FATE AND EFFECTS OF DRILLING FLUIDS AND CUTTINGS DISCHARGES IN LOWER COOK INLET, ALASKA, AND ON GEORGES BANK

.

by

J. P. Houghton, K. R. Critchlow, D. C. Lees,
and R. D. Czlapinski

Dames & Moore
Seattle, Washington

With contributions from

R. C. Miller, R. P. Britch, and J. A. Mills

NORTHERN TECHNICAL SERVICES
Anchorage, Alaska

Final Report
Outer Continental Shelf Environmental Assessment Program
Research Unit 602

15 April 1981

TABLE OF CONTENTS

TABLE OF CONTENTS (continued)

TABLE OF CONTENTS (continued)

TABLE OF CONTENTS (continued)

TABLE OF CONTENTS (continued)

TABLE OF CONTENTS (continued)

FATE AND EFFECTS OF DRILLING FLUIDS AND CUTTINGS DISCHARGES IN LOWER COOK INLET, ALASKA, AND ON GEORGES BANK

EXECUTIVE SUNMARY

BACKGROUND

The prospect of major exploratory drilling for petroleum hydrocarbons off the northeast and northwest coasts of the United States has generated concern from regulatory agencies, the fishing industry, and citizens alike, regarding the extent to which such activities might affect marine ecosystems and resources. Drilling fluids and formation rock cuttings comprise the majority of the material discharged from offshore drilling vessels. These materials could impact marine environments either through direct burial of bottom organisms, toxicity of mud components or contaminants including trace metals, biocides, and petroleum hydrocarbons, or through changes in the physical quality of the environment (e.g., suspended sediment load in the water column or grain-size distribution of sediments).

In 1977 a lawsuit was brought against the Department of Interior by the English Bay (Alaska) Native Corporation, the New England Fish Company, and several environmental groups regarding impacts of the proposed lower Cook Inlet OCS lease sale. As part of the settlement of that suit, it was agreed that an analysis of the toxicity of drilling mud and cuttings to lower Cook Inlet organisms would be performed by the Bureau of Land Management (BLM). In partial response to this provision, BLM funded this study of the likely fate and potential impacts of drilling fluids and cuttings discharged in lower Cook Inlet. Recent controversy over potential exploratory drilling impacts on Georges Bank led to expansion of the scope of this impact analysis to include that area.

OBJECTIVES

Specific objectives of this study were to:

1. Review information on the physical-chemical properties of drilling muds and their behavior in seawater (transport, dilution, deposition, flocculation, chemical transformations, etc.) and, based on this, define potential biological concerns.

2* Synthesize information available from previous studies on the physical and chemical fates and biological effects, both acute and chronic, of drilling muds and cuttings.

3. Based on (1) and (2), define potential critical pathways of drilling muds and their constituents within lower Cook Inlet and Georges Bank, and infer potential and probable ecosystem effects. Recommend any studies which should be performed to test hypotheses regarding these potential effects.

The following paragraphs summarize study results and conclusion as well as potential areas for additional research.

PROPERTIES OF DRILLING FLUIDS AND THE DRILLING PROCESS

Drilling fluids or "muds" are essential to controlled and efficient drilling and serve many diverse functions to that end, Among the most important are the removal of cuttings from the hole, control of formation pressures, and lubrication and cooling of the drill bit and drill pipe. A wide variety of naturally occurring minerals (e.g., bentonite, barite), simple chemicals (e.g., sodium hydroxide, sodium bicarbonate, potassium chloride), complex organic compounds (e.g. , lignosulfonates, formaldehydes, and other materials is combined to form the drilling fluid for each well. As a result there is a wide array of compositions that can be called "whole drilling muds," even for a relatively specific category of wells (e.g., offshore wells 3,000 m in depth or greater). Drilling fluid composition is also altered with depth within a given well to counteract increasing formation pressures and to compensate for higher temperatures and other complexities. This variability greatly complicates prediction of impacts and comparisons between impact monitoring studies. For example, estimated total quantities of barium discharged from two recent offshore wells were 2,270 and 436,160 kg.

Extensive laboratory testing has demonstrated that the bulk of materials present in drilling fluids (e.g. , barite, bentonite) are relatively nontoxic chemically but contribute to high suspended solids levels. Other materials present such as heavy metals, biocides, and petroleum hydrocarbons may be highly toxic. They may also accumulate in tissues and potentially could be passed to higher trophic levels although biomagnification has not been demonstrated for drilling fluids.

During the first 50 to 150 m of drilling, cuttings are discharged directly- at the seafloor, probably forming the nucleus of a cuttings pile in most environments. After a conductor pipe has been set, circulated mud and cuttings are returned to the drilling vessel. Each vessel is equipped with several mechanical devices to clean cuttings from the mud to allow recycling of the mud back into the hole. Coarser cuttings are discharged essentially continuously during drilling at relatively low rates. Larger volumes of mud and finer cuttings require discharge periodically at much higher rates, but for relatively short periods--from a few minutes to 3 hr.

Drilling fluids and cuttings discharged in the water column offshore have been shown to separate into two relatively distinct components: an upper plume containing liquids and finer silts and clays; and a lower plume containing the bulk of discharged solids, cuttings, and caked or flocculated. muds. Each of the plumes has its primary effects on a different component of the marine biosphere. The upper, or near-surface, plume may affect drifting or free-swimming (planktonic or nektonic) species of the mid to upper (pelagic) portions of the water column while the lower or bottom-impinging plume affects benthic and demersal species living in, on, or in close association with the bottom. A variety of models has been used with varying success to describe the physical behavior of these discharge.

BEHAVIOR AND POTENTIAL BIOLOGICAL EFFECTS

Pelagic Impacts

All field and modeling studies reported to date have indicated that high rates of dilution of drilling fluids in the surface plume, on the order of 10,000:1, occur within a relatively short distance (e.g., 100 m) of the discharge. Several investigators have found that in areas of relatively low current all water quality parameters measured (e.g., temperature, salinity, dissolved oxygen, suspended solids, transmittance, and trace metals) approach background levels within about 1,000 m of the discharge except for suspended solids. The surface plume gradually settles at greater distances. In an environment of much stronger currents (viz., lower Cook Inlet), a measurable decrease in water transmissivity was reported across a narrow plume at distances in excess of 10 km from the discharge point with dilution occurring relatively more slowly beyond the 10,000:1 achieved at 100 m.

Within the zone a few meters downcurrent of the downpipe, whole mud concentrations exceeding measured 96-hr LC_{50} values* for many species could be experienced infrequently for 15 min to 3 hr by species actively swimming to maintain themselves in the plume. The likelihood of significant numbers of nektonic organisms remaining in this area long enough to suffer mortalities or other irreversible stress is considered remote because of the limited size of the near-field discharge area and the intermittant nature of the high-volume discharges. In the zone from a few meters to 100 m from the discharge, whole mud concentrations exceeding measured 96-hr LC_{50} values for the most sensitive species and the most toxic muds tested to date could be experienced infrequently, again for up to about 3 hr, by active swimmers choosing to maintain themselves in the plume. The likelihood of this occurring is somewhat less remote given the known tendencies of fish to congregate around offshore rigs but is still very low. The limited duration and frequency of these high volume discharges would again make the likelihood of significant mortalities or stress extremely remote. Beyond 100 m from the discharge, although concentrations will not drop as rapidly, they will be further reduced below 96-hour LC_{50} values for any tests reported to date. Thus, no acute effects are likely in this region.

Organisms remaining within a few meters of the discharge during routine, near-continuous, low-rate discharges could receive a long-term exposure to concentrations that approach those found to be lethal to the most sensitive organisms bioassayed to date. Probably few, if any, nektonic organisms would remain in this near-field dilution zone long enough to experience a lethal dose from continuous discharges occasionally interspersed with higher volume discharges. However, in areas with relatively moderate currents such as some parts of Georges Bank, fish congregating around the drilling vessel could experience some degree of sublethal stress unless they actively avoided the plume. Degree of avoidance or attraction of motile organisms to drilling muds has not been adequately explored. In any case, only a negligible

● The 96-hr LC_{50} is that concentration causing mortality of 50 percent of organisms tested in 96-hr exposure.

fraction of the population of any given species in the region of the drilling activity would be at risk to such sublethal stresses,

Planktonic organisms would receive a maximum exposure to drilling effluents if, once entrained in the plume at the downpipe during a bulk discharge, they remained in it during its dilution and dispersion by currents. Exposure to this type of rapidly declining dose has not been attempted in laboratory tests. However, available data suggest a slight possibility that the high initial concentration would cause some mortalities of crustacean plankton, including shrimp and crab larvae, particularly if they entered the plume at a highly sensitive stage of ecdysis (molting]. Sensitivity of fish eggs or larvae to drilling fluids has not been reported in the literature but is likely to be no greater than that of larval crustaceans. The percentage of any planktonic population potentially affected would be negligible because of the narrow width and depth of the discharge plume and the brief duration and low frequency of mud dumps of this volume at any well.

In summary, based on all available Information, it appears that the likelihood of significant impacts on pelagic plankton and nekton from drilling mud and cuttings discharges is remote, both in lower Cook Inlet and on Georges Bank. The potential exists and remains to be explored that some rig-associated fish could incorporate some heavy metals into their tissues.

Benthic Impacts

The degree of impact of drilling fluids and cuttings on benthic and demersal species is highly dependent on a number of local environmental variables (depth, current and wave regimes, substrate type, etc.) and on the nature and volume of the discharges including cutting sizes and the depth of the downpipe. Impacts can be considered to fall into two relatively distinct categories: short-term effects of mud toxicity and burial by mud and/or cuttings; and longer term effects of chemical contamination and physical alteration of the sediments.

The extent of the seafloor area where accumulation rates of cuttings and mud are great enough to cause stress or mortalities to benthic or demersal organisms (either due to burial or toxic effects) will vary with the above-mentioned factors. Extremes would range from the situation described for central lower Cook Inlet, where dynamic conditions precluded formation of any cuttings pile and where cuttings were widely dispersed and entrained vertically into the seabed, to the situation existing in the Gulf of Mexico where cuttings piles typically about 1 m in height and 50 m in diameter have been reported. At the mid-Atlantic exploratory well the zone of visible cuttings was 150 to 170 m across.

In very dynamic areas, both in situ bioassays and benthic sampling have shown little evidence of effect on infauna or on epibenthic crustaceans at distances of 100 m or greater from the well. However, even in these very dynamic areas, nearly complete disruption of benthic communities within 25 to 50 m of the well must be assumed due to seafloor discharge of cuttings during placement of the collector pipe and due to placement of the baseplate, if used. In moderately deep water (100 m and deeper) with moderate or low currents, a patchwork pattern of muds and cuttings accumulations may occur and be accompanied by significant reductions in infauna in areas where accumulations are most evident.

The severity of the Impacts due to burial is inversely related to the hydrodynamic energy level of the area, but the areal extent of the impacts is directly related to the area's energy level; thus, in low-energy environments a severe impact will be felt by infauna over a small area, but in higher-energy environments lesser impacts (partial mortality, changes in species composition) will occur over larger areas.

Motile epifauna (including demersal fish) is unlikely to suffer any direct mortality and may be attracted to the rig vicinity by the disturbance and increased food availability. On the other hand, changes in the physical or chemical nature of the bottom may preclude use of the area for some critical biological activity, for example by increasing the content of fines in coarse sediments used for spawning. Local reductions in productivity of infaunal prey organisms will also affect epibenthic species.

Effects resulting from physical alteration of the bottom, e.g., cuttings or mud accumulations that change sea floor topography and/or grain size, will tend to revert toward their predrilling conditions at a rate directly proportional to the rate at which natural processes are affecting the bottom. In an area such as the central portion of lower Cook Inlet, currents are so strong that no prolonged accumulation of mud or cuttings is possible. Cuttings are entrained into sandwaves of approximately similar particle sizes moving along the bottom and finer materials, including muds adhering to cuttings, are picked up by the currents and dispersed widely from the drill site. Within a very short period of time (a few weeks) it is unlikely that mud or cuttings would be detectable at the drill site.

At less dynamic sites, where cuttings and mudcake discharged exceed sizes transportable by normal bottom currents, return to predrilling conditions will occur more slowly. In shallow waters, severe storms will resuspend mud and disperse cuttings, working them into the finer ambient bottom sediments. In deeper waters, where little wave surge is felt, biological activity will mix drilling deposits with natural sediments, and natural deposition of coastal sediments will continuously dilute cuttings and mud. However, many years may be required before overburden completely isolates the drilling deposits from biogenic reworking.

Presence of cuttings is unlikely to have any significant adverse effect other than very localized burial of some infauna. The 300 m^3 of cuttings produced from a typical well, if spread evenly 0.5 cm deep, would cover an area of 60,000 m^2 (6 ha or 14.8 acres) perhaps killing a majority of infauna present and significantly altering its future character (not necessarily adversely) due to increased coarseness of materials. This assumed area is considerably larger than the largest area of visible cuttings accumulation reported in the literature. Within one to several years the cuttings and their associated impacts would likely be undetectable in most environments due to resuspension and transport and to working of cuttings into the bottom.

Physical effects of drilling muds deposited on the bottom will be short-lived. However, presence of significant mud concentrations in the surficial sediments could be expected to have significant adverse, effects on the existing infaunal community and could inhibit settlement of many types of organisms (e.g., Tagatz et al. 1980). The persistence of drilling mud in the surficial sediments is again dependent on degree of current and wave surge felt at the bottom, as well as biogenic activity. This material is expected to be rapidly dispersed horizontally (within a period of a few months) by bottom currents, and vertically by biogenic activities, even in the less dynamic areas of lower Cook Inlet and Georges Bank. Nonetheless, mortality or loss of recruitment in key species could occur over a limited area, potentially affecting benthic species composition for 1 to several years.

The majority of benthic impact studies to date have found little evidence of significant physical, chemical, or biological effects extending beyond 800 to 1,000 m downcurrent from a well site. However, reports available from a mid-Atlantic well monitoring study leave open the possibility that significant reductions in benthos and increases in trace metals levels may have extended up to 3,200 m or farther downcurrent from the well site. Since this is the only deep water (>100 m) study reported to date, and until clarification of its apparent results can be obtained, a considerable degree of conservatism has been imposed on impact analyses of deep water wells in environments with relatively low near-bottom energy regimes.

A discharge of 500 m^3 of mud solids from an entire 3,000-m well spread evenly 0.5 mm deep would affect an area of 1,000,000 m^2 (100 ha, 50 acres) assuming (very conservatively) that there is no removal of mud from the area during the duration of the well. In reality, in all environments much of the material will be dispersed beyond the limits of detectability before completion of the drilling (e.g., Meek and Ray 1980). It can be concluded that, in moderate- to low-energy environments, accumulations of cuttings and muds on the bottom have the potential to cause relatively severe impacts on infauna up to perhaps 100 to 200 m downcurrent of the discharge and less severe changes in species composition and abundance perhaps as far as 1 to 3 km downcurrent.

In addition to these relatively short-term acute, albeit localized effects, chemicals present in the drilling muds may be ingested by bottom-feeding organisms and become incorporated into their tissues. The heavy metals arsenic, barium, cadmium, chromium, lead, mercury, nickel, vanadium, and zinc may increase up to one to two orders of magnitude above background in sediments within 100 m of the drilling rigs, In addition to environmental variables, the source and metals content of components comprising the mud system in use, as well as the chemistry of the formations being drilled, govern the relative increases in these various metals. At greater distances (to 1,000 m downcurrent) more abundant chemicals may be increased to perhaps one order of magnitude or less above background.

Quantities of metals discharged in the course of a typical well (e.g., some 1,378 $\pm$ kg chromium, 33 kg lead) would produce concentrations of 1.38 and 0.033 g/m^2 total chromium and lead, respectively, if spread evenly over 1,000,000 m^2 (assuming very conservatively that all metals are in the bottom-impinging plume). If uniformly mixed with the top 5 cm of sediment this would result in an elevation of total chromium in the sediment of about 17 mg/kg and 0.4 mg/kg for total lead. The value for chromium is on the same order of magnitude as, and the value for lead is an order of magnitude less than, background values (using total digestion) off the northeastern U.S. coast (ERCO 1980) and would be unlikely to cause significant biological effects.

Regardless of the rate of the dispersion process and degree of detectability, virtually all additions of metals to the marine environment will remain there, in some form, indefinitely. The only real significance of such additions, however, is in the degree to which they reduce the "fitness" (ability to survive and. reproduce) of local organisms, or the degree to which they accumulate in the tissues of local organisms and are transmitted through the food web, affecting the "fitness" of the receptor. Two studies indicate that in order to attain the same body burden of a heavy metal, the concentration of the metal in particulate form must be two or more orders of magnitude higher than if the metal were in solution. This is an area in which additional and very sophisticated study is needed. The majority of the total metals discharged with drilling fluids and cuttings is in forms that are essentially biologically inert. However, some fraction of metals released is in biologically available forms. Several studies to date have shown elevated tissue levels of barium, chromium, lead, and mercury in organisms in the proximity of drilling mud discharges. At the present time, the significance or effects of heavy metals accumulations in animal tissues is largely unknown as is the relationship, if any, between these metals accumulations and histopathological or physiological changes in the receptors. Although our present ability to interpret the significance of accumulations of metals in animal tissue is limited, it appears that significant effects due to drilling fluid discharges are unlikely beyond 3 km downcurrent of a discharge site.

