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Ecological consequences of environmental perturbations associated with offshore hydrocarbon production: a perspective on long-term exposures in the Gulf of Mexico

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Abstract: A synthesis of the literature on benthic responses to marine pollution suggests that macroinfaunal and meiofaunal communities exhibit repeatable patterns of response to sedimentary contamination generally detectable at high taxonomic levels (even phylum). These responses appear to be jointly driven by intrinsic physiological and ecological characteristics of higher taxa, such that crustaceans (especially amphipods and harpacticoids) and echinoderms are sensitive to toxics whereas polychaetes, oligochaetes, and nematodes (especially non-selective deposit feeders) are enhanced by organic enrichment. Application of this model to the GOOMEX results implies involvement of both toxicity and organic enrichment. Results of toxicity tests and comparisons of observed contaminant concentrations to known effects levels imply that metals drive the toxicity response. We conclude that (1) long-lasting effects of drilling activity exist in the sedimentary environment around gas production platforms, (2) dual effects of toxicity and organic enrichment probably drive readily detectable responses in benthic meiofauna and macroinfauna to 100–200 m, and (3) the failure to detect evidence of exposure or sublethal impacts on fishes and most larger invertebrates is a joint consequence of their mobility over the relevant scales of environmental change and their negligible exposure to hydrocarbons and other contaminants.

Résumé : Une synthèse des articles portant sur la réponse du benthos à la pollution des mers paraît indiquer que les communautés constituées de l’endofaune macroscopique et de la méiofaune ont des profils répétables de réponse à la contamination des sédiments qui sont généralement observables à des niveaux taxonomiques élevés (même à celui du phylum). Ces réponses semblent être alimentées à la fois par des caractéristiques écologiques et physiologiques intrinsèques des taxons supérieurs : p. ex., les crustacés (particulièrement les amphipodes et les harpacticoïdes) et les échinodermes sont sensibles aux substances toxiques tandis que les polychètes, les oligochètes et les nématodes (particulièrement les dépositivores non sélectifs) tirent parti de l’enrichissement en matières organiques. L’application de ce modèle aux résultats obtenus dans le cadre du projet GOOMEX fait intervenir la toxicité et l’enrichissement en matières organiques comme facteurs. Les résultats des tests de toxicité et les rapprochements entre des concentrations observées de contaminants et des niveaux d’effets connus paraissent indiquer que les métaux sont les principaux agents de la toxicité. Nous parvenons aux conclusions suivantes : 1) les forages produisent des effets durables dans l’environnement sédimentaire autour des plates-formes de production gazière, 2) les effets combinés de la toxicité et de l’enrichissement en matières organiques sont probablement à l’origine des réponses facilement détectables de la méiofaune benthique et de l’endofaune macroscopique jusqu’à 100–200 m et 3) le fait de ne pas détecter de signes d’exposition ou d’effets sublétaux chez le poisson et la plupart des grands invertébrés est le résultat de leur grande mobilité par rapport à l’échelle des changements dans l’environnement et de leur exposition négligeable aux hydrocarbures et à d’autres contaminants.
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Introduction

One of the most challenging problems in ecology is to separate the impacts of human disturbance from a background of natural spatial and temporal variation in ecological systems and thereby identify the ecological consequences of anthro-

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pogenic perturbations to the natural environment (Levin 1992; Peterson 1993). There is enhanced urgency for provision of such information so as to inform properly the public policy debates over the wisdom of conducting certain economically rewarding but environmentally transforming activities (Lubchenco et al. 1991). Where the environmental signal resulting from the perturbation is large relative to the background variation, detection of ecological impacts is rendered relatively straightforward (Green 1979). However, the longer-term consequences of chronic disruptions of the environment are much less readily evaluated (e.g., Carney 1987). When chronic long-term disturbances act through sublethal effects on organisms, relating the consequences of those sublethal changes to the parameters of true public concern, the population abundances of valued species and the ability to sustain provision of ecosystem goods and services into the future, becomes especially problematic (Underwood and Peterson 1988).

Considerable controversy has arisen over the biological consequences of long-term oil and gas production and the advisability of further development of oil and gas fields on the continental shelf off several regions of the United States (NRC 1989, 1991, 1992; DOI 1992). A substantial body of technical data on the ecological impacts of oil spills in the marine environment serves to evaluate that particular risk in offshore hydrocarbon development and production (NRC 1975, 1985). Our understanding, however, of the consequences of many of the more subtle environmental changes associated with offshore hydrocarbon production is extremely limited. For example, the ecological significance of long-term chronic exposures to low-level releases of many chemicals associated with hydrocarbon production activities is largely unknown (NRC 1985; Boesch et al. 1987; Capuzzo 1987). Although such processes as discharge of produced waters and discharge and seafloor accumulation of drilling muds and cuttings, as well as chronic low-level releases of hydrocarbons around production platforms, do not induce environmental signals of anything like the magnitude of oil spills, these chronic environmental perturbations and the biological exposures continue to operate over long periods of time and over wide areas of the shelf. Consequently, they can induce substantial ecological change (Gray et al. 1990; Lissner et al. 1991; Osenberg et al. 1992; Olsgard and Gray 1995). Reviews of the environmental and ecological impacts of offshore oil and gas development (NRC 1975, 1985; Boesch and Rabalais 1987; Kingston 1992) have identified the filling of this information gap as the most important research priority to improve public decision making on proposals to develop additional hydrocarbon resources on the continental shelf.

Any study of the biological consequences of a long-term history of hydrocarbon production on the continental shelf must recognize certain important discontinuities in the system that influence the results and affect their interpretation. Contaminants of possible concern are released into the liquid medium, the seawater, but are rapidly sorted by their specific gravity and chemical properties into those that deposit onto the seafloor and those that remain in water. Contaminants remaining in water possess intrinsically broad spatial scales of many kilometres, consistent with the transport dynamics of the medium. However, the dilution associated with mixing processes in water produces a rapidly diffused environmental signal with short temporal persistence. In contrast, those contaminants deposited onto the seafloor have short spatial scales of up to a few kilometres but long temporal persistence, as dictated by the much slower rates of transport and mixing of the solid medium. Similarly, the organisms that may be affected by exposure to contaminants possess broadly discordant spatial and temporal scales. Benthic invertebrates living in sediments are largely sedentary and exhibit relatively short life times, especially the meiofauna with characteristic scales of weeks to months. Larger pelagic invertebrates and fishes exhibit much less site fidelity on scales relevant to hydrocarbon platform effects, yet live long enough (on scales of years) to exhibit possible responses to chronic exposures. Thus, the environmental and biological discontinuities have important implications for design of any study of impacts and interpretation of any observed responses.

GOOMEX (the Gulf of Mexico Offshore Operations Monitoring Experiment) is a research project designed to begin assessment of the major environmental effects and ecological consequences of the joint set of processes associated with a long-term (decades) history of drilling and gas production in the Gulf of Mexico (Kennicutt et al. 1996*a*). Three active gas production platforms off the Texas Gulf of Mexico coast with long histories of drilling activity, ending 6–12 yr prior to study, were sampled in a radial design extending from <50 to 3000 m away from the platform to assess long-term impacts on environmental variables and biotic responses. A suite of environmental parameters in the sediments covaried as a function of distance from platforms: sand, hydrocarbons, metals, and inorganic carbon were all elevated out to a distance of 100–200 m. Gradients were steepest at the deepest (125 m) and most diffuse at the shallowest platform (29 m), where physical transport processes were most intense. Evidence of localized organic enrichment appeared in the form of development of summer hypoxia and nutrient release in bottom waters around shallower platforms, but otherwise, water samples showed no detectable signals of platform presence.

