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Impact of offshore oil production installations on the benthos of the North Sea

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Input of contaminants into the sea associated with offshore oil drilling and production include accidental spillage, discharge of cuttings and discharge of production water. Of these, oil discharged on drilling cuttings is by far the greatest source of oil pollution in the North Sea from these operations, having peaked in 1985 at 25 880 tonnes. The response to the seabed fauna to these inputs has been shown to follow established patterns in which there may be high individual abundance of a few species close to the source of contamination (organic enrichment effect) or a reduced number of individuals with few species close to the installation (smothering or toxic effect). Diversity shows a similar pattern to species richness, both are low in the immediate vicinity of the installation and, in most cases, attaining preoperational levels within 2000. High levels of hydrocarbon contamination have also been shown to be concentrated around installations. There are indications that a fall in diversity can be expected when total hydrocarbon concentrations in the sediment reach 50–60 ppm. There is also increasing evidence to suggest that for some areas where there has been intensive drilling/production activity (e.g. Shetland Basin), there has been a significant rise in hydrocarbon levels in the sediment at distances between 5 and 10 km from installations.

Key words: oil pollution; benthos; North Sea; oil production platforms; environmental impact; hydrocarbon contamination.

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Introduction

The North Sea hydrocarbon producing industry began in 1959 with the discovery of the Groningen onshore gas field by Shell in the Netherlands. Exploration wells drilled in England revealed similar rock strata indicating that large hydrocarbon reservoirs could exist in the southern basin of the North Sea. The West Sole gas field was the first significant discovery and the first gas brought ashore in 1967. Continued exploration of the Southern Basin showed that the hydrocarbon accumulations were predominantly gaseous and exploration activities moved farther north to the central North Sea and the East Shetland Basin. Discoveries of exploitable oil reserves quickly followed, the first being the Ekofisk field in the Norwegian Sector in 1969 followed by Montrose (1969), Forties (1970) and Brent (1971) in the UK Sector. The first oil discovered in the Danish Sector was at the Dan field (1971). Since then there has been a proliferation of developments with over 150 installations currently in place.

Major inputs associated with drilling and production

Input of material into the sea associated with offshore drilling and production include:

(1) accidental spillage,
(2) discharge of drill cuttings,
(3) discharge of production water.

Discharged drilling cuttings are by far the greatest source of oil finding its way to the seabed of the North Sea. The oil comes from the mud used to lubricate the drilling bit, to carry cuttings to the surface and to control reservoir pressure. Originally, these muds were in aqueous suspension, later, oil was used to replace the water because of its greater suitability for drilling through North Sea rock strata. These contain shales, clay stones and salts which either soften and swell or dissolve in aqueous solution causing sticking of the drill strings or collapse of the well.

Figure 1 shows the quantities of oil on cuttings discharged since 1981. Diesel oil was extensively used as a

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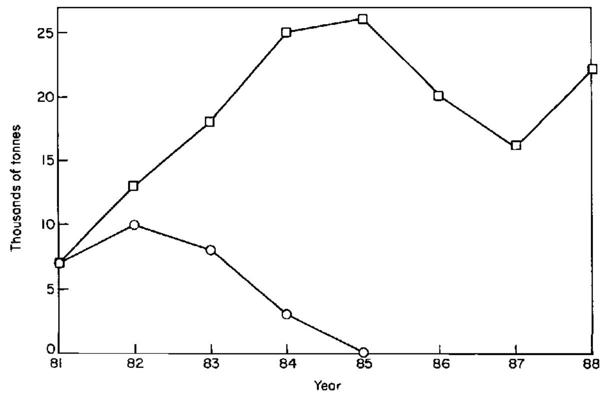

Figure 1. Quantities of oil discharged to the North Sea sea bed on drilling cuttings (PARCOM, 1991). —□— = total oil, —○— = diesel only.

drilling mud base oil prior to 1985 because of its low cost and availability. After this, it was replaced with base oils in which the aromatic components had been removed. These were shown to be less toxic using standard 96-h LD_{50} toxicity tests on *Crangon* (Blackman *et al.*, 1982).