CRITICAL PATHWAYS AND POTENTIAL ECOSYSTEM EFFECTS

Lower Cook Inlet

Cook Inlet is a large tidal estuary located in south-central Alaska on the northwest edge of the Gulf of Alaska. The lower inlet is characterized by wide tidal variations? complex net circulation patterns (including the presence of tidal rips), and large seasonal variations in inflows of fresh water, much of it containing high concentrations of fine-grained glacial sediments.

Cook Inlet contains marine biological resources of considerable economic, ecological, social, and aesthetic value. Moreover, the biological productivity of lower Cook Inlet may be a major energy source for neighboring ecosystems. Many of the economically important organisms in lower Cook Inlet are members of, or dependent on, the benthos (i.e., organisms that live or or on the bottom). Clams, amphipods, and polychaetes (sea worms) are often abundant and provide a food resource for larger predators such as king, tanner, and Dungeness *crab* as well as shrimp, Pacific halibut, and other fish. Distribution of organisms on deep water bottoms is often irregular with concentrations in some areas but few of the same species in adjacent areas. These distribution patterns are poorly understood for many species but are often in response to substrate type, depth, current, recruitment patterns, and food availability.

Exploratory drilling in lower Cook Inlet to date has failed to detect commercial quantities of hydrocarbons. Although some additional wells may be drilled in the next few years, the chances of a significant discovery appear low. However, another OCS lease sale (NO. 60) Includes Shelikof Strait to the south . Moreover, drilling in state waters around the periphery of the inlet may also result in additions of drilling fluids and cuttings to the inlet.

The hydrodynamic regime in the majority of lower Cook Inlet is ideally suited to minimize the impact of drilling fluid and cuttings discharges. Strong surface currents will rapidly dilute the upper plume of fluids and finer particles such that no impacts will be felt in pelagic plankton or nekton. Cuttings impinging on the bottom will be rapidly dispersed and worked into the bottom sediments by near-bottom currents and biogenic activity. Mud solids will be scrubbed from the cuttings, resuspended, and transported from the site.

Only in the southern and northeastern portions of the Cook Inlet lease area will bottom conditions allow accumulations of mud and cuttings that could affect benthos. Cuttings and possibly mud accumulations could reduce benthic infauna and attached epifauna over a limited area (up to 60,000 m^2, less than 15 acres per well). In the deeper areas of the southern inlet dispersion of mud and cuttings could take several weeks or months and there is a potential that changes in species composition and abundance could occur over an area as large as 1,000,000 m2 (250 acres). However, episodic high currents reported in these deeper waters would resuspend muds and transport them from the area. Thus, any observed impacts should be relatively short-lived, e.g., 1 to 2 yr.

The ultimate fate of the majority of drilling fluid solids and associated contaminants released in lower Cook Inlet will be distribution over the bottom of Shelikof Strait between Kodiak and Afognak Islands and the Alaskan Peninsula. Quantities of mud released under the BLM (1976) development scenario, if spread evenly over this area, would be undetectable chemically and insignificant biologically.

Georges Bank

Georges Bank comprises an area of about 25,920 km^2 off the northeast coast of the United States, east-southeast of Cape Cod. The bank is shallowest in its northwestern portion where the depth may be 5 to 6 m in areas such as Cultivator and Georges Shoals. Extending to the east and south of the shoals, much of the bank ranges in depth between 60 and 80 m. Georges Bank circulation is complex with the principal feature being a clockwise gyre around the bank in water less than 60 m deep.

The gyre may not be entirely closed in all seasons, but most of the water within the gyre may be recirculated. Near-surface flows over deeper water (and entrained pollutants) may leave the bank at four locations: the northwest corner of the bank east of the Great South Channel, the eastern edge of the bank adjacent to Northeast Channel, the southern flank of the bank, and the southwest corner of the bank adjacent to Great South Channel. Subsurface flows may also leave the bank at four locations: in deeper waters on the steep northern flank, at the north-eastern corner, along the southern flank, and at the southwestern corner.

The flow of water along the southern flank between 60 and 100 m is primarily along the isobath. It has been estimated that 70 percent of this flow leaves the bank at the southwest corner and crosses the Great South Channel where it continues westerly along the continental shelf. The remainder of this flow (30 percent or less) swings northward as part of the Georges Bank circulation and may eventually flow into the Gulf of Maine or continue around the bank and exit at other locations. In water depths greater than 100 m along the southern flank it is likely that flow is down the slope toward the submarine canyons and deeper waters. Tidal currents are moderately strong in the shallow areas of the bank above 60 m depth and decrease appreciably with increasing depth. Currents within the submarine canyons on the southern flank of Georges Bank periodically attain high velocities associated with tidal fluctuation, internal waves, turbidity flows, and storms.

Georges Bank is a highly productive biological environment which supports a substantial fishing industry of great commercial importance to New England. Substantial research efforts have been made to determine the underlying basis for the high level of biological production and understand the fluctuations (principally decline) of harvestable stocks, so that these stocks can be managed effectively. Much of the sustained high level of production is attributed to upwelling of nutrient-laden water supporting a high level of phytoplankton production which in turn is the principal source of energy for pelagic and benthic food webs. The benthic invertebrate fauna on the southern flank is generally characterized by high biomass in shallow water but is rapidly diminished with increased depth. Sea scallops and American lobster are the two most important commercially exploited shellfish resources. Surveys indicate a broad pattern of groundfish abundance in the southern part of the bank that corresponds with that of the benthic invertebrates; namely, abundance is highest in shallow water and declines with increased depth. Most of the southern area (including the Lease Sale 42 area) is moderately low to moderately high in resource abundance compared to other portions of the bank. Yellowtail flounder is the most important species over most of this area (less than 60 m depth) while silver hake, pollock, and other bakes are also important, especially in deeper water.

There is concern that exploration and development of petroleum resources on Georges Bank would adversely affect the living marine resources not only on the bank but also in surrounding areas. It has been hypothesized that drilling fluids discharged into the water column at various locations and water depths within the lease areas would eventually be transported through the very productive submarine canyons to deeper offshore waters, along the southern flank across Great South

Channel and deposited in the Mud Patch, or along the southern and western sides of the bank with ultimate deposition in the Gulf of Maine.

Current plans for exploratory drilling and low to high estimates of development drilling in the Lease Sale 42 EIS were used in the formulation of a drilling scenario. The physical-chemical and biological fates and effects of drilling fluids were assessed in two contexts. The first was in terms of fate and effects in the vicinity of a single drilling operation that could be extrapolated to cumulative fate and effects within the lease area for the drilling scenario. The second was in terms of ultimate fate and effects in hypothesized areas of eventual deposition. These assessments necessitated making numerous assumptions in the absence of reliable or directly applicable data. In several instances lower and upper limits of effects were developed; upper limits are thought to be conservatively high (highly unlikely to occur) and lower limits are thought to be more probable.

The principal sources of information applicable to assessment of drilling effects on Georges Bank are studies conducted to monitor drilling fluids dispersion during drilling of C.O.S.T. well Atlantic G-1 in 48 m of water on the bank and the more extensive studies conducted in the middle Atlantic before, during, and after drilling of an exploratory well in 120 m of water. The results of these studies were used to estimate the fate and effects of drilling in the lease area, allowing for reasonable differences in environment and drilling depths.

As in other regions, there is little basis for concluding that significant adverse effects would be detectable among various components of the pelagic community (plankton and nekton) in the Georges Bank lease area. The benthic environment within the lease area will be affected by the deposition of drill cuttings and mud solids with associated chemical additives. Drill cuttings and mud solids will affect sessile and sedentary benthic invertebrates due to burial and suffocation. A larger area of bottom will be affected by deposition and transport of fine solids and adsorbed chemicals which in sufficient concentration may have chronic or acutely toxic effects on benthic invertebrates.

It is anticipated that adverse impacts on the benthic environment will be greater around wells drilled in deeper water despite the fact that benthic organisms are more abundant in shallow water. This is because higher rates of dispersion and dilution occur in shallow water, thus reducing the exposure of the smaller area of bottom initially affected. In deeper water increased trajectory through the water column disperses drilling fluids over a larger area of bottom initially but dispersion following deposition would take longer than in shallow water.

Based on benthic invertebrate biomass data for the lease area and lower and upper estimates of bottom area potentially affected, projections of drilling impacts were made. A well drilled in 55 m of water would potentially affect a bottom area of 0.01 to 0.17 km^2 which supports 8,675 to 133,070 kg of benthic invertebrate biomass. Most exploratory drilling is expected to occur at an average depth of 85 m where 0.28 to 1.77 km^2 of bottom and 62,770 to 392,310 kg of invertebrates would be potentially affected. In deep water (135 m) about 2.01 to 8.04 km^2 of bottom would be affected which would support 118,630 to 474,506 kg of invertebrates. During the 3-yr period of exploration it is expected that 13.4 to 70.06 km^2 of bottom and 2,175 to 12,779 mt of invertebrate biomass would be potentially affected. Since drilling during the development phase will be concentrated at the locations of platforms, the total area of bottom potentially affected will be relatively low compared to the number of wells drilled. Under the low development scenario, about $.4 to 44.6 km^2 of bottom and 1,343 to 7,847 mt of invertebrate biomass would be potentially affected. Under the high development scenario, about 25.1 to 126.9 km^2 of bottom and 3,580 to 20,551 mt of invertebrate biomass would be potentially affected. For the 11- to 14-yr period in which exploration and development would occur, approximately 3,519 to 33,3oO mt of benthic invertebrate biomass would potentially be affected. This amounts to about 320 to 2,379 mt/yr.

It can be assumed that there is a 10-percent conversion of prey biomass to predator biomass. Thus, the 320 to 2,379 mt of invertebrate biomass potentially affected each year would support 32 to 238 mt of benthic fish or invertebrate predators and scavengers. For comparison, the total United States and foreign fleet catch of these organisms averaged 188,736 mt from 1972 to 1975. In this context, the potential impact on the benthos could reduce feeding opportunities for some 0.02 to 0.13 percent of the benthic fish and invertebrate catch. Because of the conservatism of assumptions made at every step in the development of this scenario, it is highly unlikely that quantities of fish and shellfish actually lost to the effects of the effluents would approach even this low figure (0.02 percent).

To assess potential effects of accumulation of drilling mud within the Mud Patch and Gulf of Maine (hypothetical sinks), it was assumed that all of the mud solids and chemicals discharged over the life of the field would be deposited in each area and mixed in the top 5 cm of sediments. The resultant concentrations of barium, chromium, and zinc, the most abundant metals, would probably be undetectable against ambient and analytical variation. Similar calculations were made for Gilbert Canyon; it was assumed that about 11 percent of the drilling fluids produced in 1 yr would be deposited in the head of the canyon. Concentration of chromium and zinc would be undetectable against ambient variation, but concentrations of barium would be above ambient. In reality, the amount of drilling fluids transported toward the canyons would be dispersed through more than one canyon; thus metals concentrations would be lower yet. Increased concentrations of suspended solids in the canyons might occur, but background data are not yet available to judge the significance of this effect. A significant Increase of suspended solids could adversely affect sessile filter-feeding organisms such as corals and sponges. A field study is in progress to assess this possible impact.

Field and laboratory studies of the effects of drilling muds and natural sediments contaminated by heavy metals provide ample evidence of bioaccumulation (uptake) of these metals in tissues of benthic organisms. Circumstantial evidence suggests that biomagnification of these metals through the food web does not occur. However, a definitive study of this problem has yet to be done so that biomagnification of metals on Georges Bank remains an improbable but unresolved issue.

CONCLUSIONS

1. Extensive laboratory testing has demonstrated that the bulk of materials present in drilling fluids (e.g., barite, bentonite) are relatively nontoxic chemically but contribute to high suspended solids levels. Other materials present in lesser quantities such as heavy metals, biocides, and petroleum hydrocarbons may be highly toxic. Whole mud mixtures are less toxic than the sum of the toxicities of their component parts because physical and chemical associations formed within the mixture render many components biologically unavailable.

2. All field and monitoring studies have shown that high rates of dilution of drilling fluids occur within a relatively short distance of the discharge and that background levels for most water quality parameters are approached within 1,000 m.

3. The likelihood of significant impacts on pelagic plankton and nekton from drilling mud and cuttings discharges appears remote, both in lower Cook Inlet and on Georges Bank.

4. The degree of impact of drilling fluids and cuttings on benthic and demersal species is highly dependent on a number of local environmental variables (depth, current and wave regimes, substrate type, etc.) and on the nature and volume of the discharges including cutting sizes and the depth of the downpipe. Impacts can be considered to fall into two relatively distinct categories: short-term, lethal effects of mud toxicity and burial by mud and/or cuttings; and longer term effects of chemical contamination and physical alteration of the sediments which may alter recruitment.

5. The majority of benthic impact studies to date have found little evidence of significant physical, chemical, or biological effects extending beyond 800 to 1,000 m downcurrent from a well site. In moderate- to low-energy environments, accumulations of cuttings and muds on the bottom have the potential to cause relatively severe impacts on infauna up to perhaps 100 to 200 m downcurrent of the discharge and less severe changes in species composition and abundance perhaps as far as 1 to 3 km downcurrent.

6. Effects resulting from physical alteration of the bottom, e.g., cuttings or mud accumulations that change sea floor topography and/or grain size, will tend to revert toward their predrilling conditions at a rate directly proportional to the rate at which natural processes (cog.~ currents) are affecting the bottom, i.e., over a period of weeks or months in dynamic areas and over a period of months or years in less dynamic areas.

7. The hydrodynamic regime in the majority of lower Cook Inlet is ideally suited to minimize the impact of drilling fluid and cuttings discharges. Cuttings impinging on the bottom will be rapidly dispersed and worked into the bottom sediments by near-bottom currents and biogenic activity. Mud solids will be scrubbed from the cuttings, resuspended, and transported from the site. Only in the southern and northeastern portions of the Cook Inlet lease area will bottom conditions allow accumulations of mud and cuttings that could affect benthos for up to 1 to 2 yr.

   If the total quantity of mud released from the BLM (1976) development scenario for lower Cook Inlet were transported to the most likely ultimate sink (Shelikof Strait) and spread evenly on the bottom, it would be undetectable chemically and insignificant biologically.

8. The benthic environment in the Georges Bank lease area will be affected by the deposition of drill cuttings and mud solids with associated chemical additives. Drill cuttings and mud solids will affect sessile and sedentary benthic invertebrates due to burial and suffocation within 100 to 200 m of the discharge. A larger area of bottom, up to 1 to 3 km downcurrent, may be affected by deposition and transport of fine solids and adsorbed chemicals which in sufficient concentration may have chronic or acutely toxic effects on benthic invertebrates. It is anticipated that adverse impacts on the benthic environment will be greater around wells drilled in deeper water although benthic organisms are more abundant in shallow water.

   The 320 to 2,379 mt of invertebrate biomass conservatively estimated as potentially affected each year during exploration and drilling would support 32 to 238 mt of demersal fish or invertebrate predators and scavengers. In this context, the potential impact on the benthos would affect 0.02 to 0.13 percent of the total U.S. and foreign demersal fish and invertebrate catch from 1972 to 1975.

9. The likelihood of measurable or biologically significant quantities of drilling fluids accumulating in the potential depositional sinks off Georges Bank is remote. Minor effects in the submarine canyons are possible under the conservative worst-case impact scenario but the real likelihood is considered to be very low.

ADDITIONAL AREAS FOR RESEARCH

Examination of existing literature and the development of conservative (worst-case) estimates for environmental impacts indicate insignificant impacts would result from drilling mud discharges. While conclusions may remain essentially the same with additional information, the following areas of research may be appropriate in order to supplant the assumptions that were made.

The extent to which drilling fluid discharges can alter the physical and chemical properties of sediments in the vicinity of wells drilled in relatively deep water (>100 m) and in relatively low-energy environments has not been adequately determined. Completion of data processing and a re-analysis of data from the mid-Atlantic C.O.S.T. well may provide the required information. If not, a similar study, with adequate controls and data analysis, should be conducted at one of the deeper early wells on Georges Bank.

Interpretation of results of field and laboratory monitoring studies with respect to drilling fluid impacts is severely limited by our incomplete knowledge of the significance of trace metals uptake by marine organisms, their ability to detoxify metals, and the significance of metals-contaminated prey to higher trophic levels. Also needed is information to relate realistically achievable levels of metals contamination of sediments at a mud discharge site to effects on benthic organisms and populations.

1. INTRODUCTION

The prospect of major exploratory drilling for petroleum hydrocarbons off the northeast and northwest coasts of the United States has generated concern from regulatory agencies, the fishing industry, and citizens alike regarding the extent to which such activities might affect marine ecosystems and resources. Potential impacts could stem from presence and movement of drilling and support vessels, overloading of port facilities, accidental spills of oil or other hazardous materials, and routine discharges from drilling vessels. Drilling fluids and formation rock cuttings comprise the majority of the material discharged from offshore drilling vessels and are the subject of this report.