Analyses of biological variables showed that benthic meio- and macroinfaunal samples from boxcores provided several sensitive indicators of environmental change whereas physiological analyses of 16 fishes and five mobile invertebrates did not reveal detectable responses (EROD, AHH detoxification enzymes, biliary PAH metabolites, P4501A induction). Densities of harpacticoid copepods and total meiofauna were depressed around two platforms whereas densities of nonselective deposit-feeding nematodes tended to be enhanced. Amphipod densities were depressed near all platforms, but densities of polychaetous annelids and total macroinfauna were greatly enhanced around two platforms.

In this paper, we first present an original synthetic review of how benthic communities respond to pollution in ways that may allow discrimination among multiple causes. We then synthesize the results of GOOMEX Phase I in light of this review to interpret GOOMEX patterns. Finally, we compare GOOMEX results with analogous previously published data on impacts of offshore oil and gas exploration and production activities, showing how the scope of biological impacts of long-term exposures derived from gas production platforms in the Gulf of Mexico is small relative to impacts in the North Sea where oil-based drilling muds were employed.

Use of benthic biological responses to separate effects of confounded physical forcing variables

Confounding of environmental variables

Covariance in multiple environmental variables is typical of most anthropogenic discharges into marine environments (Pearson and Rosenberg 1978). When several environmental variables are confounded in their patterns of distribution, it becomes difficult to identify which factor, factors, or interaction of factors is responsible for observed biological responses. If the suite of environmental variables associated with a particular anthropogenic activity were always confounded in the same way and to the same degree, then there would be little practical motivation to tease apart their effects. If, on the other hand, various management alternatives could influence some factors independent of others, then understanding causation would be in the interest of effective management. The possibility of independently controlling environmental variables and their deleterious effects exists for the management of the complex of operations associated with offshore production platforms. For example, Olsgard and Gray (1995) suggested that use of oil-based drilling muds greatly expands the spatial scale of contamination and biological effects, as compared with water-based muds. Obvious potential for improved management motivates us to provide a synthetic overview of the literature on benthic pollution responses to provide tools to help unravel the confounded effects operating at the GOOMEX platform sites.

Confounded environmental variables in anthropogenic discharges into marine environments characteristically include two separate classes of variables, organic enrichment and toxicants. For example, the discharge of treated sewage typically includes both labile organic matter and also heavy metals, as in the Los Angeles County discharge of treated municipal wastewater off Palos Verdes (Swartz et al. 1986) and in a classic study of the Firth of Clyde in Scotland (Pearson 1987). In the North Sea platform studies, sediments near the platforms were organically enriched and also had elevated total hydrocarbon and metals concentrations (Gray et al. 1990; Olsgard and Gray 1995). This dual character of petroleum hydrocarbon releases is evident in virtually every study of environmental effects of oil spills and of natural petroleum seeps (e.g., Spies and DesMarais 1983; Braddock et al. 1995). Even in cases of pure organic enrichment, if fluxes of organic matter are too great, so as to overload the aerobic degradation capacity of the microbes, creation of toxic chemicals, especially H_2S, and oxygen depletion produce a toxic component to the local environmental change. Teasing apart the contributions of organic enrichment and of toxicity becomes perhaps the central task of evaluating the causes of biological responses to release of petroleum and other discharges to the marine environment (e.g., Spies et al. 1988; Agard et al. 1993).

Synthetic model of benthic biotic response to contamination

The current status of our understanding of benthic community response to pollution incorporates an implicit but as yet unarticulated recognition of the duality of potential effects of pollution. It is becoming evident that, even though individual species within a higher taxon can vary greatly in their sensitivity to environmental change, benthic biological responses to contamination are detectable at higher taxonomic levels. For macrofauna, detection of impacts is possible at the level of the phylum (Warwick 1988*a*, 1988*b*), and at least in some cases, phyletic analysis provides superior discrimination (Agard et al. 1993; Warwick and Clarke 1993). The ability of higher taxonomic levels to detect impacts of pollution is also evident for the meiofauna, although it may apply here to families (Heip et al. 1988) better than to phyla (see, however, Raffaelli and Mason 1981).

We propose that the biological basis for this dual response to pollution rests upon intrinsic physiological and ecological differences among higher taxa. Echinoderms and crustaceans, especially amphipods and some harpacticoid copepods, are highly sensitive to toxic chemicals in their environment. It is by design that the standard United States EPA biotoxicity tests for benthic invertebrates involve an echinoderm (sea urchin reproductive stages) and an amphipod (*Rhepoxinius*) so that testing uses the most sensitive indicators of pollution toxicity. In analyses of community responses to marine pollution that involve toxicity, echinoderms and crustaceans, at least amphipods and some groups of harpacticoids, typically show large declines. In contrast, polychaetes, oligochaetes, and nematodes are not especially sensitive to toxic chemicals and also include species with opportunistic life histories and appropriate feeding types (especially nonselective deposit feeders) that render them capable of utilizing organic materials in organic pollution. Consequently, polychaetes, oligochaetes, and nematodes (at least nonselective deposit feeders) typically show substantial increases under organic pollution. It is this dual effect of organic pollution upon different groups of benthic meiofauna and macrofauna that makes the ordination techniques of benthic community analysis so effective in discriminating the effects of that pollution at higher levels of taxonomic classification, including the phylum level for macrofauna (Warwick and Clarke 1993).

The evidence to support this synthetic model of benthic biological response to pollution in the marine environment comes from review of an extensive suite of studies of marine pollution. It is extremely difficult to find studies of benthic community response to pollution where the only environmental variable influencing biological patterns is toxic contamination. Typically, toxicity and organic enrichment covary. Cases in which only one of these usually confounded components of anthropogenic discharges into the marine environment exists would allow clear isolation of the two components and separate assessment of their impacts on the benthos.

Perhaps the most unequivocal example of a well-studied and unconfounded gradient in a marine discharge comes from the study of the effects of the cooling water discharge from the San Onofre Nuclear Generating Station on the shelf of the Southern California Bight (MRC 1989). As seawater is used for cooling and discharged onto the shelf, natural organic detritus is created and discharged in the form of dead phytoplankton, zooplankton, larval fish, and macerated macrophytes. There are no detectable toxic chemical contaminants in the discharge or in the sediments. Also, the organic loading from this detritus does not exceed the capacity of the microbial degradation system. Only slight increases in sediment organic content and phaeopigment concentration exist in the vicinity of the diffusers, although the increased seston flux is clearly evident. In response to this discharge of detritus and modest organic enrichment of the sediments, increased abundances in virtually all major taxa of macrofauna were detected using rigorous BACI designs (Green 1979; Stewart-Oaten et al. 1986), with effects extending to 3.5–6.7 km downcoast. As is typical even of discharges that confound organic enrichment with toxic chemical additions, the polychaetes and nematodes were enhanced in abundance. But unlike those perturbations that include contaminants, the crustaceans, including amphipods, ostracods, tanaids, and mysids, were also enhanced in abundance. In addition, there was no evidence of depression in abundance of echinoderms, which were uncommon in the system. Although there was little effect of the discharge on benthic biomass, this is likely to be a consequence of the near-field predation by enhanced abundances of most demersal fish species (MRC 1989).

