PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY B BIOLOGICAL SCIENCES

Field Effects of Platform Discharges on Benthic Macrofauna [and Discussion]

P. F. Kingston, Lynda M. Warren, R. G. Hughes, R. Earll, J. G. Parker and J. S. Gray

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Field effects of platform discharges on benthic macrofauna

By P. F. Kingston

Institute of Offshore Engineering, Heriot-Watt University, Research Park, Riccarton, Edinburgh EH14 4AS, U.K.

Although there were originally no statutory obligations for North Sea oilfield developers to monitor the environmental impact of their activities, many companies undertook such studies voluntarily.

The central and northern North Sea is principally a level-bottom habitat and can be broadly considered as being dominated by variations of the classical *Amphiura* benthic community. Early approaches to monitoring studies involved the use of grids of sampling stations extending several kilometres in every direction from the proposed site of the installation. More recently it has been found that the major impact on the environment is from the discharge of oil-based drilling cuttings at the platforms and drilling rigs. Efforts are now concentrated closer to the installations, using transects starting as near to the source of the discharge as possible.

By using community parameters such as diversity and equitability, it has been shown that the fauna responds with a dramatic drop in values of these measures close to the platform. However, in most surveys, background values are regained between 500 and 1000 m from the installation. This seems to be the case regardless of whether diesel or low toxicity oil-based drilling fluids are used. Numbers of individuals and biomass responded in a similar way at some installations using ‘low toxicity’ oil-based drilling muds but increased at others using diesel oil-base. The latter response is similar to that of areas of great organic enrichment while the drop in numbers is more indicative of disturbed or toxic conditions. The markedly patchy distribution of drilling cuttings around the production platforms calls into question the sampling strategies that have been adopted for offshore surveys in the past. The extreme variation of figures, particularly oil levels in sediments, makes it almost impossible to establish firm connections between cause and effect.

The effects of the discharge of cuttings on the benthic environment has been shown to be very severe, but only in a very localized area around the installations. It is suggested that attention is now focused on the persistence of the oil in the cuttings and that future monitoring strategies should include this in their scope.

INTRODUCTION

The North Sea has been a focus of study for European marine biologists since the last century. This relatively small sea area is still one of the most productive fishing areas in the world and as such holds considerable public attention as a major resource for the countries that border it. Considerable effort has been spent studying and monitoring North Sea fisheries and there is a wealth of data available mainly concerned with fishing statistics and the effects of natural and man-induced factors on the long-term changes in fish stocks. Until the discovery of oil in the North Sea, the man-induced factors that concerned fishing interests and governments were principally overfishing and pollution (mainly coastal). Because a large proportion of the North Sea fish catch comes from the central and northern North Sea, the development of the oilfields in these areas naturally caused concern (figure 1). Nevertheless it was not until 1984, over ten years after the first production platforms were placed in position, that any statutory obligation was placed on operators to monitor the environmental impact of their activities. Although British authorities did not enforce environmental monitoring in the vicinity of platforms, many operators initiated their own programmes of pre-operational surveys and monitoring.

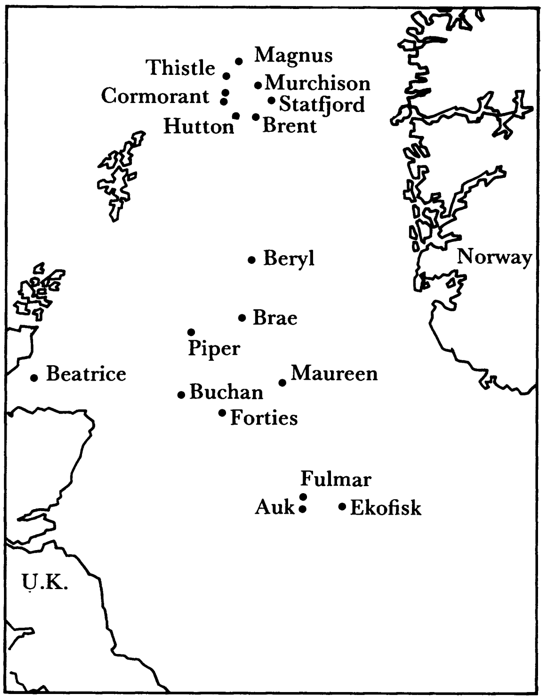

FIGURE 1. Major North Sea oilfields.

With no statutory requirement for an operator to monitor the impact of its offshore activity, it is not surprising that the approach to the problem varied considerably between companies. Two main lines of investigation finally emerged: (1) physical and chemical analysis of the seabed sediments and (2) monitoring of benthic macrofauna. The concentration of the studies around the major oilfields has led to an unprecedented wealth of information about the benthos of localized areas of the central and northern North Sea being accumulated. This contrasts with the paucity of information available for the rest of the area (Kingston & Rachor 1982). The aim of this paper is to consider the effects of oilfield development (particularly discharges) on the benthic environment. However, before doing so, it is worth considering the distribution of benthic communities in the area as a whole.

Benthic communities

For the most part, the central and northern North Sea supports benthic faunal assemblages that can be equated broadly to the classical *Amphiura* community, first described by Petersen (1914) for Danish inshore waters, and later by Jones (1950) (as Boreal offshore muddy sand and mud associations). In the broadest sense, these benthic associations include the foraminiferan-dominated communities of the soft muds of the Fladen Ground (McIntyre 1961), and the Forties area (Hartley 1979) and many that appear to conform with the time-honoured definitions of *Echinocardium–filiformis* and *Brissopsis – chiajei* communities (Buchan (Oil Pollution Research Unit (O.P.R.U.) 1981, 1983), and Brae (Institute of Offshore Engineering (I.O.E.) 1982*b*), (unpublished reports). The complex and variable sediments that are found in the area result in a host of intermediate communities, all of which are basically similar and, from the persistence of *Amphiura*, can be included in Petersen's, (1914) broad label.

The coarser sediments of the area around Magnus (British Petroleum) and Murchison (Conoco) support communities that may be described as variants of the 'deep *Venus*' communities of Petersen (1914), with the muddier areas to the south again tending towards *Amphiura*-type associations. Although these are very broad generalizations they serve to illustrate the dominance of mud and muddy sand associations over most of this area.

Relationship of communities with the sediment

Level-bottom communities, such as occur all over the North Sea, are composed predominantly of infaunal animals, that is, they live within the sediment, either moving through it or using it as a support for their burrows. The sediment not only offers support and protection, but is also a source of food. Benthic communities occurring in mud or muddy sand are characteristically dominated by deposit feeding species and small predatory forms feeding on meiofauna. This is reflected in the distribution of faunal groups within the community which are usually heavily dominated by the Polychaeta, the majority of which are sedentary forms feeding either directly or indirectly on the sediment. Offshore communities such as these are therefore heavily reliant on the sediment as a principal source of food and are thus very vulnerable to the consequences of sediment contamination.

History of North Sea benthic monitoring

Although originally there was no legal requirement for United Kingdom sector offshore operators to perform environmental studies around their installations, many undertook to do so to establish the status of the seabed environment before and during drilling operations and oil production. In the early days of North Sea oil development, attempts were made to predict the area of potential environmental damage to establish suitable sampling programmes. At that time it was thought that the major input of oil contaminants would be in the form of oily water resulting from platform drainage, production water and formation water (Department of the Environment 1976). No emphasis was placed on the dumping of drilling cuttings since at that time the use of oil-based muds was not anticipated. Indeed few studies had sampling stations within the 500 m prohibited zone that had been set up to protect the installations.

