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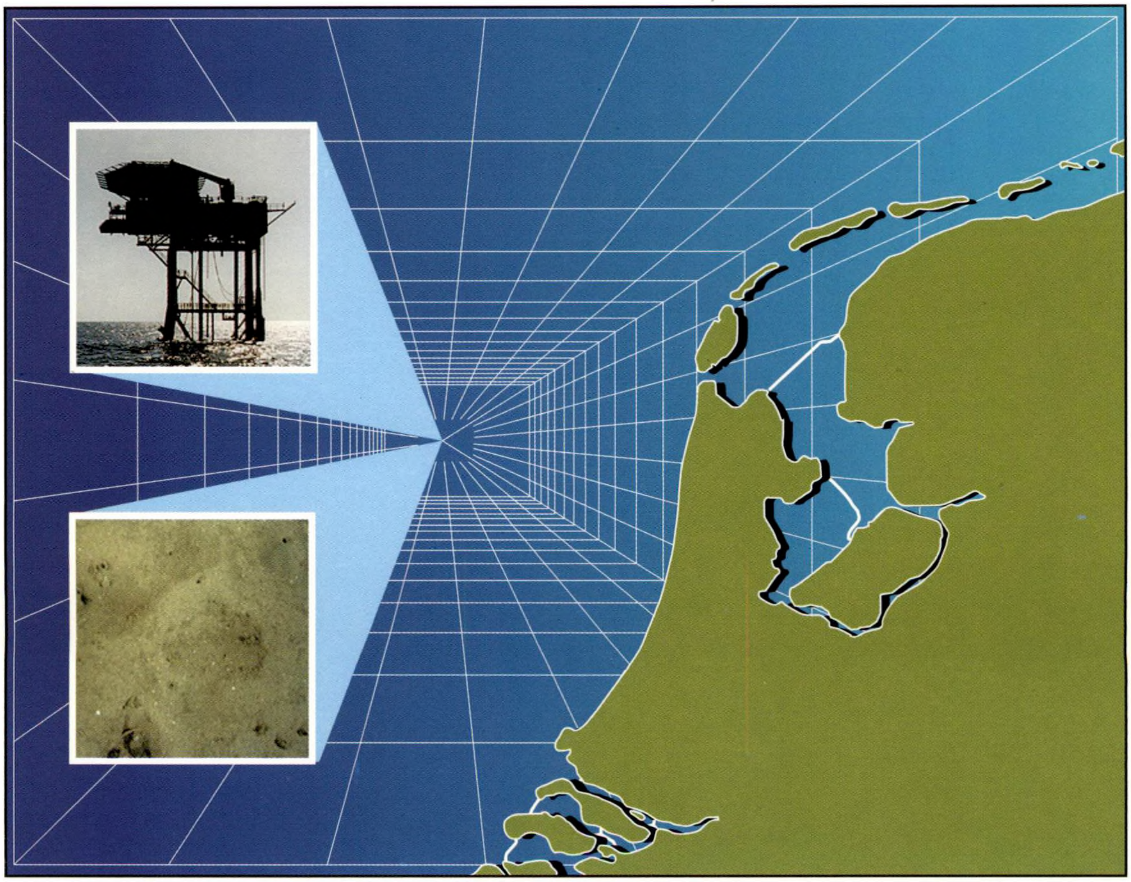

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LONG-TERM EFFECTS OF OBM CUTTING DISCHARGES IN THE SANDY EROSION AREA OF THE DUTCH CONTINENTAL SHELF

R. Daan, M. Mulder

This study was commissioned by
the North Sea Directorate (RWS)
and also carried out in the framework
of the Dutch collaboration programme
'Policy Linked Ecological Research North Sea and Wadden Sea' (BEON)

NETHERLANDS INSTITUTE FOR SEA RESEARCH

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SUMMARY AND CONCLUSIONS

During drilling activities in the North Sea there has been an extensive use of oil based drilling muds (OBM) in the 80's and early 90's. With the discharges of drill cuttings substantial amounts of oil reached the seabed in those years. Research on the environmental impact of these discharges, based on the assessment of effects on the benthic fauna community, has been carried out on the Dutch Continental Shelf since 1985. From 1993 there is a complete ban on dumping of OBM-contaminated cuttings. However, research on the long-term effects of former discharges and, in particular, on the spatial extent of these effects was continued to assess possible recovery of sediment quality and benthic fauna.

In 1993 a study was carried out at location P6b in the sandy erosion area in the southern part of the Dutch Continental Shelf. At platform P6b 4 wells had been drilled. The first well was drilled with OBM in 1985 and a first environmental survey was carried out in September 1985, 2 months after completion of the well. Later in 1985 and in 1986 2 more wells were drilled with water based muds (WBM) and the fourth well was drilled in 1987 using OBM again. This report presents the results of the 1993 survey, which took place 6 years after drilling of the last well.

Sediment sampling was mainly concentrated along a transect in the residual current direction of P6b. Sampling stations were chosen at distances ranging from 25 to 5000 m from the platform. Analyses included sediment grainsize characteristics, chemical analyses and faunistic descriptions. A few stations were also sampled in perpendicular directions, but only analysed for some physico-chemical characteristics and numbers of sea urchins (*Echinocardium cordatum*, specimens ≥15 mm).

In the residual current direction the chemical analyses revealed substantially elevated oil concentrations up to 100 m from the platform, but traces of oil were visually observed up to 250 m. Concentrations of Ba were above background level up to 250 m too. At 100 m elevated concentrations of oil and Ba were found to a depth of at least 20 cm in the sediment. There hardly seems to be any degradation of oil in the deeper anaerobic sediment layers. At distances ≥500 m and at stations in perpendicular directions at distances ≥250 m no traces were found of the former discharges.

Very close to the platform (at 25 m) oil and Ba concentrations were somewhat elevated, but lower than at 100 m. A depression in the seabed at this station and the presence of large amounts of old shell fragments indicated that the sandy top layer had been removed by increased turbulence and erosion of the seabed around the platform legs. Increased erosion might also have resulted in transport of discharged material away from the platform.

In the benthic macrofauna composition an accumulation of effects was found at 100 m and 250 m (residual current direction). At these stations the fauna was considerably impoverished. At 500 m only the absence of adult *E. cordatum* indicated a long-term effect of the former discharges. In fact the absence of *E. cordatum* at this station should probably be considered as the long-term consequence of a short-term effect (*i.e.* extermination of the species due to OBM contamination of the sediment in the period immediately after drilling) and not as an actual effect of contamination at the long term, since the source of disturbance could no longer be demonstrated.

In view of the gradient observed between 100 and 500 m, the fauna composition at 25 m from the platform was anomalous. At this station an unexpectedly high number of taxa was found and, in fact, only the absence of some OBM sensitive species was indicative of an environmental effect. However, the species composition was different from that at all other stations, probably due to the anomalous sediment conditions at this station.

The recovery potential of the macrofauna is discussed with special reference to the life cycle of the sensitive indicator species *E. cordatum*. Based on this discussion it is suggested to plan a follow-up survey at P6b in 1997.

The results and conclusions of this study may be summarized as follows:

1. Elevated oil concentrations (up to 300 $mg{\cdot}kg^{-1}$ dry sediment) were found up to 100 m (residual current direction) from the platform. At 250 m the chemical analyses did not show elevated concentrations, but traces of oil were visually observed during the fieldwork. Elevated Ba concentrations confirmed the presence of discharged material at this station.

2. At 100 m oil was found to a depth of at least 20 cm in the sediment. At 250 m Ba concentrations were highest in the upper 10 cm, but also at 15-20 cm the concentrations were substantially elevated, indicating that much of the discharged material is stored in the deeper sediment layers.

3. In the residual current direction no traces of discharged material were observed at distances ≥500 m. In perpendicular directions no traces were found at distances ≥250 m.

4. An accumulation of biological effects was found at 100 m and 250 m (res. curr. direction) from the platform. The fauna was substantially impoverished at these stations, even at relatively low oil concentrations (250 m).

5. Adult *Echinocardium cordatum* were absent up to 500 m from the platform.

6. At 25 m from the platform the fauna composition was different from all other stations, but not really impoverished. It is suggested that increased turbulence around the platform legs may have caused increased erosion of the seabed so that old banks of shells and shell fragments were uncovered, which were colonized by a macrofauna community with a different composition.

7. Based on the above findings it is concluded that environmental effects around an OBM location in the erosion area of the Dutch Continental Shelf were still detectable 6 years after termination of the discharges of OBM contaminated drill cuttings.

SAMENVATTING EN CONCLUSIES

In de 80-er jaren werd op de Noordzee bij olie- en gasboringen veelal oliehoudende boorspoeling (OBM) gebruikt. Restanten daarvan werden met het opgeboorde gruis op de zeebodem geloosd. Sedert 1985 wordt op het Nederlands Continentaal Plat onderzoek verricht naar de milieueffekten van deze lozingen, in het bijzonder naar de effekten op het benthische systeem rond de lokaties waar deze spoelingen zijn gebruikt. Met ingang van 1993 is een volledig verbod ingevoerd op het lozen van oliehoudend boorgruis op het NCP. Het onderzoek naar lange-termijn effekten, en met name naar de ruimtelijke omvang daarvan, gaat echter door om een mogelijk herstel van sedimentcondities en bodemfauna vast te stellen.

In 1993 is een veldonderzoek uitgevoerd bij lokatie P6b in het zandige erosiegebied in het zuidelijke deel van het Nederlands Continentaal Plat. Op lokatie P6b zijn in totaal 4 boringen verricht. De eerste boring vond plaats in 1985 en werd uitgevoerd met OBM. Een eerste veldsurvey werd in september van hetzelfde jaar uitgevoerd, 2 maanden na de boring. Later in dat jaar en in 1986 werden nog eens 2 boringen verricht, nu met gebruikmaking van uitsluitend boorspoeling op waterbasis (WBM). De laatste boring vond plaats in 1987 en hierbij werd weer gebruik gemaakt van OBM. In dit rapport worden de resultaten van de in 1993 uitgevoerde survey gepresenteerd, die 6 jaar na de laatste lozing plaatsvond.

Bodembemonstering was in hoofdzaak geconcentreerd op een aantal stations langs een raai in de reststroomrichting van P6b. De stations werden gekozen op afstanden variërend van 25 tot 5000 m van het platform. De bodemmonsters werden geanalyseerd op korrelgrootte-samenstelling, olie- en Bariumconcentraties en makrofaunasamenstelling. In dwarsstroomse en tegenstroomse richting werden ook enkele stations bemonsterd. Van deze monsters vond slechts een beperkte fysisch-chemische analyse plaats en werden alleen de aantallen zee-egels (*Echinocardium cordatum*, exemplaren ≥15 mm) in het veld geteld.

Uit de chemische analyses bleken in de reststroomrichting verhoogde olieconcentraties voor te komen tot op 100 m van het platform, maar tijdens het veldwerk waren ook oliesporen te zien op 250 m. Barium-concentraties op dit station waren ook hoger dan natuurlijke achtergrondwaarden. Op 100 m werden verhoogde olie- en Ba-concentraties vastgesteld tot op minstens 20 cm diep in het sediment. In de diepere anaerobe sedimentlagen lijkt nauwelijks afbraak van olie plaats te vinden. In de reststroomrichting werden vanaf 500 m geen restanten van geloosd materiaal meer aangetroffen, in andere richtingen al niet meer vanaf 250 m.

Vlak bij het platform (op 25 m) werden weliswaar enigszins verhoogde olie- en Ba-concentraties gevonden, maar deze waren lager dan op 100 m. Op dit station bleek een soort uitholling in de zeebodem voor te komen en de aanwezigheid van grote hoeveelheden oud schelpengruis in de monsters doet vermoeden dat de zandige toplaag hier is verdwenen, kennelijk als gevolg van turbulente stromingen rond de poten van het platform, waardoor de zeebodem ter plaatse sterk kan zijn geërodeerd. Deze plaatselijk toegenomen erosie kan ook tot gevolg hebben gehad dat geloosd materiaal uit de direkte omgeving van het platform weg is gespoeld.