The discharge of oil with drilling cuttings appears to have peaked in 1985 with a recorded 25 880 tonnes in that year. In 1986 and 1987 the fall in oil price led to a reduction in activity but this subsequently recovered. The concentration of oil with cuttings should reduce in the future as stricter limits are set by more and more North Sea states.

Production water is made up of formation water (the water associated with oil in the reservoir) and from breakthrough of water injected into the reservoir to maintain pressure and oil production. As the oil field ages, more and more water is produced relative to the oil recovered. At present, approximately 4500 tonnes of oil are discharged to the sea per year through this medium (PARCOM, 1991). Accidental oil spills contribute relatively small quantities of oil to the overall total discharged to the North Sea. Although spills are frequent (250 were recorded by the UK Department of Energy in 1987 alone) they are usually less than one tonne. The spills generally result in a sheen in the water around platforms and can be detected by aerial surveillance.

Environmental monitoring approach

The seabed of the North Sea is essentially a sedimentary habitat. The biological communities that live there are composed largely of infauna which live within the sediment and are heavily reliant upon it as a food source. Most infauna are relatively immobile and are thus potentially very vulnerable to the effects of sediment contamination. Monitoring for marine environmental effects of offshore oil developments has, as a consequence, focused on identifying changes in benthic community structure.

In the early days of North Sea oil development, attempts were made to predict the area of potential environmental damage to establish relevant 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 and production and formation water (Department of the Environment, 1976). No emphasis was placed on the discharge of drilling cuttings since, at that time, the use of oil-based muds was not anticipated. Few studies had sampling stations within the 500 m prohibited zone that had been set up to protect the installations.

After the first exploration phase when the production platform became operational, it was soon realized that the major effects on the environment were going to be very localized and so sampling strategy switched from a wide grid approach to transects which originated very close to the platforms following the line of prevailing bottom currents. The most common approach currently used is to sample the seabed by 0.1 m^2 area grab sampler at stations placed, 200, 500, 800, 1200, 2500 and 5000 m from the installation. The sediment is sieved through either 0.5- or 1.0-mm mesh aperture sieves and the retained material analysed at the laboratory. Samples for physical and chemical analysis of the sediments are taken at the same time (Kingston, 1987).

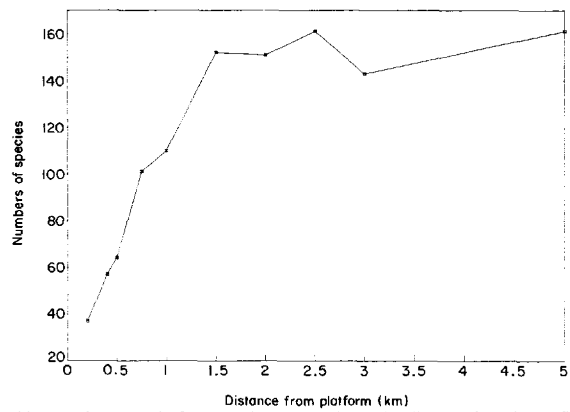

Figure 2. Number of benthic macrofaunal species from sample stations at increasing distances from the Statfjord Bravo oil production platform 1984 (from Matheson *et al.*, 1986).

Biological impacts

The effect of discharging a large quantity of solids on to the seabed will have an immediate effect on the benthos directly underneath. Most monitoring surveys have been concerned with measuring the intensity of this impact and the spread of its effect. Typically, species richness falls the nearer a production platform is approached (Fig. 2). This is to be expected since it reflects the increasing gradient of disturbance towards the point of cuttings discharge.

Diversity indices, such as the Shannon–Wiener index (H_s) (Shannon and Weaver, 1963), have long been used as a measure of environmental health. The theory behind their use is based on the premise that communities with high diversity result from less environmental stress than those with low diversity. The validity of this assumption has often been questioned. However, where gross pollution is involved, such a measure appears to be quite useful for comparative purposes (Kingston, 1987).

