The species always tended to increase abundance within 1000 m from the platform,

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•In this context it is worth noting that members of the genus *Montacuta* are commensals of echinoids (e.g. Gage 1966) and *M. ferruginosa* generally lives attached to the spines of *Echinocardium cordatum*. This may raise the question how the distribution of *E. cordatum* was related to that of *M. ferruginosa*. In the numerical abundance patterns of the 2 species was no clear relationship, but it seems plausible that the presence of *M. ferruginosa* depends on the presence of larger specimens of *E. cordatum*. Data on the size distribution of *E. cordatum* are not available, but if this is true, it is conceivable that *M. ferruginosa* might be indirectly indicative of sediment contamination and that, in fact, the absence of larger specimens of the host species is the direct response. This idea is supported by the results of experiments in mesocosms, where adult *E. cordatum* proved to be strongly sensitive to sediment contamination
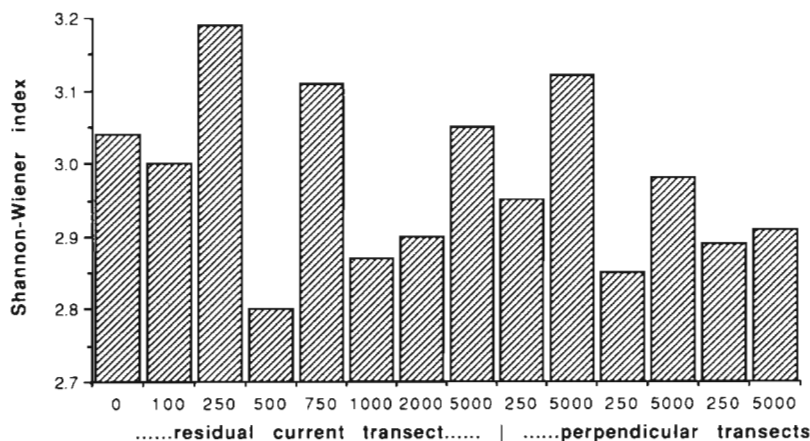
Fig. 11. Diversity at the residual current transect and at perpendicular transects: Shannon-Wiener index using $\log_e$-transformed data

but abruptly disappeared within 50 m, at contamination levels beyond 10 000 mg oil kg^{-1} dry sediment. At F18.9, however, where no platform is present, any positive effect of the absence of fishing activity is absent, and this possibly could explain why the abundance of this low-sensitive species gradually decreased with increasing contamination.

An increase in abundance of typical opportunists was only observed within 250 m. Two species (*Anaitides groenlandica* and *Capitella capitata*) were found almost exclusively within this area, however, without becoming dominant. *A. groenlandica* has been shown to thrive under enrichment by organic pollution (Pearson et al. 1983) and *C. capitata* is well known to be abundant under gross organic enrichment, including areas affected by oil pollution (e.g. Pearson & Rosenberg 1978, Gray 1982, Davies et al. 1984, Levell et al. 1989). Both species are relatively rare in undisturbed sediment and their more or less frequent occurrence within 250 m from the discharge site indicates pollution within this zone. This supports the statement that opportunistic species need not necessarily be abundant or even dominant to indicate environmental stress. The fact that the densities of *A. groenlandica* and *C. capitata* were only slightly enhanced at contamination levels of 250 to 450 mg oil kg^{-1} dry sediment suggests (in accordance with Gray et al. 1990) that colonisation by opportunists occurs late in the sequence of responses to stressors. Dominant occurrence of such species can only be expected under grossly polluted conditions around platforms where several wells have been drilled.

Traditional methods to quantify diversity were not used in this study. Commonly used indices like the Shannon-Wiener index and the Brillouin index have been shown to be very sensitive to the abundance of one dominant species (Mulder et al. 1988). The latter

authors calculated these indices for stations around drill site L4-a (also in the Dutch sector) and found a dramatic increase of diversity in the immediate vicinity of the platform due to the absence of the dominant species, *Amphiura filiformis*. When this species was excluded from the calculations no trend in diversity could be found. We used relative macrofauna abundance as an alternative measure of diversity. The method has several advantages although a handicap of the parameter may be that its attributed value is always relative and depends on the number of stations sampled. It provides an illustrative graphic presentation of an overall shift in fauna abundance and differences in mean relative abundance are statistically verifiable. Moreover, in contrast to traditional diversity indices, all species have an equal share in the computation of mean relative abundance. As a consequence, its attributed value is not disproportionally affected by the abundance of one species. In order to compare the sensitivity of the method with a usual measure of diversity we calculated Shannon-Wiener indices for the fauna at the stations around F18-9. The results (Fig. 11) illustrate that the index seems to fluctuate within a rather narrow range of 2.8 to 3.2 and does not show any pattern that is related to distance from platform or oil concentration (Fig. 2). Gray (1989) and Gray et al. (1990) concluded that a significant reduction in diversity may be a final response to stressors and should be expected only in a severely disturbed environment. We agree with their view, but we suggest that relative abundance may serve as a more sensitive measure of diversity than traditional indices.

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