Predictions of a total area of up to 11 $\text{km}^2\ \text{d}^{-1}$ being affected by platform discharges with oil levels in excess of 10 $\mu\text{g}\ \text{l}^{-1}$ in the 500 m zone (Department of the Environment 1976) prompted operators to opt for surveys which endeavoured to cover as wide an area as possible with extensive grids of 20–30 sample stations. This resulted in excellent background information about various areas in the North Sea that had never been studied with such intensity before.

With the development of more and more oil-based mud drilling operations it soon became clear that any effects on the environment were going to be very localized and so sampling strategy switched from the wide grid approach to transects which originated very close to the platforms and emphasized the line of prevailing bottom currents.

Sampling methods

Obtaining reliable quantitative samples of offshore sediments with its fauna is surprisingly difficult. The method employed in almost all North Sea surveys has involved the use of some sort of bottom grab sampler.

The majority of surveys have used either the van Veen, Day or Smith McIntyre grabs. Each takes a sample of 0.1 m^2, the depth of penetration depending upon the firmness of the substratum. The usual practice has been to take five grab samples from each site for faunal analysis and one or two for physical and chemical analysis of the sediments. Recently there has been a trend towards reducing the number of faunal samples to two per station. The fauna are separated from the sediments by screening, by using either a 0.5 mm or 1.0 mm aperture mesh. The material retained is then fixed and preserved for analysis in the laboratory. Such methods have been used almost universally in North Sea studies and were employed in all the surveys that are to be discussed here.

CHANGES IN COMMUNITY STRUCTURE ASSOCIATED WITH PLATFORM ACTIVITY

Methods of measurement

In most benthic studies undertaken in the North Sea oilfields changes in community structure have been measured principally by looking for changes in species abundance distribution, that is, the way in which individuals are allocated to species in a given community. The most widely used approach has been to attempt to measure diversity. In an ecological context, diversity refers to two community components; the first is species richness, that is, the total number of species in the community and the second their equitability, that is, the evenness with which the individuals in the community are distributed among species. Many indices of diversity have been suggested. For comparison, one of the most commonly used indices, the Shannon–Wiener Index, ($H_{(s)}$) has been used here. This is a measure of how difficult it would be to predict correctly the species identity of the next individual collected from the community under study and is based on information theory (Shannon & Weaver 1963). The formula for its calculation is

$$H_{(s)} = -\sum p_i \log_2 p_i,$$

where p_i = the proportion of the ith species.

Diversity indices such as this have been widely used as a means of integrating the complexity of a community into a single measure that can be used to monitor pollution-induced change. The theory behind their use is based on the premise that communities with a high diversity result from less environmental stress than those with a low diversity. The validity of this assumption has often been questioned, however, where gross pollution is involved, such measures appear to be quite useful for comparative purposes.

The equitability component of diversity has also been frequently used in North Sea oil related survey work to indicate the degree to which a species abundance distribution may be dominated by a proportion of its members. One of the most commonly used indices is J (Pielou 1966). This gives the ratio of the measured value of $H_{(s)}$ to the theoretical value if all species were represented by equal numbers of individuals and is expressed as

$$J = \frac{H_{(s)}}{H_{(\max)}} \quad \text{or} \quad \frac{H_{(s)}}{\log_2 S},$$

where S = number of species.

The final diversity measure that will be referred to here, that of Hurlbert (1971), is based on an algorithm of Sanders (1968). This generates a curve by interpolating the number of species that would have been recorded had a series of progressively smaller samples been taken instead of the original. Because the diversity of the sample is represented by the shape of the curve produced (the steeper the curve the greater the diversity), this 'rarefaction' technique allows the comparison of samples of different sizes.

Changes in diversity

Figure 2 shows the values of $H_{(s)}$ with respect to distance from five North Sea oil production platforms, Brent (Shell), Murchison (Conoco), Statfjord (Mobil, Norway), and Beatrice (Britoil, data from Addy *et al.* (1984)). The graphs show a striking similarity in the way in which the diversity of the benthos is affected. The maximum and minimum $H_{(s)}$ values obtained from a range of pre-operational benthic surveys are also indicated (I.O.E. 1978, 1981, 1982*b*).

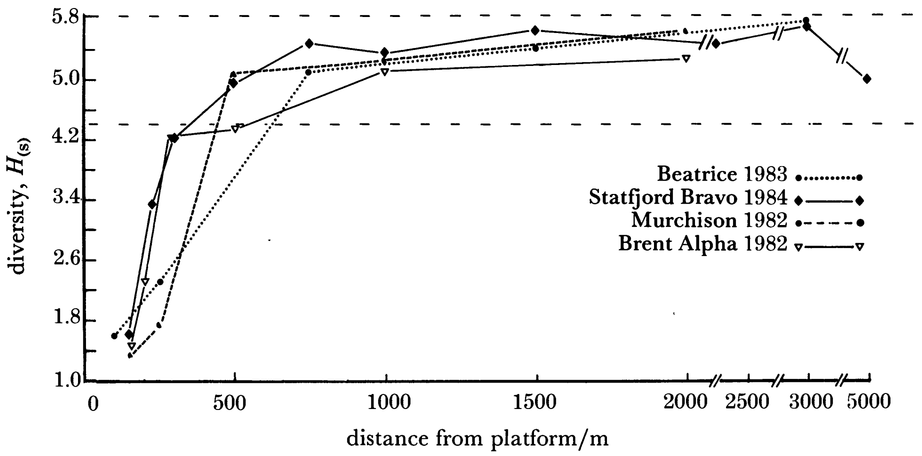

FIGURE 2. Values of Shannon–Wiener diversity index ($H_{(s)}$) with respect to distance from four North Sea oil production platforms. Broken lines indicate maximum and minimum values obtained from pre-operational surveys.

It can be seen that 'pre-operational' values of $H_{(s)}$ are reached for all platforms between 500 and 750 m from the installation suggesting that the extent to which community structure is disrupted, as defined by $H_{(s)}$, is confined to a relatively small area around each platform. A similar picture emerges when the rarefaction curves are examined (figure 3). As with the $H_{(s)}$ figures, the upper and lower limits of curves obtained on pre-operational surveys at the same or nearby sites are shown as dotted lines. The extent of the effect, as indicated by the upward progression of each curve with increasing distance from the platform, supports the figures obtained from the Shannon–Wiener diversity measurement showing containment within 750 m for these locations. However, within this zone the drop in diversity as the platform is approached is dramatic, indicating a gross change in community structure and suggesting gross disturbance of the seabed environment at the proximal stations.

Changes in equitability

The marked drop in diversity in the vicinity of the production platforms is echoed by a similar pattern of response for the equitability measure J used here (figure 4). Values of J, like $H_{(s)}$, increase with distance from the platforms and appear to stabilize at a distance between 500