Diversity, which is greatly influenced by species richness, follows a similar response pattern. Pre-operational levels of the Shannon–Wiener Index (H_s), one of the most commonly used indices, varies between 4.0 and 6.0 in the northern and Central North Sea (Kingston, 1987). Figure 3 gives combined data for surveys carried out between 1982 and 1988 and shows that the relationship between macrobenthic diversity and distance from a production platform has differed little over the years. To equate the H_s values obtained from a range of monitoring studies using different sampling and analytical techniques, the diversity has been expressed as a ratio to "background" levels in the area. For the most part, "background levels" are reached for all installations within 1500 m suggesting that the extent to which the benthic community structure is disrupted, as defined by H_s is confined to a relatively small area around each platform. However, within this zone there is a rapid drop in H_s, reflecting gross disturbance near the installations.

Whilst the response of species richness and diversity is similar around all installations, the number of individuals shows at least two types of response (Fig. 4). The most common response is an increase in individual abundance towards the source of pollution. Table 1 shows the top five ranking species from two transects, from two production platforms in the Statfjord field. Statfjord Alpha has been in place 6 years, during which time 27 wells had been drilled using oil-based drilling mud. Statfjord Charlie, a concrete gravity platform, was placed in position a few days before the survey (Matheson *et al.*, 1986). This type of response is indicative of a predominant organic enrichment effect with huge numbers of individuals representing relatively few species. This suggests that the material being discharged is relatively non-toxic and is being degraded by the sediment biota.

Figure 4 also shows a response in which the number of individuals falls in the vicinity of the platform. This suggests that the discharged material is inhibiting the growth and survival of the macrofauna. Such a response could be the result of physical smothering very close to the installation. However, at distances greater than 100 m, it is more likely to have resulted from a direct or indirect toxic effect (Kingston, 1987).

Diesel oil, once widely used as a base oil, is now banned on the basis of the toxicity of its high aromatic hydrocarbon content. Since 1985, there has been exclusive use of more highly refined, low aromatic base oils (see Fig. 1) which should theoretically have had less impact on the seabed environment. In practice, however, the switch to

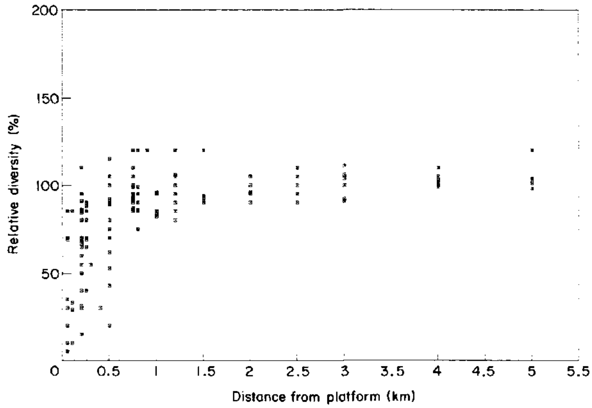

Figure 3. Relationship between benthic faunal diversity (H_s) and distance from production platforms for several North Sea installations.

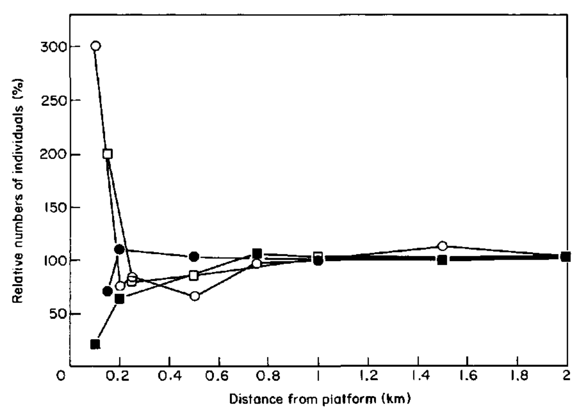

Figure 4. Relationship between number of macrofaunal individuals and distance from production platform for Statfjord Bravo (1984), Brent Alfa (1982), Murchison (1982) and Beatrice (1983) expressed as the percentage of the abundance at the most distant station (Kingston, 1987). —■— = Beatrice 83, —○— = Statfjord B. 84, —●— = Murchison 82, —□— = Brent A. 82.

the so-called "low toxicity" drilling muds made little difference (Kingston, 1987; Reiersen *et al.*, 1989). Figure 5 shows the total numbers of individuals at Statfjord B where diesel base muds were used almost exclusively (Matheson *et al.*, 1986) and Statfjord C, where low aromatic muds were used exclusively. Both platforms had been operational for between 2 and 4 years when these results were obtained. Both show a classical organic enrichment effect.