The San Onofre example contrasts sharply with the case of the Los Angeles County outfall at Palos Verdes (Swartz et al. 1986; LACSD 1990). This Los Angeles County wastewater discharge differs from the San Onofre discharge in that not only is there organic enrichment but also an introduction of toxic contaminants, including DDT, PCB’s, H_2S, hydrocarbons, and metals. Polychaetous annelids as a higher taxonomic group are enhanced in abundance near the discharge source, with the response driven by several opportunistic, rather nonselective deposit feeders. In this case, which includes toxicity, echinoderms as a group are grossly depressed around the outfall (Tetra Tech 1981; Swartz et al. 1986). Amphipods also decline in abundance near the outfall, determined largely by the loss of the usually dominant species. Meiofaunal community responses were not assessed in this system. Thus, the inclusion of toxic chemicals in the discharge to the shelf of the Southern California Bight does little to affect the positive polychaete response to enrichment as documented nearby at San Onofre where no chemical contamination occurred; nevertheless, the addition of toxics altered the responses of the physiologically sensitive macrofaunal echinoderms and amphipods, which showed greatly reduced rather than enhanced densities. Thus, this contrast of the two discharges serves as a means of demonstrating how dual effects of enrichment and toxicity influence the benthic community response in a way that allows some substantial degree of separation of the effects.

In the case of the Palos Verdes sewage discharge, studies of the fish responses in the early 1970’s, when the treatment was minimal, also showed differences from the San Onofre response. In the immediate vicinity of the source, fish abundance was depressed over about 10.5 km^2 whereas an area of 4 km^2 of enhanced fish abundance occurred somewhat farther away (Mearns et al. 1976). The discharge area was an epicenter for fish diseases such as fin rot in Dover sole, rex sole, and calico rockfish, and the fishes showed bioaccumulation of DDT and PCB (Tetra Tech 1981). Unlike the San Onofre case, the fish community was selectively altered, with species that feed on benthic polychaetes and other seafloor invertebrates enhanced in abundance and those feeding more pelagically depressed in abundance (Tetra Tech 1984).

Other examples of the effects of anthropogenic discharges into the marine environment on benthic community biology involve substantial confounding of organic loading and toxic chemical enhancement. Review of these studies is useful in evaluating whether the patterns of polychaete, oligochaete, and nematode enhancement and echinoderm and crustacean depression are general. Even though separate causation cannot be unequivocally ascribed in these cases of confounded environmental forcings, a common pattern should emerge if the model is supportable. Table 1 presents a review of relevant studies from the literature on soft-sediment benthic community response to joint gradients in organic enrichment and toxic chemicals. This overview includes analyses of effects of oil spills, natural petroleum seeps, sewage discharges, and industrial discharges, as well as some experimental mesocosm and field studies. For the macroinfauna, the patterns of enhancement in polychaetous annelids, typically driven by certain non-selective deposit feeders, and of depression in echinoderms and amphipods are compellingly consistent. For the meiofauna, there appears to be more need to analyze different families or trophic groups of both nematodes and harpacticoids separately, but there is also evidence here of general enhancement of nonselective deposit feeders among nematodes and declines in some harpacticoids (as discussed also in Coull and Chandler 1992). One limitation in application of this synthetic model is the difficulty in defining objectively the feeding status for bulk feeders such as most macroinfauna and meiofauna. Development of objective criteria for both trophic group and also opportunistic life history is an important but challenging goal for future refinement of this pollution response model. Nevertheless, applying effective taxonomic criteria for evaluating the macroinfaunal community response does not require any trophic characterization.

Overview of physical environmental transformations and interpretation of biological responses around gas production platforms in GOOMEX

Methods

A summary of how abiotic parameters varied among platforms and around each platform is presented in Table 2, based on results in Kennicutt et al. (1996*b*), where detailed methods also appear. Sampling for sediments and benthic meio- and macroinfauna was conducted during four cruises over two years (January and June in 1993 and 1994) in a radial design around each platform with distances ranging from <50 to 3000 m. Larger invertebrates and demersal fishes were sampled by replicate trawls near and far from each platform. The three platforms were located at varying distances from the Texas Gulf of Mexico coast in water depths of 29, 80, and 125 m. This difference among platforms in water depth led to important distinctions in their physical, chemical, and sedimentological settings. Physical energy at the seafloor decreased with depth across the range occupied by the three platforms, leading to substantial fining of the bottom sediments with increasing water depth. Furthermore, this difference in water depth resulted in differing degrees of seasonality in water properties (temperature, salinity, and dissolved oxygen) at the bottom, with the shallowest platform experiencing the greatest seasonal signals. The complete history of drilling and discharge activity around each platform is

Table 1. Effects of anthropogenic pollution on benthic communities in the marine environment.

Pollution case study	Organic enrichment	Toxic chemicals	Benthos enhanced	Benthos suppressed	Source(s)
Macroinfauna					
Exxon Valdez oil spill	Yes, with evident stimulation of oil-degrading bacteria	Yes, with elevated PAH's, etc.	Total polychaetes enhanced as well as *Nereis*, *Nepthys*, *Polydora*, and *Lucina* in eelgrass beds	Total crustaceans and total echinoderms occasionally show reductions (never increases), while total amphipods declined as well as a crab (*Telmessus*) and a seastar (*Dermasterias*)	Jewett et al. 1994; Braddock et al. 1995
Amoco Cadiz oil spill	Yes	Yes	Total polychaetes enhanced	Total echinoderms and total crustaceans declined, as well as amphipods	Dauvin 1984, 1987; Warwick and Clarke 1993
Florida oil spill	Yes	Yes	Opportunistic, surface deposit-feeding polychaetes increased, especially *Capitella capitata, Mediomastus ambiseta*	Several ampeliscid amphipods declined	Sanders et al. 1972, 1980; Sanders 1978
Irini oil spill	Yes	Yes	Unclear from data available	Amphipods (*Gammarus* spp.) and isopods (*Idotea* spp.) declined	Notini 1978
Arrow oil spill	Yes	Yes	Unclear from data available	An amphipod (*Gammarus oceanicus*) was selectively reduced	Thomas 1978
Esso Essen oil spill	Yes	Yes	Unclear from data available	Amphipods in intertidal and subtidal declined greatly	Stander and Venter 1968
General M.C. Meigs oil spill	Yes	Yes	Unclear from data available	Sea urchin *Strongylocentrotus purpuratus* suffered evident lethal and sublethal impacts	Clarke et al. 1978

Table 1 (*continued*).