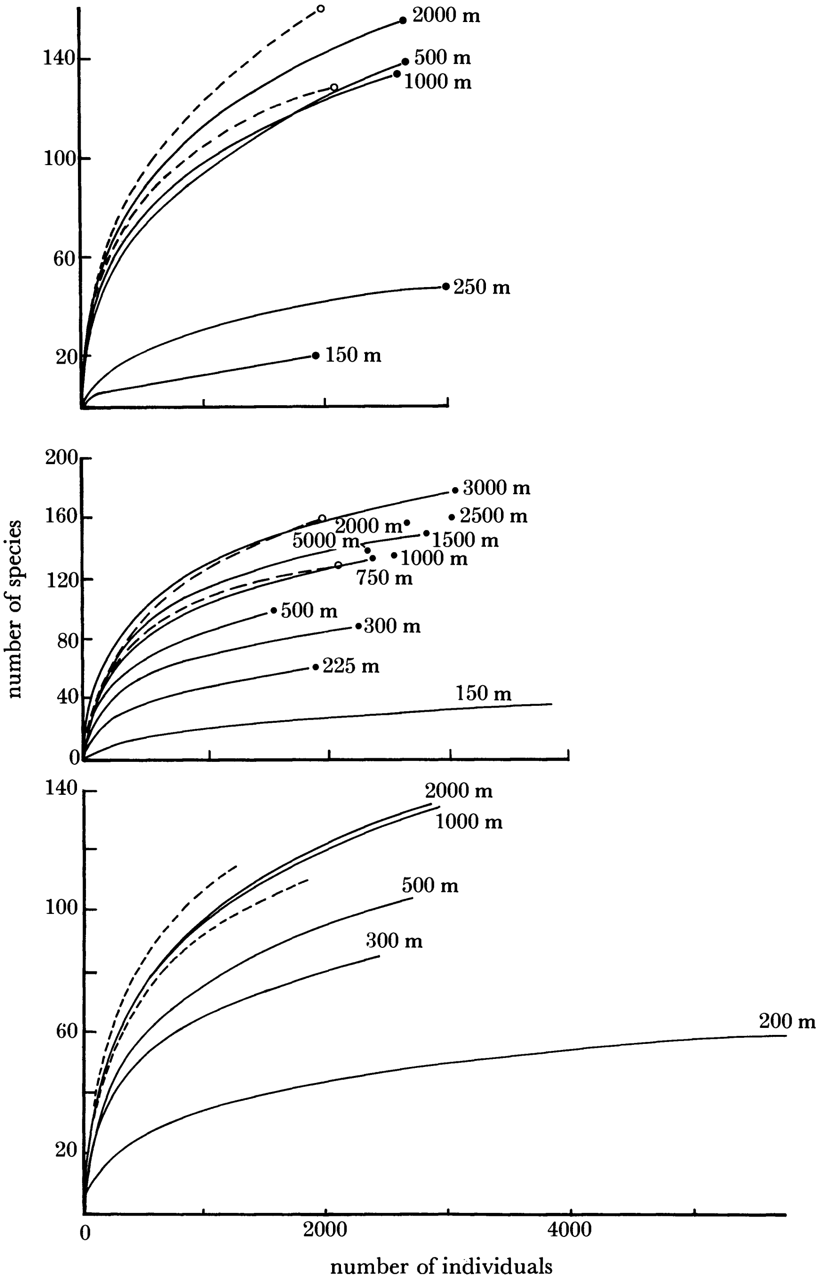

Figure 3. Hurlbert rarefaction curves for Murchison (top graph), Statfjord B (middle graph) and Brent Alpha (bottom graph). Dotted lines give limits for pre-operational surveys either at the same location or nearby fields.

and 750 m. The very low values of J recorded at the inner stations are indicative of a species abundance distribution that is greatly dominated by a few individuals and is a classical response to environmental stress (Gray 1976).

Changes in numbers of species and individuals

Diversity, as has already been said, incorporates two properties of a faunal community. One of these, equitability, has already been shown to reflect the trends in diversity; the other, species richness, as might be expected also follows the same general trend. To enable a comparison

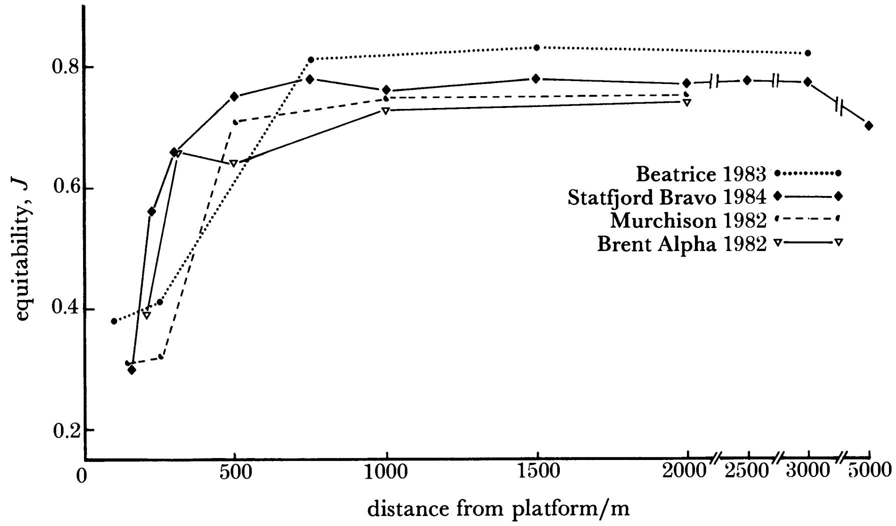

FIGURE 4. Values of Pielou's equitability index (J) with respect to distance from four North Sea oil production platforms.

of data obtained with the variety of sampling methods employed in the studies under consideration here, figures relating to species numbers have been standardized by expressing the number of species for each platform as a percentage of the number recorded at the most distant station. These are presented in figure 5. A full list of the data from which these values were derived, together with information regarding sampling frequency and size of sieve mesh used to separate the fauna from the sediment sample, is given in table 1.

The fact that species richness mirrors diversity is not surprising, although it is clear that it is a more variable parameter. The most important feature of figure 5, however, is the very low numbers of species found at the stations closest to the platforms, particularly at Beatrice and Murchison, where the representation was 16% or less of the value for the most distant station of the transects.

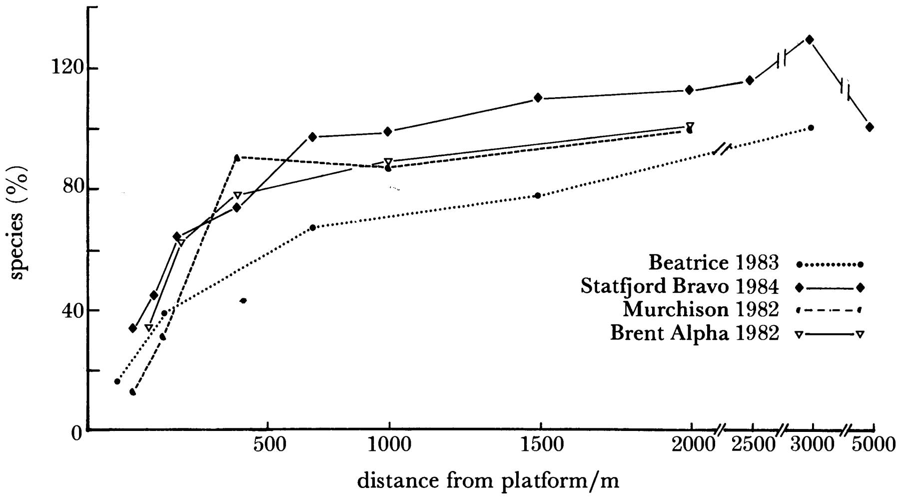

FIGURE 5. Number of species with respect to distance from four North Sea oil production platforms expressed as the percentage of number at the most distance sampling site.