Drilling fluids or "muds" are essential to controlled and efficient drilling and serve several diverse functions listed and described in Section 2.1.2. Drilling vessels are equipped with several mechanical devices to clean mud from the cuttings to allow recycling of the mud back into the. hole. Coarser cuttings are discharged essentially continuously during drilling at relatively low rates. Larger volumes of mud and finer cuttings require discharge periodically and at much higher rates for relatively short periods--from a few minutes to 3 hr (Houghton et al. 1980a).

The physical fate and biological effects of these types of discharges in temperate and sub-Arctic marine waters have received little attention until recently. Studies of drilling fluids and cuttings dispersion and biological effects of discharges were conducted by Dames & Moore (1978a) at the lower Cook Inlet continental offshore stratigraphic test (C.O.S.T.) well and by Exxon Production Research and EG&G in the Baltimore Canyon area of the mid-Atlantic outer continental shelf (OCS) (Ayers et al. 1980a; Robson et al. 1980; Mariani et al. 1980; and Menzie et al. 1980). These two studies provide the primary information base for extrapolation to the remaining areas of lower Cook Inlet and to Georges Bank.

In 1977 a lawsuit was brought against the Department of Interior by the English Bay Native Corporation, the New England Fish Company, and several environmental groups regarding the proposed lease sale in Cook Inlet. The plaintiffs were concerned that the environment of lower Cook Inlet and the rich shrimp, crab, and salmon fisheries there would be damaged by the proposed OCS oil and gas development. As part of the settlement of that suit, it was agreed that an analysis of the toxicity of drilling mud and cuttings to lower Cook Inlet organisms would be performed by the Bureau of Land Management (BLM). This agency is responsible for setting regulations and stipulations concerning disposal of drilling muds and cuttings. BLM, through the National Oceanic and Atmospheric Administration (NOAA) and the Outer Continental Shelf Environmental Assessment Program (OCSEAP), contracted with the Auke Bay Laboratory of the National Marine Fisheries Service (NMFS) to perform drilling fluid bioassays on larvae of commercially important crustaceans from lower Cook Inlet (Carls and Rice 1981). In further response to the English Bay lawsuit, BLM similarly funded the present study of the likely fate and potential impacts of drilling fluids and cuttings discharged in lower Cook Inlet.

Recent controversy over potential. exploratory drilling impacts led to expansion of this impact analysis to include Georges Bank, also a major fisheries resource area. After a 3-yr legal dispute, the commonwealth of Massachusetts Attorney General's office, the Conservation Law Foundation of Boston, and the United States Departments of Commerce and Interior have recently reached a settlement to allow exploration for oil and gas to proceed on Georges Bank, one of the world's richest fishing grounds (Environment Reporter, January 9, 1981). This agreement mandates various environmental safeguards and free access to all federal studies concerned with Georges Bank.

Specific objectives of this study were to:

1. Review information on the physical-chemical properties of drilling muds and cuttings and their behavior in seawater (flocculation, chemical transformations, etc.) and, based on this, define potential biological concerns.

2. Synthesize information available from previous studies on the physical and chemical fates and biological effects, both acute and chronic, of drilling muds and cuttings.

3* Based on (1) and (2), define potential critical pathways of drilling muds and their constituents within lower Cook Inlet and Georges Bank, and infer potential and probable ecosystem effects. Recommend any studies which should be performed to test hypotheses regarding these potential effects.

Items 1 and 2, literature review and synthesis, are discussed in Chapter 2 of this report. The lower Cook Inlet and Georges Bank analyses are to be found in Chapters 3 and 4, respectively. Chapter 5 contains a list of references cited In this report. Appendix A lists persons knowledgeable in fate and effects of drilling fluids and cuttings. Drilling mud products, components , uses, and reports are covered in Appendix B. Tables summarizing recently reported laboratory studies of toxicity of whole muds to marine organisms as well as bioavailability of trace metals contained in drilling fluids are contained in Appendix C.

2. LITERATURE REVIEW AND SYNTHESIS

2.1 DRILLING FLUIDS AND DRILLING PROCESSES

This section presents a summary of general drilling methodology and a synthesis of available information on physical-chemical aspects of drilling fluids and on their behavior upon discharge into the marine environment

2.1.1 General Drilling Methodology

With few exceptions, all oil wells drilled today use the rotary method which was introduced around 1900. The rotary method involves the penetration of geologic formations with a rotating bit, the removal of formation cuttings from the borehole with circulating drilling fluid, and the removal of solids from the fluid. Equipment required for rotary drilling is illustrated in Figure 2-1.

The bit, most commonly a three-cone rolling cutter bit, advances by fracturing or grinding the rock with the bit teeth while rotating against the bottom of the hole. The axes of the cones are set slightly to the left of center which imparts a scraping action to the bit.

The bit is rotated by means of the drill string, which is composed of lengths of high-strength steel pipe. Each length (or joint) normally measures approximately 10 m (30 ft) long by 9 to 13 cm (3-1/2 to 5 in) in diameter and has threaded couplings that transmit torque. Heavier-walled pipe, such as drill collars, stabilizers, or roller reamers, that collectively make up the bottom hole assembly, are placed at the base of the drill string above the bit and provide directional stability and weight for drilling. In addition to rotating the bit, the drill string also serves to transport drilling mud to the bit which is then circulated back up the hole outside the drill string.

The drill string is turned in the borehole by the surface rotating equipment. A multi-sided joint of pipe, the kelly, is connected to the upper end of the drill string. The kelly passes through the kelly bushing, set in the rotary table, which provides the primary rotary motion.

Special support and hoisting equipment are necessary to support the weight of the drill string from the surface and, when necessary, to remove the string from the borehole. The draw works, together with a multi-sheave block-and-tackle system, provide the mechanical power necessary to lift the drill string. The stationary block, or crown block, is mounted at the top of a supportive structure called the derrick. A movable block, the traveling block, is suspended beneath the crown block by wire rope, one ●nd of which is wound around the drum of the draw works hoist, and spooled between the sheaves off the crown and traveling blocks.

Although drilling mud circulation systems can vary considerably, systems presently used for oil ●nd gas development and exploration have

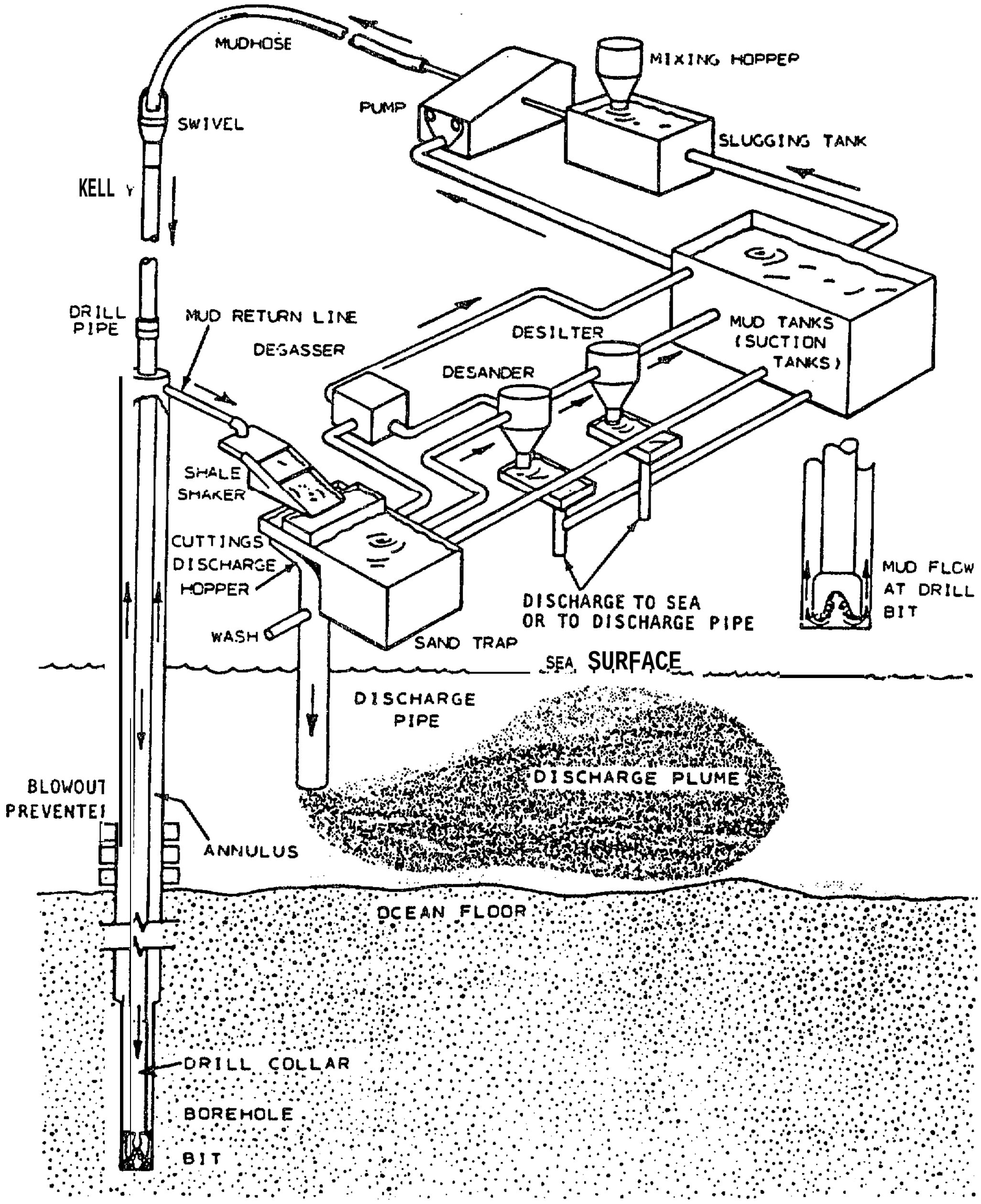


FIGURE 2-1 DIAGRAMMATIC OF ROTARY DRILLING AND SOLIDS CONTROL EQUIPMENT (ECOMAR, INC. 1978)

many components in common. The drilling fluid is pumped from tanks, proceeds to the standpipe (a long vertical pipe attached to the derrick) and then enters the swivel via the rotary hose. The mud travels through the swivel into the kelly and down the drill string to the bit. The bit usually is equipped with three jet nozzles, which eject mud from the bit at a high velocity (minimum of 60 to 75 m [200 to 250 ft]/see). The jets enable the fluid to scour the bottom of the hole and keep the teeth on the cones free of previously drilled cuttings. From the bit, the mud moves up the annular space between the drill string and the borehole to the surface at velocities that keep the fluid in laminar flow, carrying the cuttings with it. Mechanical devices such as shakers, sand traps, desanders, desilters, mud cleaners, and centrifuges are used to remove formation cuttings from the drilling mud once it reaches the surface. Cuttings are typically discharged from the rig, and the processed mud is returned to the mud tanks for recirculation in the well.

At the start of the well, seawater may be used to drill the upper 50 to 100 m of the well prior to setting the surface conductor pipe. During this period bentonite and other mud components are not normally added to the seawater, and cuttings are shunted directly from the hole at the seafloor. After setting and cementing the conductor pipe and base plate, drilling fluids (normally freshwater muds) are recirculated back to the drilling rig, and effluents are discharged through the rig's disposal system.

2.1.2 Purpose and Use of Drilling Fluids

Drilling muds were introduced with the advent of rotary drilling around 1900. The original purpose of the fluid, then a simple clay-water mixture, was to continuously remove cuttings from the borehole. Drilling mud has since evolved into a complex colloidal thixotropic* slurry which promotes efficient drilling and well completion while maximizing formation productivity. The primary functions of drilling mud include:

1. Removal and transport of cuttings to the surface
2. Control of formation pressures encountered during drilling
3. Maintenance of borehole stability with an impermeable filter cake
4. Protection of productive formations by minimizing wellbore damage
5. Protection against corrosion
6. Cooling and lubrication of the bit and drill string
7. Prevention of lost circulation.

Each of these functions is described in more detail below.

*Capable of forming a rigid gel structure when quiescent and of returning to a fluid state upon agitation.

2.1.2.1 Cuttings Removal and Transport

The rate at which formation cuttings and cavings are removed and transported to the surface is determined by the density of the particles and by the properties and annular velocity of the drilling mud. The slip velocity of the cuttings (downward component due to gravity] is affected by the shear characteristics and density of the mud. Water base muds may be made more viscous by additions of bentonite, drilled solids or chemical additives, or by flocculation of the solids.

The thixotropic property of drilling fluid ensures that cuttings remain suspended in the fluid column when the fluid is not circulating. This property can be altered by changing the colloidal content of the mud or by altering the valence of these colloids with chemical additives.

2.1.2.2 Control of Formation Pressures

Hydrostatic pressure maintained within the annulus by drilling fluid overbalances formation-fluid pressures and prevents the uncontrolled flow of oil, gas, and water into the well bore. As such, mud programs are normally designed to handle the highest anticipated formation pressure.

To prevent the open borehole from caving in and to protect weak formations from being fractured by high density drilling mud, the open hole is lined with steel pipe called casing. Usually two or more casing strings are run into the hole in telescope fashion. The first string, or surface pipe, is set at relatively shallow depths of from 150 to 760 m (500 to 2,500 ft). This string is to protect ground water systems from contamination and provide adequate security to the blowout preventer system. The casing strings that follow are run, when necessary, into successively smaller holes until total depth is reached. To establish a bond between the casing and the hole, a cement slurry is pumped down the casing, out the bottom through a casing shoe, and up the annular space between the casing and the hole. Sometimes cement is pumped into the annulus above the shoe through a stage-collar. The cement requires about 8 to 12 hr to set. Drilling then resumes with a bit smaller than the inside diameter of the last string of casing.

2.1.2.3 Maintenance of Borehole Stability

The hydrostatic pressure exerted by the drilling fluid and the thin filter cake (in the order of 0.8 to 1.6 mm [1/32 to 2/32 in] thick) deposited on the walls of unconsolidated formations prevent the formation from caving into the borehole. The thickness of the filter cake can become excessive with mud filtrate invasion and this may increase the potential for "stuck pipe."

2.1.2.4 Protection of Productive Formations

Formation damage introduced by invasion of drilling fluid filtrates or mud solids plugging the formation interstices is minimized by maintaining low filtration rates in the productive zone. The key to formation protection is a distribution of particles in the drilling mud which prevents infiltration to the formation interstices. Particles ranging in size from 1 to 200 μ (microns) are required to bridge the individual pores. Colloidal solids, such as bentonite, and subcolloidal solids, such as polymers, act to complete the seal on the formation. Furthermore, properly maintained mud filtrate salinity, using polyvalent salts, helps prevent clay hydration by reducing the cation exchange capacity with clay particles in the productive zone.

2.1.2.5 Corrosion Protection

presence of oxygen, carbon dioxide, or hydrogen sulfide dissolved in drilling muds can result in corrosion and premature failure of the drill pipe. Most of these problems can be minimized by removing or neutralizing these corrosive agents. Scavengers, such as sodium sulfite, may be used to remove oxygen from the system. Elevated pH in the mud also tends to minimize corrosion.

2.1.2.6 Cooling and Lubrication

Heat generated by friction as the bit scrapes the formation and as the drill string rotates against the walls of the borehole is absorbed by circulating drilling fluid. Drilling fluids also lubricate the bit, drill string, and casing during drilling. Lubricants such as bentonite, oil, detergents, graphite, asphalts, surfactants, and emulsifiers may be added to increase lubricity, resulting in prolonged equipment life, decreased torque, and reduced pump pressures. The ability of a drilling mud to absorb and transport heat depends upon its specific heat and the circulation volume.

2.1.2.7 Lost Circulation Prevention

Lost circulation is the loss of substantial quantities of whole mud into a formation. This is evidenced by a partial or complete loss of returns to the mud pit from the annulus. The annular mud level may also drop from the surface to a mud column height equivalent to the static pressure of the encountered formation. This resulting loss of mud hydrostatic pressure can lead to underpressurization of other zones increasing the potential for a blowout. Adding new mud to make up for losses, along with the addition of specialized lost circulation materials, can become very costly. Another potential problem is drill pipe sticking. Finally, the loss of whole mud into a potential producing zone will inevitably result in wellbore damage reducing oil and gas productivity.

Lost circulation can be combatted by:

1. Carefully maintaining mud weight
2. Using aerated muds
3. Employing a host of additives designed to plug the permeable formation
4. Drilling with air or gas
5. Spotting a cement plug Into the lost circulation zone
6. Setting an intermediate string of casing below the point of lost circulation.

2.1.3 Properties of Drilling Muds

A number of parameters such as weight, funnel and plastic viscosities, yield point, gel strength, and pH are used to describe the characteristics of drilling muds. Although these parameters are usually most meaningful to rig personnel, the following discussion is useful as a further description of the purpose of drilling muds.

2.1.3.1 Mud Weight

The mud weight is simply the density of the drilling fluid and is typically reported in terms of pounds per gallon (ppg) or pounds per cubic feet (lb/ft^3).* The mud weight is normally measured with a mud balance which includes a mud cup attached to one end of a balance beam. Mud weight may vary from around 7 to more than 30 ppg depending on composition. Most normal muds range from about 9.5 to 10.0 ppg; with deeper holes mud weight up to 13 to 15 ppg may be used. Unusual downhole pressures may necessitate mud weights of up to 20 ppg. For comparison, freshwater weighs about 8.3 ppg. Barite, with specific gravity of 4.3 to 4.5, is most commonly used to achieve higher mud weights.