Pollution case study	Organic enrichment	Toxic chemicals	Benthos enhanced	Benthos suppressed	Source(s)
Palos Verdes sewage wastewater discharge	Yes, with detectable organic C, N enhancement	Yes, with DDT, PCB, heavy metals, and H_2S elevated	Total polychaetes enhanced, as well as *Tharyx* spp., *Capitella capitata, Mediomastus* spp., *Schistomeringos longicornis*, and *Ophryotrocha* spp.	Total echinoderms reduced as well as ophiuroid *Amphiodia urtica*, sea cucumber *Parastichopus parvimensus*, sea urchin *Lytechinus anamensus*, and seastar *Luidia foliolata*; amphipod *Heterophoxus oculatus* also reduced	Tetra Tech 1981; Swartz et al. 1986; LACSD 1990
San Onofre Nuclear Generating Station cooling water discharge	Yes, with evident organic C and phaeopigment enhancement	No	Total polychaetes, total crustaceans, total amphipods, total molluscs all enhanced	None	MRC 1989
Firth of Clyde sewage sludge disposal	Yes, with organic C and N elevated	Yes, with Cd elevated along with other metals	Total polychaetes enhanced	Total echinoderms, total crustaceans both depressed	Pearson 1978; Clarke and Ainsworth 1993
Swedish pulp mill discharge	Yes	Unclear	Total polychaetes enhanced, especially *Capitella capitata* and other opportunistic deposit feeders	Total echinoderms depressed	Rosenberg 1972
Antarctic sediment contamination around Winter Quarters Bay	Presumably, in that hydrocarbon levels are elevated	Yes, with PCB, hydrocarbons, and heavy metals elevated	In most contaminated areas, *Capitella* and *Ophryotrocha* en-, hanced, while in modest contamination, *Tharyx* and *Haploscoloplos* enhanced	Total crustaceans especially amphipods, isopods, tanaids	Lenihan and Oliver 1995
Industrial pollution gradient in fjord near Oslo	Presumably	Yes, heavy metal concentrations elevated	Deposit-feeding polychaetes may be elevated	Total echinoderm biomass is clearly depressed, especially an echinoid	Gray et al. 1988
Gradient in oil-based drilling muds around production	Possibly, although modest	Yes, with TPH and heavy metal concentrations elevated	Group of polychaetes was enhanced at severely polluted	Echinoderm *Amphiura filiformis* plus a diverse suite of species	Gray et al. 1990; Olsgard and Gray 1995

Table 1 (*continued*).

Pollution case study	Organic enrichment	Toxic chemicals	Benthos enhanced	Benthos suppressed	Source(s)
Gradient in oil-based drilling muds around an exploration site	Presumably, in that hydrocarbons were elevated	Yes, with total oil concentrations elevated	Only one species, a polychaete, showed significant enhancement	Dominant echinoderm *Amphiura filiformis* declined and two crustaceans and a molllusc exhibited far-reaching sensitivity	Daan et al. 1990, 1992; Krœncke et al. 1992
Experimental crude oil addition in mesocosm	Probably not because of short-term nature of experiment	Yes	None (time frame too short to test)	Total echinoderms, especially the ophiuroid *Ophiura affinis*, depressed	Gray et al. 1988
Natural oil seep and refinery discharges in Trinidad	Yes, with organic C elevated	Yes, with PAH elevation at seep and refinery and metals elevated at refinery	Total polychaetes enhanced, especially in biomass at the seep	Unclear from data available	Agard et al. 1993
Natural oil seep	Yes, with enhanced microbial production	Yes, with PAH elevation	Oligochaetes and many deposit-feeding polychaetes enhanced	The only abundant echinoderm *Lytechinus pictus* and the only abundant amphipod *Paraphoxus abronius* depressed	Spies et al. 1980
Natural oil seep	Yes: TOC, TON, and nonoil organics all elevated	Yes, with total extractable hydrocarbons elevated; no metals assayed	Only nematodes as a group were enhanced	Amphipods, copepods, and ostracods were eliminated and polychaetes, oligochaetes, bivalves, and cumaceans all greatly depressed	Steichen et al. 1996
Experimental fuel oil addition in mesocosm	Possibly, given 25-wk exposure to oil	Yes	Time frame probably too short to test	Total amphipod abundance declined by 98%	Grassle et al. 1981
Field experiment of crude oil addition to tide pools	Probably not because of short-term nature of experiment	Yes	Time frame too short to test	Negative effects on amphipods, isopods, tanaids	Bonsdorff and Nelson 1981
Meta-analysis of all benthic community data for NE Atlantic	Yes	Yes	Total polychaetes are enhanced	Total echinoderms and total crustaceans are depressed	Warwick and Clarke 1993

Table 1 (*concluded*).

Pollution case study	Organic enrichment	Toxic chemicals	Benthos enhanced	Benthos suppressed	Source(s)
			Meiofauna		
Review of marine pollution events	Yes	Yes	Nematodes are enhanced	Harpacticoid copepods are depressed	Raffaelli and Mason 1981
Raw domestic sewage discharge	Yes	Probable	Copepod/nematode ratio is enhanced by pollution		Vidakovic 1983
Organic enrichment	Yes	No	Copepod/nematode ratio is enhanced with organic enrichment		Gee et al. 1985
Organic enrichment	Yes	Probable	Copepod/nematode ratio is enhanced with organic enrichment		Moore and Pearson 1986
Natural oil seep	Yes, with enhanced microbial production	Yes, with PAH elevation		Nematode/harpacticoid ratio is enhanced with oil addition	Montagna et al. 1987
Review of organic pollution in marine sediments	Yes	Usually yes	Nonselective deposit-feeding nematodes generally enhanced	Some other nematode groups may be depressed	Heip et al. 1985
Industrial pollution gradient in fjord near Oslo	Presumably	Yes, heavy metal concentrations elevated	Total nematodes are enhanced as well as some harpacticoid copepod groups	Unclear from data available	Heip et al. 1988
Meta-analysis of all benthic community data for NE Atlantic	Yes	Yes	Total nematodes are generally enhanced	Harpacticoids, etc., not analyzed	Warwick and Clarke 1993

Table 2. Summary of abiotic environmental variables and biological responses around each platform (MAI-686, MU-A85, and HI-A389) studied in GOOMEX.