TABLE 1. SUMMARY OF DATA FROM WHICH VALUES IN FIGURES 5 AND 6 WERE DERIVED TOGETHER WITH SAMPLING METHODS AND DRILLING HISTORY INFORMATION

Platform	Brent (1982)		Statfjord Bravo (1984)		Murchison (1982)		Beatrice† (1983)	
first well drilled	1977		1982		1980		1978	
no. of wells drilled	17		13		20		21	
type of drilling mud	diesel		diesel		WBM (3)‡ diesel (17)		WBM (13)‡ LTM (8)§	
sieve size used/mm	0.5		0.5		0.5		1.0	
sampling frequency (per 0.1 m^2)	5		5		5		2	
distance from platform/m	N	S	N	S	N	S	N	S
100	—	—	—	—	—	—	140	19
150	—	—	7590	46	1911	20	—	—
200	5745	60	—	—	—	—	—	—
225	—	—	1923	61	—	—	—	—
250	—	—	—	—	2975	48	416	45
300	2406	86	2274	87	—	—	—	—
500	2679	105	1576	100	2695	138	—	—
750	—	—	2402	132	—	—	661	78
800	—	—	—	—	—	—	—	—
1000	2894	135	2580	134	2621	134	—	—
1200	—	—	—	—	—	—	—	—
1500	—	—	2855	149	—	—	591	91
2000	2852	136	2695	154	2675	154	—	—
2500	—	—	3064	158	—	—	—	—
3000	—	—	3110	177	—	—	—	—
5000	—	—	2347	136	—	—	618	117

† From Addy *et al.* (1984), data for NW transect only.
‡ WBM, water-based mud.
§ LTM, low-toxicity oil-based mud.

If the numbers of individuals are plotted in a similar way a different picture emerges (figure 6). The responses of individual abundances for each of the platforms appear to group into three categories:

(1) platforms where there is an increase in numbers of individuals as the installation is approached (Brent and Statfjord B);

(2) platforms where there is a decrease in numbers of individuals as the installation is approached (Beatrice);

(3) platforms that appear to exhibit an intermediate condition where there is a slight increase in numbers followed by a slight decrease at the innermost stations (Murchison).

In the case of Brent and Statfjord B the response of the individual abundances to the presence of the platform and its activity appears to follow a sequence very similar to that elicited from a point source of organic enrichment (Pearson & Rosenberg 1978).

At Beatrice, the total numbers of individuals are considerably depressed near to the platforms suggesting that conditions are less favourable for the support of the large populations of benthic animals that are able to survive in the vicinity of Brent and Statfjord B.

The situation at Murchison is less clear. At the station closest to the platform (150 m) there were less than 30% fewer individuals than at the most distant stations and at 250 m 10% more (cf. 320% more individuals at the proximal station at Statfjord B and almost 80% fewer at some of the inner stations at Beatrice). This suggests either an intermediate effect or perhaps a transitional condition from one extreme to the other.

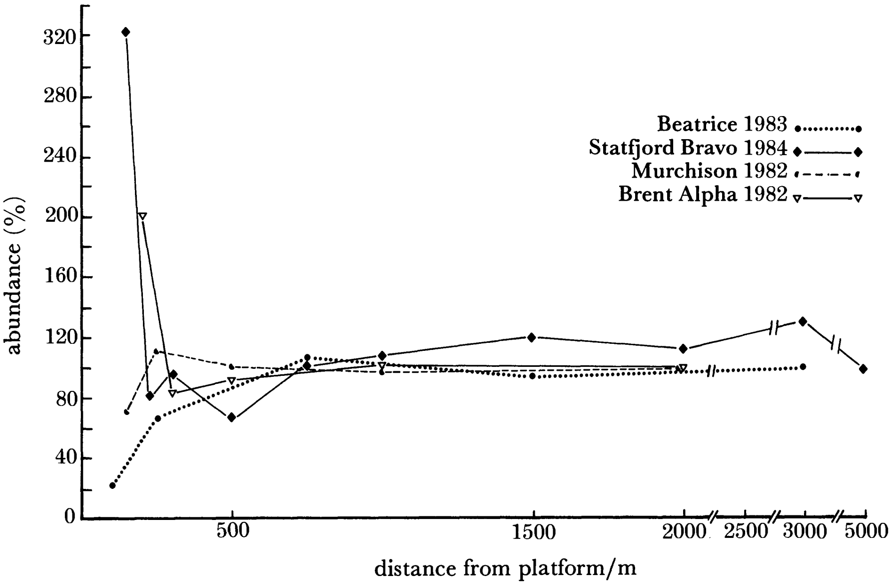

FIGURE 6. Individual abundances with respect to distance from four North Sea oil production platforms expressed as the percentage of the abundance at the most distance station.

Patterns in spatial distribution

The benthic faunal parameters considered so far have dealt in statistical terms exclusively with no regard to individual species identity. Clearly there have been considerable changes in community structure in the vicinity of the production platforms and the question arises whether these responses can be attributed to the same species in each case. In a recent study done at the Statfjord oilfield (Matheson *et al.* 1986) three detailed surveys were done around each of the production platforms Statfjord Alpha, Bravo and Charlie. At the time of the survey, which was conducted in 1984, Statfjord Alpha had a six-year drilling history, Statfjord Bravo had a two-year history and Statfjord Charlie, a concrete gravity platform, had been in place for less than two weeks.

The data obtained were subjected to presence–absence classification analysis using Jaccard's coefficient of similarity:

$$S_J = a/(a+b+c),$$

where a = number of species occurring in both samples; b = number of species occurring in b only, and c = number of species occurring in c only.

The results of the analysis are shown as a dendrogram in figure 7. The stations cluster into five main groups which appear to correspond to two possible environmental régimes:

(1) groups 1 and 2, stations within an area of effect responding to discharges at Statfjord Alpha and Bravo;

(2) groups 3–5, stations unaffected by drilling activity, representing undisturbed communities, each group approximately corresponding to the area around a particular platform.

The validation of groupings 1 and 2 in terms of the community parameters previously discussed is given by Matheson *et al.* (1986). The important point here is that these groups refer to the species identity of the faunal communities at each station and suggest a strong element of similarity between the stations under the influence of platform discharge. Similar

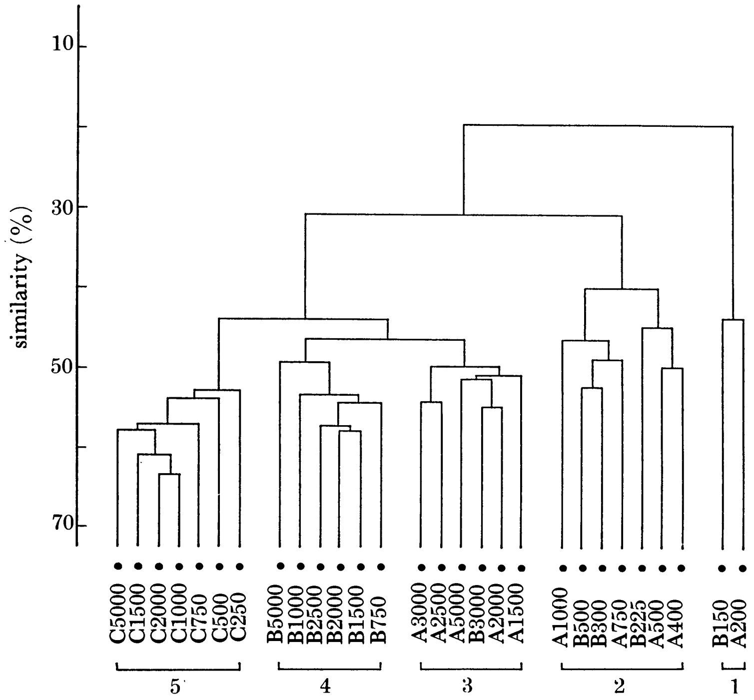

FIGURE 7. Cluster dendrogram using Jaccard's coefficient of similarity on faunal presence–absence data; Statfjord (1984).

patterns of spatial distribution have been demonstrated for many other North Sea installations, for example, Murchison (I.O.E. 1981), Magnus, (I.O.E. 1984*a*), Hutton (I.O.E. 1981), Brent (I.O.E. 1982*a*).

Faunal responses

Table 2 shows the top faunal ranked species from a similar range of stations sampled at Brent Alpha, Murchison and Statfjord Bravo. The data from the proximal station for each platform display two striking features:

(1) the remarkable similarity of the species making up the lists;

(2) the fact that in each case these five species account for between 89–99% of the total numbers of individuals from the station.

