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The Impact of Oily Discharges on the Meiobenthos of the North Sea [and Discussion]

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The impact of oily discharges on the meiobenthos of the North Sea

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The impact of hydrocarbon discharges on the intertidal and subtidal meiobenthos of the North Sea is examined primarily by a consideration of two field investigations. The first study examines the effects of an oil refinery discharge on intertidal meiofauna in the Firth of Forth, while the second describes the impact of oil platform discharges on the surrounding meiobenthos.

The impact of the refinery effluent is only clearly distinguishable upstream of the discharge, as downstream the effects are confused with those of a second petrochemical discharge. The meiofaunal community is only strongly affected on the upper shore and this appears to be chiefly the result of an organic enrichment effect causing a raising of the redox potential discontinuity (RPD) layer. All meiofaunal taxa examined are sharply reduced in density and species richness within 320 m of the discharge but at 600–900 m from the discharge meiofaunal densities are enhanced or depressed, relative to clean sediments, dependent upon the seasonal pattern of the RPD layer. Farther down the shore the impact is only felt at most by a slight reduction in species richness and subtle change in species abundance patterns on the middle shore for a distance of about 600 m. The meiofaunal responses to the petrochemical discharges seem similar to those described for the macrofauna in the same area, although a small meiofaunal population persists in the most polluted sediments in the absence of macrofauna.

The discharge of drilling cuttings, contaminated with oil-based drilling mud, was found to strongly modify meiofaunal densities within 800 m of the Beryl A Platform. Nematode densities are strongly reduced in the vicinity of the platform and it is thought that the impact on this infaunal taxon may be due to slow degradation within the sediment of toxic fractions of the diesel base of the drilling mud. By contrast copepod densities were greatly enhanced in one survey and the difference in impact is considered to be due to the epibenthic habit of the species involved, enabling them to flourish in conditions of high food or low predation and competition or all three. The species involved seem typical members of meiofaunal communities of organically enriched sediments. Some improvement in meiofaunal densities throughout the period 1984–85 is thought to be possibly the result of a switch from diesel-based to low-toxicity drilling muds.

It is concluded from these and other studies that hydrocarbon discharges into the North Sea are unlikely to be causing extensive damage to meiofaunal communities.

1. INTRODUCTION

At a meeting on the environmental effects of North Sea oil and gas developments, interest in the impact on benthic organisms is focused on the implications of drilling platform activities for the surrounding benthos. The effects of the discharge of drill cuttings, contaminated with oil or water-based drilling mud, on the community structure of the macrobenthos is routinely monitored at many platforms and so the identification of broad patterns of response is now possible (Davies *et al.* 1984; Kingston, this symposium). However, metazoans passing through a 500 μm mesh sieve (meiofauna) have hitherto been overlooked in platform monitoring studies and yet there is a *prima facie* cause for concern about possible damage to meiofaunal communities. The great mass of the meiofauna is permanently associated with the sediment, few species having a planktonic larval phase, and thus adverse sedimentary conditions must be tolerated by all life stages. Also, meiofaunal species are dependent upon the sediment for suitable food supplies, very few suspension feeders being known.

The paucity of knowledge regarding meiofauna necessitates a broad approach to the appraisal of potential damage by oily discharges. Knowledge about the impact of oil pollution on meiofaunal communities is very limited and concerns largely the effect of spillages on the total density of the major meiofaunal groups, such as nematodes and copeods, or at best examines one of these groups at the species level. While the investigation of meiofaunal communities at the level of species does present some taxonomic problems, this should not provide justification for overlooking this component of the ecosystem. Indeed, meiofauna offers a number of advantages for employment in effects monitoring (Heip 1980; Platt & Warwick 1980; Raffaelli & Mason 1981).

This contribution aims to assess the impact of platform and other chronic discharges of oily wastes on North Sea meiobenthos, partly by a consideration of the limited amount of published literature but largely by examination of some of the results from two continuing field investigations. One of these concerns a recently initiated programme of meiofaunal monitoring around an oil platform, while the other study examines in more detail the impact of an oil refinery discharge on meiofaunal community structure.

2. Effects of hydrocarbon discharges on intertidal meiobenthos

(*a*) *Refinery impact*: *the Grangemouth field study*

(i) *Study area and methods*

British Petroleum Oil Grangemouth Refinery Ltd is located along the banks of the Forth Estuary, Scotland, beside British Petroleum Chemicals Ltd (Grangemouth). The adjacent shore consists of an extensive mudflat, which receives an oily effluent from the refinery of about 15–25 Ml d^{-1} comprising ballast water, boiler and cooling tower blowdown and process water (figure 1). About 500 m from the refinery discharge point British Petroleum Chemicals discharges an effluent of 6–9 Ml d^{-1}, which includes organic solvents, ammonium salts and small amounts of oil. There are also two small sewage discharges to the mudflats (McLusky 1982). The mudflats in the area have been extensively reclaimed and for the most part only extend upwards to a little above mid-tide level. The highest region of the mudflats is found along the shoreline receiving the petrochemical effluents, which discharge at the top of the mudflats at about the level of mean high water neaps. The salinity in this region of the estuary is generally within the range 19–32‰ (Bagheri & McLusky 1982, C. G. Moore, personal observations). The estuary mouth is to the east of Grangemouth.

The impact of the petrochemical effluents was investigated by surveying the meiofauna and certain physical and chemical environmental parameters in late July 1984. As interest was

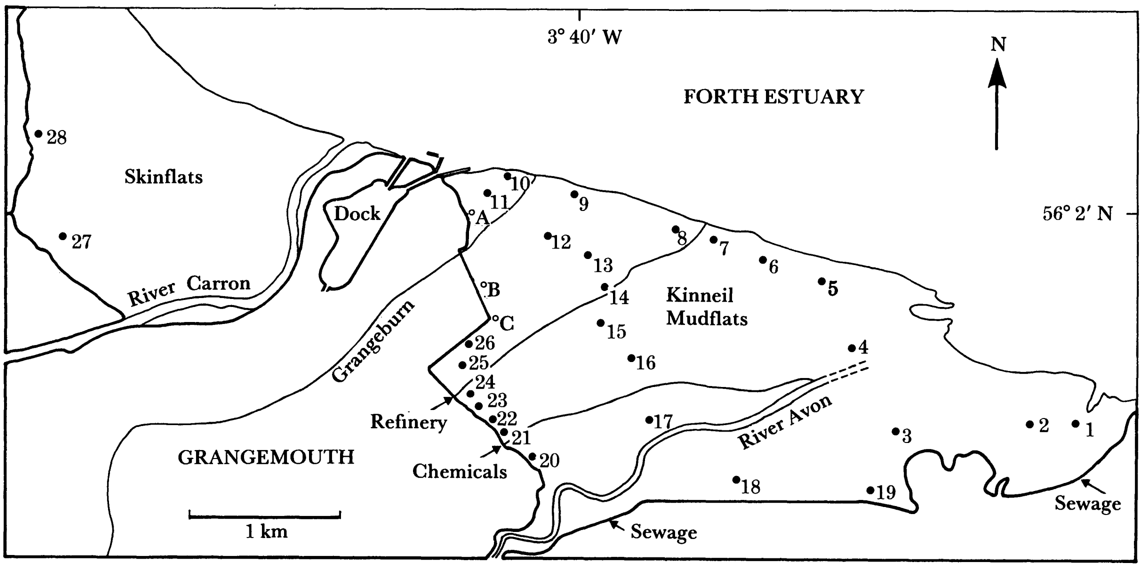

FIGURE 1. Grangemouth mudflats in the Forth Estuary, showing the location of sampling sites and effluent discharges. The sites are located along three longitudinal transects at approximately MLWN (sites 1–10), MTL (11–19) and MHWN (20–28). A, B and C are meiofaunal production study sites.

centred on the impact on community structure at different intertidal heights, a total of 28 sampling sites were located along longitudinal transects at approximately MLWN, MTL and MHWN. Because of the restriction of the upper shore mudflat to the close vicinity of the discharges, two control sites for the MHWN transect were located on a similar mudflat at Skinflats to the west of Grangemouth.