Characteristic	MAI-686	MU-A85	HI-A389
Environmental variables			
Physical attributes[a]			
Water depth	29 m	80 m	125 m
Location	Nearshore	Intermediate	Offshore
Energy setting	High	Medium–low	Low
Seasonality of bottom environment	High	Medium	Low
Shunting depth	Near surface	Near bottom	Near bottom
Time since last drilling	12 yr	7 yr	6 yr
Physicochemical[a] (ranges given for 3000 m to 100–50 m distances)			
Oxygen levels in bottom waters	Seasonal hypoxia near platform	Seasonal hypoxia near platform	Oxycline impingement
Organic carbon decrease	Yes (from 0.79 to 0.35–0.42%)	Yes (from 0.93 to 0.55–0.62%)	Maybe (from 1.4 to 1.0–1.1%)
Inorganic carbon enrichment	Yes (from 0.19 to 0.31–0.36%)	Yes (from 0.77 to 0.86–1.0%)	Maybe (from 1.62 to 1.96–2.66%)
Contaminants[a] (from 3000 to within 50–100 m the platform)			
Hydrocarbons	Low (e.g., averaged 50 ppb PAH)	Low–medium (e.g., from 27 to 126–181 ppb PAH)	Medium (e.g., from 32 to 103–256 ppb PAH)
Trace metals	Low (e.g., from 0.05 to 0.09–0.13 ppm Cd)	Medium (e.g., from 0.05 to 0.25–0.46 ppm Cd)	High (e.g., from 0.08 to 0.65–6.4 ppm Cd)
Sand content	High (from 27 to 60 to >73%)	High (from <12 to 55–67%)	High (from <4 to 33–40%)
Biological responses			
Macroinfauna[b]			
Abundance	Little change	Higher by 70% near-field	Higher by a factor of 2–4 near-field
Polychaete abundance	Little change	Higher by 90% near-field	Higher by a factor of 3–5 near-field
Amphipod abundance	Lower by a factor of 4–12 near-field	Lower by a factor of 4–5 near-field	Lower by a factor of 3–5 near-field
Ratio of polychaetes/amphipods	6–10 times higher near-field	8–10 times higher near-field	20–30 times higher near-field
Meiofauna[b]			
Density	Higher by a factor of 2–3 far-field	Slightly higher far-field, but directionally dependent	50% higher near-field
Nematode abundance	Lower by a factor of 2 near-field	Lower by a factor of 2 near-field	60–80% higher near-field
Harpacticoid abundance	Lower by a factor of 2 near-field	Little change	Lower by a factor of 3 near-field
Ratio of nematodes/harpacticoids	Little change	Little change	4–5 times higher near-field
Life history: gravid females	3 times higher near-field	No difference between near and far field	3 times higher near-field

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Table 2 (*concluded*).

Characteristic	MAI-686	MU-A85	HI-A389
Life history: clutch volume	Higher far-field	Higher far-field	Higher near-field
Life history: clutch size	No difference between near and far field	Higher far-field	Higher far-field
Harpacticoid genetic variability	2 times higher far-field	1.5 times higher far-field	2.3 times higher far-field
Megafaunal invertebrates[c]			
Catch per unit effort	Significant differences, but complex distribution among species	Significant differences, but complex distribution among species	Higher near-field (but few differences)
Size-frequency distribution	Significant differences, but complex distribution among species	Individuals larger far-field	Individuals larger near-field
Histopathology	Significant differences, but complex distribution among species	Intensity higher near-field	Few differences
Sex ratios	Significant differences, but complex distribution among species	Significant differences, but complex distribution among species	Females more abundant near-field
Porewater toxicity[d]	Toxicity detected near-field	No difference between near and far field	Toxicity detected near-field
Biomarkers of aromatic hydrocarbon exposure[e]			
Invertebrates (5 species)	Low AHH activity	Low AHH activity	Low AHH activity
Fish (16 species)			
EROD activity	Low and no response to distance	Low and no response to distance	Low and no response to distance
PAH metabolites in bile	No response to distance	No response to distance	No response to distance
P4501A mRNA	No response to distance	No response to distance	No response to distance

[a] From Kennicutt et al. (1996*b*).
[b] From Montaga and Harper (1996).
[c] From Ellis et al. (1996).
[d] From Carr et al. (1996).
[e] From McDonald et al. (1996).

unavailable, but certain clear distinctions exist (Kennicutt et al. 1996*a*). Shunting of drilling muds and cuttings occurred with near-surface discharge at the shallowest platform and near-bottom discharge at the two deeper platforms. The time since the last drilling varied somewhat among platforms from 6 to 12 yrs before sampling. Platforms were still in production at the time of sampling.

Effects on environmental variables

The physicochemical environment was clearly influenced by the presence of and/or activities associated with the platforms (Table 2). In the GOOMEX Phase I data set, as in previous analyses of effects of anthropogenic discharges in the marine environment (e.g., Pearson and Rosenberg 1978; Gray et al. 1990; Olsgard and Gray 1995), strong covariance exists in the patterns of change in many environmental variables with distance away from the offshore production platforms. From knowledge of what are likely to be the most important forcing variables for biological responses, we identify four major types of environmental variables that show strong but confounded responses to distance along this gradient. Sands, hydrocarbons, metals, and organic inputs were all elevated near platforms (Table 2). The form of this covariance between coarse-grained sediments and organic and inorganic pollutants is highly unusual because contaminants typically bind to and become associated with fine-grained particles.

First, sand-sized particles were greatly enriched around all platforms, as a consequence of both discharge of drill cuttings and sand-cleaning of the structure. Sands increased from a background of about 30% to 70% at the shallow platform MAI-686, from about 10% to 65% at the intermediate platform MU-A85, and from about 5% to 40% at the deepest platform HI-A389. The proportion of fine sediments decreased along this gradient of increased sand content towards platforms.

Second, hydrocarbons (PAH's, AH's, and UCM) were also modestly enhanced near platforms, but this increase was strong only at the deepest platform in the low-energy setting. Detectable contamination extended to 100–200 m, although not symetrically in every direction. Even at HI-A389 where the pattern was strong, hydrocarbon concentrations were relatively low, with PAH levels well below established biological effects thresholds and their composition reflected substantial degradation. In general, the distribution of hydrocarbons remained constant across cruises. Only in isolated pockets at the shallowest platform were recent sources of hydrocarbon release evident, perhaps coming from a seep or pipe leakage.

Third, metal concentrations (Ag, Ba, Cd, Hg, Pb, and Zn especially) increased out to 100–200 m around platforms, with the intensity of the pattern varying directly with platform depth. Trace metals concentrations in the near field exceeded levels known to cause biological effects in many locations. Concentrations of heavy metals in pore waters, although not well correlated with solid-phase concentrations probably because of porewater sampling constraints, were also elevated at certain sampling sites to a maximum distance of 100 m. Most heavy metals showed strong correlations with Ba, although Pb, Zn, and Cd were shown also to be accumulating from some source after initial release of cuttings, perhaps from produced waters (Kennicutt et al. 1996*b*).

Fourth, although little change was detectable in ambient water properties with increasing proximity to platforms (Kennicutt et al. 1996*b*), oxygen depression and enhancement of some nutrients (silicate, phosphate, and/or nitrate) in bottom waters around the shallower platforms indicate organic enrichment and enhanced benthic decomposition processes. Hypoxia developed in the vicinity of the shallowest platform MAI-686 in summer and enhanced nutrient levels were detectable in bottom waters. A suggestion of this same response appeared around the platform at intermediate depth but not at the deepest platform. Inorganic carbon was enhanced in sediments near the platforms, reflecting results of past discharge of cuttings through carbonate-bearing strata and a rain of biogenic shell and test debris from benthic animals occupying the platform. The percent organic carbon in surface sediments actually declined in the near field but not in proportion to the degree of dilution by sands, implying possible organic enrichment.

Biological responses

The major patterns in biological responses (Table 2) resulting from the suite of environmental gradients at the gas production platforms studied in GOOMEX can be interpreted largely as consequences of two of the four types of environmental forcings, organic enrichment and metals toxicity. The hydrocarbons occur in concentrations that seem too low to be important contributors to the observed toxicological effects. For example, total PAH was generally less than 100 ng/g (Kennicutt et al. 1996*b*), which is an order of magnitude lower than what Spies (1987) suggested is needed to induce biological response. The pattern of increased sand content doubtless affects benthic invertebrates, but the observed trends in benthic abundances run opposite to the usual biotic responses to sediment texture. The emergence in benthic meiofaunal and macroinfaunal communities of patterns that are broadly consistent with other documented responses to organic enrichment and sediment toxicity, despite the sediment size gradient, leads us to conclude that the sediment grain size pattern is unlikely to be the primary driver of the observed biological responses.