It is also apparent from the table that some species are more abundant at the 500 m stations than at either of the others, whereas others reach their maximal numbers away from the platforms. This is illustrated for the Brent Alpha fauna in figure 8.

The three types of faunal distributions more or less conform with the *r*, *T* and *K* strategists suggested by Gray (1979) as adaptive strategies to pollution: *r* strategists are able to mature and reproduce very rapidly and therefore quickly colonize and dominate areas subject to disturbance; *T* strategists are less fecund but are able to tolerate stressful conditions and therefore out-compete less tolerant species: *K* strategists are controlled by the normal forces of interspecific competition.

In this case the *r* strategists are represented by species such as *Capitella capitata*, which is able to switch reproductive modes from pelagic to benthic larvae (Grassle & Grassle 1977), the

Table 2. Top five ranked species from three stations at comparable distances from the Brent (1982), Murchison (1982) and Statfjord Bravo (1984) platforms

Brent			Murchison			Statfjord Bravo		
species	no. per 0.5 m²	cum (%)	species	no. per 0.5 m²	cum (%)	species	no. per 0.5 m²	cum (%)
200 m			150 m			150 m		
1. Ctenodrilidae	3460	60.2	*Ophryotrocha puerilis*	1438	75.2	*Ophryotrocha puerilis*	5176	68.2
2. *Capitella capitata*	760	73.5	*Ophryotrocha* sp.	185	84.9	Ctenodrilidae	948	80.7
3. *Pholoe minuta*	398	80.4	*Spiophanes* sp.	147	92.6	*Capitella capitata*	922	92.8
4. *Ophryotrocha puerilis*	273	85.1	*Pseudopolydora paucibranchiata*	70	96.3	*Pseudopolydora paucibranchiata*	218	95.7
5. *Thyasira* sp.	241	89.3	*Capitella capitata*	54	99.1	*Pholoe minuta*	93	96.9
500 m			500 m			500 m		
1. *Pholoe minuta*	525	19.8	*Exogone verugera*	338	12.5	*Pholoe minuta*	250	15.9
2. *Prionospio cirrifera*	359	33.4	*Caulleriella killariensis*	305	23.9	*Pseudopolydora paucibranchiata*	175	27.0
3. *Thyasira croulinensis*	345	46.4	*Pholoe minuta*	206	31.5	*Ophiura affinis* (juvenile)	114	34.2
4. *T. pygmaea*	299	57.7	*Spiophanes* sp.	204	39.1	*Exogone verugera*	104	40.8
5. *T. succisa*	217	65.9	*Pseudopolydora paucibranchiata*	111	43.2	*Glycera capitata*	71	45.3
1000 m			1000 m			1000 m		
1. *Thyasira croulinensis*	367	12.8	*Exogone verugera*	241	9.2	*Exogone verugera*	247	9.6
2. *T. pygmaea*	279	22.5	*Glyphanostomum macroglossum*	184	16.2	*Pholoe minuta*	224	18.3
3. *T. succisa*	233	31.0	*Protodorvillea kefersteini*	171	22.7	*Pseudopolydora paucibranchiata*	179	25.2
4. *Myriochele* sp.	188	37.6	*Spiophanes* sp.	164	29.0	*Ophiura affinis* (juvenile)	170	31.8
5. *Pholoe minuta*	179	43.8	*Caulleriella killariensis*	146	34.6	*Glycera capitata*	142	37.3

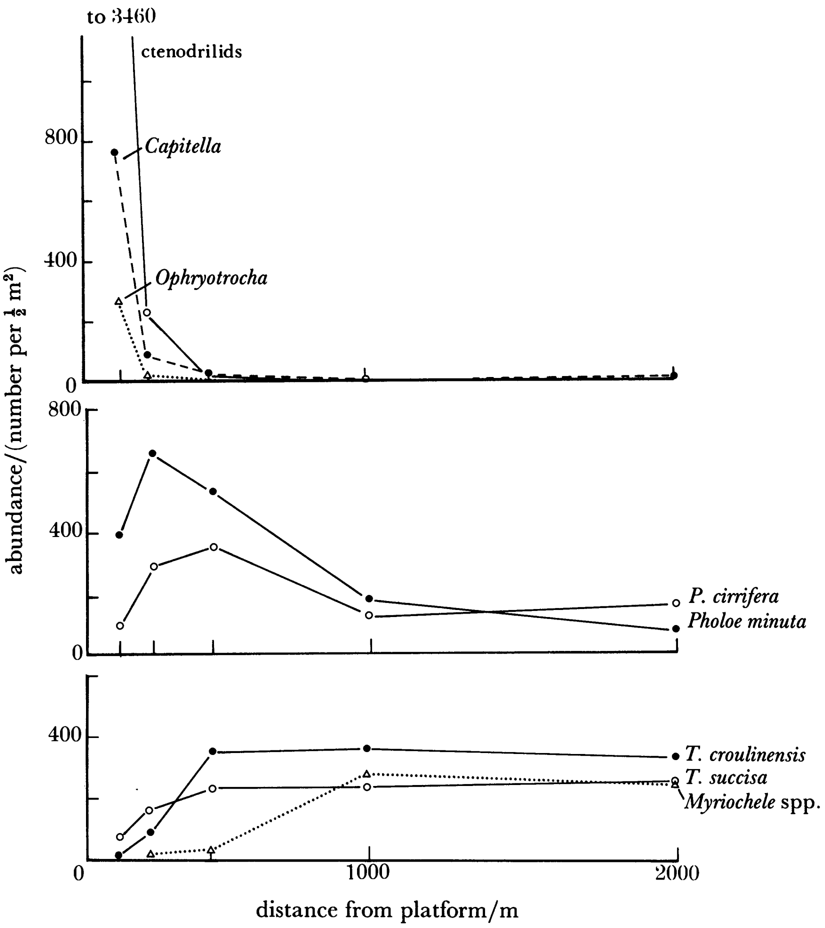

FIGURE 8. Selected examples of three types of abundance variations of benthic species under the effects of disturbance (from Kingston 1983).

Ctenodrilidae, which are able to reproduce vegetatively by fragmentation (Fauvel 1927), or *Ophryotrocha* which is able to change its mode of reproduction to suit local conditions (Åkesson 1973). The *T* strategists are possibly represented by species such as *Pholoe minuta*, *Prionospio cirrifera* (Brent, Alpha), *Pseudopolydora paucibranchiata* (Murchison and Statfjord Bravo) and other species not represented in the top five rankings. These species may be interpreted as being tolerant of slight pollution and are able to increase in numbers by filling the niche vacated by the more sensitive species. The *K* strategists include most of the remaining species which are unable to compete where there is environmental stress and so decrease in numbers as the platform and its point source of contamination are approached.

DISCUSSION

It cannot be denied that the installation and operation of an oil production platform will have a profound effect on the benthic environment in its immediate vicinity. The mere act of placing a structure on the seabed will disturb its inhabitants. The dumping of material whether inert or toxic is bound to result in the physical destruction of the communities underneath. The important questions here concern the spread, toxicities and persistence of the discharge.

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Zones of effect

There is plenty of evidence that the zones of effect are quite limited in their extent and that disruption of the biological system may extend no further than 500–1000 m from drilling platforms where there is a point source of contamination (see figure 7; Davies *et al.* 1984; Addy *et al.* 1984). Whether these zones have stabilized or not is open to question. It could be argued that the observations thus far reported represent only a transitory phase on a route to more widespread environmental damage. It is certainly true that the longer a drilling platform has been in operation, the wider the affected area. Matheson *et al.* (1986) demonstrated this for the Statfjord Field. Here the zone of biological effect, confined to 500–750 m at the Bravo platform with its two-year drilling history, was significantly greater (750–1000 m) at the Alpha platform, at which drilling had been taking place for six years.