At each site triplicate core samples of area 5.5 cm^2 were taken to a depth of 3 cm for meiofauna. The meiofauna passing through a 500 μm aperture sieve, but retained on a 63 μm sieve, was extracted by Ludox centrifugation (McIntyre & Warwick 1984). Cores were also taken for, *inter alia*, grain size analysis by the dry sieving and pipette methods (Buchanan 1984), determination of the redox potential depth profile (Pearson & Stanley 1979) and hydrocarbon analysis of the surface 3 cm of mud. Total aromatics were determined by UV spectrophotometry using a chrysene standard, fluorescence intensity being measured at 360 nm with excitation at 310 nm (Anon. 1976). Total aliphatics were determined by IR spectrophotometry with a crude-oil standard, absorbance being measured at 2930 cm^{-1}.

(ii) *Results*

Although both petrochemical effluents have cut distinct channels in the mud, much oil is stranded at the top of the shore. There is a clear concentration gradient with distance from the discharge point (figure 2). Total aliphatic hydrocarbon concentrations in dried sediment at MHWN range from 2451 to 5981 μg g^{-1}, total aromatics from 6 to 158 μg g^{-1}. Oil content of the mud decreases with distance down the shore, although a clear concentration gradient in both aliphatics and aromatics with distance from the effluent channel is discernible at MTL but not at MLWN.

The high organic loadings of both discharges have strongly influenced the redox conditions of the sediment at MHWN (figure 3), with the redox potential discontinuity layer (RPD) at a depth

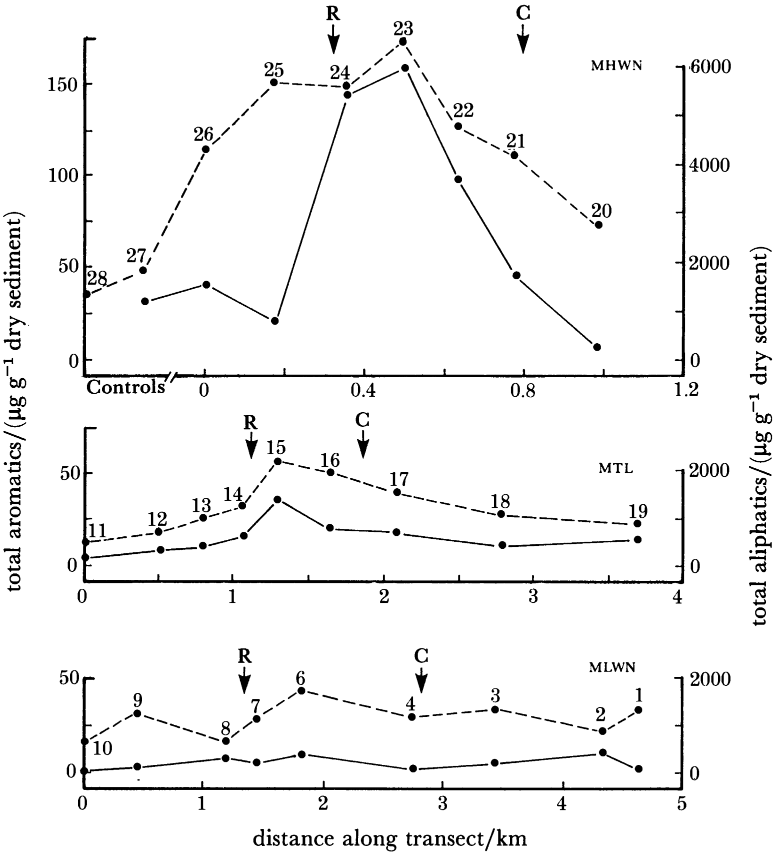

FIGURE 2. Concentration of total aliphatic hydrocarbons (dashed line) and total aromatic hydrocarbons (solid line) at sites (numbered) along transects at three heights on Grangemouth mudflats, 25–27 July 1984. R and C denote positions of British Petroleum Refinery and British Petroleum Chemicals effluent channels.

of about 2 mm, compared with 20–21 mm at a similar tidal level at the control sites and 20–25 mm along the MTL and MLWN transects (apart from a single site).

The petrochemical discharges cause a gross reduction in the density of all meiobenthic taxa recorded at MHWN for a distance of at least 200–300 m from both effluent channels, although there is some recovery of nematode numbers between the discharges, and of nematode and annelid numbers at the ends of the transect (figure 3). Maximum copepod density in this region is only five individuals per 10 cm². Along the mid and low tide transects there is no clear evidence of meiofaunal density changes in response to the refinery discharge. Mean densities of nematodes, copepods and annelids are respectively 1219, 274 and 205 individuals per 10 cm² at MTL and 1692, 51 and 66 individuals per 10 cm² at MLWN.

Meiofaunal species richness exhibits a clear response to the effluents at MHWN, with the minimum of just 7 species being recorded at sites within 180 m of the refinery discharge, rising to 17 species 320 m upstream of the discharge and 20–29 species at the control sites (figure 4). The evenness pattern (reflected also in the Shannon–Wiener diversity index) is quite the opposite to what might be expected. Dominance is reduced in the most polluted sediments, as no species can flourish in such harsh conditions. The pattern of species richness along the MTL transect suggests that this is a more sensitive indicator of perturbation of the community than density. Richness is depressed over a considerable distance in the area around the effluent