2.1.3,2 Funnel Viscosity

Funnel viscosity provides an indication of the drilling mud's ability to flow. In oil fieldwork, the funnel viscosity is most commonly measured using a Marsh funnel which is simply a 1-qt funnel. Drilling mud is poured into the top of the funnel while the bottom orifice is blocked. The funnel viscosity is the time required to drain the funnel and is reported in units of sec/qt at the mud temperature tested. For comparison, freshwater would have a funnel viscosity of 26 ± 0.5 sec/qt at 21°C. In drilling muds, the funnel viscosity may range from 35 to more than 300 sec/qt; however, values of 38 to 60 sec/qt are most common.

2.1.3.3 Plastic viscosity

Plastic viscosity is a measure of the internal resistance to flow attributable to the amount, type, and size of solids present in the drilling mud. The plastic viscosity is normally obtained from a direct-reading, concentric-cylinder, rotary viscometer. The standard field unit for measuring plastic viscosity is a Farm VG Meter. The viscometer provides readings at rotating speeds of 300 and 600 rpms and the plastic viscosity is reported as the difference between these two readings. Plastic viscosity is reported in units of centipoise. Typically the plastic viscosity may range from the value for the mud weight (in ppg) to three or four times the mud weight. depending upon the type of drilling mud.

* 1 ppg = 120 g/l, 1 lb/ft^3 = 16.2 g/l.

2.1.3.4 Gel Strength

Gel strength is a measure of the ability of a colloid to form gels. It measures the same interparticle forces of a fluid that determine the yield point except that while gel strength is measured under static conditions, yield point is measured under dynamic conditions.

The common gel-strength measurements are the initial and the 10-min gels. The measured initial gel strength of a fluid is the maximum reading taken from a direct-reading viscometer after the fluid has been quiescent for 10 sec and is reported in lb/100 ft^2. The measured 10-min gel stength of a fluid is the maximum reading taken from a direct-reading viscometer after the fluid has been quiescent for 10 min. This reading is also reported in lb/100 ft^2.

2.1.3.5 pH

The pH of a drilling mud indicates its relative acidity or alkalinity. On the pH scale, the acidity range is from less than 1 to just below 7 and the alkalinity range is from just above 7 to 14. A pH of 7 is neutral. Muds are nearly always alkaline. Typical pH range for drilling muds is 9.0 to 10.5; however, high pH muds can range up to 12.5 or 13.0. Mud pH affects the dispersibility of clays, volubility of various products and chemicals, corrosion of steel materials, and mud theological properties.

There are two principal methods of determining the pH of drilling muds . The strip method is based on the effect of acids or alkalies on the color of certain chemical indicators found on strips of pH paper. The pH strips are placed on the surface of the drilling mud and the resulting color compared to a standard chart. The electrometric (pH meter) method is based on the voltage developed between two special electrodes when they are immersed in the drilling mud. The latter method is more accurate.

2.1.4 Classification of Mud Types

There are two general types of drilling muds: water base muds and oil base muds. Water base muds are most commonly used, while oil base muds are expensive and normally used only in situations where water base muds do not perform adequately or are likely to cause formation damage during completion. Discussions provided herein are primarily limited to water base muds since discharge of oil base muds is prohibited on the United States OCS.

Numerous classification schemes presently characterize water base drilling fluids (Rogers 1963; McGlothin and Krause 1980; IMCO Services undated). The following sections describe some of the broad categories of water base muds and provide typical make-up formulae (Table 2-l). Properties of eight drilling muds defined by the operators for use in the mid-Atlantic OCS and subjected to the EPA Region II standard bioassays are given in Appendix B, Table B-3.

TABLE 2-1

TYPICAL MAKE-UP FORMULAE FOR COMMON WATER BASE DRILLING FLUIDS

Component	Purpose	Typical Makeup
a. Freshwater Muds (McGlothlin and Krause 1900)		
Fresh Water	Liquid Base	
Bentonite	Weighting Agent, Viscosifier	20 ppb [a]
Caustic. Soda	pH Control	0.5 ppb
b. Low Solids Muds (IMCO Services, Milchem)		
Fresh Water	Liquid Base	
Bentonite	Weighting Agent, Viscosifier	8-14 ppb
Caustic Soda	pH Control	0.5 ppb
Soda Ash	Calcium Remover	0.25 ppb
Polymer	Bentonite Extender	0.05 ppb
c. Lignosulfonate Muds (McGlothlin and Krause 1980)		
Fresh or Salt Water	Liquid Base	
Bentonite	weighting Agent, Viscosifier	20-25 ppb
Chrome Lignosulfonate	Thinner	10 ppb
Caustic Soda	pH Control	0.5-1.0 ppb
d. Lignite and Tannin Muds (Monaghan et al. 1977, Milchem)		
Fresh Water	Liquid Base	
Bentonite	Weighting Agent, Viscosifier	20 ppb
Quebracho or Tannins	Thinner	1-4 ppb
Caustic Soda	pH Control	0.25-1.0 ppb
SAPP (Sodium Acid Pyro-phosphate)	Deflocculant	Variable
Soda Ash	Calcium Remover	Variable
Sodium Bicarbonate	Calcium Remover	Variable
e. Lime Muds (IMCO Services, Milchem)		
Fresh or Salt Water	Liquid Base	1.0-8.5 ppb
Lime	Weighting Agent	1.0-8.0 ppb
Chrome Lignosulfonate	Thinner	1.0-7.0 ppb
Caustic Soda	pH Control	0.5-1.5 ppb
Starch	Filtration Control	1.0-2.0 ppb
f. Gyp Muds (IMCO *Services*, Milchem)		
Fresh or Salt Water	Liquid Base	
Gypsum	Weighting Agent	4-8 ppb
Chrome Lignosulfonate	Thinner	1-8 ppb
Caustic Soda	pH Control	0.5-1.5 ppb
Starch	Filtration Control	1-6 ppb
g. Saltwater Muds (IMCO Services)		
Salt Water	Liquid Base	
Bentonite or Attapulgite	Weighting Agent	15-25 ppb
Modified Lignosulfonate	Thinner	4-6 ppb
Caustic Soda	pH Control	1-2 ppb
h. Potassium Muds (Milchem)		
Fresh Water	Liquid Base	
Bentonite	Weighting Agent, Viscosifier	6-8 ppb
Polymer	Bentonite Extender	0.12-0.5 ppb
Caustic Soda	pH Control	0.5 ppb
Potassium Chloride	Inhibition	10-17 ppb
Starch	Filtration Control	Variable

(o) Pounds per barrel.

2.1.4.1 Freshwater Muds

Freshwater muds are typically composed of water, bentonite (sodium montmorillonite) and drilled solids, and are characterized by sodium chloride (NaCl) and calcium (Ca^{++}) concentrations of less than 10,000 and 120 ppm, respectively. Caustic soda (NaOH) is added to maintain the pH in the 9.0 to 9.5 range.

Bentonite will generally hydrate sufficiently to furnish the desired viscosity and fluid loss properties. Lime may be added to supplement the viscosity (IMCO Services undated), and a phosphate or tannin dispersant will lower excessive viscosity (Rogers 1963). Freshwater muds are susceptible to contamination by salt, cement, gypsum, and high solids content. Numerous specific additives and treatments are available which control these conditions.

2.1.4.2 Low Solids Muds

Muds which contain less than 7 percent solids by volume (Rogers 1963) and which are nonweighted are classified as low solids muds. Low solids muds allow an increased rate of penetration, reduce cost of circulation, improve hydraulics, and lessen wear on drilling bits and pumping equipment.

A freshwater low solids mud would typically contain bentonite, a bentonite extender, caustic soda, and soda ash. Various polymers may be used instead of clay in low solids mud systems since they achieve the effect of bentonite clays at 1/20 the volume. Polymer systems can also function effectively with brackish or saline make-up water. However, the application of a polymer system is limited by calcium concentrations exceeding 300 ppm, salt concentrations in excess of 5,000 ppm, downhole temperatures greater than 120°C, and high drilled solids values. Although polymer systems are normally nondispersed, chrome lignosulfonate can be used to deflocculate clay solids without destroying the effects of the polymer.

2.1.4.3 Inhibitive Muds

An inhibitive mud is one which does not appreciably alter a formation once it has been cut by the bit. This quality implies that it resists disintegration and hydration of drilled solids, retards hydration of commercial clays, and stabilizes the well bore. Inhibitive water base muds are formed by the addition of various electrolytes or selected thinners in sufficient quantity to retard hydration. Inhibitive muds include lignosulfonate, lignite, calcium base, saltwater, and potassium base systems.

Lignosulfonate Muds

Lignosulfonate serves primarily as a deflocculant or thinner in drilling fluid systems. Lignosulfonate muds are extremely flexible and are readily altered to meet variable downhole conditions. In some areas light chemical treatments of caustic soda and lignosulfonate, supplemented with phosphate, are used in the upper portions of a well.

In the lower hole, higher concentrations of lignosulfonate may offer such advantages as fluid loss control, maximum dispersion, temperature stability (at 177°C and above), borehole stability and resistance to contamination from cement, salt, and gypsum.

Lignosulfonates contain a heavy metal function by forming a cloud-like polyanionic structure which neutralizes positively-charged clay particles and prevents flocculation. Additionally, the presence of an associated metal ion minimizes deterioration of lignosulfonate polymers under high temperatures. Chrome is the most commonly used metal ion associated with lignosulfonate polymers. However, other less environmentally deleterious metals, such as iron, have been combined with lignosulfonates and successfully used in mud systems (Lloyd 1980).

Lignite and Tannin Muds

Lignitic materials are normally used for filtration control and are sometimes used as thinners in low solids, freshwater muds. However, lignosulfonates are generally more effective as thinners. caustic soda is normally used with lignitic materials for pH control.

Additives rich in tannin, principally quebracho, were used as thinners prior to the advent of lignosulfonate in the late 1950s. This material, derived from the quebracho tree, normally has a pH of 3.8. The primary drawback of these muds is that quebracho becomes unstable at downhole temperatures above 116°C and loses its effectiveness in systems containing excess salt or calcium.

Calcium Base Muds

Calcium base muds may be used if bentonite and shales are encountered during drilling. High concentrations of calcium convert sodium clays to calcium clays and minimize their hydrate volume. Major types of calcium treated muds include lime muds, gypsum (or gyp) muds, and calcium chloride muds.

Lime muds are used when inhibition of reactive clays is desired and to improve the mud's tolerance to salt, anhydrite, and drilled solids . Because lime muds tend to solidify at elevated temperatures, they are seldom used at bottom hole temperatures in excess of 135 to 149°C. Because of their resistance to contaminants, lime muds are also commonly used in areas where saltwater flows may be encountered or where cement sections are drilled.

Gyp muds were used primarily for drilling massive sections of anhydrite or gypsum formations. Because of the limited Volubility of $CaSO_4$ in water, additional gypsum or anhydrite will not dissolve in the mud system but will be carried to the surface as a solid. Gyp muds are generally more resistant to salt and high temperatures than lime muds.

Calcium chloride muds were developed primarily for improved inhibition of hydratable shales. Higher soluble calcium in the filtrate and a moderate alkalinity are believed to be the key factors in minimizing shale hydration. This highly inhibitive system permits less dispersion of drilled solids and greater hole stability. Calcium chloride. a calcium lignosulfonate, and lime are normally required to break over the mud.

Saltwater Muds

Muds may be classified as saltwater muds when they contain over 10,000 ppm salt (Rogers 1963) and have not been converted to another type of mud. Salt muds may be used when salt is encountered while drilling, to control resistivity, and to inhibit bentonitic shales. Seawater muds may also be used merely to avoid the logistic problem of bringing fresh make-up water to offshore drill sites.

Attapulgite clay is most commonly used as a viscosifier in muds containing salt in excess of 35,000 ppm, while montmorillonite clays are used at lower salt concentrations. Guar gum is used as a viscosifier and fluid loss control additive; asbestos fiber is also an effective viscosifier. Starch is most commonly used to control fluid loss, paraformaldehyde is used to prevent fermentation, and soap-type defoamers are normally recommended for use in saltwater muds.

When massive salt sections ($NaCl$, $CaCl_2$, KCl, $MgCl_2$, or any combination) are encountered in the formation, the mud system is saturated with a similar salt to avoid severe hole enlargement. Salt concentrations of 125 pounds per barrel are common for saturated saltwater muds. These muds cause considerable difficulty in formation evaluation by electric logging techniques.

Potassium Base Muds

Potassium (KCl) inhibitive muds are commonly used to prevent tight hole problems associated with drilling soft formations where excessive sloughing and borehole problems (in shales) are encountered, and as drilling or workover fluids where the productive zone is water sensitive. XC-polymers, prehydrated bentonite, guar gum, and hydroxyethyl cellulose may be used as viscosifiers in KCl muds. Drispac or CMC may be used in reducing filtration. Caustic soda may be used to adjust the pH.

2.1.5 Drilling Mud Additives

Chemical additives enhance the properties of drilling mud and give it the characteristics necessary to alleviate problems peculiar to each drilling operation. Although over 1,000 additives are commercially available, these represent less than a hundred distinct chemical compounds of which only a dozen are typically used in any single well. Some of the more common additives are listed by trade name in Table B-1 (Appendix B), categorized according to their primary function. Physical-chemical characteristics of common mud components, as well as conditions of their use, are detailed in Table B-2 (Appendix 'B}.

Functions of some common drilling mud chemical additives are described below:

1. Alkalinity and pH Control: caustic soda, sodium carbonate, sodium bicarbonate, and lime are commonly used to control the alkalinity of the drilling fluid and secondarily to control bacterial growth.

2. Bactericide: paraformaldehyde, alkylamines, caustic soda, lime, and starch preservatives are typically used as bactericides to reduce the bacteria count in the mud system. Halogenated phenols are no longer permitted for OCS use.

3. Calcium Removers: caustic soda, soda ash, sodium bicarbonate, and certain polyphosphates are added to control the calcium buildup which prevents proper functioning of drilling equipment.

4. Corrosion Inhibitors: hydrated lime and amine salts are added to drilling fluids to reduce corrosion potential.

5. Defoamers: Aluminum strearate and sodium aryl sulfonate are commonly used and 'are designed to reduce foaming action that occurs particularly in brackish waters and saturated saltwater muds .

6. Emulsifiers: ethyl hexanol, silicone compounds, modified lignosulfonates, and anionic and nonionic products are used as emulsifiers to create a homogeneous mixture of two liquids.

7. Filtrate Loss Reducers: bentonite clays, a range of cellulose polymers such as sodium carboxymethyl cellulose (CMC) "and hydroxyethyl cellulose (HEC), and pregelatinized starch are added to drilling fluid to prevent the Invasion of the liquid phase into the formation.

0. Flocculants: salt (or brine), hydrated lime, gypsum, and sodium tetraphosphate cause suspended colloids to group into "floes" and settle out.

9. Foaming Agents: these products (see Table B-1 of Appendix B for trade names) are designed to foam in the presence of water and allow air or gas drilling through formations producing water.

10. Lost Circulation Materials: wood chips or fibers, mica, sawdust, leather, nut shells, cellophane, shredded rubber, fibrous mineral wool, and perlite are all used to plug pores in the wellbore wall and to reduce or stop fluid 105s into the formation.

11. Lubricants: certain hydrocarbons, mineral and vegetable oils, graphite powder, and soaps are used as lubricants to reduce the coefficient of friction between the drill bit and the formation.

12 Shale Control Inhibitors: gypsum, sodium silicate, polymers, limes, and salt reduce caving caused by swelling or hydrous disintegration of shales.

13. Surface Active Agents (Surfactants): emulsifiers, de-emulsifiers, arid flocculants reduce the relationship between viscosity and solids concentration, vary the gel strength, and reduce the fluid's plastic viscosity.

14. Thinners: lignosulfonates, tannins, and various polyphosphates are used as thinners since most of these also remove solids. Thinners act by deflocculating randomly associated clay particles.

15. Weighting Materials: products with high specific gravity, predominantly barite, calcite, ferrophosphate ores, siderite, and iron oxides (hematite), are used to increase drilling mud weight.

16. Petroleum hydrocarbons: these products (usually diesel oil) may be added to mud systems for specialized purposes such as freeing a stuck pipe. Hydraulic testing of blowout preventers also requires use of hydrocarbons which may be discharged directly to the environment.

2.1.6 Downhole Changes to Drilling Fluids

Physical-chemical properties of each drilling fluid are influenced by make-up components and special additives, synergistic effects between these materials, and effects of conditions encountered during drilling. Downhole changes in a mud's characteristics caused by heat and pressure are difficult to document with complete accuracy. However, such changes may have bearing on the physical fate and biological impacts of effluents discharged into the marine environment.