The macroinfaunal community data reveal a pattern of change with distance from the platforms (Table 2) that is consistent with earlier studies of low-level organic and chemical discharges to the marine environment (Table 1). Detailed data and statistical test results for the benthic macro- and meiofauna appear in Montagna and Harper (1996). Total macroinfaunal densities were enhanced at 50- and somewhat to 100-m distances at two platforms (Table 2), as a consequence of the enhanced abundances of polychaetous and oligochaetous annelids (Table 3). This pattern was absent at the shallowest site, MAI-686, where the relatively high-energy physical environment has led to more extensive dispersion of materials discharged from this platform. Species contributing most to polychaete enhancement were two *Cirratulus* and one *Cirriformia* species at HI-A389 and a *Spiophanes, Paramphinome*, and *Golfingia* species at MU-A85. Enhancement of polychaete and oligochaete abundances is typical in cases of modest organic pollution in marine sediments and is probably a consequence of organic enrichment in accord with the synthetic model of causation. Physical disturbance in the form of particulate deposition (see Gray 1982) also may contribute to enhancement of annelid densities, but the underlying mecha-

Table 3. Changes with distance (m) from platform in the most diagnostic response variables for meiofauna and macrofauna.

Platform MAI-686					
Distance	500	50	100	200	3000
Polychaetes	710	689	630	625	589
Distance	500	3000	200	50	100
Amphipods	156	130	74	34	13
Distance	100	50	200	500	3000
Ratio of polychaetes/amphipods	48	20	8.4	4.6	4.5
Distance	500	3000	200	50	100
Nonselective deposit-feeding (nsdf) nematodes	469	438	425	398	342
Distance	3000	500	200	100	50
Harpacticoid copepods	449	402	297	205	164
Distance	50	100	200	500	3000
Ratio of nsdf nematodes/copepods	2.43	1.67	1.43	1.17	0.98
Platform MU-A85					
Distance	50	100	200	500	3000
Polychaetes	812	802	566	436	419
Distance	3000	200	500	100	50
Amphipods	60	55	53	45	12
Distance	50	100	200	500	3000
Ratio of polychaetes/amphipods	67.7	17.8	10.3	8.2	7.0
Distance	200	100	50	500	3000
nsdf nematodes	178	141	140	136	74
Distance	100	50	500	100	3000
Harpacticoid copepods	212	167	166	162	156
Distance	200	50	500	200	3000
Ratio of nsdf nematodes/copepods	1.10	0.84	0.82	0.67	0.47
Platform HI-A389					
Distance	50	100	200	500	3000
Polychaetes	1807	1015	504	281	243
Distance	500	200	3000	50	100
Amphipods	30	23	22	6	5
Distance	50	100	200	3000	500
Ratio of polychaetes/amphipods	301	203	21.9	11.1	9.4
Distance	50	100	200	500	3000
nsdf nematodes	160	145	140	124	87
Distance	3000	500	200	100	50
Harpacticoid copepods	119	118	104	97	34
Distance	50	100	200	500	3000
Ratio of nsdf nematodes/copepods	4.71	1.49	1.35	1.05	0.79

Note: Densities of meiofauna are per 10 cm^2 and of macrofauna are per 1 m^2. Means connected by underlining are not significantly different at $\alpha = 0.05$ in a Tukey multiple comparison test following ANOVA.[a] Where no underlining exists, Tukey's test is invalid because of significant interactions.

[a] Data results from Montagna and Harper (1996).

nism for such responses seems likely to be opportunistic utilization of newly provided organic resources and thus just a different form of organic enrichment. Furthermore, since the vast majority of the particulate deposition ceased several years before our GOOMEX study, disturbance from deposition seems unlikely to be an important driving factor in explaining GOOMEX results.

The increase in annelid abundance occurred despite the steep gradient in sand content in the sediments: total annelids would probably be expected to be more abundant in finer sediments, not in coarser ones, over this range of sediment grades. In contrast with the polychaetes and oligochaetes, amphipod abundances were depressed around all platforms, with effects confined to 50 or 100 m (Table 3). The amphipod decline was driven largely by the response of ampeliscid species. The effect on amphipods is also consistent with the literature on modest pollution in the marine environment, and is suggestive of a toxic response. The ratio of polychaete to amphipod abundances proved to be an especially responsive indicator of biological reponse (Table 3). The trawl sampling included one echinoderm with sufficient abundance for analysis at each platform. At the shallowest site (MAI-686), that echinodern, the seastar *Astropecten duplicatus*, was a statistically significant 6–20 times more abundant at far stations (Ellis et al. 1996). At the two deeper sites, the congener *A. cingulatus* was 2–3 times more abundant in the far field, but differences were not significant for this species that was an order of magnitude less abundant than its congener at the shallow site. These echinoderm patterns are therefore consistent with a possible source of toxicity near platforms, as predicted by the synthetic model for this sensitive phylum. On the other hand, ophiuroids from core sampling failed to reveal any significant pattern with distance from platforms at any site (Montagna and Harper 1996).

Meiofaunal community responses to the presence of platforms and the environmental gradients that emanate from them (Tables 2 and 3) are also generally consistent with patterns of response observed in cases of modest organic and chemical pollution in the marine environment (see Coull and Chandler 1992). The abundance of total nematodes was enhanced at 50 and 100 m by 60–80% at the platform with the steepest environmental gradient, HI-A389, but at the shallower sites nematode abundance was depressed in the near field (Table 2). The nonselective deposit-feeding nematodes showed patterns of enhancement close to two of the platforms (Table 3). Thus, the nonselective deposit-feeding nematodes may represent a more responsive indicator of modest organic enrichment. Physical disturbance in the form of historical particulate deposition may play an important role in provision of organic resources for opportunistic nematodes. The response of nematodes and especially of nonselective deposit-feeding nematodes runs opposite to that predicted on the basis of the sediment texture gradient: nematodes and this particular trophic group of nematodes typically increase as sediments become finer in size (e.g., Coull and Chandler 1992). Consequently, the tendency for enhancement in nonselective deposit-feeding nematodes near the platform runs against expectation based on sediment character.

Total harpacticoid copepods reveal a large depression near two of the platforms, with abundance close to the platform only about 40% on average of that in the distant stations (Table 3). This effect is most intense at the HI-A389 site, where the contaminant gradient is steepest. This pattern too is consistent with the results of previous studies showing frequent sensitivity of harpacticoid copepods to toxic chemicals. As a consequence of joint and opposing responses, the ratio of nonselective deposit-feeding nematodes to copepods provided an effective discriminator among distances from the platforms (Table 3). This pattern in the nematode to copepod ratio, exhitied at all three platforms to some degree, is consistent with the original suggestion of Raffaelli and Mason (1981) that the nematode to copepod ratio responds strongly to pollutant exposure. Several studies have debated the utility of this ratio, but Raffaelli (1987) and Coull and Chandler's (1992) review suggested that there is merit to this approach provided key covariates such as sedimentology are controlled. Our results suggest that the modification of this index achieved by restricting nematodes to those in the nonselective deposit-feeding group may provide a more sensitive and interpretable response.