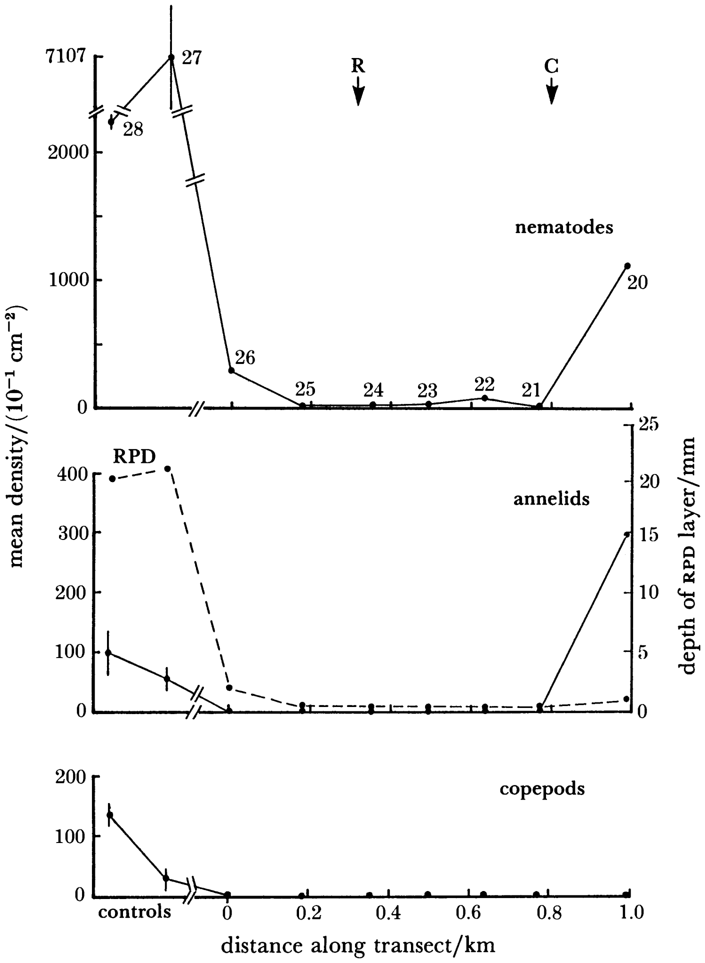

Figure 3. Mean density (with standard error bars) of the three dominant meiofaunal taxa (solid lines) and depth of the RPD layer (dashed line) along a transect at approximately MHWN on Grangemouth mudflats, 27 July 1984. R and C denote positions of British Petroleum Refinery and British Petroleum Chemicals effluent channels.

channels. The diversity and evenness measures seem unaffected by the oily discharge (although there is a strong increase in dominance just downstream of the chemical effluent channel).

Seventy-eight meiofaunal species were recorded throughout the area but the major spatial trends in species abundance patterns of the meiofaunal community can be summarized in the ordination in figure 5. The proximity of the sampling sites on the plot reflect their similarity in terms of composition of the community, except that sites at the two ends of the horseshoe configuration are in fact separated by subsequent axes (trends). Shore height is clearly important in explaining compositional differences but along the upper and mid shore transects there are community gradients related to pollution levels. Group A sites are all grossly polluted MHWN sites with a meiofauna consisting chiefly of low density populations of the nematodes *Sabatieria pulchra* and *Rhabditis marina*. The group B site at one end of the MHWN transect is similar in composition but the meiofauna is more species rich and abundant, and is strongly dominated by the nematode *Diplolaimella ocellata*. The group C site is the most distant of the MHWN transect sites from the refinery discharge and most closely resembles the MTL sites. It is dominated by

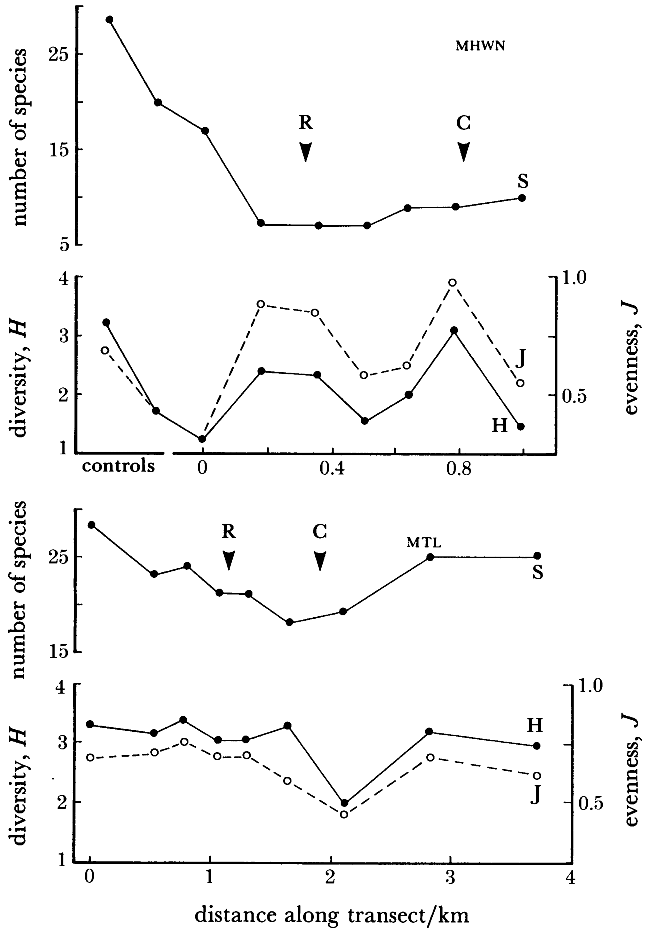

FIGURE 4. Meiofaunal species richness, Shannon–Wiener diversity (bits per individual) and Pielou evenness (*J*) along transects at approximately MHWN and MTL on Grangemouth mudflats, 25–27 July 1984. Values are based on all specimens of copepods, polychaetes and oligochaetes found in triplicate 5.5 cm^2 cores at each site plus nematodes present in a sample of 200 specimens from each site. R and C denote positions of British Petroleum Refinery and British Petroleum Chemicals effluent channels.

the nematodes *Hypodontolaimus balticus*, *Daptonema setosum* and *Tripyloides gracilis*, and the polychaete *Manayunkia aestuarina*. The MHWN control sites at Skinflats are more similar to the MTL sites than the MHWN transect sites, although of these they most closely approach the group C site but support many species that were virtually absent on the upper shore transect, notably the nematodes *Ptycholaimellus ponticus*, *Metachromadora remanei* and *Microlaimus globiceps*, and all copepod species. The group C site most closely resembles the most atypical, and presumably the most pollution-perturbed, MTL site (group D). This site, just downstream of the chemical effluent channel, is distinct from the other MTL sites by the high density of *Daptonema setosum* and a flourishing population of the copepod *Mesochra lilljeborgi*. The remaining MTL sites show a variation in species composition and abundance apparently related to their distance from the refinery channel, with group E sites lying within about 600 m of the channel and group F sites beyond this distance. The difference in the meiofaunal communities between these groups is rather subtle but is most clearly exemplified by modest enhancement of the polychaete *Capitella capitata* and strong enhancement of the copepod *Platychelipus littoralis* within group E. Group G consists of the lower shore sites.

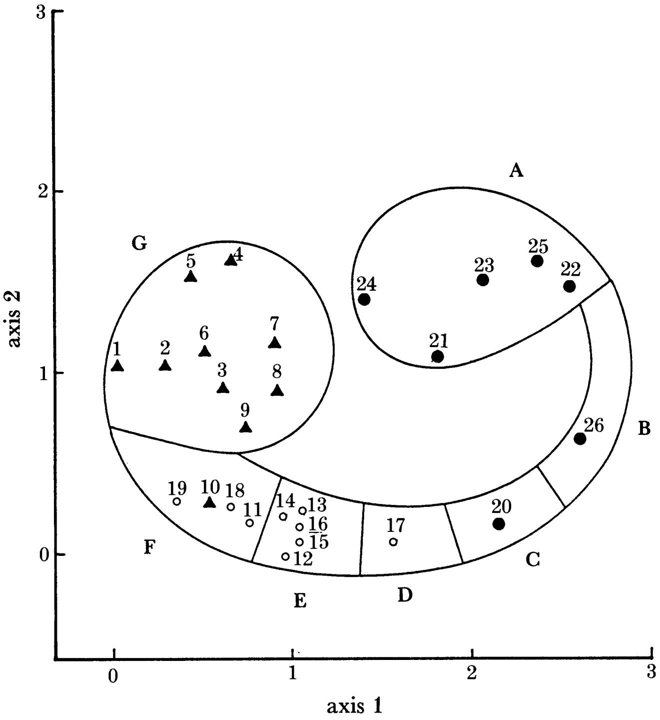

FIGURE 5. Ordination (detrended correspondence analysis) of sites at approximately MLWN (triangles), MTL (open circles) and MHWN (filled circles) on Grangemouth mudflats, based on $\log(x+1)$ transformed densities of nematode, copepod and annelid species. Letters denote site groupings. Axes are scaled in standard deviation units.