In the case of the Statfjord installations comparisons of zones of effect may be made with a reasonable amount of confidence because the platforms are geographically very near to one another and are subjected to broadly similar hydrographic conditions. However, platforms in different localities and run by different operators will, in addition to a range of drilling histories, have widely differing spread characteristics of cuttings based upon local tidal flow, height of discharge chute and nature of discharge. To attempt to establish generalized zones of effect based upon data subject to such a range of variables inevitably must lead to zones of such wide overlap as to be of little practical use. However, in none of the studies cited here has there been any detectable deleterious effects on the benthic communities outside 1000 m from the platform. In most cases community parameters return to background values soon after 500 m.

Toxicity of discharges

The toxicity of drilling cuttings arises principally from the use of oil-based drilling muds and the considerable quantities of base-oil that adhere to the cuttings after they are dumped. Diesel-oil was used as the original base-oil in these muds because it was readily available and cheap. The final washed cuttings that were discharged to the seabed may have contained 6–17% by mass diesel-oil (Blackman & Law 1981). Diesel contains a relatively high concentration (20–30%) of low molecular mass aromatic substances and is known to be toxic to marine organisms. Recent concern in the United Kingdom over the effect these diesel oil-based drilling muds might be having on the seabed environment has culminated in United Kingdom Government legislation to control the use of oil-based drilling muds and to encourage the use of low aromatic content base-oils (the so called 'low toxicity' base-oils). The United Kingdom legislation prohibits the discharge of whole muds, requires the use of efficient solids-control equipment for low-toxicity muds and specifies additional treatment equipment where diesel-based muds are used. Similarly in Norway the discharge of whole oil-based muds is forbidden. The State Pollution Control Authority (S.P.C.A.) must approve the installation's treatment systems for oil-contaminated cuttings. The S.P.C.A. classify drilling muds as toxic (e.g. diesel-base) moderately toxic (e.g. low aromatic oil-base) and low toxic (e.g. water-base) using acute toxicity tests. In Denmark diesel-based mud has been used on only one occasion and cuttings were brought ashore for treatment and disposal. Drilling with low aromatic oil-base mud has been permitted on an experimental basis for the development of the Dan and Tyra fields. In Denmark, permits for drilling using a specific mud system are granted only on a case by case basis. In the Netherlands provisional approval has been given to the use of oil-based muds containing less than 5% aromatics by mass providing they meet specified toxicity-test requirements. These, and controls over discharges of contaminated cuttings, are provisional and under review. The effect has been an almost total switch from diesel-base to the use of low toxicity oil-base muds in the North Sea.

Community parameters such as diversity, equitability and species richness have been shown to respond quite dramatically to the influence of discharge of drill cuttings both for the oilfields considered here (figures 3–5) and at other parts of the North Sea (Davies *et al.* 1984).

If this response is then related to total levels of hydrocarbon in the sediment a very strong negative correlation can be demonstrated. An example is shown in table 3. This is not surprising when the concentrations of hydrocarbons in the sediment relative to distance from the platforms is considered. Figure 9 shows such values from several North Sea oilfields, following a trend that is the inverse of that found for species richness and diversity (Davies *et al.* 1984). However, the use of such community parameters tell us little about the nature of the cause of effect. A drop in diversity, for example, could equally well be signalling toxicity or organic enrichment because responses of both conditions could lead to a drop in number of species with an increase

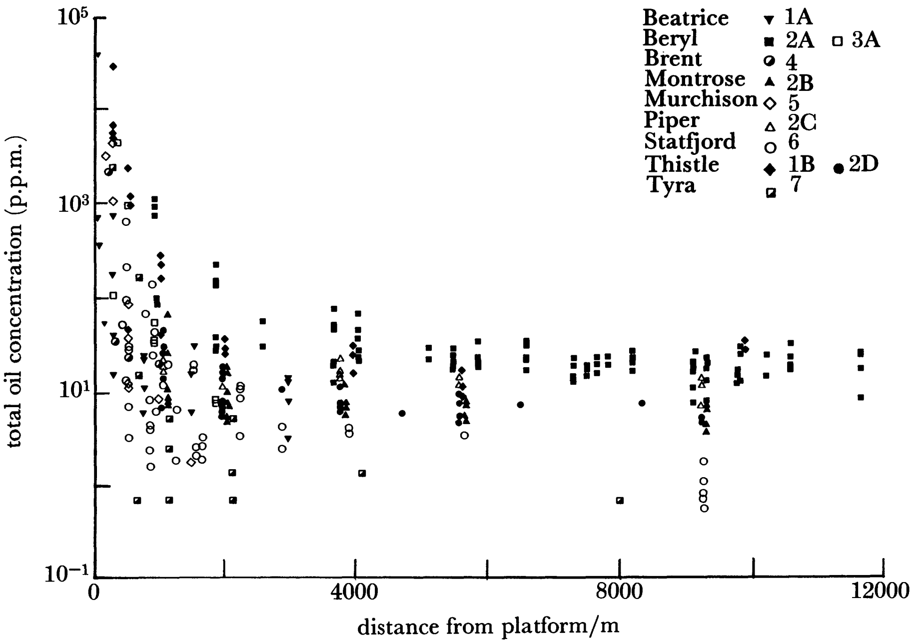

FIGURE 9. The concentration of total oil related to distance from a production platform (from Davies *et al.* 1984).

TABLE 3. VALUES OF PEARSON'S PRODUCT MOMENT CORRELATIONS FOR DIVERSITY ($H_{(S)}$), NUMBER OF SPECIES (S) AND NUMBERS OF INDIVIDUALS (N) WITH RESPECT TO THE PERCENTAGE ORGANIC AND TOTAL OIL CONTENT OF SEDIMENTS AROUND STATFJORD ALPHA AND BRAVO PRODUCTION PLATFORMS

	Statfjord Alpha			Statfjord Bravo		
	% org.	total oil IR	total oil UV	% org.	total oil IR	total oil UV
$H_{(S)}$	−0.852	−0.76	−0.916	−0.346	−0.928	−0.948
S	−0.756	−0.755	−0.880	−0.183	−0.827	−0.817
N	0.761	0.982	0.884	0.327	0.763	0.827

in dominance of opportunistic or pollution tolerant forms. Change in diversity is thus a good measure of environmental disturbance and little more. Pearson & Rosenberg's (1978) classical response to organic enrichment will not apply if the levels of toxic substances prevent the opportunistic species from thriving. Rygg (1986) has shown that in Orkdalsfjorden, where heavy metal contamination from effluents has a toxic effect, populations, as one might expect, are diminished. Thus, one might expect an increase in the total number of individuals where organic pollution dominates environmental insult and a reduction where toxicity is the more important factor.

Figure 6 shows that both types of response can be recognized around North Sea production platforms. The interesting feature of the figures, however, is that the organic enrichment effect appears here to be associated with the use of diesel oil-based muds (Brent A and Statfjord B) and the 'toxic effect' with the use of 'low toxicity' oil-based muds (Beatrice).

Blackman *et al.* (1983) have shown that most 'low toxicity' base-oils are at least an order of magnitude less toxic than the diesel equivalent when appraised using the brown shrimp, *Crangon crangon*, in 96 h LC_{50} tests. However, the results they obtained were very variable, the measured differences in their toxicity being attributed to normal experimental variability. Not only did Blackman *et al.* (1983) find that the alternative base-oils were less toxic, but also that the toxicity of the base-oils varied much more than that of the muds which were formulated from them. In addition, the toxicity of the drilling mud with the base-oil added was lower than that of the base-oil alone. They concluded that the acute toxicity of the base-oil and the drilling mud formulated from it bore no strict relation, even when the same manufacturer's mud-solids formula is used with a range of different oils.