2.1.6.1 Downhole Temperatures

Bottomhole temperatures of wells range from a low of 27° to over 238°C (Rogers 1963), with temperatures increasing on an average depth gradient of about -10°C per 300 m (1,000 ft). Carney and Harris's (1975) survey of 1974 petroleum engineering literature indicated 98.5 percent of wells drilled in the United States had static bottomhole temperatures of less than 121°C, while 1.3 percent were between 121 and 177°C, and 0.2 percent were greater than 177°C. Circulating drilling fluids are typically cooler than the maximum borehole value because heat is lost to the atmosphere during the mud's circulation through surface equipment. Circulating top-hole temperatures of 52 to 57°C are common, and those of 93°C are not unknown. Circulating bottomhole temperatures are generally within 10°C of the true bottomhole value.

Elevated downhole temperatures may have detrimental effects upon mud components and whole drilling fluids. Extremely high temperatures encountered during drilling catalyze or expedite degradation, neutralization, and hydrolysis reactions in drilling muds. The products of these reactions differ chemically and may be more toxic than the parent compounds (Zitko 1975). Carney and Harris (1975) grouped common mud components according to their temperature stability (Table 2-2). These data give the practical limits for use of individual additives but do not represent their actual temperature degradation.

The temperature groupings described by Carney and Harris [19,75) are quite flexible, since overlapping of some of these materials does occur in regard to temperature functionality, and thermal stability of components may change when they are combined in a whole mud system. For example, certain bentonite/guar complexes form a rigid gel structure above 204°C (Carney and Harris 1975) and lime base muds solidify at temperatures between 135 and 149°C (Milchem undated). Due to these interactions, temperature functionality is most accurately determined under the conditions of the drilling mud system employed.

The practical thermal limits for mud components are typically set by empirical data collected during the drilling process. However, the thermal stability of certain drilling fluid components have been detailed and these results are summarized here.

Mud additives that are considered less temperature stable (<149°C) include starches, xanthan gums, guars, vinylacetate/maleic anhydride copolymers, and polyphosphates. Guar gums, starches, and xanthan gum undergo oxidative temperature degradation in the presence of oxidizing agents. Depolymerization of starch molecules is dependent upon exposure temperature, length of exposure, and the pH of the mud system. Starches are generaly stable to 107°C and are more stable under alkaline (pH=10) than acid conditions, although rapid degradation occurs above pH 11 (Thomas 1979). Starches are also subject to enzymatic degradation, which accelerates at higher temperatures, but the addition of bactericide, usually paraformaldehydes, to the mud system generally prevents this action.

Xanthan gums deacetylate at pH values greater than 9, but this has little effect on the viscosity of the mud system. The presence of salts or trivalent metal cations (such as those contained in chrome or lead lignosulfonates) increases xanthan stability.

Polyphosphates, such as the mud products Oilfos and sodium acid pyrophosphate (SAPP), revert to orthophosphates at temperatures greater than 79°C and function as flocculants rather than dispersants (Milchem undated). These components are seldom used at well depths exceeding 2,134 m (7,000 ft).

Carboxymethyl cellulose (CMC) and cellulose derivatives (stable to 177°C) degrade thermally by the breaking of polymer chains, resulting in a decrease in apparent viscosity of the mud system. Cellulose degradation is influenced by the pH, oxygen content, and metal ion concentrations in the mud system.

CMC is relatively temperature stable when stored or used in anoxic alkaline conditions (Thomas 1979). Reversible depolymerization of molecules can occur at temperatures greater than 93°C (Carney and

TABLE 2-2

TEMPERATURE STABILITY OF COMMON DRILLING MUD ADDITIVES

Less Than 121° C	Greater Than 177° C
Starches	Bentonites
Guar gum	Attapulgites
Xanthan gum	Barium sulfate
Polyphosphates	Calcite
	Iron carbonate
	Iron oxide
121° to 177° C	Lead sulfide
	Sodium chloride
Sodium and calcium lignosulfonates	Potassium chloride
Tannins	Calcium sulfate
Cellulose derivatives	Calcium chloride
Polyvinyl acetates\Maleic anhydride copolymers	Sodium hydroxide
Some surfactants	Calcium hydroxide
Some corrosion inhibitors	Potassium hydroxide
Carboxymethyl cellulose (CMC)	Mined lignites
Hydroxyethyl cellulose	Causticized lignites
	Sulfoalkylated lignites
	Modified lignosulfonates
	Acrylates and acrylamides
	Lost circulation materials
	Asphaltenes and gilsonites

Source: Carney & Harris 1975.

Harris 1975) but normal viscosity returns upon cooling As the temperature is increased above 121 to 149°C, scission of the polymer chains decreases the degree of polymerization (DP) and there is a permanent viscosity reduction

In the presence of oxygen under highly alkaline conditions, oxidative degradation of the cellulose polymer chain results in permanent viscosity reductions [Thomas 1979). The pH of the mud system is critical to this reaction, Wheatham (1958) found that a pH of 12.3 minimized the rate of degradation at 177°C, while Thomas (1979) noted polymers are most stable at pH greater than 10, and viscosity changes are reversible under these alkaline conditions. The presence of trivalent metal cations (such as in chrome or iron lignosulfonates) also increase thermal stability of some cellulose derivatives by inducing cross--linking of the polymer chains.

The thermal stability of lignosulfonates was examined by Skelly and Kjellstrand (1966) in a study which exposed a bentonite/barite/lignosulfonate slurry to varying temperatures at a pH of 10 Under conditions of this study, lignosulfonate degradation began at 166°C and progressed continuously until serious decomposition was noted at 232°C. The main gaseous decomposition product was carbon dioxide; hydrogen sulfide evolved at temperatures greater than 210°C and carbon monoxide and trace levels of methyl mercaptan were noted. As would be expected, the rate of gas evolution increased with temperature.

2.1 6.2 Salt and Formation Water Contamination

Salt contamination of drilling mud may arise from several sources. The presence of NaCl, $NaSO_4$, $CaSO_4$, etc. in makeup waters may introduce these salts to the mud system in ionic form. Further contamination may occur from dissolved salt concentrations in formation fluids and from drilling through salt-bearing formations. Most formation waters are brines, characterized by an abundance of chlorides, mostly sodium chloride, and have concentrations of dissolved solids several times greater than that of seawater. The total amount of mineral matter commonly found dissolved in oil-field waters range from a few mg/l (nearly fresh water) up to approximately 300,000 mg/l (heavy brine]. However, the common range is generally from 80,000 to $00,000 mg/l Concentrations of inorganic components in formation waters are shown in Table 2-3. Potential disposal alternatives are treatment and discharge from the production platforms or reinfection into subsurface formations.

Salt contamination is extremely deleterious to freshwater-clay muds. Viscosity increases sharply as the salt content of the fluid fraction increases from 0 to 1 percent. At concentrations greater than 1 percent, the fluid loss properties of the mud are also jeopardized.

In addition to the foregoing effects of salt on the whole mud system, certain individual additives are influenced by salt. For example sodium acid pyrophosphate (SAPP) functions less effectively as a dispersant at low sodium chloride values while carboxymethyl cellulose (CMC) becomes unstable at 50,000 ppm NaCl.

TABLE 2-3

TYPICAL CONCENTRATION RANGES
OF INORGANIC COMPONENTS IN PRODUCED WATERS

Component	Formation Waters	Seawater
cobalt (co)	<5 ppb	0.27 ppb
Chromium (Cr)	0 - 10 ppb	0.04 - 0.07 ppb
Copper (Cu)	o - 150 ppb	1 - 15 ppb
Potassium (K)	45 - 800 ppm	380 ppm
Lithium (Li)	o - 15 ppm	0.1 ppm
Magnesium (Mg)	30 - 6,000 ppm	1,272 ppm
Manganese (Mn)	1.7 - 950 ppb	1 - 10 ppb
Nickel (Ni)	o - 15 ppb	5.4 ppb
Tin (Sri)	1 - 12 ppb	3 ppb
Strontium (Sr)	10 - 450 ppm	13 ppm
Titanium (Ti)	0 - 10 ppb	present
Vanadium (V)	o - 1 ppb	0.3 ppb
Zirconium (Zr)	o - 10 ppb	--

Source: Rittenhouse et al 1969, in BLM 1977.

2.1.6 3 Cement Contamination

Cement contamination is experienced by every mud during the drilling of a well when casing is cemented and plugs are drilled out. Cement contains compounds of tricalcium silicate, calcium silicate, and tri-calcium aluminate, all of which react with water to form calcium hydroxide ($Ca(OH)_2$). It is the calcium hydroxide (caustic lime) released by cement reacting with water that causes most of the difficulty associ-ated with cement contamination. Caustic lime in drilling fluids causes chemical reactions which are detrimental to rheological and fluid loss properties. The evolution of hydroxyl radicals (OH^-) from the reaction increases the pH drastically, and the calcium may "react with bentonite forming calcium bentonite in a base ion exchange reaction. Viscosity and gel strength increase as a result of both these effects.

Freshwater clay systems are flocculated by cementing, resulting in increased rheology and fluid loss. The severity of flocculation depends upon the mud solids content, type and concentration of deflocculant additives, and the quantity of incorporated cement. An additional problem that can occur as a result of cement contamination is high temperature solidification.

After contamination, chemical treatment is required to maintain a low-calcium drilling fluid by removing calcium and excess lime from the system as an inert calcium precipitate. The removal of 100 mg/l calcium originating from lime requires treatment with 0.0735 pound per barrel (ppb) sodium bicarbonate or O 097 ppb SAPP (Milchem undated). Additions of 3.2 to 3.6 kg (7 to 8 lb) of lignite also effectively remove 1 ppb lime as a calcium salt of humic acid. Following the removal of excess calcium ions, the mud is usually treated with deflocculants and other chemical additives to reduce flocculation, gel strength, and high temperature gelation properties. As an alternative treatment, the contaminated system can be converted to a calcium base mud (see Section 2.1.4.3)

2.1.6.4 Gypsum or Anhydrite Contamination

Gypsum (gyp) or anhydrite contamination results from drilling through beds of this material ranging from several inch-wide stringers to deposits nearly 300 m (1,000 ft) thick. Gyp and anydrite are names for two forms of the chemical compound calcium sulfate ($CaSO_4$).

The contaminating effect of gyp or anhydrite is similar to cement contamination in that both contribute calcium ions, which flocculate sodium bentonite as calcium bentonite in a base ion exchange reaction. Unlike cement, anhydrite does not cause a pH increase since it supplies a sulfate radical ($SO_4^=$) instead of an hydroxyl radical. The sulfate radical contributes to flocculation of clay solids, although its effect is small compared to calcium ions.

In lightly treated muds a small amount of anhydrite increases the theological properties of a mud. The severity of change depends to a great degree on the bentonite content. When anhydrite concentrations cause the calcium ions to increase beyond 200 ppm, viscosity may fluctuate drastically and fluid loss may become more difficult to control. As anhydrite concentrations increase toward maximum volubility of approximately 600 ppm, a 'base exchange" or change in bentonite characteristics occurs. Flow properties tend to decrease, gel strengths increase, and fluid loss becomes very difficult to control. The final result is a mud of high water content, low viscosity, and low gel strength.

A gyp-contaminated drilling fluid can be maintained as a low-calcium fluid by chemically precipitating calcium with additions of sodium bicarbonate, SAPP, and soda ash. Additions of barium carbonate may also be used to precipitate both the calcium ion and the sulfate radical. " As an alternative treatment, the contaminated system may be converted to a gyp base inhibitive mud (see Section 2.1.4.3).

2 1.6.5 Hydrocarbon Contamination

When drilling through hydrocarbon-bearing formations, varying levels of petroleum hydrocarbons may become incorporated Into the mud system. Produced waters are passed through oil/water separators, further filtered, and treated to meet EPA standards before being discharged. Discharge of oil-contaminated muds is tightly controlled and these muds are not treated in depth in this report.

2.1.6.6 Drilled Solids

Solids may enter the drilling fluid either in the form of cuttings or cavings from the sidewall of the borehole. Solids may either be chemically inert, in which case modifications to the drilling mud are primarily physical in nature, or they may chemically react with the drilling fluid to alter its physical and chemical properties (as discussed in the preceding sections). The physical and chemical properties and effects of drilled solids are dependent on the drilling techniques used and geologic conditions encountered and, as such, are highly variable. Physical properties of drilled solids are discussed in more detail in the following sections. Approximate volumes of drilled solids calculated by BLM for a typical exploratory well (4,600 m) and development (production) well (3,000 m) are presented in Table 2-4. Actual volumes measured (Ray and Meek 1980) and calculated (Monaghan et al. 1977) for other wells have been substantially smaller.

TABLE 2-4

DRILL CUTTINGS FROM TYPICAL(a) EXPLORATION AND DEVELOPMENT WELLS

Drilling Interval		Well Diameter		Drill Cuttings: Exploratory		Drill Cuttings: Development	
(m)	(ft)	(cm)	(in)	Volume (bbl)	Weight (t)	Volume (bbl)	Weight (t)
0-46	0-150	90	36	187	72	187	72
46-300	150-1,000	80	32	846	332	846	332
300-1,370	1,000-4,500	50	20	1,361	534	1,361	534
1,370-3,000	4,500-10,000	38	15	1,206	506	1,206	506
3,000-3,660	10,000-12,000	38	15	439	184	--	--
3,660-4,600	12,000-15,000	25	10	291	131	--	--
Total				4,330 (690 m^3)	1,759 (1.60 x 10^6 kg)	3,413 (543 m^3)	1,444 (1.31 x 10^6 kg)

(a) Hypothetical well depths: Exploratory - 4,600 m (15,000 ft)
Development - 3,000 m (10,000 ft)

Source: BLM 1977.

2.1.7 Solids Control

Drilled solids that enter the drilling fluid in the form of cuttings or cavings from encountered formations are removed before the fluid is recirculated down the borehole since high solids content in drilling fluid have the following adverse effects:

1. Increased drilling fluid maintenance costs
2. Difficulty in maintaining optimum theological properties
3. Increased frequency of differential sticking
4. Reduced penetration rate
5. Decreased bit life and increased wear on pumps and drill pipe
6. Increased circulating pressure losses
7. Increased pressure control problems.

Drilling solids may be removed from the drilling mud by settling, by dilution, or by removal with mechanical devices. Removal by settling is generally restricted to low viscosity, low density muds. Dilution reduces solids concentrations by increasing the fluid volume. Since removal by settling is generally restrictive and removal by dilution is usually inefficient and expensive removal by mechanical methods is the preferred" method.

Drilled solids range in size from less than a micron (colloidal) to greater than 10 mm (coarse]. The actual size is dependent on the formation materials, drilling rate, and many other factors. Without proper solids control equipment, cuttings will simply recirculate through the bit and be ground to even finer particle size. Generally, the larger the cutting size, the easier it is to remove.

Mud solids are normally referred to by their size in units of microns. Table 2-5 provides a breakdown of the terminology used for the various sized particles. As a point of reference, bentonite, a primary component of drilling mud, is predominantly less than 2 μ, or colloidal in size. In accordance with API specifications, barite should contain 97 and 95 percent of the particles less than 74 μ and 44 μ, respectively.

TABLE 2-5

SIZE CLASSIFICATION OF SOLIDS IN DRILLING MUDS

Size Classification	Size Range (μ)	Typical Solids System Control Source	Settling Velocity (cm/see)
Coarse	>2,000	Shale Shaker	>20
Intermediate	250-2,000	Shale Shaker	2-20
Medium	74-250	Shale Shaker, Sand Trap, Desander, Mud Cleaner	0.4-2
Fine	44-74	Desilter, Decanting Centrifuge	0.2-0.4
Ultra fine	2-44	Desilter, Decanting Centrifuge	<<0.01-0.2[(a)]
colloidal	0-2	---	<<0.01[(a)]

(a) Does not consider flocculation.

The primary mechanical solids removal devices, listed in order of most efficient operation, are the shale shaker, sand trap, hydrocyclone desander, hydrocyclone desilter, and centrifuge. These devices are described in the following sections.

2.1.7.1 Shale Shakers

As mud and cuttings reach the surface they flow first onto the shale shaker via a large diameter flowline. The shaker is a vibrating screen designed to remove large cuttings from the drilling fluid The particle size a shale shaker can effectively remove and the liquid throughput capacity are dependent upon the size and shape of the apertures in the screen. Shaker screens come in numerous sizes of either square or oblong mesh, and are described according to mesh size, open dimension between wires (in microns), and percent open area. Typical mesh areas available for use on a vibrating screen are presented on Table 2-6. Standard shaker screens generally remove particles larger than 440 μ (Marshall and Brandt 1978) and fine screen shakers using cloth finer than 30 μ have become popular in the last decade for removal of particles down to approximately 120 μ . If a shaker unit utilizes multiple screens in series, the particle size separation is determined by the finest mesh (bottom) screen.

2.1.7.2 Sand Trap

Inadequate removal of large solids by the shaker due to screen damage or shaker bypasses is compensated for by the sand trap, which receives all liquid slurry passing through or bypassing the shaker unit. The sand trap (or "shale trap," or "settling tank") is a gravity settling compartment which functions according to Stokes' Law for the settling of spherical solids in liquid media. Formation cuttings and cavings which settle to the bottom (generally sand-sized particles ranging from 74 to 21OD) are discharged in a manner which minimizes whole mud losses, Large quantities of barite may settle from weighted drilling fluids passing through the sand trap. Provision for shunting shaker discharge slurry directly to the next active processing unit (bypassing the sand trap) is advisable to control costly barite losses. The sand trap should only be bypassed if all other solids removal units are functioning optimally.