Aan de hand van de samenstelling van de benthische fauna kon een accumulatie van effekten worden vastgesteld op zowel 100 m als 250 m (reststroomrichting). De fauna was hier aanmerkelijk verarmd. Op 500 m wees alleen nog het ontbreken van volwassen *E. cordatum* op een lange-termijn effekt van de vroegere lozingen. De afwezigheid van *E. cordatum* op dit station moet echter gezien worden als een gevolg op de langere termijn van een vroeger opgetreden effekt, nl. sterfte onder deze soort als gevolg van verontreiniging van het sediment met OBM. Van een latent optredend effekt lijkt geen sprake, aangezien de aanwezigheid van de bron van verstoring (OBM) op dit station niet meer kon worden aangetoond.

Gezien de duidelijke gradient die tussen 100 en 500 m in de faunasamenstelling werd waargenomen, was te verwachten geweest dat het 25 m station een wellicht nog armere macrofauna te zien zou hebben gegeven. De faunasamenstelling was hier echter wel sterk afwijkend, maar niet bij uitstek arm. In feite werd zelfs een onverwacht groot aantal taxa aangetroffen en was alleen het ontbreken van enkele zeer gevoelige soorten indicatief voor een effekt van de lozingen. Kennelijk heeft de afwijkende bodemsamenstelling ter plaatse geleid tot een specifieke habitat die door een fauna met een afwijkende samenstelling is gekoloniseerd.

De mogelijkheden voor herstel van de bodemfauna en de snelheid daarvan (met name op enige honderden meters afstand) zijn bediscussieerd, met name aan de hand van de levenscyclus van de gevoelige indicatorsoort *E. cordatum*. Op basis van deze discussie wordt aanbevolen een eventuele vervolgsurvey bij P6b rond 1997 uit te voeren.

De resultaten en conclusies kunnen als volgt worden samengevat:

1. Verhoogde olieconcentraties (tot 300 mg·kg^{-1} droog sediment) werden aangetroffen tot op 100 m (reststroomrichting) van het platform. Op 250 m toonden de chemische analyses geen olie aan, hoewel tijdens het veldwerk in een aantal monsters wel degelijk oliesporen werden waargenomen. Verhoogde Ba-concentraties bevestigden dat op dit station nog steeds restanten van het geloosde materiaal aanwezig waren.

2. Op 100 m van het platform (reststroomrichting)

werd olie in het sediment aangetroffen tot op tenminste 20 cm diep. Op 250 m waren Ba-concentraties het hoogst in de bovenste 10 cm van het sediment, maar ook op 15-20 cm werden nog aanmerkelijk verhoogde concentraties aangetroffen, hetgeen er op duidt dat een belangrijk deel van het geloosde materiaal nog aanwezig is in diepere sedimentlagen.

3. In de reststroomrichting werden vanaf 500 m van het platform geen olie of andere restanten van geloosd materiaal aangetroffen. In tegengestelde en dwarsstroomse richtingen was dit al vanaf 250 m het geval.

4. Een accumulatie van biologische effekten werd aangetroffen op zowel 100 m als 250 m van het platform. Op deze stations was sprake van een sterk verarmde macrofauna en dat met name op 250 m bij relatief lage olieconcentraties.

5. Grote *Echinocardium cordatum* ontbraken tot op 500 m van het platform.

6. Op 25 m van het platform werd een fauna-samenstelling aangetroffen die sterk afwijkend was van die van alle overige stations, maar niet bij uitstek arm. Mogelijk zijn turbulente stromingen rond de poten van het platform er de oorzaak van geweest dat hier een holte in de zeebodem is uitgeschuurd, waardoor dieper gelegen banken van schelpengruis bloot zijn komen liggen, die door een fauna met een afwijkende samenstelling is gekoloniseerd.

7. Op basis van bovengenoemde resultaten kan geconcludeerd worden dat zes jaar na een OBM-boring in de erosiezone van het Nederlands Continentaal Plat milieueffekten van lozingen van met OBM verontreinigd boorgruis rond de betreffende lokatie nog steeds konden worden aangetoond.

1 INTRODUCTION

1.1 GENERAL PART

Oil based drilling muds (OBM) have been extensively used during drilling activities in the North Sea in the 80's and the early 90's. Although drill cuttings from the wells bored generally passed one or more treatment facilities to separate mud from the cuttings before these were discharged, there were always substantial amounts of adhering residuals of base oil that reached the seabed in this way. Concern about the environmental risk of these dumpings has led to benthic monitoring studies in all North Sea sectors. OBM are still in use but the extent of discharges has considerably decreased. Due to agreements between industry and national authorities or to national regulations, there are no longer discharges of OBM cuttings in the Norwegian, Danish, German and Dutch sectors since 1 January 1993 (ANONYMOUS, 1994). When wells are drilled with OBM at installations in these sectors, the drill cuttings are brought ashore for treatment and disposal. Only in the UK sector dumping of OBM cuttings is still going on, but various systems were developed to reduce the oil content of the material dumped. Cuttings are treated down to an oil content of 5-6% now before being discharged (ANONYMOUS, 1994).

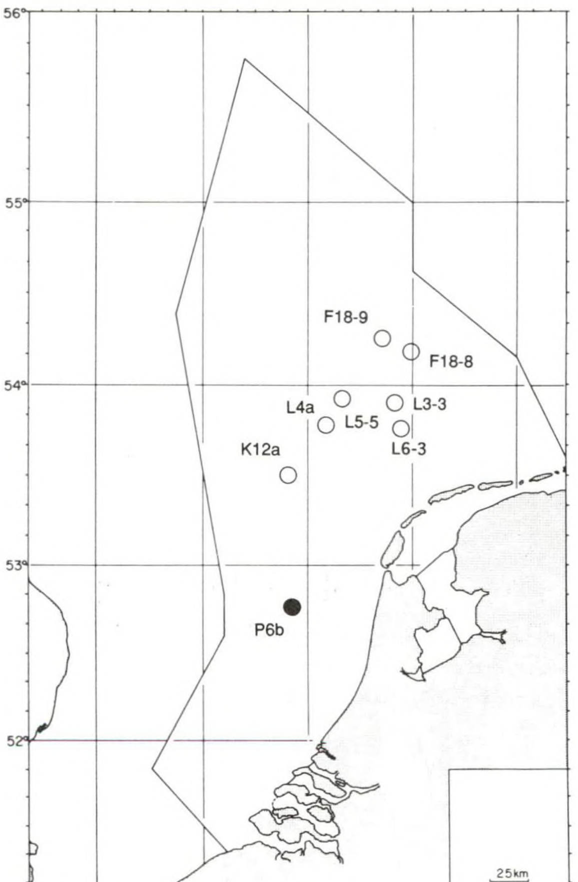

Fig. 1. Position of platform P6b. Open circles are drilling locations investigated in previous studies. Solid line: border of the Dutch part of the Continental Shelf.

With the termination of OBM cutting discharges, further investigations on the associated short-term effects have come to an end in the Dutch sector. However, in view of possible future clean-up measures for the seabed around abandoned well sites, the long-term effect of OBM cutting discharges is still subject of interest.

The Dutch sector can be roughly subdivided in a sandy erosion area in the south, an area of net sedimentation in the north and an intermediate transition zone in between. A frequent monitoring programme has been running since 1985 at location K12a in the transition zone. The last field survey at this location was carried out in 1992, 8 years after dumping of OBM cuttings (DAAN & MULDER, 1993). The results of this long-term study indicated that there was a decrease in the spatial extent of environmental effects, with clear signs of recovery of sediment conditions and macrofauna at 500 m from the platform and beyond that distance. However, closer to the platform elevated oil concentrations were still observed, particularly in the deeper sediment layers. Biological effects could still be identified and at 100 m from the platform an accumulation of effects became manifest by a severely impoverished benthic macrofauna. Up to now, data on long-term effects are lacking from locations in the erosion area and the sedimentation area. Because of the hydrographical differences in the three areas, it is conceivable that there may be also differences in (re-)distribution and degradation rates of oil in the sediments and in the persistence of associated effects on the benthic infauna. Therefore, the attention has moved to long-term studies in these areas to estimate the extent of oil contaminated areas around former OBM discharge sites and to assess the degree of biological deterioration, *c.q.* of possible recovery of the benthic macrofauna communities. This report presents the results of a study at location P6b in the erosion area, six years after the last OBM cuttings were dumped at this location.

Platform P6b is situated in the southern part of the Dutch sector, in ±30 m waterdepth (Fig. 1). The sediment consists of fine and coarse sand, whereas the silt fraction (<63 μm) is less than 1% (KUIPER & GROENEWOUD, 1986). At P6b four wells have been drilled, two of them with OBM based on low-tox oil (Table 1). All drill cuttings were discharged on the seabed. Fig. 1 shows also the other locations that have been studied in preceding years.

A first field survey, aimed to assess short-term effects, has been carried out already in September 1985, two months after completion of the first well.

TABLE 1
Information on drilling location P6b.

Position	52°44'17" N 03°48'18" E
Area	Erosion zone; fine and coarse sand; Silt<1%; depth appr. 30 m.
Drilling activities	June 1985- OBM drilling Oct. 1985 - WBM drilling Jan. 1986 - WBM drilling Aug. 1987 - OBM drilling
Emission 1st OBM drilling 2nd OBM drilling	184 tonnes of low-tox oil 104 tonnes of low-tox oil
Platform	Present

Former effect study: Survey Sept. 1985 (Mulder *et al.*, 1987; Kuiper & Groenewoud, 1986).

The chemical sediment analyses of that survey revealed high oil concentrations in the sediment up to 250 m from the platform (residual current direction) and slightly elevated concentrations up to 1000 m (KUIPER & GROENEWOUD, 1986). Biological effects, in terms of reduced species richness and macrofauna abundance, were detectable up to 750 m (MULDER *et al.*, 1987). However, the abundance patterns of the sea urchin *Echinocardium cordatum* and the bivalve *Montacuta ferruginosa*, two species that later have been shown to be very sensitive to OBM contamination, indicated that there were effects up to >1000 m.

The present survey was carried out in August 1993, *i.e.* eight years after the first survey and six years after the last discharge of OBM cuttings. The results of this survey will be compared with those of the first survey of 1985.

1.2 ACKNOWLEDGEMENTS

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Dr. W. Zevenboom (RWS, North Sea Directorate), chairwoman
Drs. J. Asjes (RWS, North Sea Directorate), secretary
Ing. M. de Krieger (RWS, North Sea Directorate)

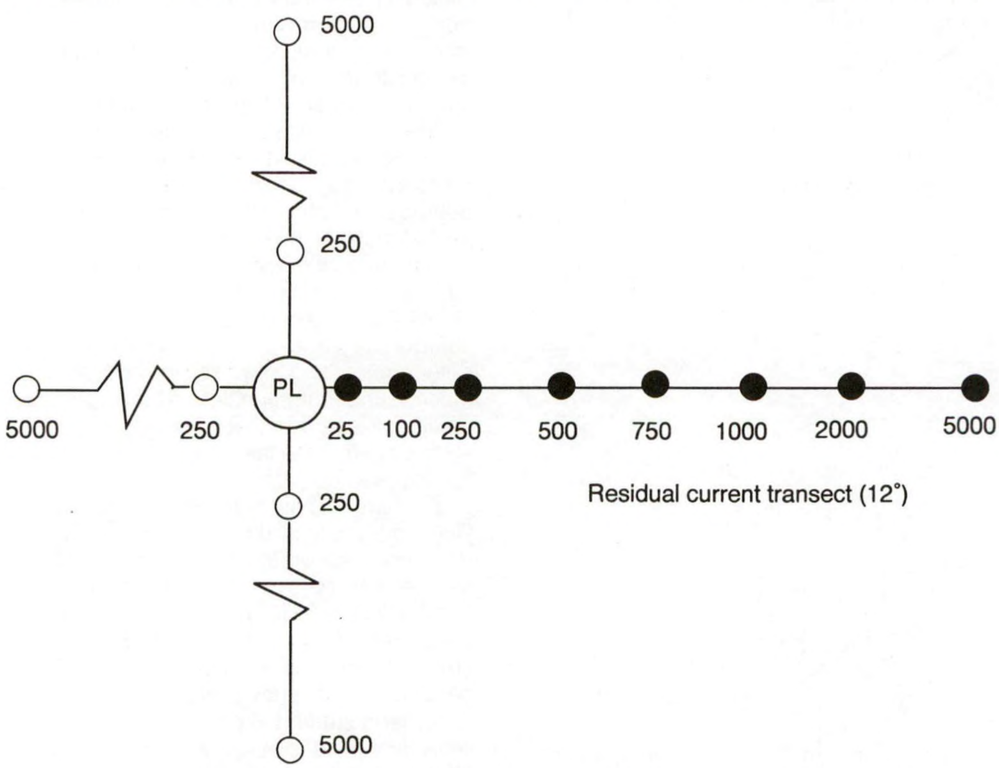

Fig. 2. Positions of the sampling stations along a cross-shaped transect. Solid circles: samples analysed for macrofauna.