This suggests a certain element of unpredictability in the performance of an oil-based mud in the field regardless of the base-oil used and might go some way to explaining why the field observations on faunal response are at variance with laboratory evidence based on *Crangon crangon* 96 h LC_{50} toxicity tests.

Persistence of contaminating oil

It is only relatively recently that the question of persistence of the toxic effects of discharged drilling cuttings, in the context of North Sea operations, has been addressed with any seriousness. The rate at which degradation of the toxic components of the discharge takes place will affect, not only how quickly the area returns to normal after drilling stops, but also how far the toxic effects will spread. Most of the evidence presently available comes from exprimental work. This is hardly surprising because there are few developments in the North Sea where drilling activity has ceased altogether.

The large numbers of individuals recorded close to the production platforms at some oilfields investigated indicate that there is considerable biological activity regardless of the potentially toxic nature of the discharges. The enhanced number of individuals of macrofauna at the innermost stations at Brent A (see figure 6) is also reflected in the values for standing crop biomass which increase dramatically at this station (figure 10). While this reinforces the notion that the benthic fauna is responding to organic pollution at this site, it can also be inferred that considerable biodegradation of the contaminating oil might be taking place because it is difficult to see where else the energy required to sustain the dense populations would be coming from. Brent A is one of the few studies in which biomass determination has been undertaken (I.O.E. 1982*a*).

The standing crop biomass value of just under 5.0 g m^{-2} ash free dry weight (AFDW) is not

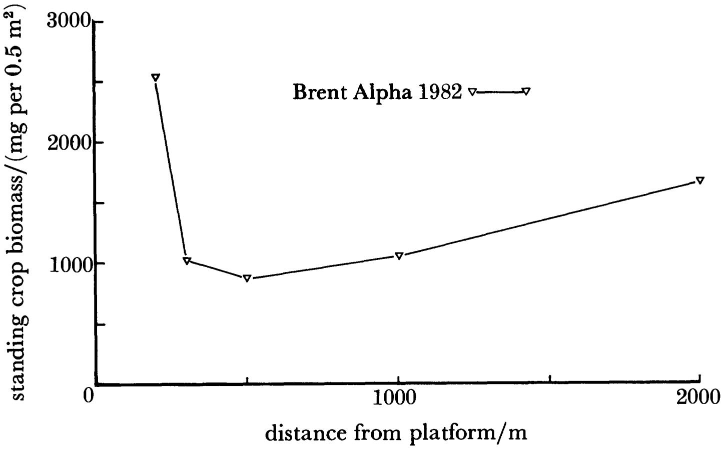

FIGURE 10. Changes in standing crop biomass with respect to distance from Brent A platform (totals for up to ten species ranked by biomass (I.O.E. 1982*a*)).

particularly high compared with other North Sea muddy bottom habitats (Buchanan & Warwick 1974; Rachor 1982; Creutzberg *et al.* 1984). However, it must be remembered that, unlike these unpolluted areas, the members of the fauna immediately around the production platforms are composed almost exclusively of small species the majority of which have individual AFDWs of less than 0.1 mg. Most of the species were earlier identified as the opportunistic species associated with organic pollution and as such are characterized by having very rapid population turnovers. Small species with short life cycles may have very great production/biomass (P/B) ratios. Values of 14 have been reported for some species of *Ophryotrocha* (Tennant 1984).

It is unfortunate that so few data exist regarding the distribution of biomass around the production platforms because the relevance of this to the eventual fate of the discharged material cannot be overemphasized. For approximate comparison, biomass values for the 200 m station at Statfjord Alpha have been prepared from individual abundance data and applying the biomass values for the principal species obtained from the 1982 Brent A study. Values for the Beatrice platform have also been prepared, this time by simply multiplying the individual abundance figures by the mean AFDW of *Capitella capitata*, because this species accounted for up to 98% of the individuals at the inner stations (Addy *et al.* 1984). The results are given in table 4. If the P/B ratio values for *Ophryotrocha* are applied to the biomass values obtained at Statfjord Alpha (it was the most abundant species at 200 m at over 16000 per 0.5 m^2) then possible annual production rates of over 40 g m^{-2} per year can be expected for

TABLE 4. BIOMASS OF TOP FIVE SPECIES (RANKED BY ABUNDANCE) FROM BRENT A AND BIOMASS ESTIMATES† FOR STATFJORD ALPHA AND BEATRICE DERIVED FROM BRENT BIOMASS VALUES FOR INDIVIDUAL SPECIES

platform	distance/m	biomass/(mg m^{-2})	% organic	sieve size/mm
Brent A	200	2379	1.94	0.5
Statfjord A	200	3270†	1.22	0.5
Statfjord A	200	516†	1.22	1.0
Beatrice‡	65–100	66–221†	*ca.* 10–5	1.0
Beatrice‡	250	50–166†	*ca.* 1	1.0

‡ Original figures from Addy *et al.* (1984), values for SSW and NNE transects given.

the top three opportunists alone. This is over 20 times the production rate reported by Buchanan & Warwick (1974) for a muddy bottom community off the Northumberland Coast.

Regardless of the fact that the only oil-based muds used at Beatrice have been of the 'low toxicity' type (Addy *et al.* 1984), derived values indicate that the standing crop biomass of macrofauna around this platform is less than that around the installations where diesel-based muds have dominated drilling activity. Such a response could be explained if the relative toxicity of the two types of drilling mud is not the main factor in determining the biodegradability of the hydrocarbon content of the cuttings. There is an increasing amount of evidence to support this contention.

Blackman *et al.* (1983) reported 'the formation of heavy algal and some fungal mats on the sediment surface' of some of the test tanks used for settlement trials. One of these was a tank containing diesel. Gillam *et al.* (1986) have shown that one of the organisms responsible for these surface mats, *Streptomyces* sp., is twice as efficient as utilizing diesel than it is at utilizing 'low toxicity' base-oil at diesel concentrations of less than 3% by volume. They go on to suggest that, although potentially more toxic than the more refined base-oils, diesel-oils may possibly be broken down at a greater rate in the marine environment owing to the greater diversity of potential carbon sources provided by the more complex diesel-oil.

The evidence presented here has suggested that, at least in the case of Brent A and Statfjord Alpha, macrofaunal activity of a few opportunistic species has been greatly enhanced by the use of diesel-based drilling muds when compared with the results obtained by Addy *et al.* (1984) for the Beatrice oilfield at which 'low toxicity' drilling muds were used.

There is simply not enough evidence available yet to enable firm conclusions to be reached regarding the cause of the drop in number of individuals near this installation. The high levels of organic matter in the sediments immediately around the platform suggest that not only is there very little physical spread of cuttings but also that the rate of dispersion–breakdown of the oil is too slow to prevent accumulation taking place. In addition, the less stringent washing treatment of cuttings, required when dealing with 'low toxicity' oil-based muds, may lead to greater amounts of oil finding its way to the seabed. Similar decreases in individual abundance have been observed around other North Sea platforms using 'low toxicity' drilling muds exclusively (I.O.E. 1986), but without the enhanced organic matter levels reported by Addy *et al.* (1984) for the Beatrice platform. Similarly, decreases in individual abundance (although not so severe) were found at Murchison (see figure 6) where, up to the time of the survey diesel muds had been used. Again organic matter levels in the sediment here, at approximately 1%, were a fraction of that at the Beatrice platform.