2.1.7.3 Hydrocyclones

The 'finest cuts" on the full-flow circulating rate of unweighed muds are made in hydrocyclone units. Hydrocyclone centrifugal separators depend upon particle separation by size and specific gravity and are utilized as desanders desilters, and barite reclaimers.

Hydrocyclones are fed by centrifugal pumps. The efficient operation of these slurry-handling pumps is thwarted by badly gas-cut muds. Although shale shakers generally remove the majority of the gas from a gas-cut mud, a degasser may be placed between the sand trap and the first hydrocyclone to separate entrained gas from the drilling mud. It is generally accepted among field drilling equipment personnel that degassing equipment is not necessary if the yield point of the mud is 6 lb/100 ft^2 or less.

The centrifugal pump feeds drilling mud through a tangential aperture into the large end of the cone-shaped unit and initiates a whirling motion. A short pipe, or "vortex finder, extends axially from the top of the unit into the barrel of the hydrocyclone past the inlet. The vortex creates a downward spiraling velocity which forces the whirling fluid toward the apex of the cone. Heavier and/or larger solids are forced outward toward the wall of the cone following modifications of

TABLE 2-6

TYPICAL SHAKER SCREEN SPECIFICATIONS

Mesh	Wire Diameter (inches)	Aperture Size (microns]	Percent Open Area
8x8	0.028	2464	60.2
loxlo	0.025	1905	56.3
12X12	0.023	1524	51.8
14X14	0.020	1295	51.0
16X16	0.018	1130	50.7
18X18	0.018	955	45.8
20X20	0.017	838	43.6
8x20	0 .032x.020	2362x762	45.7
20x30	0.015	889x465	39.5
20x30	0.012	541	40.8
30X40	0.010	592x38 1	42.5
40x36	0.010	381x452	40.5
40X40	0.010	381	36.0
50X40	0 .0085	292x419	38.3
50X50	0.009	279	30.3
60x40	0.009	200x406	31.1
60X60	0.0075	234	30.5
70X30	0.0075	178x660	40.3
80X80	0.0055	178	31.4
100x100	0 .0045	140	30.3
120X120	0.0037	117	30.9

Source: Milchem undated.

Stokes's Law, while lighter, finer particles move toward the cone's center. Larger particles and a small amount of adhering fluid pass out of the cone's apex, which is smaller than the vortex opening by design. The remainder of the fluid and smaller solids reverse direction, pass back up the cone's center, and are discharged through the vortex finder and overflow opening.

The cut or degree of separation effected by the hydrocyclone is determined by the largest inside diameter of the conical position relative to the apex size. Desanders are typically 15 cm (6 in) in diameter and remove low-gravity particles larger than 74P . Desilters are normally 10 cm (4 in) in diameter and remove particles larger than 15 to 25 µ . Clay ejectors, which reclaim barite from solids control equipment discharges, are about 5 cm (2 in) in diameter.

The use of desilters and desanders may be too expensive in the case of a valuable liquid phase or weighted mud system. In this case, a mud cleaner, which combines a desilter and a fine mesh screen (74 to 100 µ or finer), may be used to process the entire mud flow.

Most drilling muds will be relatively clean after treatment by a shale shaker, desander, and desilter. However, in cases where the formation is very hard, the mud has been poorly maintained, or solids control equipment is not functioning property, it may be necessary to remove fines from the drilling fluid with a centrifuge.

2.1.7.4 Centrifuges

Centrifuges use centrifugal force, as do hydrocyclones, to hasten the settling rate for particles. The decanting centrifuge is the only liquid-solids separation device that can remove all free liquid from the separated solids, leaving only absorbed or "bound" liquids.

The decanting centrifuge consists of a rotating cone-shaped drum and a screw conveyor within the drum. The high speed of rotation of the drum forces larger and/or heavier particles to the outside wall, where they are scraped into the discharge by the conveyor. This material leaves the drum through a discharge port and is generally returned to the circulating mud system. Lighter, finer particles are retained in the liquid fraction and are discharged through a liquid discharge port as waste. A decanting centrifuge system is extremely efficient and can separate solids down to 3 to 5 µ (colloidal fractions). Properly operated, a centrifuge will salvage 90 to 95 percent of the barite from a drilling fluid.

2.1.8 Drilling Fluid Discharges

Drilling fluid discharges may be either continuous *or* intermittent during the drilling process. Continuous discharges include those released primarily from solids control equipment such as the shakers, desander, desilter, or centrifuge. Discharges from the shakers occur continuously while drilling. Discharges from the desander and desilter vary depending on the condition of the mud, although typically they last on the order of 3 hr/day when drilling is in progress. Discharges from the centrifuge may occur every 2 to 4 days of drilling and normally last for less than several hours. It should be noted that during the period when an exploratory drilling vessel is on station, actual drilling may be in progress only 50 percent of the time or less (J. Ray, Shell Oil Company, personal communication).

Intermittent discharges include those which are periodically required either while cementing, to control the mud rheology, during changeout of the mud system, or at the end of the well. Intermittent discharges are typically a high rate discharge and, in most cases, are considered as instantaneous.

Discharge volumes, rates, and quality are highly variable and depend on the type of drilling rig, solids contol equipment available, rig plumbing, standard drilling procedures used by various operators, hole depth, and numerous other factors. Drilling fluid discharges for three types of drilling vessels (jack-up, drillship, and semisubmersible) are presented on Table 2-7. Houghton et al. (1980a) provide a further breakdown of discharge volumes and rates from the Ocean Ranger, a semi-submersible, which operated in lower Cook Inlet in 1977. These data are summarized on Table 2-B. Although there are recognized differences from rig to rig and even from well to well, data contained on Table 2-8 should be fairly representative of 'normal" drilling fluid discharges with the possible exception of flushing water. Cumulative plots of discharges of whole mud and barite from the mid-Atlantic exploratory well from Ayers et al. (1980a) are presented in Figure 2-2.

The physical and chemical properties and constituents of drilling fluids also are highly variable, both from well to well and with depth in any given well. As an example, Meek and Ray (1980) reported the total quantity of barium discharged in the Tanner Bank well (depth: 3,419 m) to be 2,270 kg. Ayers et al. (1980a) report that .436, 160 kg of barium were discharged from the mid-Atlantic well, drilled to a depth of 4,970 m. Concentrations of chromium were 2 to 3 times greater in muds used in the mid-Atlantic as compared to those used on Tanner Bank. Samples analyzed near the beginning, at mid-depth, and near the end of the mid-Atlantic well had 24,000, 17S,000, and 306,000 mg/dry kg of barium, respectively, and 790, 910, and 1,007 mg/dry kg of chromium, respectively, reflecting the increased weight and complexity of the deeper hole muds.

2.1.9 Drilling Mud Recording Procedures

Most information on the properties of drilling mud used on a specific well are contained on the 'Drilling Mud Report." This report is filled out by the mud engineer, usually an employee of the mud supplier, and provided to the operator on a daily basis. The format of these reports has been set by the American Petroleum Institute (API); consequently, they vary only slightly from mud company to mud company. Examples of blank reports are provided in Appendix B, (Figures B-1 through B-3).

In most exploratory wells, these reports are considered as proprietary data, consequently, their availability is limited. This is

TABLE 2-7

DRILLING FLUID DISCHARGES FOR SELECTED DRILLING VESSELS IN LOWER COOK INLET

Type of Vessel	Type of Discharge	Discharge Volume or Rate
Jack-Up	Solids Control Equipment	
	Mud and Cuttings	Avg: 310 bbl/day; max: 380 bbl/day[a]
	Wash Water	Avg: 5,000 bbl/day; max: 6,000 bbl/day
	Excess Cement	360 bbl at three depths
	Excess Drilling Mud	2,000 bbl at end of well
Drillship	Solids Control Equipment	
	Mud and Cuttings	Avg: 310 bbl/day
	Wash Water	Avg: 4,800 bbl/day
	Excess Cement	25 bbl at various depths
	Excess Drilling Mud	710 bbl after setting outer conductor 1,200 bbl after setting inner conductor 2,000 bbl at end of well
Semi-Submersible	Solids Control Equipment	
	Muds and Cuttings	Avg: 150 bbl/day
	Wash Water	Avg: 180 bbl/day
	Excess Drilling Mud	1,000 bbl after surface hole 2,000 bbl at end of weil

(a) 1 bbl = 0.16m^3

Source: After Houghton et al. 1980a.

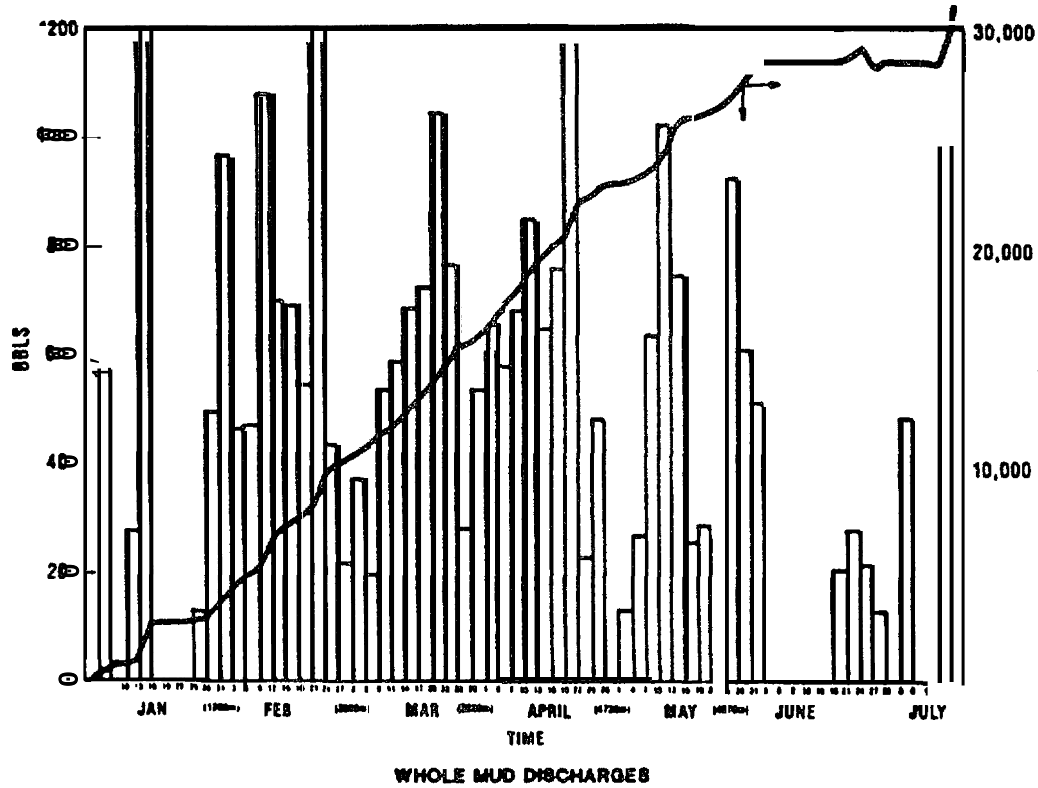
TABLE 2-8

SUMMARY OF DRILLING FLUID DISCHARGES FROM THE OCEAN RANGER IN LOWER COOK INLET

Type of Discharge	Volumetric Composition	Discharge Frequency	Discharge Rate	Flushing Water
Shakers	50% Cuttings 7.5% Dry Mud Components 42.5% Water	Continuous while drilling	1-2 bbl/hr	470 bbl/hr[(a)]
Desander	25% Sand 75% Water	2-3 hr/day while drilling	3 bbl/hr	10/bbl/hr[(a)]
Desilter	22.5% Silt 2.58 Dry Mud Components 75% Water	2-3 hr/day while drilling	16-17 bbl/hr	40 bbl/hr[(a)]
Centrifuge	1% Dry Mud Components 99% Water	1-3 hr as required	30 bbl/hr	4 bbl/hr
Sand Trap	20.0% Sand 7.5% Dry Mud Components 72.5% Water	Every 2-3[(b)] days	88 bbl/in 2-10 min	520 bbl/hr
Sample Trap	15% Dry Mud Components and Cuttings 85% Water	Every 2-3[(b)] days	15 bbl/hr 5-10 min	520 bbl/hr
Dilution to Control Rheology	10-15% Dry Mud Components 85-90% Water	Less than 3 per well	700 bbl/hr (max. 200 bbl)	520 bbl/hr
Cementing	10-15% Dry Mud Components 85-908 Water	3-6 times per well[(b)]	10 bbl/min for up to 20 min	520 bbl/hr
End of Well Discharge	10-15% Dry Mud Components 85-908 Water	Once per well[(b)]	700 bbl/hr for up to 3 hr	520 bbl/hr

(a) Flushing water was run continuously, even during times of no drilling; this mode of operation is not typical of all drilling vessels.
(b) Not discharged while drilling.

Source: From EPA permit applications.



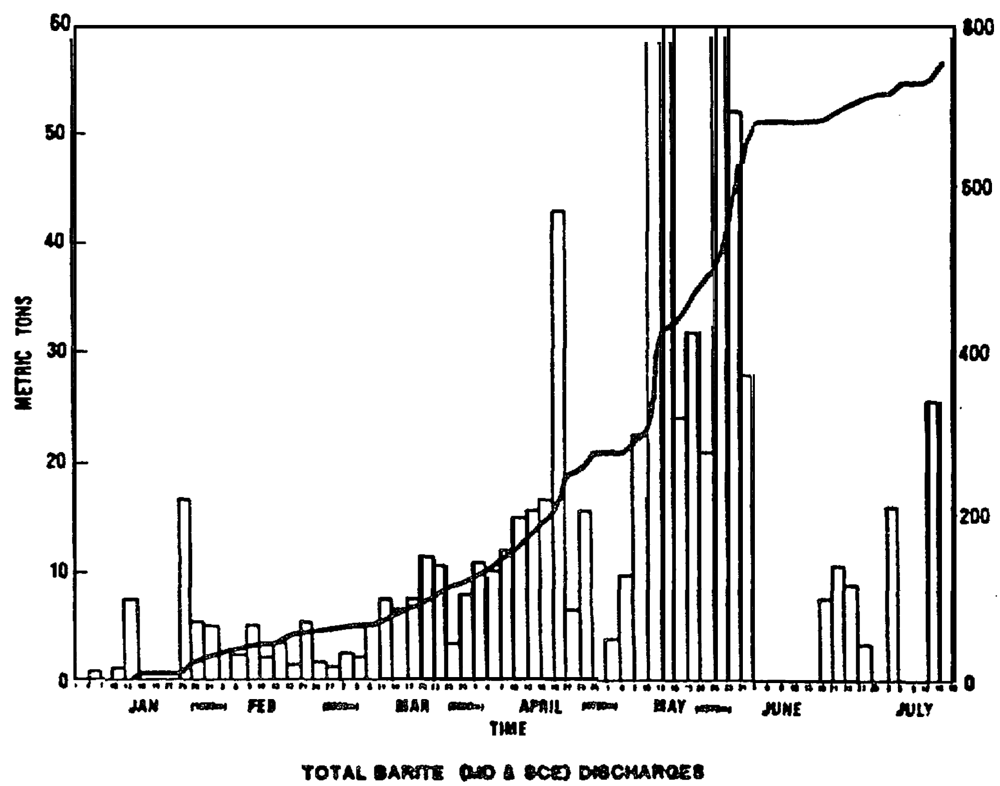


FIGURE 2-2 MID-ATLANTIC MONITORING PROGRAM HISTOGRAM AND CUMULATIVE CURVE OF WHOLE MUD AND TOTAL BARITE (MD & SCE) DISCHARGES (AYERS ET AL. 1980a)

particularly true of joint venture drilling operations including more than one participant, since the operator is legally bound to hold well data in strict confidentiality in accordance with the conditions of the agreement signed with the participating companies. Summaries of certain data contained on these reports may, however, be released under some circumstances, such as for use in scientific/research endeavors.

Components added to the mud system are also recorded on a daily basis, usually on the "Drilling Mud Report." Separate records are also maintained by the operator on component usage and stock on hand, primarily for inventory control. Although the detailed composition of the drilling mud at any one time is difficult to ascertain, it can be roughly approximated by totaling the components used to date and taking into account usage of soilds controls and other rig equipment.

Detailed records are not normally maintained which document drilling muds or components recovered or recycled. Normally barite is the only component in water base drilling muds which is recovered on a routine basis. Volumes of recovered barite may be estimated by knowing the hours of use and the efficiency of the centrifuge, the primary piece of equipment used to recover barite. Recycling of water base drilling muds is not a common practice in Alaska, primarily because of logistics constraints in transport of fluids. In addition, physical and chemical characteristics of the drilling mud at the end of a well are generally such that it would be unsuitable for efficient initial drilling in a new well.

Detailed discharge records for offshore wells are normally not maintained. Estimates of discharges can, however, be obtained knowing the hours of usage arid characteristics of various solids control and other equipment as itemized on the "Drilling Mud Report." Some solids control equipment vendors, such as Swaco, have recently begun to document such discharge, primarily to demonstrate the efficiency of their equipment. These data are generally compiled on the "Solids Control Report" which is filled out on a daily basis by the equipment vendor representative. An example of a "Solids control Report" is contained in Appendix B (Figure B-4). To date, this report has been used on an extremely limited basis in Alaska.