Relationship between oil contamination and diversity (H_s)

There is a strong inverse relationship between diversity (H_s) and concentrations of oil in the sediments. Figure 6 shows the combined data for two North Sea oilfields (Matheson *et al.*, 1986; Mair *et al.*, 1987). Reductions in diversity appear to begin around hydrocarbon concentrations of 50–60 ppm. Other authors suggest a wider

Table 1. Top five ranking taxa for each station (0.5-mm sieve), Statfjord Field, June 1984 (after Matheson *et al.*, 1986).

	No/0.5 m^2	Cumulative (%)		No/0.5 m^2	Cumulative (%)
Alpha 200 m			Charlie 250 m		
Ophryotrocha puerilis	16 855	55.3	*Ophiura affinis* juv	187	9.7
Raphidrilus sp	13 569	96.5	*Modiolus phaseolinus* juv	145	17.2
Capitella capitata	881	98.9	*Yoldiella tomlini*	97	22.2
Pseudopolydora paucibranchiata	131	99.4	*Glycera capitata*	92	27.0
Cirratulus cirratus	33	99.5	*Lima subauriculata*	81	31.2
Alpha 500 m			Charlie 500 m		
Raphidrilis sp	3649	42.9	*Modiolus phaseolinus*	540	16.2
Ophryotrocha puerilis	2033	66.9	*Exogone hebes*	213	22.6
Capitella capitata	1852	88.7	*Lima subauriculata*	149	27.1
Chaetozone setosa	319	92.4	*Glycera capitata*	146	31.4
Pseudopolydora paucibranchiata	119	93.8	*Macandrevia cranium* juv	136	35.5
Alpha 1500 m			Charlie 1500		
Exogone verugera	274	10.4	*Ophiura affinis* juv	397	14.3
Pholoe minuta	222	18.6	*Exogone hebes*	192	21.2
Caulleriella alata	216	26.7	*Modiolus phaseolinus* juv	153	26.7
Oligochaete type	185	33.6	*Lima subauriculata*	152	32.2
Modiolus phaseolinus juv	130	38.5	*Protodorvillea kefersteini*	121	36.5
Alpha 2000 m			Charlie 2000 m		
Ophiura affinis	370	11.2	*Lima subauriculata*	265	8.9
Exogone verugera	289	20.0	*Exogone hebes*	216	16.1
Oligochaete type 1	224	26.8	*Ophiura affinis* juv	196	22.7
Venus ovata	160	31.7	*Modiolus phaseolinus* juv	174	28.5
Protodorvillea kefersteini	150	36.2	*Venus ovata*	145	33.4

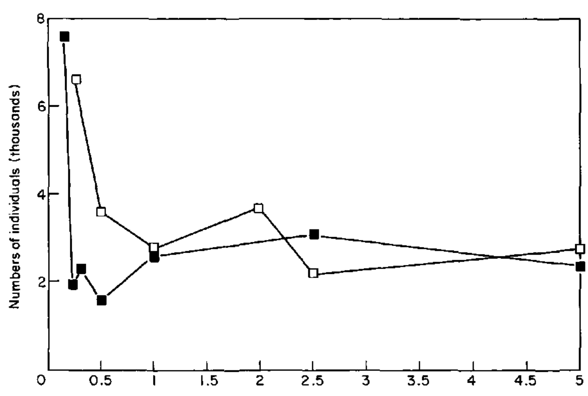

Figure 5. Number of individuals at Statfjord Bravo and Statfjord Charlie with respect to distance after similar drilling time spans. Diesel oil base and low aromatic oil base were used, respectively. —■— = Statfjord B, —□— = Statfjord C.

range between 10 ppm and 100 ppm (Reiersen *et al.*, 1988).