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2 METHODS

2.1 SAMPLING

The survey at P6b was carried out in the 3rd week of August 1993. Sampling stations were chosen along a cross-shaped transect, the main axis running parallel to the residual current direction (Fig. 2). The 100-m and 250-m stations in the residual current direction were approached twice and both times 5 grab samples (Van Veen grab, 0.2 m^2) were collected. At each of the other stations 10 samples were collected. From each sample small duplicate sediment cores (diameter 28 mm, depth 10 cm) were taken for chemical and grainsize analyses. The pooled sediment subsamples of each station were thoroughly homogenised and immediately frozen at -20° until later analysis in the laboratory. The contents of the grab were washed through a sieve (mesh size 1 mm). During sieving the numbers of *Echinocardium cordatum* (specimens ≥15 mm) were counted in 8 samples at each station. The remaining macrofauna was preserved in a 6% neutralized formaldehyde solution.

At the 100-m station an additional boxcore sample was collected to assess vertical profiles of oil and Ba concentrations in the sediment. Subsamples were taken from the sediment layers 0-2 cm, 2-10 cm and 25-30 cm and further treated in the same way as the routine sediment samples.

2.2 LABORATORY ANALYSES

In fact, field samples were collected in excess and not all samples were analysed. Table 2 gives an overview of the analyses that were applied to the samples of each station.

2.2.1 GRAINSIZE ANALYSIS

Grainsize analyses were performed to verify if the natural sediment composition is more or less homogeneous in the area investigated. The analytical procedures are described in detail by GROENEWOUD & SCHOLTEN (1992a).

2.2.2 BARIUM ANALYSIS

Barite is a substantial constituent of drilling muds. Because of its inertia Barite provides a good indicator for the dispersal of discharged material, in particular of the smaller grain size fractions. Concentrations of Ba in the sediment were determined as follows:

About 10 grammes of sediment were dried for 2

TABLE 2

Schedule of analyses of the samples collected at P6b.Grainsize = analysis of grainsize distribution. Oil concentration = analysis of oil concentration in the sediment. Ba concentration = analysis of Ba concentration in the sediment. *E. cordatum* = on board countings of *Echinocardium cordatum*, specimens >15 mm. Fauna analyses = complete fauna analyses (6 samples per station).

Station		*Grainsize*	*Oil concentration*	*Ba concentration*	*Vert. profiles*	*E. cordatum*	*Fauna analyses*
Transect	*Distance*						
12°	25 m	X	X	X		X	X
	100 m	2X	2X	2X	X	X	X
	250 m	2X	2X	2X		X	X
	500 m	X	X	X		X	X
	750 m	X		X		X	X
	1000 m	X		X		X	X
	2000 m	X				X	X
	5000 m	X		X		X	X
102°	250 m			X		X	
	5000 m			X		X	
192°	250 m			X		X	
	5000 m			X		X	
282°	250 m			X		X	
	5000 m			X		X	

hours at 105°C. Then 2 grammes were homogenized and destructed by means of sulphuric acid and hydrogen peroxide. After settling, the barium content of the destruate was determined using inductive coupled plasma atomic emission spectrometry (ICP-AES).

2.2.3 OIL ANALYSIS

Oil analyses of sediment samples were performed using the gas chromatograph mass spectrometer (GCMS) technique. Concentrations of alkanes (C_{10} - C_{30}), unidentified complex matter (UCM) and 'other components' were quantified. The analytical procedures are described in detail by GROENEWOUD & SCHOLTEN (1992a).

2.2.4 FAUNA ANALYSIS

Macrofauna analyses were performed on 6 samples of each of 8 stations at the residual current transect. Routine methods of sorting and identification are described by MULDER *et al.* (1988).

2.2.5 STATISTICAL PROCEDURES

Possible shifts in the macrofauna community were tested by comparing the relative abundance of all identified species at each of the stations (ANOVA). This method is also described in detail by DAAN *et al.* (1990).

Possible gradients in the distribution patterns of individual species were tested by logit regression (see *e.g.* JONGMAN *et al.*, 1987). The regression was applied to those species of which at least 20 specimens were found. The method was also used in former studies and more details about its application are given in DAAN *et al.* (1990). However, a fundamental improvement was introduced compared to the procedure applied in former studies. Details of the complete procedure as performed now are given in the appendix, but the principles are shortly outlined here.

In fact, the usual procedure provides a test of the Hypothesis H_0 that the probability (π) of a species being present in a sample does not depend on distance to the platform against the alternative hypothesis H_1 that there is a systematic increase or decrease of p with increasing distance from the platform. In other words model (0):

$$\text{logit}(\pi) = \ln(\pi/1-\pi) = \exp(b_0) \quad (1)$$

is tested against model (1):

$$\text{logit}(\pi) = \ln(\pi/1-\pi) = \exp(b_0+b_1{*}d) \quad (2)$$

where d is distance to platform and b_0 and b_1 are model parameters.

For both models the model parameters are estimated according to the maximum likelihood principle,

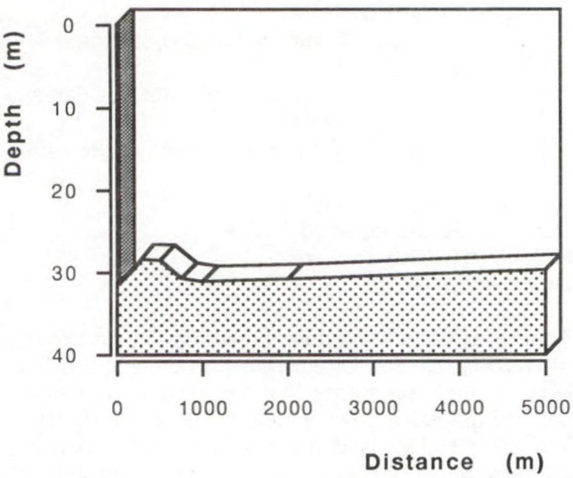

Fig. 3. Depth profile along the residual current transect (uncorrected for tidal differences).

following an iterative procedure. The goodness of fit of both models can now be compared on the basis of their log-likelihood. If the difference in log-likelihood of model (1) and model (0) exceeds a certain critical value H_0 is rejected in favour of H_1 and it is decided that the frequency of occurrence of the species significantly depends on distance to platform.

This was the primary procedure and is performed here too. However, acceptance of H_1 does not necessarily mean that Model (1) gives a perfect fit. There still may be a considerable deviation of the observed values and the fitted values. This may be due to overdispersion in the data, *i.e.* the assumption of binomial variance is unrealistic and the variance in the data is greater than predicted by the binomial model (MCCULLAGH & NELDER, 1983). Therefore model (1) is further tested against the full model:

$$\text{logit}(\pi) = \ln(\pi/1-\pi) = \exp(b_i)$$

where b_i is directly estimated from the relative frequency of occurrence of the species at the i^{th} station.

When the difference in log-likelihood between the full Model and Model (1) is large this may be reason to decide that a possible significant gradient in frequency of occurrence as established by the first test is due to over-dispersion in the data.

3 RESULTS

3.1 SEABED CHARACTERISTICS

Depth recordings (uncorrected for tidally induced differences) showed that there was a depression in the seabed within 100 m of the platform, followed by an elevation at 100-250 m (Fig. 3). The depression might have been caused by erosion due to turbulent currents around the platform legs. At the 25 m station the

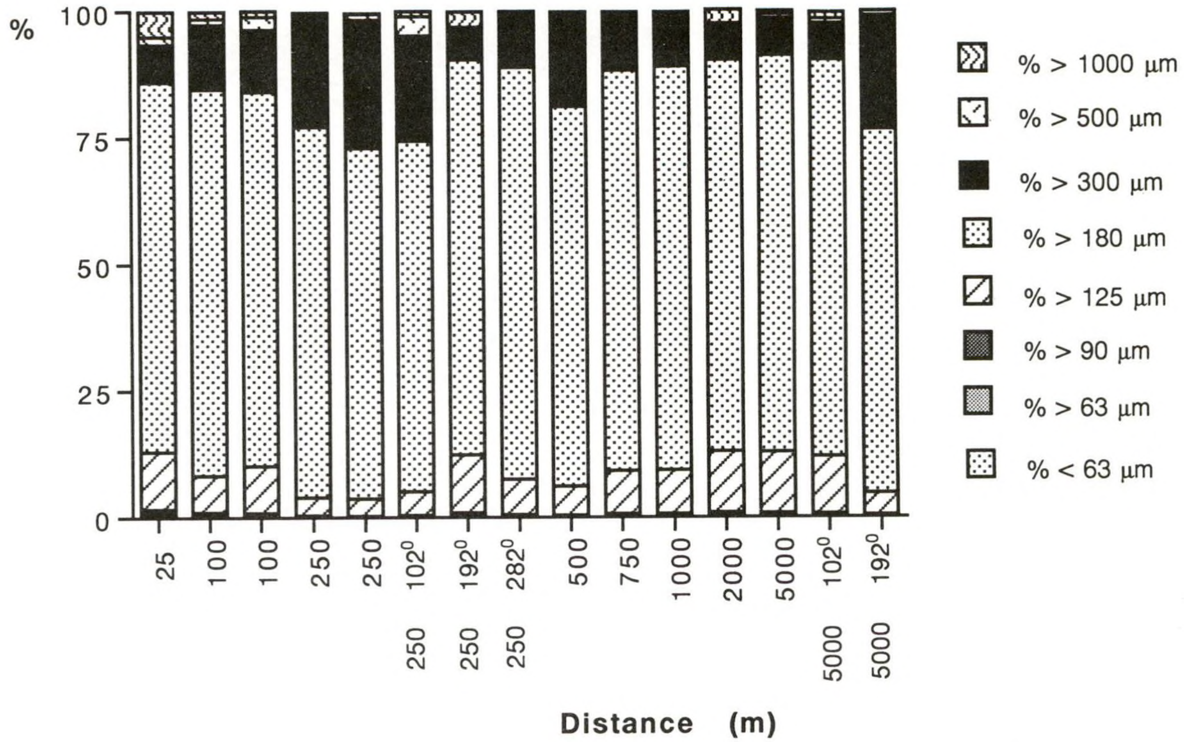

Fig. 4. Grainsize distribution along the residual current transect (data from GROENEWOUD, 1994). The size fractions 63-90 mm and < 63 mm are not visible, because they were extremely low. For details see Table 9.

samples contained large amounts of shell fragments, most remnants of old *Donax* and *Spisula* banks, but also shells of *Mytilus edulis*. The latter must have been living attached to the legs of the platform, since this species does not occur on the seabed by nature in this area. It is conceivable that erosion has removed the finer material of the superficial sediment layers and that, as a result, deeper layers containing much old shells were uncovered.

The sediment along the residual current transect consisted mainly of fine to coarse sand (Fig. 4). The grainsize fraction 180-300 µm contributed 70-80%. Coarser material (grainsize >300 µm) was consistently present in all samples and contributed 10-25%. Particularly at 250 m the coarse fraction was relatively large. Very coarse material (>1000 µm) was found in the vicinity of the platform and at 2000 m. This material consisted probably of shell grit. The silt fraction (<63 mm) was far below 1% at all stations and does not appear therefore in the figure. However, the data listed in Table 9 show that the silt fraction was somewhat elevated at 25 m and 100 m compared to the other stations.