2.2 PHYSICAL AND CHEMICAL BEHAVIOR AND FATE OF DISCHARGE

Numerous studies have been conducted in recent years to assess the fate and effect of drilling mud and cuttings on the marine environment. The principal objectives of these studies have been to predict the behavior of mud, cuttings, and other by-products of drilling after they are discharged into the water column, and to estimate their concentrations and spatial and temporal extent. The following sections provide an overview of the short- and long-term physical and chemical fate and effects of discharged drilling fluids as interpreted from previous investigations. These discussions relate primarily to discharges from the drilling rig near the water surface (about 10-m depth). Initial deposition of cuttings at the seafloor during the first 50 to 150 m of the hole is not treated by any of the models but has an obvious effect on empirical results and may well form the nucleus for formation of a cuttings pile, even in rather dynamic environments.

2.2.1 Short-Term Behavior of Discharged Materials

Discharged drilling effluents typically separate into a lower plume and an upper plume Immediately after release. The lower plume contains the bulk of the discharged solids (in the form of drilled cuttings, adhering mud, and flocculated clays) and descends rapidly to the seafloor near the vicinity of the discharge source (Ayers et al. 1980a; Dames & Moore 1978a, Ecomar, Inc. 1978). On the other hand, the upper plume, composed of fine silts and clays (micron-sized or smaller) with low settling rates (less than 0.001 cm/see), can be carried large distances before settling to the bottom.

Liquid components of drilling fluids consist of the water fraction of the drilling muds (typically 85 percent of mud by volume) and possibly small amounts of formation waters. Large volumes of flushing water may be flowing from the downpipe as well (Table 2-8). These liquid components would undergo the same general dispersion characteristics as would the fine particle fractions in the upper plume.

Field studies of drilling fluid discharges indicate that the bulk of discharged material is carried downward and at least some distance downcurrent if significant ambient currents are present at the time of discharge (Ayers et al. 1980b). At the Tanner Bank disposal site, it was estimated that 70 to 90 percent of discharged material was transported away from the immediate drilling site under the influence of ambient currents (Meek and Ray 1980; Ecomar, Inc. 1978). Since cement used in drilling operations exhibits the same general physical characteristics as drilling mud (i.e. it is a slurry), its behavior is expected to be similar to that of drilling mud upon discharge.

2.2.1.1 Behavior of Fluids

Lighter mud and clay particles, approximately 5 to 7 percent of discharged solids (Ayers et al. 1980a,b) and liquid portions of the drilling effluent discharges form a diffuse cloud in the upper portion of the water column and are advected away from the source with the current. Dispersion of this upper plume has been described by numerous observers who have documented changes in total suspended solids and water quality parameters following drilling fluid discharges.

Aerial observers of discharged mud and cuttings at Tanner Bank off the California coast (Ecomar, Inc. 197S) characterized the fate of the upper plume. They reported that dense and clear areas in the water column exemplified the radical nature and heterogeneity of the plume close to the discharge source. Near the source, the plume appeared to be a complex billowing cloud of particles intermixed with clear water becoming increasingly homogeneous with time and distance.

The fate of the upper plume for the Tanner Bank study was related to current velocities and surface conditions which created turbulence around the discharge source. During low currents, upper plume components appeared to sink more rapidly, increasing the plume's visual depth near the discharge source. During periods of higher currents, drilling fluid and particulate were advected to greater distances from the source, and slightly less vertical descent of ma terials was observed. Some portion of the discharge, even under the lowest recorded current conditions persisted in the surface waters for some distance from the discharge source. (Dames & Moore 1978a, Houghton et al. 1980a, in their studies in lower Cook Inlet, made similar observations and likened the persistence of the slightly buoyant. freshwater-base fluid in the surface waters to the behavior of a thermal plume.) At increasingly greater distances, advection and dispersion continue to influence the suspended remnants of the discharge, and, with time, the discharge plume became more homogeneous with few areas of visibly elevated concentration.

Monitoring of hydrographic variables following drilling effluent discharge indicates that transmittance (as affected by suspended sediments) is the water quality parameter most significantly affected by the discharge. Sampling at a Tanner Bank platform indicated pH, dissolved oxygen, and salinity returned to background levels at less than 100 m downcurrent, while normal transmittance levels were not restored until 200 m downcurrent (Ecomar, Inc. 1978). Studies by Ayers et al. (1980a,b) in the mid-Atlantic and the Gulf of Mexico substantiate this result. Transmittance values take longer than suspended solids and other parameters to return to background levels due to the large number of colloidal particles present in mud. These particles continue to scatter light effectively even when present in concentrations too low to significantly contribute to the weight of suspended solids. Additional studies indicated background levels for suspended solids were reached within 500 and 1,000 m for 275 bbl/hr and 1,000 bbl/hr discharges, respectively, in the Gulf of Mexico (Ayers et al. 1980b) and within 350 to 600 m downcurrent for 500 bbl/hr and 275 bbl/hr discharges, respectively, from a mid-Atlantic platform (Ayers et al. 1980a).

Ray and Shinn (1975) documented total suspended solids levels of 80 and 20 mg/l at a depth of 40 m and at distances of approximately 10 and 20 m from the discharge point, respectively, fallowing discharges from a Gulf of Mexico platform. Theoretically derived curves estimated dilutions at this site ranged from 100 to 1,000:1 at approximately 300 m from the discharge source. Fluorescent dye studies in lower Cook Inlet indicated that turbulent mixing set up by flow around the underwater portions of the semi-submersible drilling vessel in currents exceeding 5 cm/sec was sufficient to cause dilutions of 10,000:1 within 100 m of the discharge point (Houghton et al. 1980a). Although dye studies indicated rapid mixing of the effluent, slightly reduced transmissivity in the water column was detected at distances up to 13 km from the discharge point. Transmittance in the plume was measured by making a transect across the plume from a high volume discharge marked by a drogue moving with the main mass of the plume. Values were compared to transmittance at each side of the plume which were representative of ambient values.

2.2.1.2 Behavior of Solids

The bulk of discharged solids typically drops rapidly to the seafloor as a plume of solid particles. The transit time of this material is generally so brief that the influence of currents is minimal in laterally transporting the material while in the water column.

Observations indicate that the lower plume Impacts the bottom within meters downcurrent of the source (Ayers et al. 1980a, b). The degree and spatial extent of cuttings accumulation is determined by the particle's settling velocity, as determined by its dimensions and specific gravity and the ambient currents (Ecomar, Inc. 1978).

Field observations of cuttings dispersion and deposition have been reported for conditions of varying current regimes, water depths, and discharge modes. Ecomar, Inc. (1978), presented data from intermittent mud and cuttings discharges at the Tanner Bank drill site in water depth of 60 m. A lower plume, composed of large cuttings (>0.5 mm), flocculated mud, and coalesced finer cuttings, settled rapidly to the bottom even with average currents of 21 cm/sec and bottom surges up to 36 cm/sec. The bulk of the deposited material settled near the platform or directly downcurrent. Bottom grab samples taken prior to and after the drilling operation and sediment traps detected discharge-induced sedimentation within 120 m of the source; measurable induced sedimentation was not found at a sampling location 915 m south of the drill site.

Similar sampling programs by other authors have demonstrated the near-field deposition of the lower plume. Underwater observations of high volume, high rate instantaneous discharges in 23 m of water in the Gulf of Mexico showed the lower plume impacted the seafloor within 10 m downcurrent of the discharge source (Ayers et al. 1980b, Brandsma et al. 1980). In another study conducted in a shallow Arctic sea with a low current regime, direct observations and settling pan samples indicated solid fractions of drilling effluent discharged below the ice were deposited near the source. Particles greater than 45μ, assumed to be formation cuttings, were primarily deposited within 6 m of point of discharge (Miller et al. 1980). Deposition of solids was also limited to the nearfield for bulk discharges of 550 and 220 bbl in the mid-Atlantic (Ayers et al. 1980a) and for instantaneous and continuous releases in lower Cook Inlet (Dames & Moore 1978a) and off the coast of Louisana (Ray and Shinn 1975).

Since oceanographic conditions such as currents and waves continuously act to modify the bottom sediments, it is extremely difficult to measure total initial deposition at any given point. One method which has shown limited success is deployment of sediment traps.

As part of the Tanner Bank Study (Ecomar, Inc. 1978; Meek and Ray 1980), a total of 19 sediment traps was deployed near the seafloor at various distances from the discharge in water depths in the order of 60 m. Currents in the area averaged 21 cm/sec at the surface and 15 cm/sec near the ocean floor. Over the 85-day study period 2,854 bbl of mud and cuttings, representing 863,290 kg of solids, were discharged. Sediment traps located between 50 and 150 m distance from the source collected total solids ranging from 7 to 52 gm/m^2 per day. A control trap located approximately 900 m from the discharge collected an average of 0.8 gm/m^2 per day. Generally, measured sedimentation rates were highest in the direction of the predominant surface and mid-water current flow and decreased with increasing distance from the discharge source. Based upon the sediment trap data, it was estimated that approximately

12 percent of the discharged solids settled on the seafloor at distances of 50 to 150 m from the discharge point. Based on assumptions of settling characteristics of the solids, the majority of the sediments settled within 50 m of the discharge.

Two sediment traps were also deployed as part of the lower Cook Inlet study (Dames & Moore 1978a, Houghton et al. 1980a). Sediment traps were deployed for 19 days in water depths of approximately 60 m. Mean currents at the site ranged 'between 80 to 100 cm/sec at the surface and 40 to 50 cm/sec near the seafloor. Mean deposition in a trap deployed 100 m downcurrent of the discharge was measured at 91 $gm/m^2/day$ as compared to 78 $gm/m^2/day$ at a control location. The apparent deposition rate for drilling effluent solids of 13 $gm/m^2/day$ compares well with those reported in the Tanner Bank Study (Ecomar, Inc. 1978).

Diver observations and benthic sampling have been used to assess the fate of cuttings during and after drilling operations. Zingula (1975) observed, photographed, and sampled cuttings accumulated under a drilling rig in the Gulf of Mexico in 26 m of water. He observed crabs and gastropod digging in the cuttings pile, while groupers and red snappers were nosing in the pile, undisturbed by the chips still falling in the water. He has also examined the cuttings piles left from wells drilled at a number of locations in the Gulf of Mexico. Zingula reported that the cuttings piles are typically 1 m high when new and 50 m in diameter. The aerial outlines were circular, elongated, or starburst, depending on the history of bottom currents during the course of drilling effluent discharge.

2.2.1.3 Chemical Behavior

Barium in the form of barium sulfate (barite) is a major component in drilling fluids, often comprising 80 to 90 percent by weight of the chemical components added to prepare a drilling mud. Most elements exist in open ocean waters at concentrations several times below their volubility limits. However, barium is an exception (Hatcher and Segar 1976). The upper level of barium volubility in seawater is closely controlled by the sulfate solubility equilibrium which yields a saturated solution at 30 to 40 μ g/1. In most natural waters there is sufficient sulfate or carbonate to precipitate the barium present in the water as a virtually insoluble, nontoxic compound (USEPA 1976). Barium sulfate's insolubility keeps barium in the category of a trace element in seawater (about 20 to 100 μ g/l). Recognizing that the physical and chemical properties of barium generally will preclude the existence of the toxic soluble form under usual marine and freshwater conditions," the USEPA has declined to establish a restrictive criterion for barium as protection of aquatic life (USEPA 1976).

Once the drilling mud is discharged into seawater, the fraction of barium which will dissolve is limited by the degree of saturation. Almost all discharged barium would be expected to remain in particulate form and either disperse as suspended particulate or settle in the sediments in the direction of the prevailing currents.

The concentrations of the trace metals iron, lead, zinc, mercury, arsenic, chromium, cadmium, nickel, and copper can vary considerably in mined barite deposits (Kramer et al. 1980). Bedded deposits typically contain trace metals at or below average crystal rock abundances. However, vein deposits may show elevation of 10 to 100 times for lead, zinc, mercury, arsenic, and cadmium. Seawater volubility studies of both bedded and vein-deposited barite show metals concentrations at or below ocean background concentrations. However, tests of vein deposited barite with sulfide minerals present result in concentrations of lead and zinc above ocean background levels (Kramer et al. 1980).

Other major chemical constituents of drilling mud include aluminum and chromium. Aluminum is present only in bentonite clay. Chromium can represent up to 3 percent by weight of chrome lignosulfonate. Lead is also found in some drilling discharges and is assumed to come from pipe dope compounds (Ray and Meek 1980). These metals appear in drilling discharges in small amounts and are very difficult to detect in the field Frequently their distribution in the marine environment must be inferred from that of barium. However, such inferences are subject to error because the components may behave physically, chemically, and biologically quite differently from barium (Gettleson and Laird 1980).

Monitoring of soluble barium and chromium concentrations in the vicinity of the C.O.S.T. Atlantic G-1 well showed no significant influences within 100 m of the discharge. Laboratory experiments verified that the amount of barium or chromium which dissolves in seawater was a small fraction of the particulate-bound fraction. Concentrations of dissolved barium showed a mean value of 37± μg/l near the rig compared to 35± μg/l at a control station. Beyond 100 m from the rig, dissolved chromium could not be found above normal seawater background (0.2-3.0 μg/1) with a mean concentration of 1.8 μg/l (ENDECO 1976).

Sediments undergo diagenetic chemical changes after deposition that tend to bring them toward equilibrium with their aqueous environment. This environment itself changes significantly with time and space. Oxygen in sedimentary *pore waters* is consumed as organic matter introduced into the sediments is bacterially degraded. Unless oxygen is renewed, sulfide formation can take place as bacteria utilize sulfates for oxidation of organic matter (Hatcher and Segar 1976).

Within disturbed sediments, as is the likely condition in the Gulf of Maine, sedimentary pore waters do not maintain permanent concentrations of sulfide, but are periodically flushed with oxygenated seawater. Hatcher and Segar (1976) indicate that two important conditions must be fulfilled for metals and other constituents to be released to solution during diagenesis and to be transported back into the overlying water column . First, the decomposition of most of the detrital organic matter reaching the sediments and the equilibration of inorganic phases with seawater must take place before permanent burial of the sediment occurs. Migration of solutes into the overlying water column may thus take place by advective processes which are considerably faster than diffusion through sediments. Second, the periodic renewal of oxygen in the pore waters is necessary to either prevent metal sulfide precipitation or permit reoxidation and dissolution of such sulfides if they are reformed.

A sedimentary environment which experiences frequent resuspension of sediments is likely to be an environment which favors the release of metals to the water column Resuspension inhibits the formation of metal sulfides which bind up metals in insoluble forms, provides a reworking mechanism which exposes previously buried sediments, and generally provides, longer sediment exposure so that oxidation of organic and equilibration of inorganic phases can occur.

Numerous studies suggest that, where present, sulfides of copper, zinc, nickel, and chromium control volubility of these metals under reduced sediment conditions (Gambrell et al. 1977; Chen et al. 1976; Blom et al. 1976). Upon oxidation, an increase in the more mobile soluble, exchangeable, and carbonate fractions occurs at the expense of organic and sulfide phases. The controlling solids under oxidized conditions for these metal ions are carbonates and hydroxides which are more soluble than sulfides, resulting in potentially greater concentrations of mobile forms (Chen et al. 1976).

The chromium ion in drilling mud exists in the trivalent state (Cr^{+3}) . The natural factors in drilling mud (organics, temperature, etc.) rapidly reduce any hexavalent chromium (Cr^{+6}) to the relatively nontoxic trivalent form. Trivalent chromium has an extremely slow rate of oxidation to hexavalent chromium in aerated seawater (Gambrell et al. 1972) . Therefore, the reverse of this reaction does not significantly occur with drilling muds in seawater.

Dissolved metals are not likely to remain in that state for significant periods of time. The fine-grained suspended solids particles are excellent scavengers of metals and other contaminants. Studies by Lu et al. (1978) showed that most trace metals and other contaminants were almost totally associated with settleable (>8 μ) solids. These contaminants can be adsorbed on to the suspended material and removed to the bottom sediments as the material settles.

2.2.1.4 Factors Affecting Short-Term Behavior

The behavior of drilling effluents when discharged into the marine environment vary widely depending on the following factors:

1. Properties of the discharged materials
2* Receiving water characteristics
3. Currents and turbulence
4. Flocculation and agglomeration.

Each of these factors is discussed in some detail below.

Propertied of the Discharged Materials

The problem of characterizing mud dispersion and sedimentation is complicated by the wide variety of sediment sizes in the discharge material, as well as physical-chemical properties of the numerous individual components and the used whole drilling mud. Discharged drilling fluids typically have a mineral composition varying from fine clays to large formation cuttings (Section 2.1.8) and physical-chemical properties determined by components and downhole conditions unique to each drilling operation.

The percent of fluid in discharged materials will also affect the behavior of the resultant plume. In laboratory experiments by Bowers and Goldenblatt (1978) with dredged materials, distinct differences were noted between a "solid" and 'liquid" dump mode. For the solid dump mode, fluids comprise less than approximately 75 percent of the discharged materials on a volume basis. Conversely, fluids account for more than approximately 85 percent of the discharged materials on a volume basis for the liquid dump mode.