The degree of impact of the discharges on the meiobenthos varies seasonally. This is shown by the results of a study, currently in progress, of meiobenthic production levels in the area. Figure 6 shows the temporal pattern of densities of the three dominant taxa at three sites upstream of the refinery channel (figure 1). These sites are at the same tidal level (between MTL and MHWN) and experience strong, moderate and weak hydrocarbon contamination. Oil levels are yet to be measured but the oil pollution gradient is visibly obvious. Densities are higher at the more polluted sites in April. In July the moderately polluted site shows marked enhancement of densities, but with increasing temperature and elevation of the black layer to within a few millimetres of the surface, the densities of nematodes and copepods fall to below those of the cleanest site. This decline is even more severe at the most polluted site, where the meiofauna is almost eradicated in August and September. Thus the meiofauna at the more polluted sites exhibit both enhancement and depression of density, dependent upon the time of year and degree of pollution.

(iii) *Discussion*

It is impossible to firmly link oil levels at Grangemouth with environmental impact as the chemical effluent is also influencing the biota. The effects of the two discharges appear to be fairly similar, varying from toxicity to enrichment. The visual impact of both discharges on the biota is identical, both channels being accompanied by parallel ribbons of dense microalgae (chiefly filamentous Cyanophyceae) a little distance from their banks. Similar blue-green algal cover has been found associated with other refinery effluents by Konig (1968) and Baker (1971). The work of McLusky (1982) on the macrofauna of the area also suggests that the effluents

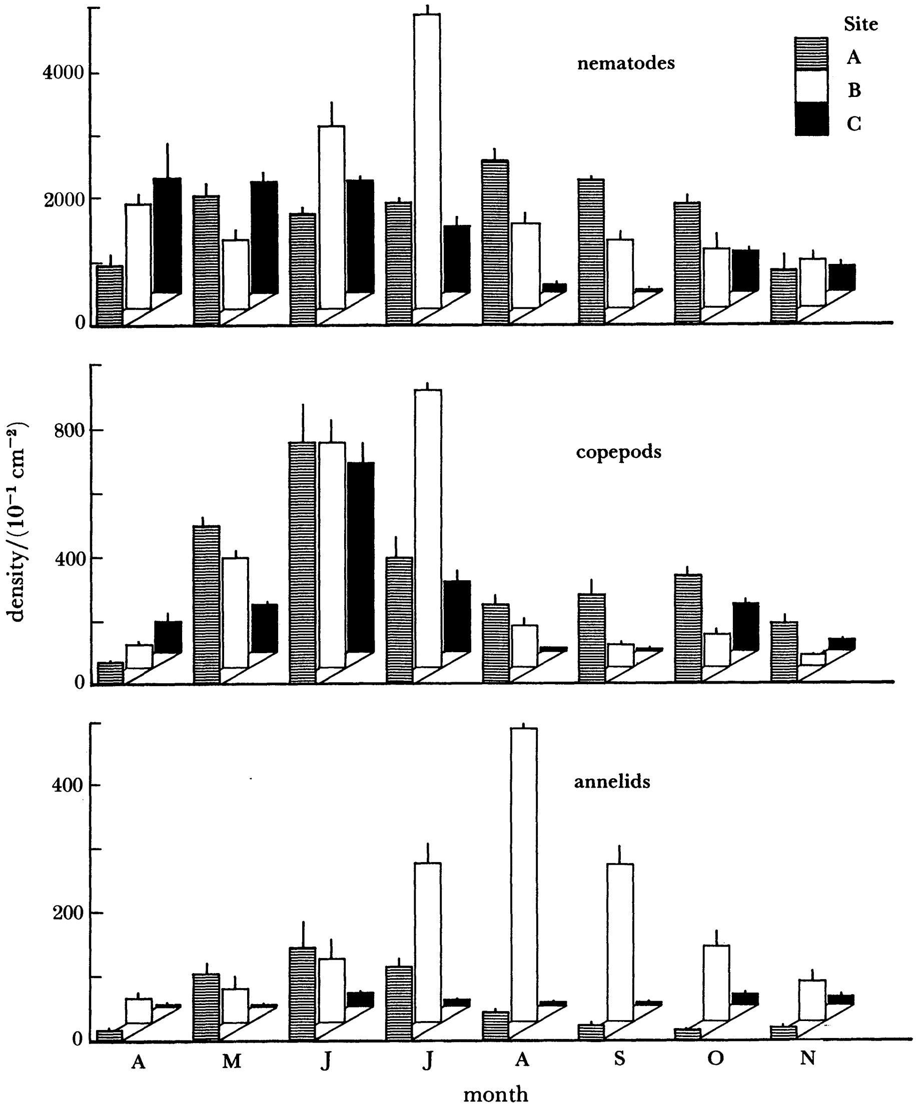

FIGURE 6. Temporal changes in mean density (with standard error bars) of the dominant meiofaunal groups in 1984 at sites between MTL and MHWN on Grangemouth mudflats. The sites experience weak (A), moderate (B) and strong (C) hydrocarbon contamination.

are having similar effects on the biota. Moreover, although the refinery effluent clearly gives rise to extremely high oil concentrations in the sediment, it cannot be assumed that the environmental impact is necessarily associated with hydrocarbon components of the effluent.

Meiofaunal responses to different levels of petrochemical pollution observed at Grangemouth may be summarized as follows:

(*a*) gross pollution: meiofaunal density is very low, most taxa virtually disappear but a few species of nematodes can persist;

(*b*) severe pollution: nematodes and annelids increase in density and species richness but copepods remain very low;

(*c*) moderate pollution: meiofaunal densities may vary from impoverishment to enrichment, dependent upon season;

(*d*) slight pollution: background densities are achieved but species richness is reduced and there is an abnormal species abundance pattern;

(*e*) minimal pollution: background densities, species richness and species composition.

It is interesting to compare this meiofaunal response to that of the macrofauna at Grangemouth, which has been monitored for several years by McLusky (1982). The patterns are very similar, McLusky identifying a similar series of response levels in terms of density and diversity. Moreover, the response of the meiofaunal community appears to broadly correspond to that of the macrofaunal community in the same region of the mudflat.

Because of the difficulty in distinguishing the impacts of the chemicals and refinery effluents downstream of the refinery, the effects of the refinery effluent are more clearly discernible in the upstream direction. The effect on the meiobenthos appears to be largely due to the consequences of organic enrichment of the sediment, causing strongly reducing conditions, although there appears to be also a localized toxic or physical effect by constituents of the effluent. McLusky (1982) also noted the resemblance of the macrofaunal response to one typical of organic enrichment.

There were subtle differences in community structure at MTL but the discharge was only strongly felt on the upper shore, where the impoverishment of the fauna can be largely explained by the reduced nature of the sediments. However, at sites within 320 m of the discharge redox conditions differed little and yet the fauna was clearly richer at 320 m. Thus there also appears to be, as expected, a strong toxic or physical response gradient in the immediate vicinity of the discharge (cf. Bagheri & McLusky 1982).