H_s is a relatively coarse measure of diversity. Pre-operational values for the northern North Sea have been shown to range between approximately H_s 4.5 and H_s 5.8 (Kingston, 1987). There is evidence emerging that certain sensitive species may be excluded by levels of sediment oil below 10 ppm, for example *Aonides paucibranchiata* (Fig. 7), but are not common enough significantly to affect overall diversity.

Figure 8 shows the relationship between (H_s) and sediment concentration of naphthalenes, phenanthrenes and

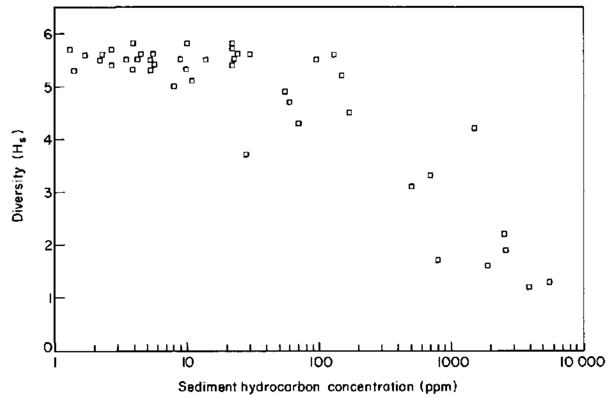

Figure 6. The relationship between diversity (H_s) and sediment oil concentration around several North Sea oil production platforms.

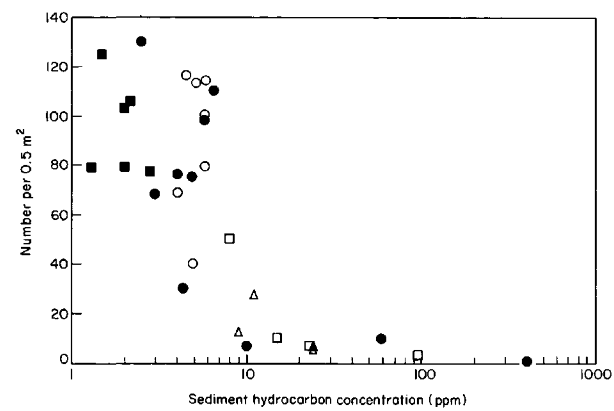

Figure 7. The relationship between numbers of the polychaete worm *Aonides paucibranchiata* and sediment hydrocarbon at two production platforms in the northern North Sea.

dibenzo-thiophenes (NPDs). These polynuclear aromatic hydrocarbons are present in diesel oil in relatively high concentrations and are generally believed to be its main toxic component. Diversity falls below preoperational levels at a much lower cuttings concentration of NPDs than would be expected from laboratory toxicity testing. The apparent response of diversity to NPDs as shown in Figure 8 shows that H_s falls below pre-operational levels at concentrations of less than 0.02 ppm, a concentration two orders of magnitude lower than that reported as being toxic in the literature (Armstrong *et al.*, 1979). This suggests that NPDs may not be the dominant agent causing the observed effects on the benthos and would go some way to explain why there was no dramatic improvement in the extent of environmental impact with the switch from diesel to low aromatic base oils.

Oil contamination of the seabed

As oil contamination spreads outwards from the cuttings piles on the seabed, the concentration of hydrocarbons in

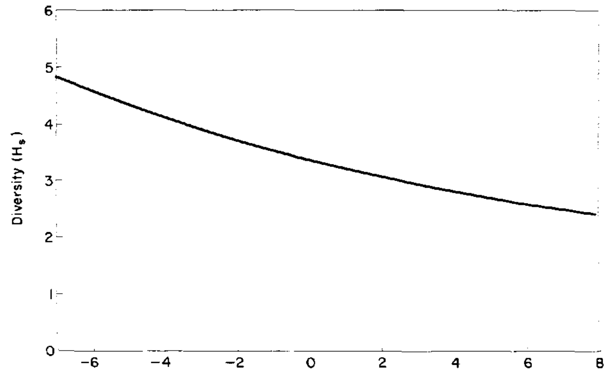

Figure 8. The relationship between diversity (H_s) and concentration of NPDs in sediment (Soxhlet extraction) around North Sea production platforms. Exponential model fitted $Y = Exp(a + bx)$ of H_s on log. NPD. F ratio = 37.47, Correlation coefficient −0.41 ($p < 0.001$).