3.2 BARIUM CONCENTRATIONS IN THE SEDIMENT

The Ba concentrations in the sediment around the platform are listed in Table 3. Interpretation of the data should take into account that Ba is usually present in the sediment in low background concentrations. GROENEWOUD & SCHOLTEN (1992) have shown that the natural background concentrations are strongly related to the silt (fraction <63 µm) content of the sediment. Because the sediment at P6b is deficient in silt, the natural Ba concentration may be expected to be very low. The mean background concentration at silt concentrations <1% can be estimated from a plot of Ba against silt given in Fig. 2 of DAAN & MULDER (1993). This concentration will be in the order of 17 $mg \cdot kg^{-1}$ dry sediment and not exceed

TABLE 3

Ba concentrations in the sediment around P6b (data from Groenewoud, 1994).

Station	*Ba mg/kg⁻¹ dry weight*
25 m	260
100 m	630
100 m	740/870
250 m	169
250 m	131
500 m	23
750 m	21
1000 m	13,7
5000 m	18,8

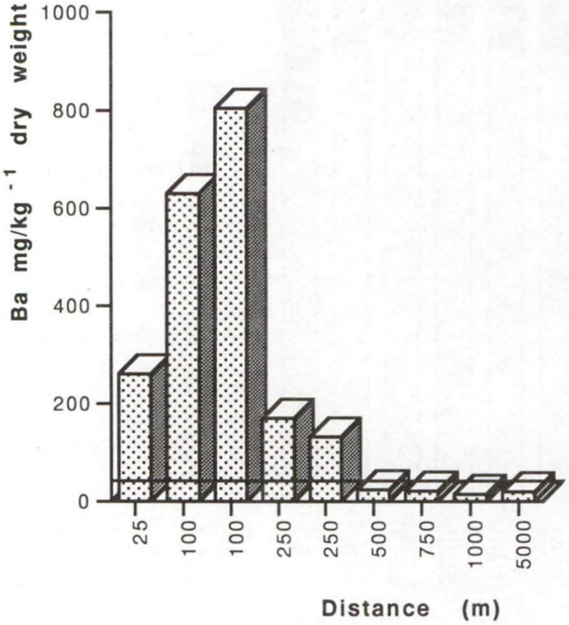

Fig. 5. Ba concentrations along the residual current transect (data from GROENEWOUD, 1994).

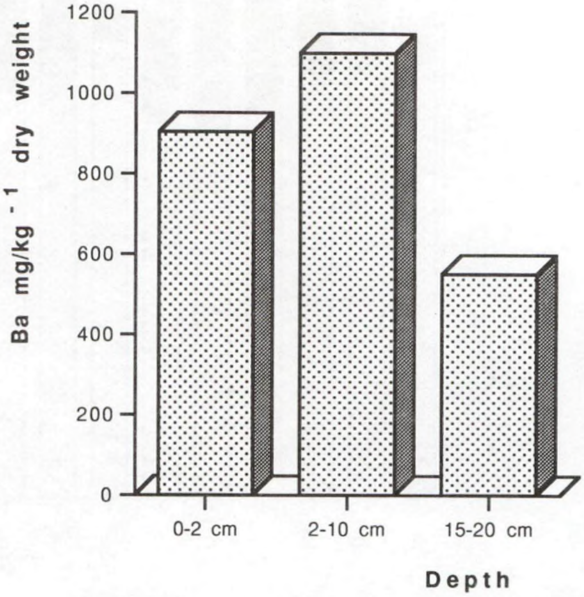

Fig. 6. Vertical profile of Ba concentrations in the sediment at 100 m (residual current transect, data from GROENEWOUD, 1994).

a maximum level of ≈35 mg·kg^{-1}. Fig. 5 shows that, along the residual current transect, the concentrations were substantially higher than maximum background level at the stations up to 250 m from the platform. At all other stations the concentrations were below the maximum background level and generally in the order of the expected background level (see also Table 3). Only at the station 250 m-192° the concentration was approximately at the maximum background level, but, in terms of elevated Ba concentrations, traces of the discharged cuttings could only be detected up to 250 m from the platform in the residual current direction.

A vertical profile of Ba in the sediment at 100 m (Fig. 6) shows that the highest concentrations were found in the upper 10 cm, but also at 15-20 cm depth the concentrations were high, indicating that much of the discharged material is stored in the deeper sediment layers.

TABLE 4

Oil concentrations at some stations at the residual current transect (data from Groenewoud, 1994).

Station		*oil conc. mg.kg-1 dry weight*
25 m		38,49
100 m		90,2
100 m		87,11
250 m		3,8
250 m		1,67
500 m		1,37
	0-2 cm	94,42
100 m	2-10 cm	301,62
	25-30 cm	86,73

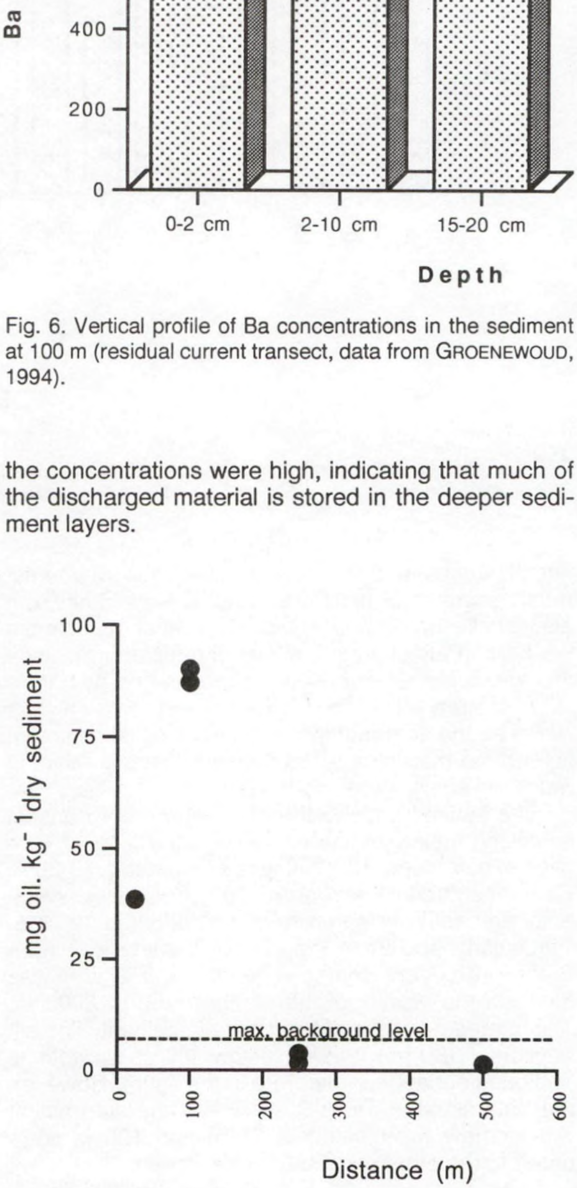

Fig. 7. Total oil concentrations at P6b (data from GROENEWOUD, 1994).

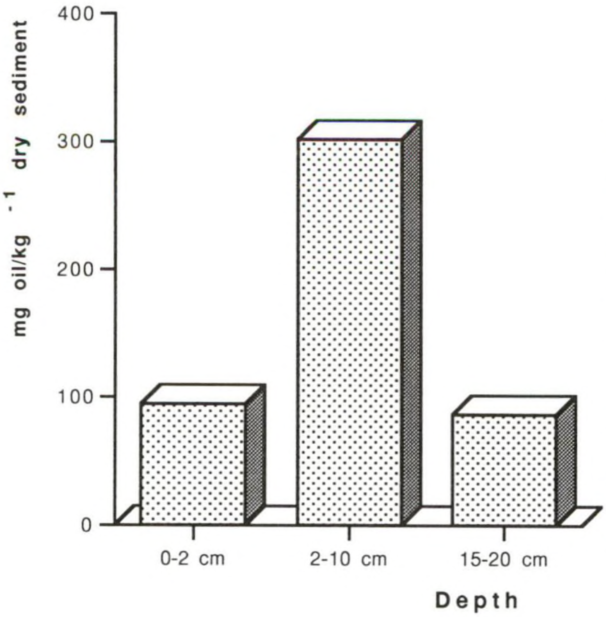

Fig. 8. Vertical profile of oil concentrations in the sediment at 100 m (residual current transect, data from GROENEWOUD, 1994).

3.3 OIL CONCENTRATIONS IN THE SEDIMENT

Oil concentrations were determined at a few stations along the residual current transect only (Table 4, Fig. 7). Elevated concentrations were found at 25 m and at 100 m, particularly at the latter station. A vertical profile of oil in a boxcore sample at this station shows that the concentration was highest in the sub-superficial sediment layer (2-10 cm depth), but also the superficial and deeper layers were obviously contaminated (Fig. 8). Visual observation during fieldwork suggested that oil contamination was severest at approximately 20 cm depth.

At 250 m the analyses did not reveal elevated oil concentrations in the sediment. Although in one of the 2 sets of pooled samples a total concentration was found that was almost 3 times as high as in the 500-m sample (see Table 4), the value of 3.8 mg·kg^{-1} dry sediment is well below the maximum background level of 7 mg·kg^{-1} adopted for the Dutch sector till now (ZEVENBOOM *et al.*, 1992). Nevertheless some traces of oil were visually observed in 4 of the original grab samples, immediately after they were collected on board of the research vessel. The absence of oil at 500 m as assessed by the chemical analysis was in correspondence with the visual observation that the sediment was clean at this station and did not show any trace of oil. Also the samples of the other stations (not analysed) all looked clean.

3.4 BIOLOGICAL FEATURES

3.4.1 FIELD OBSERVATIONS

The on board countings of *Echinocardium cordatum* revealed that large specimens (≥15 mm) were absent in the samples up to 500 m in the residual current direction from the platform (Fig. 9). At all other stations, including those in upstream and perpendicular directions, large specimens were found in 1 or more of the samples, but densities were generally low (0.6-5.6 ind·m^{-2}). Although the absence of large *E. cordatum* at the residual current stations up to 500 m from the platform was indicative of a long-term effect of the former discharges, logit regression did not reveal a significant increase in frequency of occurrence of the species in the samples with increasing distance from the discharge site.

The individual size of the animals ranged between 32 and 51 mm. The large size of these adult animals is characteristic of the sandy areas in the Southern part of the North Sea (DUINEVELD & JENNESS, 1984).

3.4.2 GENERAL FAUNA DESCRIPTION

The laboratory analyses yielded 67 identified species. In Table 5 their percentual occurrence in the samples is summarized. The original data are listed in Table 13 (Appendix). The fauna in the area was numerically dominated by juvenile *Echinocardium cordatum*, which accounted for 53% of the total fauna numbers. The species was not homogeneously distributed along the residual current transect and showed high numbers beyond 500 m from the platform, whereas it was almost absent at 100 m. Fig. 10 shows a clear gradient in the abundance pattern of juvenile *E. cordatum* and logit regression confirmed that there was a significant (5% level) increase in frequency of

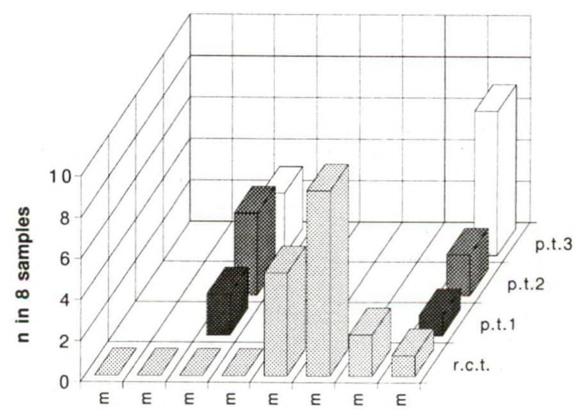

Fig. 9. Abundance of *Echinocardium cordatum* (specimens > 15 mm) around P6b.

TABLE 5

The benthic fauna at P6b, August 1993. Percentage of occurrence of each species in the total number of samples (48).