At sites between 600 and 900 m from the discharge the seasonal fluctuation in redox conditions seems to exert a major role in controlling density. The process of organic enrichment producing impoverishment of macrofauna through raising of the RPD depth is a well-known mechanism (Pearson & Rosenberg 1978) and this is exacerbated on the upper shore at Grangemouth by desiccation of the mud. However, it is known that certain meiofaunal species can tolerate such extreme consequences of organic enrichment. For example Bouwman *et al.* (1984) recorded extremely high densities of nematodes on an organically polluted upper shore mudflat in the Ems-Dollart Estuary, The Netherlands, which also suffered desiccation, with a thin (*ca.* 2 mm) aerobic layer, and an absence of macrofauna. It is difficult to compare the two studies because of the lack of detailed knowledge regarding the physical and chemical sedimentary conditions and the duration of tidal cover but clearly the habitats are somewhat different, with the Dollart area being more equivalent to Forth mudflats below MHWN in the upper reaches of the estuary. This is shown by a comparison of the salinity regimes and fauna in the Dollart area (Bouwman 1983; Bouwman *et al.* 1984) with those throughout the Forth Estuary (C. G. Moore, unpublished results).

McLusky (1982), employing a 250 μm mesh sieve, reported an azoic area within 250 m of the refinery discharge. Although such a macrofaunal azoic area may vary in extent from year to year, no macrofauna or even juvenile annelids were present in the meiofaunal samples taken in this area in late July 1984. The meiofauna samples within 165 m of the refinery discharge, however, contained a total of 11 meiofaunal species with densities from 29 to 42 individuals per 10 cm^2. Such an impoverished meiofauna is ecologically insignificant; however, the extent of seasonal density variation is unknown.

(*b*) *Oil spill and experimental studies*

The only other studies of the effects of oil on the meiofauna of muddy shores concern accidental or experimental coating by crude oil. Boucher (1985) monitored the meiofauna of a mudflat heavily contaminated by the *Amoco Cadiz* spill and failed to record any marked changes in meiofaunal density until two years after the spill. No evidence is presented to relate these changes to an oil effect. Neither Naidu *et al.* (1978) nor Fleeger & Chandler (1983) found experimental spraying of crude oil to adversely affect the meiofauna, both studies reporting an enhancement of certain taxa. Even though Fleeger & Chandler (1983) sprayed oil to a depth of 2 cm only a slight and non-significant early decrease in species richness was recorded. Decker & Fleeger (1984) examined recolonization of azoic mud that had been experimentally mixed with oil. In comparison with unoiled controls there was little effect of the presence of oil on the copepod community, even at a concentration of 3810 $\mu g\ g^{-1}$ total aromatics. Only one species was apparently affected, showing initially depressed densities, but after 60 days, enhanced densities. Similarly, copepod species richness was initially lower in heavily-oiled mud but higher than in unoiled controls after 60 days. Polychaetes and nematodes showed depressed densities in very heavily oiled sediment (3810 $\mu g\ g^{-1}$) but there were no temporally consistent differences between the densities of these taxa in unoiled sediment and sediment with an oil content of 1330 $\mu g\ g^{-1}$ total aromatics.

The effects of Grangemouth refinery effluent on the meiobenthos are clearly stronger than those recorded in the above investigations. This difference is probably mainly due to the extreme superficiality of the oxidized sediment layer at Grangemouth, which was not noted in the other studies.

From the available evidence it appears that the meiofauna of intertidal estuarine muddy sediments is surprisingly resilient to oil pollution, although the effects of high concentrations of refined oily products are unknown. So far as density changes are concerned the Grangemouth study and that of DeLaune *et al.* (1984) indicate that oil impact on the mudflat meiofauna is no more adverse than that on the macrofauna. It is too early to gauge the relative sensitivities of the two size groups concerning more subtle aspects of community structure such as diversity and species composition, which this and other studies show to be more sensitive to low pollution levels than simple density.

In contrast to the resilience of mudflat meiofauna, sandy shore communities have generally been reported as suffering impoverishment as a result of oil spills, particularly when the spill is of high aromatic content. Thus Rützler & Sterrer (1970), Wormald (1976) and Giere (1979) recorded drastic reductions in meiofaunal densities after spills of fuel oil or fuel–crude oil mixtures and reductions of one or more major taxa have been reported by Boucher (1980), Fricke *et al.* (1981) and McLachlan & Harty (1982) after spills. The general picture to emerge from these studies is that nematodes are somewhat more tolerant than interstitial harpacticoids.

3. EFFECTS OF HYDROCARBON DISCHARGES ON SUBTIDAL MEIOBENTHOS

(*a*) *Oil platform impact*: *the Beryl field study*

(i) *Study area and methods*

The Beryl field is situated 180 km southwest of the Shetland Isles. The Beryl A platform is located in 115 m of water on a bed of silty sand. Drilling commenced at Beryl A in 1976, with 37 wells completed up to May 1982 using mostly diesel-based drilling muds. After a 16 month interval drilling recommenced in September 1983 using low-toxicity drilling mud to cut a further four wells, although there was another break in drilling from January to June 1984.

As part of a more comprehensive series of surveys around North Sea oil platforms the Department of Agriculture and Fisheries for Scotland (DAFS) Marine Laboratory has monitored sediment hydrocarbons and heterotrophic hydrocarbon mineralization rates at Beryl since 1979. McIntosh *et al.* (1983) and Massie *et al.* (1985) should be consulted for methods and detailed analysis of the aromatics. In 1982 macrobenthos monitoring was included in the programme (Moore 1983) and in the surveys of 1984 and 1985 biological monitoring was extended to encompass a limited investigation of the meiobenthos.

In May 1984 single Craib cores (area 24.6 cm^2) of at least 6 cm in length were taken at nine sites for redox depth profile determination (Pearson & Stanley 1979) and meiofaunal analysis. The meiofauna retained on a 45 μm aperture sieve was extracted by the decantation method (McIntyre & Warwick 1984) and subsampled using an Elmgren splitter (Elmgren 1973). In May 1985 duplicate cores (area 25.0 cm^2) of at least 6 cm were taken by Scottish Marine Biological Association (SMBA) multiple corer at 11 sites for meiofaunal and redox analysis. Meiofauna extraction was as for 1984 except that a Ludox centrifugation stage was added (McIntyre & Warwick 1984). Grain size data are available for three sites in 1984, when core samples of the surface 4–6 cm were taken from a Smith–McIntyre grab and graded by dry sieving and pipette analysis (Buchanan 1984).

(ii) *Results*

The dumping of cuttings contaminated with drilling mud has led to very high levels of sediment hydrocarbons within 800 m of the platform (figure 7), although concentrations of these and naphthalene mineralization rates fluctuate with the level of drilling activity (McIntosh *et al.* 1983).