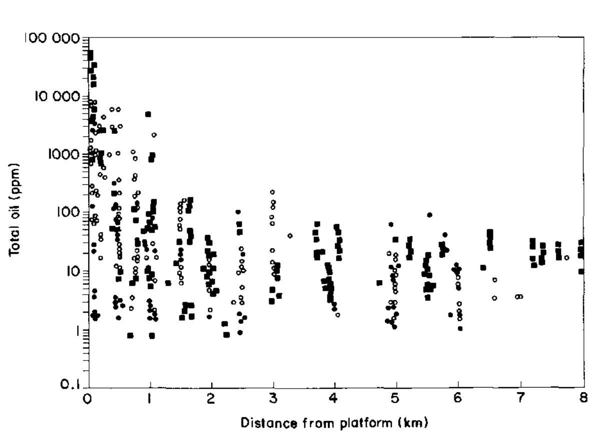

Figure 9. The relationship between sediment oil concentration and distance from North Sea oil production platforms (after Davies *et al.*, 1988).

the sediment decreases (Fig. 9). Levels of oil that have a detectable effect on the benthos (50–60 ppm) are reached for most installations in the range of 750 to 1000 m from the point of input. Very high concentrations, usually between 1000 and 10 000 times "background" are apparent close to the platform with a steep downward gradient between 500 and 1000 m from the installations. This platform is typical for most North Sea oil developments.

Although gross contamination is confined to a relatively small area around the production platforms, there is increasing evidence of a more widespread dispersion of oil in sediments. Figure 10 shows the concentration of sediment hydrocarbons at distances between 5 km and 10 km from oil production installations in the northern North Sea (Shetland Basin). The data shown in Figure 10, collected by Department of Agriculture and Fisheries for Scotland between 1980 and 1988, shows a marked rise in hydrocarbon contamination of the sediments (as UV-f diesel equivalents) over this period (Davies and Kingston, 1991).

Though some surveys display evidence of weathering of base oils at distances of 5 km and 6 km from the installation, the base oil contribution to the total hydrocarbon burden from chromatographic evidence is very small. Examples of hydrocarbon chromatographic traces

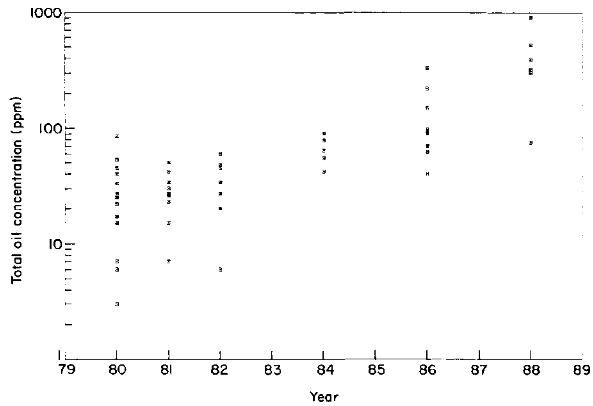

Figure 10. Graph showing increase in sediment oil concentrations in ultraviolet-fluorescence (UV-f) diesel equivalents, at distances between 5 and 10 km from production platforms in the North Sea Shetland Basin.

from extracts of sediments for near and distant sites from a production platform are given in Figure 11 together with a chromatogram for base oil extracted from the discharged cuttings. The dominant pollutant hydrocarbons that give rise to the large unresolved complex mixture (UCM) hump at the 5 km location elute at a boiling range higher than that expected for weathered drilling mud base oil. The implication of this is that the distant spread of contamination does not necessarily originate from the discharge of drilling cuttings but from sources discharging less refined hydrocarbon mixtures such as production water and increased shipping activity in the vicinity of the installations.