Attribution of the similar responses of the two different groups of crustaceans, amphipods and harpacticoid copepods, to toxicological causes is supported by the results of porewater toxicity testing (Carr et al. 1996). Toxicity tests on percent normal development and percent fertilization of sea urchins (*Arbacia punctulata*), an echinoderm, revealed a pattern of biotoxicity similar to the pattern of chemical contamination at the study sites. The embryological development test proved more sensitive than the fertilization test, with all cases of significant toxicity in the fertilization test corresponding to significances in the development test. The toxicity results reveal that, with one exception, all cases of significance came from stations within 100 m of a platform. The most compelling pattern of toxicity is derived from the most contaminated site, HI-A389, where several sites within 50 m showed significant toxicity in the sea urchin development test during two independent samplings. Examination of porewater concentrations of contaminants in these samples suggested that the observed toxicity was most likely a consequence of metals. Concentrations of several metals in sediments at these stations approached or exceeded the published probable biological effects levels (Long and Morgan 1990). Results of a novel set of toxicity tests using naupliar survival of the harpacticoid copepod *Longipedia americana* and egg production for the meiofaunal polychaete *Dinophilus gyrociliatus* provide further evidence of toxicity close to the platform (Carr et al. 1996). Both of these species proved less sensitive than the sea urchin to sediment toxicity, but stations that proved toxic to either of these meiofauna were also toxic in the sea urchin development tests. These toxicity test results, therefore, confirm the toxicity of sediments close to the platforms, especially at HI-A389. Furthermore, the toxicity was demonstrated using not only a standard test species but also species indigenous to the study region. The demonstrated toxicologic effects on the test harpacticoid provide support for the inference that the pattern of depressed abundances of harpacticoids near the platforms is indeed a response to the toxicity of sediments rather than a response to changing sediment sizes or other characteristics that also differ near platforms.

A further joint analysis of (1) the sediment contaminant data, (2) the biotoxicity results, and (3) both the macroinfauna and meiofauna community data sets employed the sediment quality triad approach (Long and Chapman 1985) to integrate these potentially related data sets. The resulting set of multivariate analyses provides formal statistical tests that support the interpretations presented here (Green and Montagna 1996). The first axis from a PCA run on the sedimentary environmental data was used for these correlations. That axis represented the linear combinations and weightings of confounded contaminants and captured differences among distances from the platforms. For both the meiofauna and the macroinfauna, the variable chosen was again the one from a PCA that separated stations: this was driven by increases towards the platforms in polychaetes and decreases in amphipods for the macroinfauna, and increases towards the platforms in nonselective deposit-feeding nematodes and decreases in harpacticoids for the meiofauna. For the biotoxicity data, there was no need for multivariate techniques to reduce the dimensionality of the data set because only a single variable, sea urchin development success, was available across all stations and thus suitable for analysis. Cross-correlations between all pairs of sediment, biotoxicology, and benthic community variables produced close relationships. Where sediment was most contaminated, the highest levels of toxicity were demonstrated, and the community compositions were altered most in favor of polychaetes relative to amphipods and of non-selective deposit-feeding nematodes relative to harpacticoids (Green and Montagna 1996). The use of macroinfaunal and meiofaunal community data represents somewhat of a replication of the test for relationships: each revealed a similarly strong set of cross-correlations with both sediment contamination and biotoxicity. These interrelationships in accordance with the sediment quality triad approach imply that toxic impacts are likely to be involved to some degree in driving community patterns around platforms. Nevertheless, the confounding of environmental variables in the distance gradient around platforms means that there are several possible explanations for the high levels of cross-correlations and that toxicity is only one possible driver of these relationships.

Various physiological and genetic results provide further evidence that crustaceans around the platforms are exhibiting sublethal responses to contaminant exposure (Montagna and Harper 1996). In the pooled data set for all harpacticoid copepods, the percentage of gravid females was greater and the percentage of juveniles was reduced in the 50-m stations around platforms. In addition, reproductive effort (egg numbers times egg sizes) for those female harpacticoids carrying eggs was reduced within 50 m of the platforms. These responses could be explained as sublethal physiological reactions of these species of crustaceans to modest levels of stress from exposure to toxicants. The demonstration in multiple species of harpacticoid copepods that genetic diversity is significantly reduced near the platforms as compared with the far-field sites also suggests detection of a sublethal response of these sensitive organisms to some aspect of the platform-associated environment.

Although the trawl sampling component of GOOMEX was not designed to measure how fish and benthic megainvertebrates varied in abundance with distance to platform, the quantitative catch per unit effort data from the trawls could still provide some indication of large abundance differences, if they existed (Ellis et al. 1996). This question has importance for interpretation of the benthic community responses. Abundances of benthic animals can be driven by top-down differences in predation pressure as well as by bottom-up differences in food supply and by toxicity. There is little evidence of substantial differences between near- and far-fields in abundance of large invertebrates captured by trawls (Ellis et al. 1996). There may be enhancement of some fishes near the platforms, as indicated by the trawl results. Enhancement of those species that utilize the hard subtrate “reef” habitat would be expected; however, bottom trawling does not represent an effective method of quantifying abundance for most of these species, either because they are too large and can avoid the net (pelagic predators like king mackerel) or because they are too closely associated with the reef structure to be properly sampled (sheepshead, snappers, and pinfish). A more accurate and complete census of fish species that utilize the platform structure as habitat would almost certainly have revealed tremendously enhanced abundances. Analysis of gut contents in small fishes showed no detectable difference in dietary composition or in gut fullness between near and far stations (Kennicutt 1995, *cited in* Montagna and Harper 1996). Nevertheless, the possible increase in fish abundance in the near field around platforms may indicate somewhat greater predation pressure, at least on macroinfauna, near the platforms. From the analogy with other studies of ecosystem response to organic enrichment, especially the San Onofre power plant study (MRC 1989) and the Los Angeles County sewage outfall study (Tetra Tech 1981, 1984), it seems more likely that enhanced demersal fish abundance occurs in response to food abundance rather than serving as a driver of benthic abundance patterns. If this were also true for the GOOMEX sites, then increased polychaete abundances in the near-field may be contributing to some increase in demersal fish. Nevertheless, the GOOMEX program cannot at present confidently evaluate the degree to which platform effects propagate through the food chain to influence populations of higher-level consumers.

Results from GOOMEX analyses do speak clearly to the question of whether the hydrocarbon contamination has detectable negative sublethal impacts on fishes (McDonald et al. 1996). No differences existed between near and far fields in P450IA activities in livers of fishes or larger invertebrates. Measurement of PAH metabolites in fish bile similarly failed to reveal evidence of any differential exposure to PAH’s between the near and far stations. Measurements of P450IA mRNA also failed to show any differential exposure to hydrocarbons as a function of distance from the platforms. The absence of evidence of hydrocarbon exposure and any physiological response in fishes may be a consequence of the intrinsic mobility of fishes. The fishes targeted by trawling for these physiological measurements generally move readily across the short contaminant gradients at the study sites, thus minimizing exposure.