The sediment samples taken in 1984 indicate that sediment structure is affected by the dumping of cuttings for a distance of at least 200 m. At sites 800 and 4800 m south of the

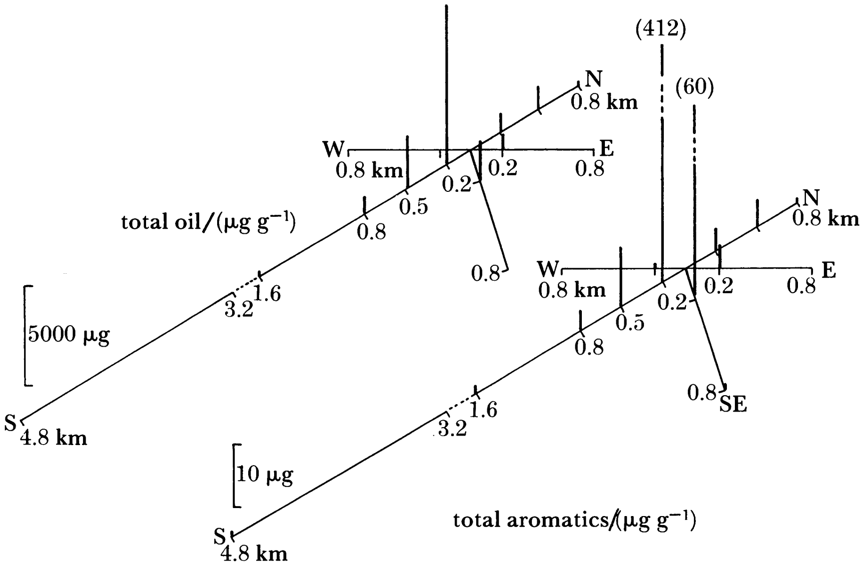

FIGURE 7. Concentration of total oil and total aromatics in sediments around the Beryl A oil platform in May 1985.

platform sediment particle size distribution was unimodal with a median diameter of 91–99 μm and 13–22 % silt–clay content. There was an additional mode in the clay range, 200 m north of the platform, reducing the median particle diameter to 60 μm and enhancing the silt–clay fraction to 51 %. Owing possibly to the reduction in permeability of the sediment around the platform, or through a mechanism of organic enrichment, the redox potential of the superficial sediments is reduced within 800 m (figure 8), with the RPD rising to 1 cm 200 m southeast of the platform in May 1985.

The pattern of meiofaunal density with distance from the platform is shown in figure 8 for the 1985 survey. The meiofauna was dominated strongly by nematodes and copepods, together representing 94–97 % of the total numbers. Both taxa show a clear response to platform pollution. Nematode density is sharply depressed within 800 m of Beryl, falling from a density of 1821–2246 individuals per 10 cm² at 3200–4800 m south of Beryl to 497 individuals per 10 cm² at a point 200 m southeast. Copepod density shows the opposite trend rising from 22–45 individuals per 10 cm² beyond 3200 m south to a peak of 720 individuals per 10 cm² 200 m southeast.

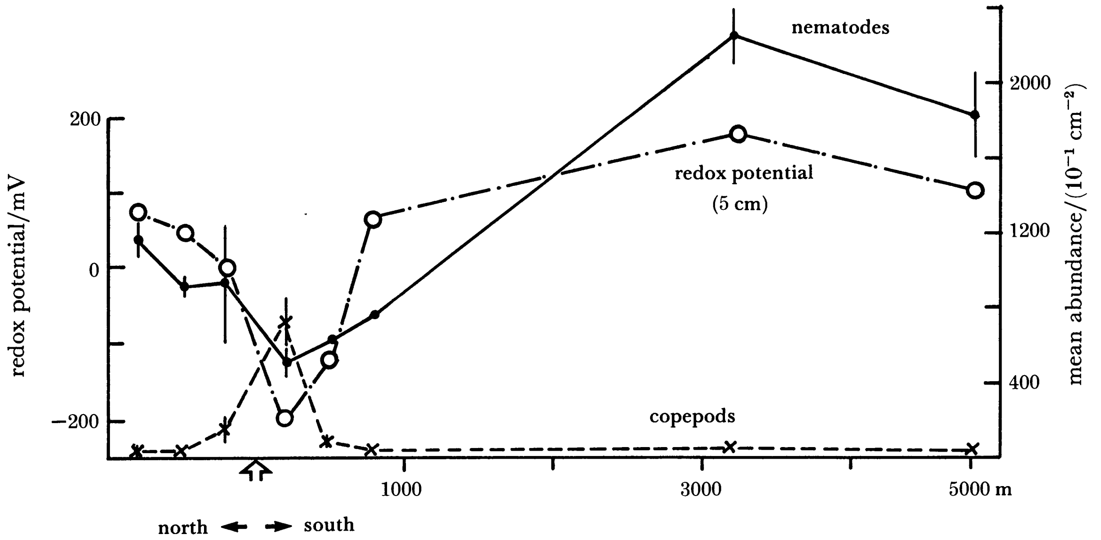

FIGURE 8. Redox potential at a sediment depth of 5 cm and mean densities of meiobenthic nematodes and copepods (with standard error bars) along a transect running north–south through the Beryl A oil platform. (200 m southeast values substituted for missing 200 m south values.)

Because of the lack of replication the 1984 density estimates must be viewed more cautiously. The nematodes displayed an even more drastic reduction in densities, falling from 1918–2439 individuals per 10 cm² at sites beyond 1600 m from the platform to 103–327 individuals per 10 cm² at sites within 500 m of the platform. There was, however, no suggestion of enhanced copepod densities near the platform.

Analysis of meiofaunal species composition has thus far included only a qualitative examination of the copepods from several 1985 sites. At 3200 m south the dominant copepods were *Amphiascus tenuiremis* and *Amphiascoides subdebilis*, whereas at four sites within 800 m of the platform the following species were dominants at one or more sites: *Proameira* aff. *P. simplex*, *Paramphiascella hyperborea*, *Paramphiascopsis longirostris* and *Ancorabolus mirabilis*. *Paramphiascopsis longirostris* copepodites were largely responsible for the enormous copepod density at the most polluted site (200 m southeast).

(iii) *Discussion*

Meiofaunal densities at the Beryl platform may be compared with the data relating to the same time of year from several studies of the nearby Fladen ground, some 140 km to the south. McIntyre (1964) records 1852–2215 nematodes and 33–50 copepods per 10 cm^2 in late April; Heip *et al.* (1983), sampling in May, record 1334–3875 nematodes and 26–66 copepods per 10 cm^2 and Faubel *et al.* (1983) record 1456–2653 nematodes and 28–80 copepods per 10 cm^2 for the period April–June. Thus the nematode and copepod densities recorded at stations beyond 800 m from Beryl seem typical background levels for this part of the North Sea, while nematode densities within 800 m are mostly depressed and copepod densities, at least within 200 m of the platform in 1985, greatly enhanced. Copepod density 200 m southeast of the platform appears to be the greatest recorded for offshore fine sediments.

The alteration in densities may have arisen through changes in the physical condition of the sediment. Complete burial of fauna will occur in the immediate vicinity of the point of discharge of drilling cuttings; even cuttings contaminated with water-based drilling mud are known to adversely affect macrofaunal diversity (Addy *et al.* 1984).

An adverse physical blanketing effect is suggested by the work of Cantelmo *et al.* (1979), who recorded a significant reduction in nematode density when sand maintained in an aquarium was given a 5 mm cover of barite, a major non-toxic constituent of drilling muds. However, the sediment employed was a medium–coarse sand mixture which presumably harboured predominantly interstitial species not adapted for fine sediment. The clean sediment at Beryl is already too fine for the development of an interstitial nematode fauna (Heip *et al.* 1985) and so the resultant change in sediment structure should have less relevance for nematode density here.

Although blanketing is probably a significant factor closer to the platform, it is not the most likely cause of the density changes. The meiofaunal data suggest that some recovery of the fauna was taking place between the surveys of 1984 and 1985 and yet drilling activity was higher before the 1985 survey than before the 1984 survey, the latter taking place after two years of relative inactivity, apart from a short spell of drilling four months beforehand.