POLYCHAETA		*Orchomenella nana*	8	*Sthenothoe marina*	2
		Lepidepecreum longicorne	2	*Sthenothoe* spec.	2
Harmothoe longisetis	6	*Leucothoe incisa*	4	*Urothoe poseidonis*	88
Sthenelais limicola	2	*Montacuta ferruginosa*	8	*Bathyporeia guilliamsoniana*	77
Pisione remota	2	*Donax vittatus*	38	*Bathyporeia elegans*	96
Eteone lactea	13	*Mactra corallina*	2	*Perioculodes longimanus*	4
Anaitides maculata	13	*Spisula elliptica*	15	*Synchelidium haplocheles*	15
Anaitides spec. juv.	4	*Spisula* spec. juv.	2	*Aora typica*	2
Eumida sanguinea	2	*Tellina fabula*	42		
Nephtys hombergii	19	*Ensis ensis*	21	ECHINODERMATA	
Nephtys cirrosa	100	*Ensis* spec. juv.	4		
Nephtys caeca	10	*Thracia phaseolina*	2	*Asterias rubens*	4
Glycera capitata	2	*Tornus subcarinatus*	2	*Ophiura texturata*	2
Glycera spec. juv.	2	*Natica alderi*	31	*Ophiura albida*	38
Glycinde nordmanni	2			*Ophiura* spec. juv.	83
Goniada maculata	44	CRUSTACEA		*Echinocardium cordatum*	23
Scoloplos armiger	50			*Echinocardium cordatum* juv.	90
Aricidea jeffreysii	2	*Crangon allmani*	2	*Echinocyamus pusillus*	23
Aricidea minuta	29	*Processa parva*	27		
Paraonis fulgens	4	*Pontophilus trispinosus*	4	OTHER TAXA	
Poecilochaetus serpens	10	*Pontophilus* spec. juv.	2		
Spio filicornis	60	*Pagurus bernhardus*	10	Nemertinea	71
Spiophanes bombyx	98	*Macropipus* spec. juv.	27	Nematoda	4
Scolelepis bonnieri	4	*Pinnotheres pisum*	2	Amphioxus	13
Magelona papillicornis	10	*Thia scutellata*	13	Turbellaria	2
Chaetozone setosa	13	*Corystes cassivelaunus*	2	Phoroniden	2
Ophelia limacina	10	*Decapoda larven*	13	Harp. copepoda	8
Euzonus flabelligerus	2	*Gastrosaccus spinifer*	6	Oligochaeta	6
Travisia forbesii	6	*Schistomysis ornata*	8		
Mediomastus gracilis	2	*Iphinoe trispinosa*	15		
Lanice conchilega	25	*Diastylis bradyi*	23		
		Megaluropus agilis	10		
MOLLUSCA		*Atylus swammerdami*	6		
		Atylus falcatus	4		
Arca lactea	2	*Hippomedon denticulatus*	4		

occurrence of juvenile *E. cordatum* in the samples with increasing distance to the platform. To a lesser extent the amphipod *Bathyporeia elegans* was also dominant, attributing 16% of total fauna numbers. This species did not show a continuous gradient in its abundance pattern, but just a local minimum in the zone 250-500 m.

There were only 5 other species that were more or less abundant (mean density ≥10 ind·m^{-2}). None of them showed a clear gradient, but 3 species displayed a similar trend as *Bathyporeia elegans*. *Nephtys cirrosa*, *Spiophanes bombyx* and *Bathyporeia guilliamsoniana* occurred in relatively low densities in the zone 250-500 m. In contrast, *Spio filicornis* showed a maximum in this zone.

The total fauna abundance was low at 100 m and 250 m and gradually increased with increasing distance to the platform (Fig. 11). The abundance at 25 m seemed not to fit in this pattern. However, the relatively high abundance at this station was largely due to high numbers of the polychaete *Lanice conchilega*. When this species is excluded from the calculation, the total numbers ranged between 200 and 400 ind·m^{-2} in the zone 25-500 m. The high numbers outside this zone were largely caused by the abundance of juvenile *E. cordatum* and *Bathyporeia elegans*. When these species are left aside, the resulting total fauna numbers ranged between 190 m^{-2} at 100 m and 250 m and 410 m^{-2} at 5000 m. Analysis of variance on log-transformed densities revealed that only the 100-m and 250-m stations had significantly lower fauna numbers than the stations further away.

From the survey carried out in 1985 (MULDER *et al.*, 1987) it was already known that the species richness in the area where P6b is situated is low compared to the more silty sediment in the northern part of the Dutch sector, *i.e.* the number of species per sample is low. At the various stations sampled along

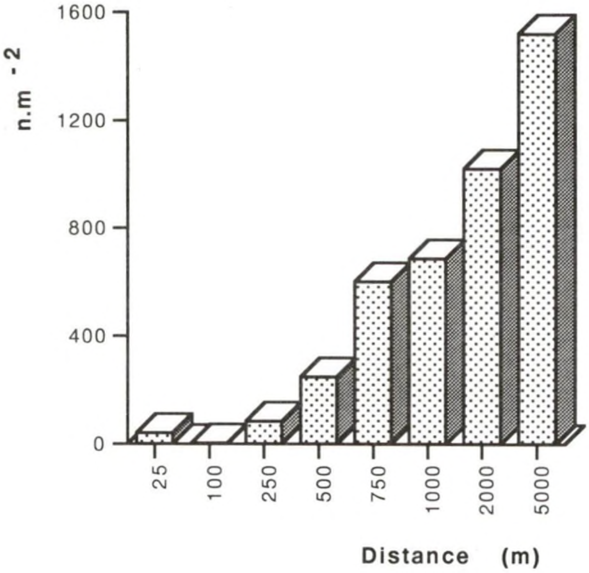

Fig. 10. Abundance pattern of juvenile *Echinocardium cordatum* along the residual current transect.

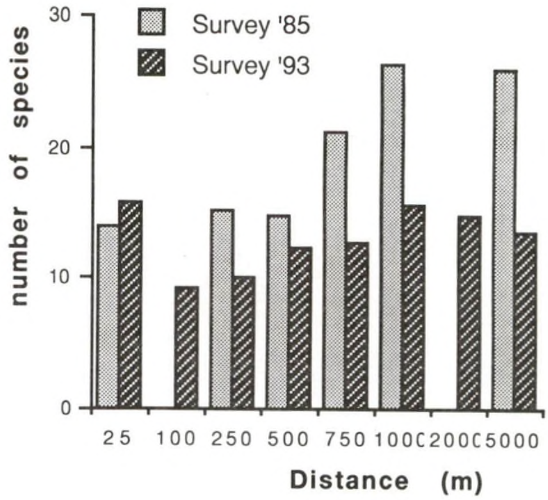

Fig. 12. Number of identified species per sample at P6b (residual current transect, surveys 1985 and 1993).

the residual current transect in 1985, the number of species per sample ranged between 14 (near the platform) and 26 (at ≥1000 m), whereas in the sedimentation zone one grab sample usually yields over 30 species. During the 1993 survey at P6b the number of species per sample ranged between 9 (at 100 m) and 16 (at 1000 m), which is even less than in 1985 (Fig. 12). At distances between 750 and 5000 m the numbers fluctuated between 13 and 16. On approach of the platform there was a continuous decrease and analysis of variance revealed that the 100-m and 250-m stations had significantly less species per sample than the stations at larger distance. At 25 m this trend was interrupted and the mean number of species per sample at this station was about the same as at the remote stations. The total number of species found (in 6 samples) at each station shows a similar pattern (Fig. 13).

3.4.3 PRESENCE-ABSENCE DATA: LOGIT REGRESSION

Possible gradients in the spatial abundance patterns of 17 individual species were tested by logit regression. The results are listed in Table 6 and show that, according to the uncorrected test, 3 species showed a significant (5% level) gradient in their spatial frequency of occurrence. All 3 species tended to occur less frequently in the samples close to the platform than at the remote stations (slope of the gradient positive). In the polychaete *Aricidea minuta* the gradient

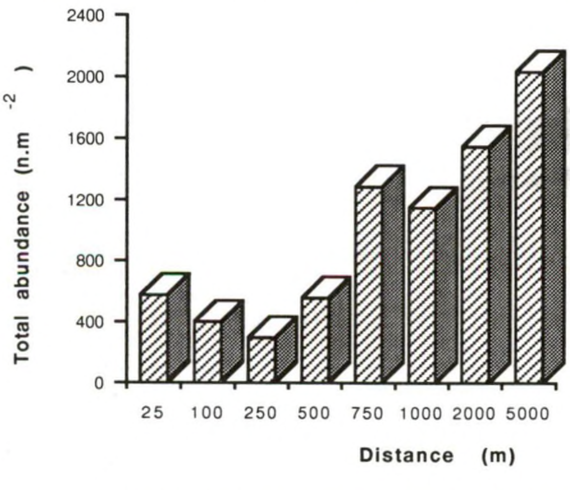

Fig. 11. Total macrofauna abundance at P6b (residual current transect).

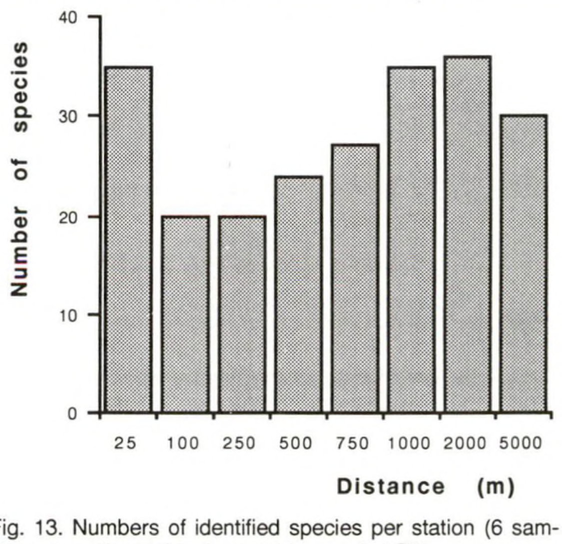

Fig. 13. Numbers of identified species per station (6 samples) along the residual current transect at P6b.

TABLE 6

List of species for which gradients in frequency of occurrence were tested by logit regression. Sign of the gradient (+/-) and significance level are indicated: += increasing frequency of occurrence away from the location; -= decreasing frequency of occurrence away from the location; 0= no gradient; n.s. = not significant.

		sign. level (%)	
	sign	*uncorr. test*	*corr. test*
Nephtys cirrosa	0	-	-
Goniada maculata	-	n.s.	n.s.
Scoloplos armiger	+	5	n.s.
Aricidea minuta	+	1	n.s.
Spio filicornis	-	n.s.	n.s.
Spiophanes bombyx	+	n.s.	n.s.
Lanice conchilega	-	n.s.	n.s.
Donax vittatus	+	n.s.	n.s.
Tellina fabula	+	n.s.	n.s.
Natica alderi	+	n.s.	n.s.
Processa parva	+	n.s.	n.s.
Urothoe poseidonis	+	n.s.	n.s.
Bathyporeia guilliamsoniana	+	n.s.	n.s.
Bathyporeia elegans	+	n.s.	n.s.
Ophiura albida	-	n.s.	n.s.
Echinocardium cordatum	+	n.s.	n.s.
Echinocardium cordatum juv.	+	5	n.s.

was also significant at the 1% level. The number of rejections of H_0 (*i.e.* frequency of occurrence is not dependent on distance to platform) is low, but still appears to be significantly (5% level) higher than should be expected if H_0 were true for all species. This implies that the probability that all 3 rejections of H_0 were statistical Type-1 errors is less than 5%. However, after correction of the test for over-dispersion it appeared that there was no species showing a significant gradient, indicating that the supposed significances as established by the uncorrected test might be due to over-dispersion.