It is likely that there are a variety of factors determining the size of populations that a cuttings pile and the immediate environs can support, not least in the total formulation of the drilling mud. The use of low-toxicity base-oils may avoid the aromatics found in the diesel, but the increased amounts of mud, as opposed to cuttings, that are likely to be deposited as a result of less stringent cleaning treatment requirements may mean that other mud additions become limiting.

The markedly patchy distribution of drilling cuttings on the seabed around the production platforms calls into question the sampling strategies that have been adopted for offshore surveys in the past, and indeed at the present. The extreme variation of figures, particularly hydrocarbon concentrations in sediments close to the platforms (see table 5) makes it very difficult to establish firm correlations between cause and effect.

The presently accepted standard of taking single samples to estimate levels of hydrocarbons

TABLE 5. CONCENTRATION OF TOTAL OIL (IR) IN RELATION TO DISTANCE FROM FIVE NORTH SEA OIL PRODUCTION PLATFORMS (MICROGRAMS PER KILOGRAM)

sampling	Brent		Murchison		Stafjord Alpha		Statfjord Beta	
distance/m	1	2	1	2	1	2	1	2
100–200	344	1993	2993	4387	52777	1314	2838	832
250–300	84	33	1050	535	4541	2182	1439	1344
500	23	22	12	11	2221	2412	80	22
800–1000	13	19	8	11	164	209	227	42
2000–2500	19	19	6	6	19	24	19	27

in the sediments in the vicinity of the cuttings pile is very unsatisfactory. The use of duplicate samples for estimating macrofauna in such variable conditions is equally dubious. The effects of drilling cuttings have clearly been shown to be highly disruptive to the seabed environment but at the same time very localized. The need to design monitoring studies to detect environmental disturbance in the very inner areas is really no longer necessary, if indeed such studies ever were. However, two aspects do remain of concern:

(1) the possible continued spread of effects;

(2) the rate of hydrocarbon degradation.

Both are interconnected in that a sustained high level of hydrocarbon degradation will restrict the area eventually affected.

Future approaches to monitoring the seabed around production platforms should now be concentrated on the persistence of the oil in the cuttings as well as maintaining a watchful eye over spread effects. Sampling strategies should focus on determining the degree of biological activity close to the platform with the aim of monitoring rates of biodegradation of the base-oils of the various mud formulations.

I am very grateful to the members of the benthic section at the Institute of Offshore Engineering who contributed to the studies described here. In this respect I particularly thank Dr Hamish Mair and Mrs Susan Hamilton. I am also grateful to Professor Cliff Johnston, Jonathan Side and Iain Matheson for helpful discussions and advice during the course of the work and preparation of this paper. Finally my thanks to Conoco (North Sea) Inc., Shell Exploration Ltd and Mobil (Norway) (on behalf of Statfjord Owners) for commissioning the studies described here and allowing the publication of the data.

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Discussion

Lynda M. Warren (*Department of Life Sciences, Goldsmiths' College, London. U.K.*). At least two of the genera of polychaetes recorded from areas close to production platforms form species complexes of morphologically very similar species distinguished mainly on ecological and physiological characteristics. Are there any indications that the species of *Capitella* and *Ophryotrocha* found vary either with distance from the platform, and hence degree of organic enrichment, or with length of time since the original disturbance? Both genera are commonly associated with unstable environments and it would be surprising if the population structures remained constant for very long. An analysis of the species composition at various sites and over a period of time might provide far more useful information concerning small changes in the environment than is available from data referring to genera only.

P. F. Kingston. Although we are aware of the existence of species complexes in *Capitella* and *Ophryotrocha*, we have not been able to distinguish between species by using ecological and physiological characteristics at the level of taxonomic resolution used here. To undertake the analysis Dr Warren proposes would be most interesting but presently is not practical given the sampling frequency of current monitoring studies.

R. G. Hughes (*School of Biological Sciences, Queen Mary College, University of London, U.K.*). Dr Kingston has related the decline in diversity and number of species only to the oil-based discharge close to the platforms. Is there any effect on these statistics of the sometimes considerable 'rain' of fouling organisms that are periodically scraped off the supporting structures and accumulate underneath the platforms?

P. F. Kingston. Enhanced productivity resulting from debris from fouling organisms has been demonstrated around offshore platforms. The best evidence for this comes from the Gulf of Mexico where productivity is very high and the water shallow (mostly less then 40 m depth). It is unlikely that in the central North Sea, where the average depth around production platforms is 100 m, that a significant amount of material from this source accumulates around the base of the structure. There is no evidence that organic material accumulating from fouling organisms has any measurable effect on the gross perturbation of benthic community structure by drilling cuttings.

R. Earll (*Marine Conservation Society, Ross on Wye, Herefordshire, U.K.*). I have two questions for Dr Kingston. Firstly, I was interested to hear Dr Kingston's comments about the bacterial mats, methanogenesis and fish farms. Could he say whether he finds animals living under or in the bacterial mats. Secondly, most people will be aware of the recent observations which have been made concerning the anoxic areas of seabed off the German coast. How would he compare the effects of oil installations on the benthos (in terms of areas covered or affected or both) with what we know about the areas affected by these anoxic events?

P. F. Kingston. To answer Dr Earll's first question, in our experience the areas directly under fish cages used on fish farms have been devoid of macrofauna. Secondly, the anoxic areas of the seabed off the German coast are caused by a variety of factors which include the high amount or organic loading originating from the Rhine, Elbe and other sources and the frontal areas occurring in the region which result in poor mixing and stratification of the water column. The anoxic conditions around oil production platforms are confined to the sediments and the area of effect is insignificant by comparison.

R. Earll. I am interested to hear Dr Kingston confirm the impression obtained from survey work on Western Isles fish farms.

J. G. Parker (*Shell Exploration and Production, Aberdeen, U.K.*). Firstly, what was the purpose of replicate sampling in the macrobenthos programme, given that samples were pooled for the subsequent numerical analysis? Secondly, does Dr Kingston have any sympathy for the view that when examining variability in benthos over a gradient it is better to take single closely spaced samples rather than replicated samples from sites located further apart?

P. F. Kingston. The sampling strategy adopted in the studies described here reflect what is practical when working offshore rather than what is ideal. Replicate samples are taken to enable estimates of individual abundance of benthic species to be obtained with an acceptable degree of precision. Benthic macrofauna is characteristically contagiously distributed and theoretically the size and number of the unit samples should reflect the degree and scale of contagion. However, offshore conditions place a considerable restraint on the number of hauls that may be made per site and the paucity of suitable benthic samplers place a further restraint on the size of the unit sample.

Experience has shown that five samples from each site using a 0.1 m^2 grab will generally yield species abundance curves for benthic data that begin to approach their asymptote. In addition, values for commonly used diversity measures also begin to approach their maximal values for North Sea benthos at this frequency per unit area of sampling. It is not usual to pool replicate benthic samples prior to enumeration of the fauna. The data here have been pooled after sample analysis where sample area is important in the stabilization of the community parameters used.

In answer to the second part of the question, the use of single, closely spaced samples in gradient analysis may be appropriate when monitoring a homogeneous benthic environment and a point source of contamination. However, sample variability resulting from the contagious distribution of benthos around production platforms and the patchy nature of the drill cuttings piles favour the approach of using replicate samples from discrete stations along a transect.

J. S. Gray (*Department of Marine Biology, University of Oslo, Norway*). Given the spatial variability that Dr Kingston records, and the clearly different benthic communities along the gradient from platforms, I would have thought that one could eliminate the need for grab sampling, sorting, identification and counting by using remote camera systems. There is a commercial system available and tested which gives rapid analysis (in minutes) and should give similar precision at less cost (see Rhoads & Germano 1982).

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