The alteration in meiofaunal densities may have arisen through organic enrichment of the sediment, with the infaunal nematodes adversely affected by the reduced sediments, while certain superficially-distributed copepod species can flourish in more oxygenated conditions where food levels are enhanced and predation pressures reduced. Indeed there are now several documented cases (see, for example, Marcotte & Coull 1974; Vidakovic 1983; Gee *et al.* 1985; Moore & Pearson 1986) of harpacticoid copepods flourishing in organically-enriched subtidal sediments. The copepod species composition within 800 m of the platform is also indicative of an organic enrichment effect, the dominant species having been recorded from organically-polluted sediments elsewhere. Thus *Paramphiascella hyperborea*, normally present in clean sediments at low density, has been found to be a very characteristic species of sediments polluted by sewage sludge off the west coast of Scotland, where *Proameira* aff. *P. simplex* was also common (although this appears to be a common and widespread species) (Moore & Pearson 1986). *Paramphiascopsis longirostris*, present in enormous numbers at the most perturbed site at Beryl, is characteristic of sewage-polluted stretches of the river Gota älv in Sweden (Tulkki 1968) and the Firth of Forth (C. G. Moore, unpublished results), while *Ancorabolus mirabilis* was found to increase in density in sediment that had been artificially organically enriched by Gee *et al.* (1985). On the other hand *Amphiascus tenuiremis*, a dominant species on the nearby Fladen ground (McIntyre 1964) and in similar sediments in the Irish Sea (Moore 1979), was only recorded beyond 800 m from the platform.

Although enhanced copepod density is consistent with an organic enrichment effect, this appears unlikely to have depressed nematodes, which are known to flourish in subtidal sediments more strongly reduced, as a result of organic pollution, than the most reduced sediments recorded at Beryl (C. G. Moore, unpublished results).

Explanation of the apparent improvement in meiofaunal density from 1984 to 1985 is complicated by the concomitant increase in drilling activity; however, the change to low-toxicity drilling mud may be implicated. Cessation of the use of diesel-based drilling mud in May 1982 may have initiated a decline in the concentration of the associated toxic fractions in the sediment in the close vicinity of the Beryl platform. Improvement at the sediment–water interface would be expected to precede that in the lower horizons and one might predict an earlier improvement in epifaunal meiofauna. The enhancement of the epifaunal copepods over background levels is perhaps due to enhanced food levels, although reduced predation and competition may also be implicated. The infaunal nematodes, being more closely bound to the sediment, where release and biodegradation of the toxic diesel fractions is perhaps slower, are possibly in an earlier stage of recovery.

A further reason for the slower recovery of nematodes may lie in the relative colonization rates of the two taxa. The superficial distribution and high swimming ability of many harpacticoids facilitates rapid dispersal. It has been shown experimentally that copepods colonize azoic sediments faster than nematodes (Scheibel 1974; Chandler & Fleeger 1983; Alongi *et al.* 1983) and this may contribute to the faster recovery of copepods at Beryl. Because of the reduced nature of the sediment near the platform, successful early nematode colonists might be expected to be species tolerant of hypoxic conditions and hence perhaps typical of subsurface horizons of clean sediments. Such species appear to have relatively slow colonization rates (Alongi *et al.* 1983).

There is also some evidence of a partial recovery in the macrobenthic community following the switch to low-toxicity drilling mud. Moore (1983) recorded a low diversity community within 600 m of the platform in 1982, dominated by the polychaetes, Cirratulidae, *Chaetozone setosa* and *Capitella capitata*. In 1985 recorded values of species richness and evenness close to the platform were higher (D. Moore, personal communication).

Alternative theories could explain the observed meiofaunal density trends. For example, copepod enhancement in 1985 may have been caused by an increase in bacterial food resulting from the renewal of dumping of cuttings before the survey. From the measurement of naphthalene degradation rates in sediment, microbial mineralization of this substance is apparently maintained at an extremely high level in the area of fluctuating meiofaunal densities. However, this heterotrophic activity may not parallel the rate of production of copepod food, which is quite unknown but may track the level of the discharge of cuttings or may be stimulated by constituents in the low-toxicity drilling mud.

(*b*) *Oil spill and experimental studies*

The impact of oiled drilling cuttings on meiofauna has been studied experimentally by Leaver *et al.* (this symposium), who compared the effects of the addition of cuttings, from drilling operations employing diesel-based and low-toxicity drilling muds, on meiofaunal density. They recorded depressed nematode and interstitial harpacticoid copepod populations, with little difference between diesel and low-toxicity treatments, while the non-interstitial harpacticoid copepods exhibited enhanced densities in low-toxicity treatments but differed little from control densities in the diesel treatment. These results are consistent with the hypothesis of enhancement of copepods at Beryl being caused by the switch to low-toxicity mud. The suppression of nematode densities in both diesel and most low-toxicity experimental treatments may suggest that use of these alternatives would produce little difference in field effects on nematodes. However, it is unlikely that the experimental results can be extrapolated directly to field conditions at Beryl. The reduction of nematodes in tanks containing drilling cuttings is likely to have been caused by the lowering in redox potential in the sediments (Leaver *et al.*, this symposium). Unlike the epibenthic copepods, the nematodes and interstitial copepods would be subject to more reduced conditions within the sediment, to which most species were perhaps intolerant, in view of their natural habitat being well-oxygenated sand. Under field conditions faster immigration of species better suited to the altered physico-chemical conditions would be likely. This experimental constraint on the facility for colonization may mask a potentiality for enhanced nematode populations in sediment enriched by low-toxicity drilling mud, which could manifest itself under field conditions. Indeed Leaver *et al.* (this symposium) suggest that fluctuations in nematode density recorded in certain of the low-toxicity treatments may suggest a potential for recovery, full recovery being prevented by lack of suitable colonists.

The work of Grassle *et al.* (1981) suggests that copepod enhancement and nematode depression may represent a typical stage in meiofaunal recovery from oil pollution of subtidal sediments. They recorded depressions in the meiofaunal density of sandy mud retained in tanks subjected to chronic addition of No. 2 fuel oil. The Crustacea (harpacticoid copepods and ostracods) were especially affected. However, two months after cessation of oil addition nematode density was still depressed whereas copepod density had increased fourfold over the density in the control tanks. The reason for the differing responses appears once again to be partly connected with the differing vertical distribution patterns, as oil levels in the overlying water decreased rapidly after cessation of oil addition, whereas sediment oil levels showed no clear reduction.

A recovery stage for oil-polluted subtidal sediments, characterized by enhancement of copepods and depression of nematodes, is also suggested by the work of Alongi *et al.* (1983), whereas the data of Elmgren *et al.* (1983) indicate an enhancement of copepod density after an initial decline after the *Tsesis* spill of fuel-oil. Nematode density did not show a clear trend. The *Amoco Cadiz* spill was found to cause rapid mortality and subsequent recovery of copepods in subtidal sand, but the nematode density suffered a long-term depression (Boucher 1985). Oviatt *et al.* (1982) repeated the experimental work of Grassle *et al.* (1981) (see above) but at a lower level of addition of fuel-oil. They too recorded a significant reduction in harpacticoids and virtual elimination of ostracods. During the recovery period copepods exhibited a slightly greater (although non-significant) density than controls, whereas ostracods remained significantly fewer. Under the lower oil régime nematode density was not significantly affected, although a lesser (but not significant) nematode density after cessation of oil addition may suggest that the oil in the sediment, that had been steadily rising in concentration throughout the period of oil addition, was beginning to exert an effect. Bakke & Johnsen (1979) failed to record any clear impact on meiofaunal density of the experimental addition of crude oil extract to enclosures placed over the sandy bottom of a Norwegian fjord; however, there was no significant accumulation of hydrocarbons in the sediment.