3.4.4 RELATIVE MACROFAUNA ABUNDANCE

A plot of the relative macrofauna abundance, calculated as the mean rank of all species at each station (Fig. 14), shows that the mean rank was low at 100 m and 250 m. There was a gradual increase with increasing distance to the platform. At 25 m the relative abundance was unexpectedly high. Analysis of variance revealed highly significant (0.1% level) differences in the mean ranks of the different stations. An LSD-test, additionally applied to test the significance of differences between individual stations (Table 7), showed that the relative abundance at 100 m and 250 m was significantly lower than at the stations between 1000 m and 5000 m, and also lower

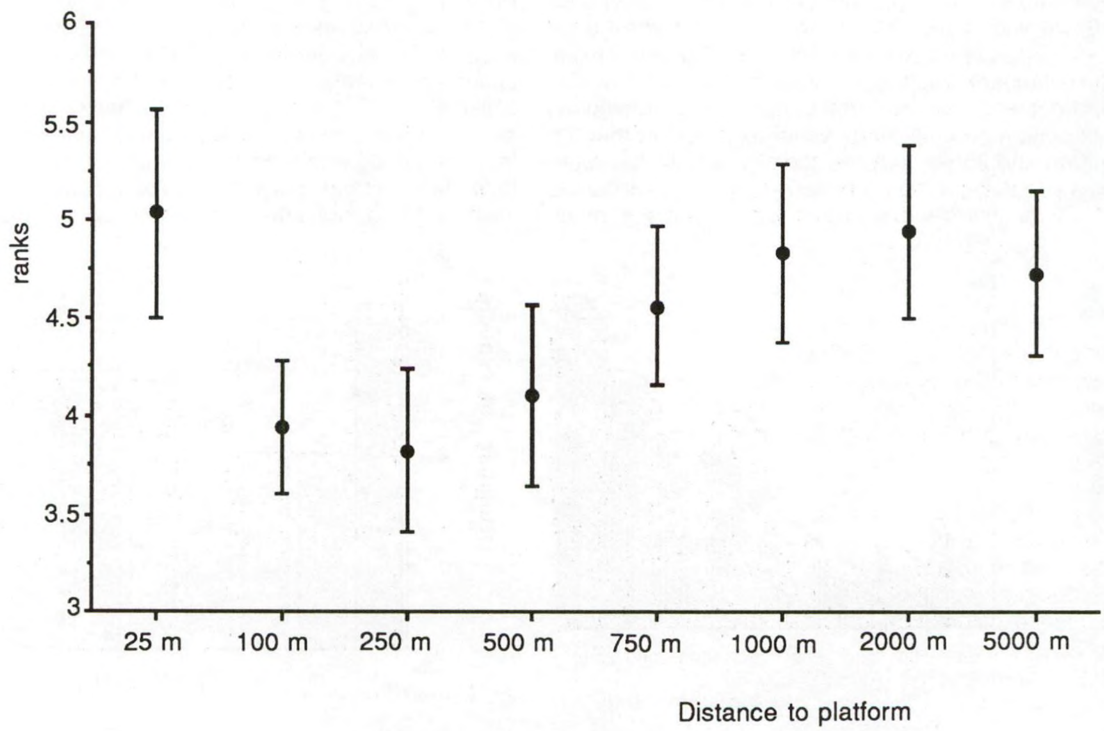

Fig. 14. Relative macrofauna abundance at P6b (mean ranks ±95% confidence limits).

TABLE 7

Statistical significance (LSD-test) of differences in relative abundance between stations at the residual current transect.

	25 m	*100 m*	*250 m*	*500 m*	*750 m*	*1000*	*2000*	*5000*
25 m	x							
100 m	0,5	x						
250 m	0,1	n.s.	x					
500 m	1	n.s.	n.s.	x				
750 m	n.s.	n.s.	5	n.s.	x			
1000 m	n.s.	1	0,5	5	n.s.	x		
2000 m	n.s.	0,5	0,1	5	n.s.	n.s.	x	
5000 m	n.s.	5	1	n.s.	n.s.	n.s.	n.s.	x

than at 25 m. At 500 m the relative abundance was still low, but not significantly different from that at the 5000-m reference station.

3.4.5 ABUNDANCE PATTERNS OF OBM SENSITIVE AND OPPORTUNISTIC SPECIES

In Table 8 a number of species is listed, which in earlier studies have shown to be susceptible to OBM cutting discharges (see DAAN *et al.*, 1990). Four opportunistic species are also excluded. The abundance patterns of all these species were inspected for the presence of possible gradients at P6b in 1993. The table shows that most species were not found or in too low numbers to recognize any pattern in their abundance. Among the species listed there were only 5 of which ≥20 specimens were found. Of these species *Echinocardium cordatum* and *Tellina fabula* seemed to occur in reduced densities in the vicinity of the platform, whereas *Lanice conchilega* was especially abundant at 25 m. Increased abundance of opportunistic species in the vicinity of the platform was not observed.

3.4.6 EFFECTS IN RELATION TO OIL CONCENTRATIONS

The biological effects observed at each of the stations investigated are illustrated in Fig. 15 in combination with the oil concentrations at these stations. An accumulation of effects was observed at both the 100-m and the 250-m stations. This seems remarkable particularly for the 250-m station, since the chemical analyses did not reveal oil concentrations that were significantly elevated above background level at this station, although traces of oil were positively observed. The occurrence of biological effects at 500 m should probably be explained as a long-term consequence of disturbance of sediment conditions in previous years, because traces of contamination were not observed here any more. At 25 m the number of effects was low compared to the 100-m station, but the chemical analyses as well as the field observations indicated that the oil concentrations at this station were indeed lower than at 100 m.

4 DISCUSSION

The chemical analyses revealed no traces of discharged material at distances >250 m in the residual current direction. At 250 m the presence of discharged material could be detected only by elevated Ba concentrations, but traces of oil were visually observed. This once more illustrates the patchy distribution of contaminants in the sediment, even within grab samples. In other directions such traces were not even found at 250 m. There seems to be an area of limited extent where the sediment is contaminated.

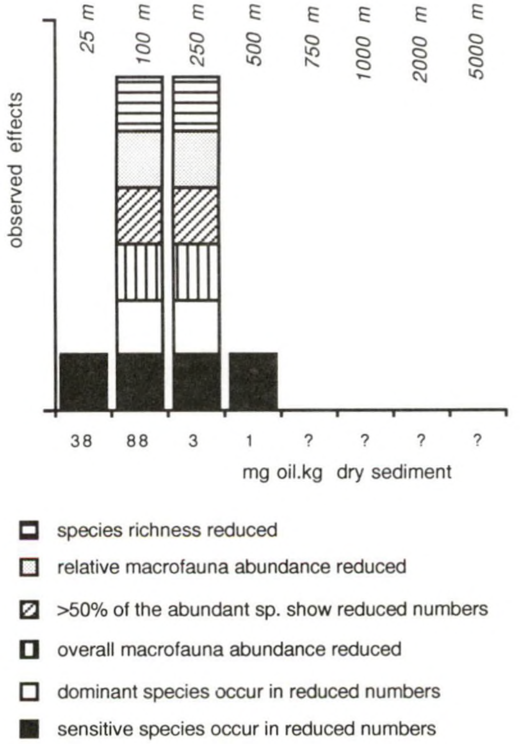

Fig. 15. Effects observed at the residual current transect at varying levels of sediment contamination.

TABLE 8

Evaluation of the abundance patterns of 37 species sensitive to OBM contamination and 4 opportunistic species.
tendency:+ = tendency for higher abundance away from the platform
- = tendency for lower abundance away from the platform
0 = no tendency for a spatial gradient
(?) = total number of specimens found < 20
(Note that the qualifications are based on the abundance patterns of the individual species and not on presence-absence data as used in logit regression).

	tendency
A. Species vulnerable to OBM contamination	
Montacuta ferruginosa	0 (?)
Scalibregma inflatum	species not found
Pholoe minuta	species not found
Amphiura filiformis	species not found
Echinocardium cordatum (≥15 mm)	+
Mysella bidentata	species not found
Nephtys hombergi	0 (?)
Lumbrineris latreilli	species not found
Chaetozone setosa	0 (?)
Owenia fusiformis	species not found
Nucula turgida	species not found
Gattyana cirrosa	species not found
Harpinia antennaria	species not found
Lagis koreni	species not found
Glycinde nordmanni	0 (?)
Cylichna cilindracea	species not found
Harmothoe longisetis	0(?)
Callianassa subterranea	species not found
Magelona papillicornis	0 (?)
Tellina fabula	+
Natica alderi	0
Spiophanes bombyx	0
Ophiodromus flexuosus	species not found
Notomastus latericeus	species not found
Lumbrineris fragilis	species not found
Amphiura chiajei	species not found
Leucothoe incisa	0 (?)
Chaetopterus variopedatus	species not found
Tharyx marioni	species not found
Ophiura albida	0
Gyptis capensis	species not found
Lanice conchilega	-
Perioculodes longimanus	0 (?)
Diplocirrus glaucus	species not found
Abra alba	species not found
Turritella communis	species not found
Sthenelais limicola	0 (?)
B. opportunistic species	
Nereis longissima	species not found
Capitella capitata	species not found
Spio filicornis	0
Anaitides groenlandica	species not found

A depth profile at 100 m showed that oil could be found up to at least 20 cm in the sediment. It seems not unlikely that deeper layers are also contaminated, but the sampler did not penetrate deeper than 20 cm in the sediment. The oil concentrations at 25 m and 100 m were considerably lower than during the first survey in 1985 at 25 m, when an extremely high concentration of 11,300 mg oil·kg^{-1} dry sediment was found (KUIPER & GROENEWOUD, 1986). However, the data are not completely comparable because analytical techniques have been considerably improved after 1985. Moreover the high concentration of 1985 was found in the top layer of the sediment (up to 8 cm depth), whereas deeper layers were not sampled. It is not clear, therefore, whether the oil has been degraded, redistributed or stored in deeper sediment layers. Particularly the presence of oil in deeper sediment layers may be long-lasting, since the anaerobic conditions in the deeper layers are unfavourable for biodegradation.

A clear gradient of decreasing effects could be observed from 100 m to 500 m, which was in correspondence with decreasing contamination levels over this part of the transect. The 25-m station did not fit in this gradient and revealed an unexpectedly high number of taxa. It seems remarkable that there were 10 species, which were found exclusively at this station and none of them was a known opportunist. At all other stations there were together only 13 species that were uniquely found at one station. Per station that number ranged between 1 and 4. Apparently the 25-m station represented a different fauna composition. This has to be explained most likely by the different structure of the sediment at this station. The depression in the seabed as revealed by the depth recordings and the presence of large amounts of old shells strongly indicate that increased erosion of the seabed close to the platform has removed the sandy top layer of the sediment, so that banks of old shells lying deeper in the sediment were uncovered. Erosion might also have resulted in transport of discharged material away from the platform, which could explain the relatively low oil concentrations observed. As a consequence the changed seabed structure could provide a particular habitat, that was recolonized by macrofauna with a different composition.

Adult specimens of *Echinocardium cordatum* were relatively rare in the whole area and due to the low numbers in the samples a powerful statistical analysis of its abundance pattern was hampered. It is not surprising therefore that logit regression detected no significant relation between its frequency of occurrence in the samples and distance to platform. Nevertheless it is remarkable that adult specimens of the species were absent up to 500 m in the residual current direction. During all previous surveys around OBM locations in the Dutch sector, where countings of *E. cordatum* included the assessment of size-frequency distributions, there was clear evidence that the radius to where specimens were absent was the largest in the residual current direction and increased for the larger size classes. A short-term study at location L5-5 in 1990 (1.5 year after drilling, see Table 12) revealed the absence of the species up to 250 m, whereas small specimens (size class 11-15 mm) turned up in the samples at 500 m and large specimens (>25 mm) only occurred at stations at ≥1000 m. In 1991 (3 years after drilling) juveniles had returned at 250 m, but specimens ≥25 mm only occurred at ≥750 m. At location K12a (OBM drilling in 1984) *E. cordatum* were counted during 6 surveys between 1985 and 1992. Of the first three surveys (1985-1987) only data on numerical abundance are available, but for the surveys of 1988, 1990 and 1992 size frequency distributions were also assessed (see Table 12). During all surveys *E. cordatum* was either absent or occurred in considerably reduced numbers at 100 m from the platform. Between 1988 and 1992 it appeared that specimens found at 100 m were always juveniles <10 mm and undoubtedly the result of the current year's spatfall. At 250 m the species seemed to be almost absent in 1985, 1986 and 1990, but in 1987, 1988 and 1992 total numbers per m^2 were in a similar range as at the stations further away from the platform. However, specimens larger than15 mm were hardly found. Up to 1990 the largest size class (25-50 mm) was only observed at the 5000-m reference station. This size class had returned in the area between 500 and 1000 m in 1992, 8 years after the discharges of OBM cuttings. Because of the low numbers of large *E. cordatum* in the samples at K12a and P6b it is not possible to accurately define the distance to where the species was affected after 8 years and 6 years respectively, but at both locations this distance seems to be in the order of 500 m.