Contrasts of hydrocarbon concentrations and of P450IA induction levels between the GOOMEX sites and other previous studies show that GOOMEX resembles an uncontaminated site (McDonald et al. 1996). Where P450IA induction has been demonstrated around natural petroleum seeps (Spies et al. 1982) and around oil production platforms in the North Sea (Davies et al. 1984), the PAH concentrations in the sediments are greatly in excess of those documented in GOOMEX. Based on review of these and other available studies, McDonald et al. (1996, table 4) conclude that sediment concentrations of PAH ranging from 3000 to 10 000 ng/g appear to be required before significant hepatic EROD activity is induced in fish. In that review, there was a significant relationship between total PAH levels in sediments and hepatic EROD activities. However, mean total PAH concentration in sediments in GOOMEX sites ranged from 21 to 428 ng/g, with most values <100 ng/g (McDonald et al. 1996). Consequently, even the early warning signals of potential sublethal toxicological response to hydrocarbon exposure are absent from the fishes caught by trawl sampling around long-standing gas production platforms in the Gulf of Mexico.

Contrast of GOOMEX results with previous studies of effects of oil and gas production activities

Analysis of data on biological responses to contamination at GOOMEX sites agrees well with results of previous analyses of effects of marine pollution in demonstrating the utility of the soft-sediment benthos as an indicator of biological response (Gray et al. 1990; Warwick 1993; Olsgard and Gray 1995). The sedentary nature of the benthos, the diversity of species within the benthos, each capable of different types of response to different contaminants, the direct contact of the benthos with the sediments, which are the repository for contaminants, and the ability of the benthos to integrate signals over relatively long periods of time all contribute to making the benthic invertebrates a superb template for environmental impact assessments. Furthermore, results of GOOMEX support the conclusions of analogous recent studies in showing that multivariate analyses of community composition represent the most sensitive method of detecting response. In the GOOMEX program, PCA on the macrofaunal and on the meiofaunal communities revealed effects extending to distances of 100–200 m from the gas production platforms, while other alternative response variables such as diversity measures had poor resolution of effects (Montagna and Harper 1996). This same demonstration of the power of multivariate community analyses appears in recent application of MDS by Gray et al. (1990) and Clarke (1993).

The question of whether community analyses of the benthos can be as successfully conducted at the family level as at the species level is not unambiguously answered. Most GOOMEX analyses show ability to detect biological response with both family-level and species-level data, although the species generally appear to provide more sensitivity (Montagna and Harper 1996). Recent work by Warwick (1988*a*, 1988*b*) and Warwick and Clarke (1993) has shown little or no reduction in resolving power by going from species to cruder levels of taxonomic distinction in using the benthos to assess environmental impacts.

Although Warwick and Clarke (1993) showed through meta-analysis of multiple studies of benthic community response to marine pollution that phyletic differences in response underlie the ability of multivariate analysis to achieve such successful and remarkable discrimination, we suggest here that the multivariate responses contain two different groups of higher taxa responding to two different components of contamination. In other words, we attempt to pose causal hypotheses for the general benthic biological response patterns that can achieve the goal of separating effects of confounded factors. In specific, it appears that echinoderm, amphipod, and harpacticoid copepods may react mostly to toxicity, while polychaetes, oligochaetes, and nonselective deposit-feeding nematodes react largely to organic enrichment (or enhanced resource availability following disturbance, which we view as invoking the same opportunistic response). This suggested means of isolating different causal mechanisms represents an important need in pollution study (NRC 1985; Agard et al. 1993) and should be viewed as an hypothesis to be tested experimentally.

One of the most interesting concerns about oil and gas production activities is how widespread biological effects range from the source, the well site. The tremendous improvement in power to detect and discriminate biological effects by development of multivariate community analytic techniques and their application to benthic community data has clarified greatly the extent of pollution effects emanating from drilling platforms (Kingston 1992). Recent analyses in the North Sea show clearly that effects range outwards from platforms to a distance of 2–6 km and beyond (Olsgard and Gray 1995). This same study also demonstrated growing areas of contamination and of biological community response several years after drilling and drill mud disposal had stopped. The scale of these patterns of contamination and pollution effects on the benthos in the North Sea is far larger than what we observed around gas production platforms off the Texas Gulf of Mexico coast. Probably the major difference causing the disparity in spatial scale of impacts is the use of oil-based drilling muds in the North Sea platforms analyzed in Olsgard and Gray (1995). Oil was not used as a lubricant in the Gulf of Mexico platforms that we studied, so this additional source of contamination was not present. Olsgard and Gray (1995) similarly mentioned that an as yet unpublished analysis of North Sea platforms where oil-based driling muds were not employed shows greatly reduced areas of contamination and biological impacts.

Our synthesis of GOOMEX results and past studies of benthic community response to marine pollution suggests that the biological response at the GOOMEX sites is caused jointly by toxic contaminants and organic enrichment. It is important therefore to identify the sources of the significant environmental forcing variables to help inform managers and potentially improve management. To the degree that toxic metals are the primary cause of the toxicity component to the benthic biological responses, one can associate most of this input with the use of barite. The heavy metals that form impurities in barite ore (Ag, Cd, Hg, Pb, and Zn) all covaried strongly with Ba, presumably because they were largely derived from barite deposition (Kennicutt et al. 1996*b*). Lead, Cd, and Zn showed patterns of concentration suggesting some additional source, probably produced waters. Organic enrichment may derive from degradation of hydrocarbons coming from a variety of low-level sources, including produced waters and from materials shed from the platform as an artificial reef. Study of an exploration site in the North Sea where no production platform existed (Daan et al. 1990, 1992; Kroencke et al. 1992) showed almost no enhancement of the opportunistic (largely polychaete) benthos that responded so strongly in the studies around drilling platforms reported in Gray et al. (1990) and Olsgard and Gray (1995). Daan et al. (1992) suggested that this difference arises from an indirect effect of platforms inhibiting trawl fishing in their vicinity and thus permitting persistence of higher densities of benthic invertebrates. However, the shedding of organic materials from platforms is an alternative explanation, consistent with the GOOMEX observations of near-platform oxygen depression and nutrient release from enhanced benthic respiration (Kennicutt et al. 1996*b*). Organic enrichment better explains why higher densities were constrained to a group of opportunistic polychaetes.

In summary, the heavy metal impurities in barite, the release of produced waters, and the organic shedding from the platforms appear to be the major determinants of biological response patterns that extend to a distance of 100–200 m away from gas production platforms on the Gulf of Mexico shelf. Under this interpretation, the necessary use of additional barite during drilling in the absence of adding a diesel oil lubricant has a cost, but that cost is small relative to the consequences of discharging oil-contaminated drill muds and cuttings. There is a possibility that release of produced waters contributes to observed biological responses, consistent with the studies of Armstrong et al. (1977) and Osenberg et al. (1992). Armstrong et al. (1977) showed effects of produced waters discharge on benthic infaunal composition to extend to 1 km distance in a 2- to 3-m-deep Texas bay. At 10–12 m depth in an offshore site of produced water discharge in California, Osenberg et al. (1992) showed effects on benthic community composition reaching only about 100 m. We cannot separate possible effects of produced waters in the GOOMEX study from physical effects of the platform and other discharges. Future research should be designed to decouple effects of platform presence from effects of materials discharges to isolate contributions of the artifical reef effect and to tease apart the now confounded effects of multiple types of discharges.

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