Data on the impact of oil pollution on subtidal meiobenthos at the species level is very sparse. Renaud-Mornant & Gourbault (1980) and Gourbault (1984) could not show that the *Amoco Cadiz* spill clearly affected species composition or diversity in sandy mud in the inner part of Morlaix Bay but Boucher (1983) recorded a long-term depression in nematode diversity and a change in species composition at a fine-sand site in the outer bay. Boucher *et al.* (1982) recorded a sharp fall in diversity and a change in the dominant nematode species in fine sand experimentally subjected to crude oil contamination, but the closed nature of the aquarium system precluded immigration. Alongi *et al.* (1983) only recorded very subtle differences in the nematode fauna colonizing oiled and clean azoic sediments at a shallow estuarine site. Montagna & Spies (1985) recorded a dramatic change in harpacticoid community structure at sites outside and within a natural submarine oil-seep area, with a gross reduction in species richness and change in species composition within the seep area. Diversity values are yet to be determined for the Beryl area but diversity is clearly very low in the immediate vicinity of the platform (200 m southeast), with one sample of 178 copepods consisting of just three species with 76% dominance by *Paramphiascopsis longirostris*.

4. Concluding remarks

It would appear from the studies reported above that North Sea oil developments are not likely to seriously endanger the contribution that meiofauna makes to the functioning of the North Sea ecosystem. Experiments around the Beryl platform suggest that platform pollution causes only a very localized impact on meiofaunal abundance. The nature of the impact, at least in 1985, probably results in an enhancement of that part of the meiofaunal production that is available to predators, the epibenthic copepods being generally regarded as the major meiofaunal group in this respect (Hicks & Coull 1983). However, whether predators such as small fish can take advantage of this production in such an environment is unknown.

Although a marked density effect has been demonstrated in the immediate vicinity of the Beryl platform, the Grangemouth study and many other meiofaunal and macrofaunal studies show that more subtle effects on community structure may be present at lower pollution levels. Thus the real area of perturbation on the meiofaunal community at the Beryl platform is quite unknown but may be expected to extend well beyond 800 m from the platform.

There are certain similarities in the impacts of the oily discharges at Grangemouth and the Beryl platform. Both faunal responses show certain characteristics commonly associated with organic enrichment, such as density enhancement of certain taxa, alteration in species composition and reduction in species richness; however, the patterns of response with distance from the discharges show a number of important differences of detail.

At Grangemouth nematode density recovery precedes that of the copepods, whereas the situation was reversed for the Beryl platform in 1985. Also, the area of apparent toxic impact at the Beryl platform extends beyond that of organic enrichment, nematodes showing no enhancement but only depression before returning to background densities well beyond the area of copepod enhancement.

These differences can be reconciled by appreciation of the distinction between the two-dimensional pollution gradient at Grangemouth and the three-dimensional gradient at the Beryl platform. The meiofauna is confined to the sediment for much of the time on the mudflat and so the response is to a simple horizontal pollution gradient and this results in an impoverished fauna of virtually only nematodes in the most strongly polluted sediments but enhancement of meiofaunal densities under moderate pollution levels. The Beryl platform pattern can be considered as a three-dimensional analogue. Again, in the most strongly polluted habitat, i.e. within the sediment near the platform, the meiofaunal community consists of an impoverished nematode fauna. Moving out of the sediment (along the vertical pollution gradient) we again experience enhancement but this is restricted to those species adapted to live at the sediment–water interface, of which the epibenthic copepods are the predominant group. Such a model suggests that a similar, albeit more gradual, transition to a zone of enhancement of nematodes and burrowing copepods may occur along the horizontal pollution gradient. The resolution of the Beryl surveys was possibly too coarse to identify such a zone. This may explain the apparent discrepancy between the results reported here and the macrofaunal response around the Beatrice platforms, where Addy *et al.* (1984) concluded that the toxic impact of low-toxicity oil-based drilling mud did not extend beyond the area exhibiting the effects of organic enrichment.

There is some evidence that both meiofauna and macrofauna around the Beryl platform are currently in a phase of recovery, which may be associated with the transition to low-toxicity drilling mud. From work (see, for example, Addy *et al.* 1984; Kingston, this symposium) on the impact of drilling mud on macrofauna it is clear that the lower-toxicity muds will continue to exert an impact on the fauna. The time period for the restoration of the meiofaunal *status quo ante* following cessation of all discharges of cuttings cannot be estimated from present data but it is interesting to note that five years after contamination of subtidal fine sand by crude oil from the *Amoco Cadiz*, although no traces of pollution of the sediment could be detected chemically, the nematode population was still showing depressed density and diversity and an altered species composition (Boucher 1983). The sensitivity of nematodes, the most abundant metazoans on the seabed, to certain types of oil pollution might have implications in the field of effects monitoring. Nematode density, a parameter that is very simple to estimate, shows a clear, temporally-consistent, spatial trend at the Beryl platform. It will be very interesting to determine to what extent this pattern is typical of drilling operations and to relate more closely the nature and sensitivity of meiofaunal and macrofaunal responses. Heip *et al.* (1985) review the subject of the role of nematodes in pollution monitoring.

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Discussion

W. A. Hamilton (*Department of Microbiology, University of Aberdeen, U.K.*). Does Dr Moore consider it likely that the effects he has recorded on the meiofauna do not derive directly from the hydrocarbon input to the system, but rather indirectly through other factors in the environment which themselves have been affected by the hydrocarbons? I am thinking particularly of sulphate-reducing bacteria and the production of sulphide.

C. G. Moore. Yes. Although it seems probable that effluent toxicity is important in the immediate vicinity of the effluent channels at the top of the shore, the major impact of the effluents on the meiofauna of the area appears to be largely a consequence of the enhancement of activity by reducing bacteria.

J. K. Rudd (*Amoco Europe and West Africa, London, U.K.*). Did Dr Moore consider the effects of variations in salinity of the refinery effluent and what happened as the effluent water became purer?

C. G. Moore. By comparing the impact of the Grangemouth petrochemical effluents with those of freshwater discharges to the mudflats, it would appear that the low salinity of the effluents is of considerably less importance than the organic loading. This is not surprising because we are dealing with an estuary, where many of the species are tolerant of wide fluctuations of salinity. The paper describes the effect of the effluents on the meiobenthic community with distance from the effluent channels, and hence under different levels of effluent contamination. The purity of the effluents is unlikely to diminish significantly with distance along the effluent channels because of the high velocities and short distances involved.

P. K. Probert (*Wimbol Limited, Swindon, Wiltshire, U.K.*). Does Dr Moore think that biodeposition from fouling organisms on the platform could contribute significantly to the organic enrichment of the sediment in the immediate vicinity of the platform?

C. G. Moore. I think this is improbable. Unlike drilling cuttings, waste material from fouling organisms is of low specific gravity and might be expected to be widely dispersed by currents in such an exposed situation.