A more detailed comparison of the 1985 and 1993 data on species level is hampered by the fact that the species composition was quite different between both years due to strongly different average abundance levels of individual species. Since the majority of benthic infauna species have a life-span that is probably ≤1 year these differences should most likely be explained by natural year to year fluctuations in settlement and survival of new generations. However, a clear difference between the 1985 and the 1993 results can be found in the number of significant gradients in individual species as detected by logit regression. In its basic form logit regression detected significant gradients in 23 species in 1985, *i.e.* 72% of the total number of species tested (see Table 11). After correction of the test statistic for possible over-dispersion there were still 8 species (25% of the total number tested) that showed a significant gradient. In the present study only 3 species (18% of the species tested) displayed a significant gradient according to the uncorrected test. After correction of the test statistic for over-dispersion there was not any species for which a gradient was significant. It is noted that over-dispersion may obscure gradients and it should not necessarily be concluded that the absence of significant gradients indicates that the survival rates of individual species are no longer affected by the original source of disturbance, which would explain that there is no significant relation between frequency of occurrence of individual species and distance to platform. Nevertheless, the difference in the numbers of significant gradients in 1985 and 1993 can be considered a clear indication that the impact on individual species has decreased during the years after the discharges were terminated. On the other hand, particularly the very low mean relative macrofauna abundance at 100 m and 250 m unmistakably indicates that there are still clear effects on the community as a whole.

Compared to 1985 the extent of the area that was affected seems to have decreased. In 1985 biological effects were detected up to 750 - 1000 m (MULDER *et al.*, 1987). In 1993 an accumulation of effects was only observed at 100 m and 250 m. At 500 m only the absence of large *E. cordatum* was indicative of a long-term effect. Because no traces of discharged material were found at this station, the source of disturbance, which in previous years may have eradicated the adult population of *E. cordatum*, seems to have disappeared. Nevertheless, it still may take several years before such adult populations will have recovered. According to DUINEVELD & JENNESS (1984) the age at which individuals reach a size of 30 mm should be estimated at ≈4 years. Therefore, the generation of juveniles that was found at the 500-m station in 1993 (and which represented undoubtedly recruitment of that year's spatfall) will reach that size not before 1997. Therefore, if a future follow-up survey would be considered, it might be advisable to plan such a survey in 1997, since recovery of adult populations should not be expected to occur before that year.

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Appendix

PROCEDURE LOGIT REGRESSION

The different variables and parameters are denoted by the following symbols:

N = numbers of stations sampled
π_i = probability of the species being present in a sample ($0 \leq \pi_i \leq 1$) at the i^{th} station (i = 1,.......,N)
d_i = distance of the i^{th} station to the platform
n_i = number of samples at the i^{th} station
y_i = observed number of samples in which the species is present at the i^{th} station
b_0, b_1 and b_i are model parameters
L is the log-likelihood of a model as a function of the π_i's and

$$L = \Sigma[(n_i-y_i)*\ln(1-\pi_i) + y_i*\ln(\pi_i)]$$

Model (0) is given by

$$\pi_i = [\exp(b_0)]/[1+\exp(b_0)]$$

Model (1) is given by

$$\pi_i = [\exp(b_0+b_1*d_i)]/[1+\exp(b_0+b_1*d_i)]$$

We now calculate the chi-square statistic

$$\chi^2 = 2*(L_1-L_0)$$

where L_0 is the maximum log-likelihood for model(0) and L_1 the maximum log-likelihood for model(1). The result is compared with the critical χ^2 value ($\alpha = 0.05$, $\nu = 1$) to decide whether model (1) fits significantly better than model (0) or not.

The second part of the procedure provides a correction of the χ^2 statistic as defined above for possible overdispersion in the data. To that end this statistic is divided by the dispersion parameter

$$\phi = 2*(L_2-L_1)/(N-2)$$

where L_2 is the maximum likelihood for the full model. The resulting statistic is compared with the critical χ^2 value ($\alpha = 0.05$, $\nu = 1$), to decide whether model (1) fits significantly better than model (0) or not.
It is noted here that ϕ is estimated from the fit of the observed values to the full model and model (1) and that the correction in fact introduces additional uncertainty of the test parameter than was initially present.

All calculations were performed in SYSTAT.

Table 9. Grainsize distribution of the sediment at P6b (data from Groenewoud, 1994).

Distance (m)	%< 63 μm	%> 63 μm	%> 90 μm	%> 125 μm	%> 180 μm	%> 300 μm	%> 500 μm	%> 1000 μm
25	0.54	0.18	0.91	11.32	72.95	7.52	1.51	5.00
100	0.45	0.11	0.40	7.22	76.38	12.83	1.08	1.36
100	0.31	0.02	0.55	9.29	73.90	12.30	2.46	1.15
250	0.08	0.03	0.16	3.58	73.16	21.67	0.78	0.18
250	0.06	0.02	0.14	3.43	69.23	25.40	1.04	0.12
250 102°	0.03	0.05	0.27	4.66	69.26	20.73	3.82	1.01
250 192°	0.09	0.09	0.63	11.48	77.90	5.85	0.63	3.04
250 282°	0.04	0.05	0.33	7.06	81.29	10.02	0.57	0.39
500	0.04	0.02	0.30	5.63	75.01	18.17	0.35	0.09
750	0.08	0.07	0.47	8.49	78.93	10.57	0.36	0.65
1000	0.08	0.04	0.45	8.62	79.63	10.12	0.34	0.36
2000	0.13	0.07	0.66	12.05	77.2	6.74	0.46	2.66
5000	0.07	0.08	0.53	12.15	78.11	7.39	0.81	0.59
5000 102°	0.02	0.08	0.51	11.32	78.23	7.24	0.84	1.32
5000 192°	0.02	0.04	0.24	4.30	71.77	22.52	0.83	0.04
100 0-2 cm	0.06	0.02	0.02	0.74	57.61	40.71	0.63	0.07
100 2-10 cm	0.03	0.02	0.00	0.89	58.03	39.94	0.80	0.10
100 25-30 cm	0.10	0.02	0.12	2.64	61.90	32.66	1.88	0.22

Table 10. Concentrations of oil components at P6b (mg/kg dry sediment), data from Groenewoud, 1994.

Station	25 m	100 m	100 m	250 m	250 m	500 m	100 m		
							0-2 cm	2-10 cm	25-30 cm
Component									
C10	0.27	0.14	0.18	0.17	0.32	0.13	0.15	0.18	0.08
C11	0.19	0.21	0.18	0.09	0.04	0.06	0.13	0.54	0.20
Naphtalene	0.33	0.60	0.51	0.04	0.04	0.02	0.46	2.20	0.71
C12	0.01	0.22	0.23	0.01	0.05	0.02	0.33	1.99	0.64
C13	0.64	1.26	1.22	0.09	0.05	0.02	1.37	4.56	1.23
C14	0.76	1.63	1.70	0.01	0.08	0.04	2.42	4.94	0.85
C15	1.24	1.78	1.79	0.08	0.06	0.04	1.98	6.05	1.78
C16	0.76	1.00	0.96	0.04	0.01	0.05	0.54	1.24	0.39
C17	0.01	0.36	0.45	0.01	0.01	0.01	0.37	1.95	0.66
Pristane	0.01	0.01	0.65	0.01	0.03	0.12	0.58	0.01	0.01
C18	0.15	0.30	0.31	0.09	0.04	0.01	0.35	0.83	0.25
Phytane	0.01	0.01	0.22	0.01	0.01	0.01	0.21	1.29	0.28
C19	0.19	0.25	0.22	0.09	0.05	0.05	0.21	0.58	0.20
C20	0.10	0.16	0.18	0.09	0.05	0.04	0.15	0.56	0.16
C21	0.19	0.26	0.29	0.12	0.08	0.04	0.32	0.51	0.13
C22	0.18	0.17	0.14	0.14	0.05	0.05	0.11	0.20	0.10
C23	0.13	0.13	0.13	0.13	0.06	0.06	0.10	0.25	0.11
Other peaks (incl. UCM)	33.30	81.73	77.76	2.57	0.64	0.60	84.62	273.75	78.95
Total	38.49	90.20	87.11	3.80	1.67	1.37	94.42	301.62	86.73

Table 11: Logit regression: Values of maximum likelihoods and test statistics before and after correction for over-dispersion.

A: P6b - September 1985

	uncorrected test			corrected test				
	$2(L_1-L_0)$	sign	sign.(%)	L_1	L_2	ϕ	$2(L_1-L_0)/\phi$	sign. (%)
Eteone longa	5.709	-	5	34.623	19.542	4.309	1.325	ns
Anaitides maculata	4.76	+	5	48.841	43.913	1.408	3.381	ns
Nephtys cirrosa	14.266	-	0.1	30.345	16.510	3.953	3.609	ns
Glycinde nordmanni	30.533	+	0.1	35.159	27.202	2.273	13.432	0.1
Scoloplos armiger	14.113	+	0.1	25.268	11.936	3.809	3.705	ns
Aricidea jeffreysi	13.517	-	0.1	49.982	24.344	7.325	1.845	ns
Poecilochaetus serpens	10.03	+	0.5	50.252	26.071	6.909	1.452	ns
Spio filicornis	4.23	-	5	3.285	3.251	0.010	427.890	0.1
Spiophanes bombyx	11.675	+	0.1	15.627	10.182	1.556	7.505	1
Scolelepis bonnieri	1.93	-	ns	51.679	42.872	2.516	0.767	ns
Magelona papillicornis	4.943	+	5	40.685	30.315	2.963	1.668	ns
Chaetozone setosa	1.904	+	ns	47.708	37.385	2.950	0.646	ns
Ophelia limacina	3.849	-	5	49.296	32.716	4.737	0.812	ns
Travisia forbesi	31.088	-	0.1	41.270	23.723	5.013	6.201	5
Owenia fusiformis	19.961	+	0.1	40.445	19.985	5.846	3.415	ns
Lanice conchilega	3.654	+	ns	49.394	36.508	3.682	0.993	ns
Montacuta ferruginosa	44.93	+	0.1	15.013	6.730	2.366	18.987	0.1
Tellina fabula	4.341	+	5	52.676	24.179	8.142	0.533	ns
Nalica alderi	7.958	+	0.5	45.593	36.508	2.596	3.066	ns
Processa parva	6.254	+	5	45.533	35.520	2.861	2.186	ns
Pontophilus trispinosus	1.752	+	ns	51.768	48.645	0.892	1.964	ns
Iphinoe trispinosa	17.086	+	0.1	44.731	28.700	4.580	3.730	ns
Megaluropus agilis	0.062	+	ns	44.358	42.331	0.579	0.107	ns
Atylus swammerdami	0.112	+	ns	37.422	30.453	1.991	0.056	ns
Leucothoe incisa	37.171	+	0.1	23.266	18.326	1.411	26.337	0.1
Urothoe poseidonis	0.005	+	ns	45.552	29.130	4.692	0.001	ns
Bathyporeia guilliams.	9.494	+	0.5	49.103	31.759	4.956	1.916	ns
Bathyporeia elegans	9.374	+	0.5	14.144	11.394	0.786	11.932	0.1
Perioculodes longimanus	3.289	+	ns	55.096	42.617	3.565	0.922	ns
Ophiura albida	0	+	ns	34.137	30.506	1.037	0.000	=
Echinocyamus pusillus	16.727	+	0.1	47.274	31.102	4.621	3.620	ns
Echinocardium cordatum	34.637	+	0.1	36.532	23.871	3.617	9.575	0.5

B: P6b - September 1993

	uncorrected test			corrected test				
	$2(L_1-L_0)$	sign	sign (%)	L_1	L_2	ϕ	$2(L_1-L_0)/\phi$	sign. (%)
Nephtys cirrosa	0.000	=	ns	0.000	0.000	0.000	0.000	-
Goniada maculata	1.132	-	ns	32.329	24.842	2.139	0.529	ns
Scoloplos armiger	4.718	+	5	30.912	10.813	5.743	0.822	ns
Aricidea minuta	7.513	+	1	25.218	16.088	2.609	2.880	ns
Spio filicornis	0.684	-	ns	31.880	21.799	2.880	0.237	ns
Spiophanes bombyx	0.019	+	ns	4.851	2.703	0.614	0.031	ns
Lanice conchilega	0.550	-	ns	26.717	10.681	4.582	0.120	ns
Donax vittatus	0.287	+	ns	31.611	23.726	2.253	0.127	ns
Tellina fabula	0.471	+	ns	32.366	20.683	3.338	0.141	ns
Natica alderi	0.067	+	ns	29.779	24.842	1.411	0.047	ns
Processa parva	0.019	+	ns	28.027	13.385	4.183	0.005	ns
Urothoe poseidonis	0.031	+	ns	18.069	13.045	1.435	0.022	ns
Bathyporeia guilliams.	0.433	+	ns	25.620	21.835	1.081	0.401	ns
Bathyporeia elegans	1.831	+	ns	7.398	3.819	1.023	1.791	ns
Ophiura albida	0.267	-	ns	31.622	29.001	0.749	0.357	ns
Echinocardium cordatum	1.813	+	ns	26.086	15.276	3.089	0.587	ns
E. cordatum juv.	4.846	+	5	13.616	2.703	3.118	1.554	ns