Discussion

The impact of North Sea oil developments now has well defined limits of gross effect which can be summarized as follows:

1. Oil levels of 1000 times "background" may be expected up to 750 m from a production platform with a highly disrupted benthic community of low diversity within this zone.
2. There is a transition from areas of high disturbance (as measured by diversity) to "background" diversity between 750 and 1500 m. Hydrocarbon levels in this region may vary from 20 to 100 times "background" level.
3. Although diversity measures appear normal between 1500 and 3000 m, effects of contaminants on sensitive benthic indicator species may be detected. Hydrocarbon levels may vary from 5 to 20 times "background" levels.
4. There is no confirmed evidence of any effect on the benthos beyond 3000 m although levels of hydrocarbons above preoperational "background" levels show a significant elevation at distances of 10 km and beyond.

It is clear that gross environmental impact takes place close to production platforms and that the effects are local in their extent. The most common effect is for there to be a large increase in the abundance of a few species. Such a response is common where there is organic enrichment of the sediment. Pearson and Rosenberg (1978) first demonstrated this in a Scottish sea loch contaminated by discharge of pulp mill waste. Spies *et al.* (1988) compared faunal community changes resulting from both biogenic (decomposing seaweed) and petrogenic sources of organic enrichment and found an essentially similar response of the fauna in both.

An elevated number of individuals close to a production platform suggests that there must be considerable biological activity despite the potentially toxic nature of some of the discharges. In the few studies in which biomass has been determined, high individual abundance has been shown to be reflected in high standing crop biomass of small polycheate species with theoretically high productivity (Kingston, 1987). This indicates that not only is the oil being actively biodegraded (the organic carbon being utilized either directly or indirectly by the macrofauna), but that this process, in some oil field developments, could be relatively rapid.

Offshore monitoring programmes have followed essentially the same strategies since their inception in the mid 1970s. Data is obtained by grab sampling, cost/time restraints limit the number of replicate hauls to between two and five at each sample station (Kingston and Riddle,

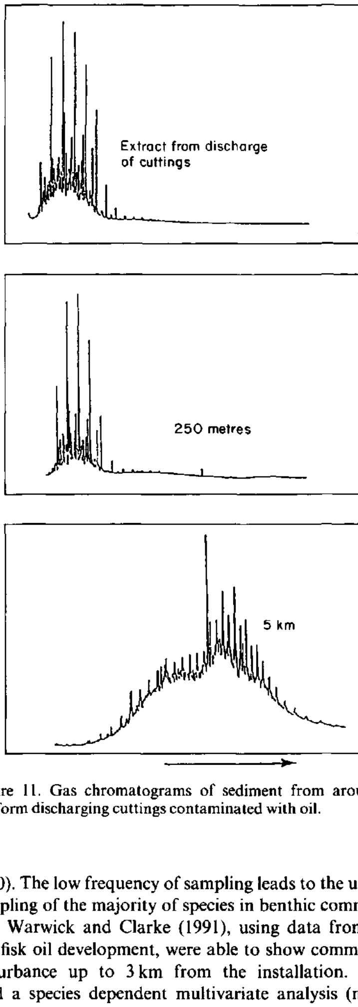

Figure 11. Gas chromatograms of sediment from around a platform discharging cuttings contaminated with oil.

1990). The low frequency of sampling leads to the under-sampling of the majority of species in benthic communities. Warwick and Clarke (1991), using data from the Ekofisk oil development, were able to show community disturbance up to 3 km from the installation. They used a species dependent multivariate analysis (multi-dimensional scaling) and compared results with that obtained using the Shannon–Wiener diversity index (H_s) which is a species independent univariate method. They found the diversity was significantly reduced only within a 250 m zone, illustrating the relatively insensitive response of this faunal parameter. Multivariate analysis has been widely used in offshore monitoring studies, however, there has been little consistency between studies in the techniques adopted. The consequence of this is that comparison between results from different surveys has been difficult and the full potential of such approaches not exploited.

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