Table 12. Densities of Echinocardium cordatum (numbers per m2) at the residual current transect and a perpendicular transect for 3 locations sampled between 1985 and 1993.
(-= station not sampled).

	r.c. transect								p. transect		
distance: (m)	0	100	250	500	750	1000	2000	5000	250	500	3000
L5-5 year											
1989-total	0	-	0	0	0	0.8	-	6.7	0	-	-
1990-total	0	0	0	12.9	3.3	4.4	-	11.4	-	-	-
>10	0	0	0	12.9	3.3	4.4	-	7.9	-	-	-
>15	0	0	0	2.9	0.8	2.5	-	5.7	-	-	-
>20	0	0	0	0	0.8	1.3	-	5.7	-	-	-
>25	0	0	0	0	0	1.3	-	2.9	-	-	-
1991-total	0	0	2.5	0	4.2	3.3	2.5	19.2	1.4	-	-
>10	0	0	0	0	4.2	3.3	2.5	19.2	1.1	-	-
>15	0	0	0	0	4.2	3.3	2.5	19.2	1.1	-	-
>20	0	0	0	0	4.2	3.3	2.5	15	1.1	-	-
>25	0	0	0	0	4.2	3.3	2.5	10	1.1	-	-
K12a year											
1985-total	-	0	5	2	205	329	-	44	48	172	79
1986-total	-	0	0	64	191	83	-	34	34	-	-
1987-total	0	21	3400	3042	3333	2797	-	3213	474	-	-
1988-total	-	94	694	867	978	-	-	430	920	-	-
>10 mm	-	2	175	306	343	-	-	195	195	-	-
>15 mm	-	0	2	30	33	-	-	39	4	-	-
>20 mm	-	0	0	11	0	-	-	20	0	-	-
>25 mm	-	0	0	0	0	-	-	2	0	-	-
1990-total	-	0	0	254	506	615	-	89	163	-	-
>10 mm	-	0	0	1.4	2.9	6.4	-	6.4	0.7	-	-
>15 mm	-	0	0	0	0	0.7	-	5	0	-	-
>20 mm	-	0	0	0	0	0	-	5	0	-	-
>25 mm	-	0	0	0	0	0	-	5	0	-	-
1992-total	-	1.9	243	137	96	41	-	-	-	-	-
>10 mm	-	0	7.5	7.5	12.5	3.8	-	-	6.9	-	-
>15 mm	-	0	0	1.9	1.9	1.3	-	-	3.8	-	-
>20 mm	-	0	0	1.3	1.3	1.3	-	-	0	-	-
>25 mm	-	0	0	1.3	0.6	0.6	-	-	0	-	-
P6b year											
1985-total	0	-	0	0	0	4.5	-	9	4	1.5	47
1993-total	40	0.8	82	248	604	689	1022	1521	-	-	-
>10	0	0	0	0	4.2	3.3	1.7	1.7	1.9	-	-
>15	0	0	0	0	4.2	3.3	1.7	1.7	1.9	-	-
>20	0	0	0	0	4.2	3.3	1.7	1.7	1.9	-	-
>25	0	0	0	0	4.2	3.3	1.7	1.7	1.9	-	-

Table 13 . Data platform P6b, survey August 1993.
Mean densities (n.m-2)
Number of samples ( ) in which species are present.
Tot. number of ind. per m2 per station.
Number of identified species.

Distance to platform (m)	25	100	250	500	750	1000	2000	5000
Number of analysed samples	6	6	6	6	6	6	6	6
POLYCHAETA								
Harmothoe longisetis						0.8 (1)	0.8 (1)	0.8 (1)
Sthenelais limicola					0.8 (1)			
Pisione remota	0.8 (1)							
Eteone lactea						2.5 (3)		3.3 (3)
Anaitides maculata	3.3 (4)	0.8 (1)						0.8 (1)
Anaitides spec. juv.		0.8 (1)				0.8 (1)		
Eumida sanguinea	0.8 (1)							
Nephtys hombergii	2.5 (3)	5.0 (3)			0.8 (1)	0.8 (1)	0.8 (1)	
Nephtys cirrosa	71.7 (6)	48.3 (6)	40.8 (6)	30.0 (6)	66.7 (6)	53.3 (6)	80.8 (6)	90.8 (6)
Nephtys caeca		2.5 (2)		0.8 (1)	0.8 (1)		0.8 (1)	
Glycera capitata	0.8 (1)							
Glycera spec. juv.	0.8 (1)							
Glycinde nordmanni	0.8 (1)							
Goniada maculata	5.8 (6)	2.5 (3)	0.8 (1)	4.2 (2)	3.3 (4)	0.8 (1)	1.7 (2)	2.5 (2)
Scoloplos armiger		0.8 (1)		8.3 (5)	8.3 (6)	10.8 (6)	0.8 (1)	9.2 (5)
Aricidea jeffreysii				1.7 (1)				
Aricidea minuta			2.5 (3)	6.7 (4)		0.8 (1)	1.7 (1)	11.7 (5)
Paraonis fulgens			0.8 (1)	0.8 (1)				
Poecilochaetus serpens	4.2 (3)					0.8 (1)		0.8 (1)
Spio filicornis	7.5 (4)	5.8 (4)	50.8 (6)	80.0 (6)	1.7 (2)	1.7 (2)	0.8 (1)	4.2 (4)
Spiophanes bombyx	95.8 (6)	74.2 (6)	11.7 (6)	20.8 (6)	34.2 (6)	40.0 (5)	107.5 (6)	138.3 (6)
Scolelepis bonnieri			0.8 (1)	0.8 (1)				
Magelona papillicornis				0.8 (1)		0.8 (1)	1.7 (2)	0.8 (1)
Chaetozone setosa						4.2 (3)		2.5 (3)
Ophelia limacina			1.7 (2)	1.7 (2)			2.5 (1)	
Euzonus flabelligerus	0.8 (1)							
Travisia forbesii				2.5 (1)	0.8 (1)			0.8 (1)
Mediomastus gracilis							4.2 (1)	
Lanice conchilega	128.3 (5)					3.3 (3)	3.3 (4)	
MOLLUSCA								
Arca lactea	0.8 (1)							
Montacuta ferruginosa					6.7 (3)	0.8 (1)		
Donax vittatus	0.8 (1)	1.7 (2)	7.5 (4)		3.3 (3)	0.8 (1)	6.7 (5)	1.7 (2)
Mactra corallina						0.8 (1)		
Spisula elliptica				4.2 (4)			0.8 (1)	1.7 (2)
Spisula spec. juv.					0.8 (1)			

Table 13 . continued.

Distance to platform (m)	25	100	250	500	750	1000	2000	5000
Number of analysed samples	6	6	6	6	6	6	6	6
Tellina fabula	0.8 (1)	2.5 (2)		0.8 (1)	4.2 (4)	18.3 (6)	5.8 (4)	4.2 (2)
Ensis ensis	0.8 (1)		1.7 (1)	4.2 (4)	1.7 (2)		1.7 (2)	
Ensis spec. juv.						0.8 (1)		0.8 (1)
Thracia phaseolina							0.8 (1)	
Tornus subcarinatus							0.8 (1)	
Natica alderi	5.0 (4)		0.8 (1)	0.8 (1)	3.3 (2)	2.5 (3)	2.5 (2)	5.0 (2)
CRUSTACEA								
Crangon allmani					0.8 (1)			
Processa parva	3.3 (1)				5.8 (3)	15.8 (4)	28.3 (5)	
Pontophilus trispinosus								1.7 (2)
Pontophilus spec. juv.	0.8 (1)							
Pagurus bernhardus	3.3 (3)	2.5 (2)						
Macropipus spec. juv.	4.2 (3)	7.5 (2)	0.8 (1)		2.5 (3)	1.7 (2)		1.7 (2)
Pinnotheres pisum			0.8 (1)					
Thia scutellata				2.5 (3)		0.8 (1)	0.8 (1)	0.8 (1)
Corystes cassivelaunus								0.8 (1)
Decapoda larven	1.7 (2)			0.8 (1)		1.7 (1)	0.8 (1)	1.7 (1)
Gastrosaccus spinifer								5.8 (3)
Schistomysis ornata			5.8 (4)					
Iphinoe trispinosa	2.5 (3)	0.8 (1)			0.8 (1)	0.8 (1)	0.8 (1)	
Diastylis bradyi	0.8 (1)	0.8 (1)			3.3 (2)	6.7 (4)	3.3 (3)	
Megaluropus agilis			0.8 (1)		0.8 (1)	1.7 (2)		0.8 (1)
Atylus swammerdami						1.7 (1)	1.7 (2)	
Atylus falcatus	2.5 (2)							
Hippomedon denticulatus						1.7 (2)		
Orchomenella nana	0.8 (1)	2.5 (1)				2.5 (2)		
Lepidepecreum longicorne	0.8 (1)							
Leucothoe incisa							2.5 (2)	
Sthenothoe marina	0.8 (1)							
Sthenothoe spec.							3.3 (1)	
Urothoe poseidonis	40.0 (6)	9.2 (5)	36.7 (6)	22.5 (6)	15.0 (4)	17.5 (5)	5.0 (4)	31.7 (6)
Bathyporeia guilliamsoniana	15.8 (5)	12.5 (5)	4.2 (3)	3.3 (3)	18.3 (6)	7.5 (5)	9.2 (5)	10.8 (5)
Bathyporeia elegans	113.3 (6)	215.0 (6)	16.7 (4)	41.7 (6)	366.7 (6)	196.7 (6)	180.8 (6)	108.3 (6)
Perioculodes longimanus	0.8 (1)						0.8 (1)	
Synchelidium haplocheles	0.8 (1)	0.8 (1)			1.7 (2)	0.8 (1)	0.8 (1)	0.8 (1)
Aora typica	0.8 (1)							
ECHINODERMATA								
Asterias rubens	0.8 (1)						0.8 (1)	
Ophiura texturata						0.8 (1)		
Ophiura albida	2.5 (2)	2.5 (2)	5.0 (3)	0.8 (1)	10.8 (2)	2.5 (3)	6.7 (4)	8.3 (1)

Table 13 . continued.

Distance to platform (m)	25	100	250	500	750	1000	2000	5000
Number of analysed samples	6	6	6	6	6	6	6	6
Ophiura spec. juv.	12.5 (5)	2.5 (2)	15.0 (6)	60.8 (6)	120.8 (6)	40.0 (5)	50.8 (5)	65.0 (5)
Echinocardium cordatum					4.2 (4)	3.3 (4)	1.7 (1)	1.7 (2)
Echinocardium cordatum juv.	40.0 (6)	0.8 (1)	81.7 (6)	247.5 (6)	600.0 (6)	685.8 (6)	1020.0 (6)	1519.2 (6)
Echinocyamus pusillus			0.8 (1)	1.7 (2)	0.8 (1)	5.0 (4)	2.5 (2)	0.8 (1)
OTHER TAXA								
Nemertinea	P (6)	P (3)	P (4)	P (3)	P (4)	P (4)	P (5)	P (5)
Nematoda	0.8 (1)						0.8 (1)	
Amphioxus	9.2 (4)			0.8 (1)		0.8 (1)		
Turbellaria								1.7 (1)
Phoroniden								P (1)
Harp. copepoda	0.8 (1)	1.7 (2)	0.8 (1)					
Oligochaeta	2.5 (2)				1.7 (1)			
Total nr. of individuals	582	403	288	551	1290	1141	1548	2040
Nr. of identified species	35	20	20	24	27	35	36	30
P=present (not counted)								

CONTENTS