The solid dump mode is characterized by a very rapid descent phase, little cloud growth, and little spread of solids upon bottom encounter. During descent, material falls much like a dense block with a trailing turbidity plume. It rapidly reaches its equilibrium velocity and entrainment is negligible so that the main cloud does not appreciably change shape during descent. Most energy is absorbed upon impact; consequently, most solids are deposited in a mound near the point of impact.

The liquid dump mode is characterized by a slower descent phase with the cloud expanding due to entrainment and by a rapid flow of material along the bottom after impact. Entrainment during the descent results in deceleration of the expanding cloud. Although Impact velocities are not as high as for equivalent solids dumps, most energy is redirected horizontally to drive the cloud rapidly along the bottom, resulting in little or no mounding of solids at the impact point.

Receiving Water Characteristics

Transport of suspended material into deep water is largely controlled by the density structure of the receiving water column. The density of seawater depends upon temperature, salinity, and pressure. In the ocean, density is often heterogeneous due to variations in temperature and salinity. The density of seawater increases by about 0.8 mg/cm^3 with an increase of salinity of 1 part per thousand. The temperature dependence is nonlinear, although a decrease of temperature of 5°C centered at 15°C will increase the density by about 1 mg/cm^3. The dependence on pressure is such that an increase in depth of about 250 m produces an increase in density of 1 mg/cm^3 (Pequegnat 1978). Variations in pressure with depth have very little effect on the settling velocity of mineral particles (silts and clays). A greater effect on the settling rate of fine particles is due to variation of viscosity with temperature. Kinematic viscosity of seawater increases as temperature declines with depth. Since Stokes's law for particle settling indicates an inverse relation to viscosity, the settling rate of the fine particles is decreased in passing through the thermocline due to an increase of viscosity and not due to the change in density.

The primary importance of density stratification is in respect to its effect on a cloud of moderately dispersed material whose effective density is slightly greater than seawater density. The arresting effect of the pycnocline on the descending cloud can lead to a collapse of the dynamic circulation within the cloud and initiate the settling stage in which the silts and possible flocculated clays will descend at their individual terminal speeds (Koh and Chang 1973; Brandsma et al. 1980).

It should not be implied, however, that collapse of the cloud necessarily occurs at the pycnocline, for if the pycnocline is fairly shallow or weak, the cloud could pass through intact and impact the seafloor before collapse.

The effect of density stratification on dispersal was significant for material discharged in the Gulf of Mexico (Ecomar, Inc. 1978). During two test discharges the lower boundaries of the upper plumes followed one of the major pycnoclines in the receiving water. The pycnocline did not concentrate the solids nor did it prevent solids from settling. It is notable that density stratification effects occurred only when the plume was already highly dispersed.

Seldom, if ever, are concentrations of suspended material from drilling effluent discharges high enough to appreciably alter the density of seawater (Drake 1971; Eittreim and Ewing 1972), although localized density changes are incorporated into mathematical models of deposition (Koh and Chang 1973) and have been suggested for real deposition processes (Bouma et al. 1969). In the presence of a strongly stratified system, such as a strong halocline or thermocline, it is questionable that the mass of suspended material is sufficient to overcome density differences imposed by temperature and salinity changes between water masses. Concentrations approaching 100 mg/l would be necessary to overcome density differences imposed by observed temperature stratification in the waters off California (Drake et al. 1972b). Concentrations of 390 to 1,720 mg/l would be required to overcome changes imposed by salinity and temperature off the east coast of the United States (Pierce 1976). In a weakly stratified system, concentrations necessary to affect the density would be much lower, and material deposition may not be impeded at all by an extremely weak system.

Currents and Turbulence

The ocean is constantly in motion, being agitated by combinations of forces from different origins. Ocean currents and turbulence are generated by surface winds, solar heating, and lunar gravitational effects. The earth's rotational and gravitational characteristics act to structure oceanic circulation. These structuring forces are called geostrophic effects or currents. Boundary conditions at the continental shelves and in shallow regions, such as estuaries, are controlled by local winds and tides.

Currents and turbulence are clearly responsible for the movement of suspended material during settling, resulting in dilution and dispersion. Houghton et al. (1980a) attributed dilutions of 10,000:1 within 100 m of a lower Cook Inlet discharge source to turbulent flow induced by a wake from a drill rig structure. In this case, the effect of turbulence on the fate of discharged material was so significant that a turbulence model (Schlichting 1968) was incorporated into the theoretical study. However, regression analyses of current velocity versus relative dilution at the Tanner Bank site indicated that changes in current velocity within a range of 2 to 46 cm/sec had little effect on dispersion and dilution of discharged material (Ray and Meek 1980). Based upon Reynolds number scaling, it is our opinion that turbulence will be induced by the drilling rig itself with current speeds approximately 5 to 10 cm/sec or greater. Therefore, it is reasonable to assume little variation in dispersion rate with current as in the Tanner Bank case.

Dilution of suspended solids is initiated in many cases by "standpipe pumping." Passing waves create a large surge of water in and out of the discharge pipe and substantial dilution of the effluent occurs. even before it enters the water column (Ray and Meek 1980; Ecomar, Inc. 1978; Ayers et al. 1980a). Other hydrodynamic processes, unique to each discharge situation, also facilitate dilution.

Flocculation and Agglomeration

Deposition of fine-grained sediment is dominated by the flocculation of suspended solids by inorganic salts. In accordance with Stokes' law, large heavy particles settle more rapidly than small, light particles. Flocculated particles, therefore, will settle faster than individual components and are less subject to transport in the water column prior to deposition.

The flocculation process Is dependent on collision and cohesion effects. The important factors that influence these effects are ambient salinity and the composition and concentration of the suspended matter. In brackish and saline waters, fine suspended particles flocculate readily on contact (Meade 1972; Gripenberg 1934; Whitehouse et al. 1960). Initially, particle collisions occur frequently in the unflocculated suspension as" gravity and turbulence cause random variations in transport direction and speed. Smaller particles flocculate readily due to their large relative surface area (Van Olphen 1966); larger grains are normally not sufficiently surface-active to flocculate with other single grains but adhere only to floes composed of many smaller grains (lCrank 1975). As larger floes are formed, transport velocities become more uniform and particle collisions less frequent. Eventually the settling velocity of the largest floes equals the velocities of the largest single grains and flocculation ceases as collisions decline.

Meade (1972) and Krone (1972) have cited the effect of flocculation on sedimentation and demonstrated how it is affected by organic and inorganic salts. But physical-chemical flocculation is not only a function of salinity (Krone 1962) but also of the cohesive nature of the particles (Einstein and Krone 1962) and of the concentration and chemical nature of the fine material (Whitehouse et al. 1960). Krone (1962) indicates that flocculation normally occurs at solids concentrations greater than 200 mg/l. Turbulence of a certain strength may also influence flocculation by increasing the frequency of interparticle collisions, but the internal shear in the water ultimately limits the maximum size and settling velocity of floes (Krone 1972), and beyond some critical point an increase of turbulence leads to disaggregation.

Fine materials suspended in the water column are subject to ingestion by filter-feeding organisms. These organisms, among others, take particles ranging in size from 1 to 50 μ and eject them in fecal pellets that range from 30 to 3,000 μ (Haven and Morales-Alamo 1972). These pellets have a density of approximately 1.2 and sink at rates typical of coarse silt or fine sand grains. Manheim et al. (1970) also report that copepods are important in composite particle formation (agglomeration) .

It is important to note that these agglomerated particles will settle faster than would individual particles. As Drake (1976) concluded, physical-chemical flocculation produces settling rate increases that range up to about one order of magnitude, whereas biological processes can account for increases of up to several orders of magnitude. However, it is expected that only a small percentage of discharged material would be affected by agglomeration by organisms in the short term, whereas physical-chemical flocculation would affect" a relatively large percentage of the discharge solids materials.

2.2.1.5 Prediction of Short-Term Behavior

Analysis of drilling mud disposal in the ocean should include determinations of the concentration of the waste material in suspension and solution, and the distribution of disposed solids in the surface waters or settled on the ocean floor. Several mathematical models have been developed in recent years to describe dredged material disposal, and these have been adapted for use in investigations of the short-term physical fate of drilling fluids and cuttings. The most elaborate of these are the Tetra Tech model (Brandsma et al. 1980) and the Dames & Moore (1978a) model (Houghton et al. 1980a), which utilize sophisticated computer programs. The Krishnappen (unpublished) and Edge-Dysart (1972) models do not consider the processes involved in ocean disposal in much detail and as a result are less complex. Although the NORTEC model (Miller et al. 1980) describes drilling effluent discharges in shallow Arctic seas, its usefulness in other geographical areas is limited. These models are described herein along with additional models and modification which are applicable to the case of drilling fluid discharge into ocean waters.

Bottom Impingement of Solids

At the simplest level, Stokes's law for particle fall through a fluid medium can be applied to cuttings and mud solids of a particular size and density to calculate. the time a particle takes to reach the seafloor. This time is thus the period during which ambient currents act on the particle to displace it laterally from the discharge site. This approach has been used to predict patterns of initial bottom impingement cuttings in several of the models discussed in the following sections.

The idealized pattern shown in Figure 2-3 represents the initial deposition which is likely under uniform conditions of current and discharge, that is, where the predominant current is tidal, and the discharge consists of a constant volume of effluent with a uniform grain size distribution. This diagram shows the initial deposition pattern (ignoring resuspension and transport and early cuttings discharge at the seafloor) for an assumed water depth of 100 m beneath the downpipe and current speeds of 350 cm/sec in the major axis and 25 cm/sec in the minor axis. Only tidal currents are considered in this idealized scheme. The occurrence of a net current would skew the distribution in the predominant [illegible] direction.

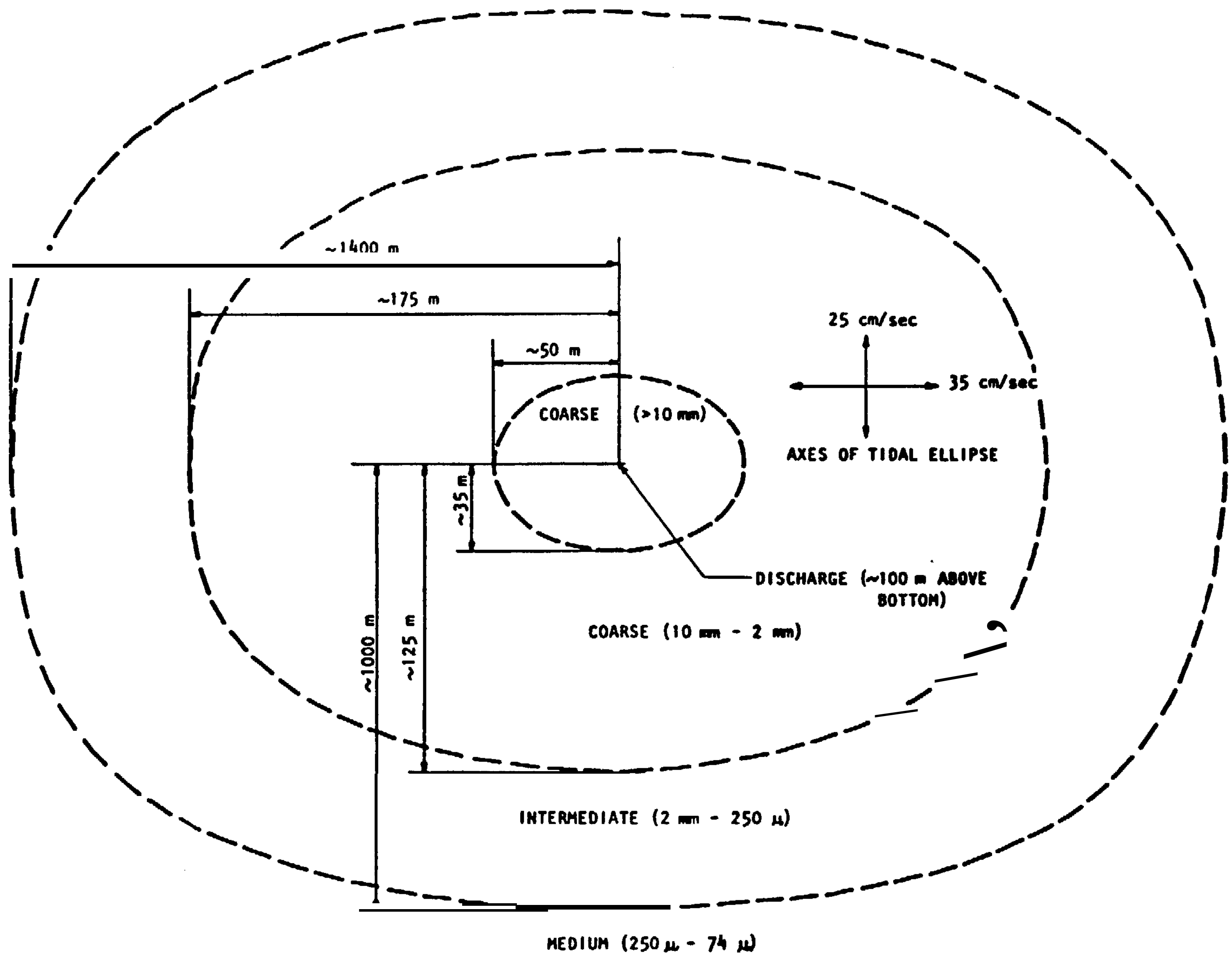


FIGURE 2-3 APPROXIMATE PATTERN OF INITIAL PARTICLE DEPOSITION

This figure shows that coarse fractions (>2,000 μ) would generally be initially deposited within 125 to 175 m of the discharge point. Intermediate fractions would be deposited beyond that limit out to a distance of 1,000 to 1,400 m. Medium fractions would be deposited beyond that. The smaller sizes of medium particles (<74 m) require settling times in excess of the semidiurnal half tidal period and are likely to be deposited during reversals of tidal flow which carry the particles back toward the point of discharge. The remainder of the solid fractions (ignoring the effects of flocculation) would remain in the water column for appreciable lengths of time. Flocculation would increase effective particle size resulting in increased settling rates.

The areas of bottom potentially affected by initial deposition of drilling solids are conservatively large (Figure 2-3). This conservatism results in part from assuming that a solids particle has no initial downward momentum upon exit from the downpipe and in part from flocculation. Imposition of a downward velocity on a discharged particle would reduce the particle's trajectory, hence reducing the distance from the well at which the particle would be deposited on the bottom. In reality areal extent of visible cuttings accumulations have been far smaller, e.g., 2000 m^2 (Zingula 1975). Moreover, depositional patterns vary in quantity and character with planar outlines of the deposits, i.e., circular, elongated, or starburst, depending on the currents at the time of release of the solids (Zingula 1975).

The rate and frequency of release from the various solids control system components (Section 2.1.8) determine how the various solids fractions become deposited in the variety of observed patterns. Cuttings discharged at the seafloor before setting the collector pipe will accumulate close to the hole in a pattern dependent only on the near-bottom currents. The shale shaker operates continuously during drilling and therefore discharges coarse through medium sized particles at a regular rate. The continuous nature of the discharge would result in the elliptical deposit form shown in Figure 2-3.

Intermittent releases will result in different patterns depending on the duration of effluent discharge and time of release within the tidal period. Successive releases of short duration can result in a starburst deposition pattern; discharge with duration significantly shorter than the tidal period can result in an elongated pattern extending in the down-current direction at the time of release. The elliptical pattern, however, represents the greatest areal extent of bottom deposition as the result of continuous discharge; other discharge modes will, theoretically, result in patterns occupying sectors of the elliptical area.

Offshore Operators' Committee (OOC) Model

The Offshore Operators' Committee (OOC) model is an evolution of earlier models for dredged material discharges developed for the Environmental Protection Agency (Bowers and Goldenblatt 1978) and the Army Corps of Engineers (Brandsma and Divorky 1976), both of which were modifications of the Koh-Chang model (197310 Although this model is still being modified, basic details have been documented by Brandsma et al. (1980).

The OOC model assumes drilling mud discharges originate as a jet from a submerged pipe at an arbitrary orientation. The behavior of material after release is considered to divide into three phases: convective descent of the jet; dynamic collapse, occurring when the descending plume either impacts the bottom or arrives at the level of neutral buoyancy; and long-term passive diffusion, commencing when transport and spreading of the plume is determined more by ambient currents and turbulence than by any dynamic character of the discharge.

Equations describing a sinking jet (convective descent phase) in a stratified ambient fluid with an arbitrary velocity distribution are those for conservation of mass, momentum, buoyancy, and solids. The jet is assumed to consist of a number of discrete classes of particles and a fluid fraction. Each particle class is described by its concentration, density, and settling velocity. The jet properties are described by its radius, velocity along the jet axis, and density. The dynamic behavior of the jet is described from a set of coordinate axes fixed on the discharging vessel with the y-axis vertically downward. The ambient density and current structures are designated with location and time. Changes in the quantities describing the jet occur with distance along the jet axis. When the jet encounters the sea bottom or a depth where the jet density equals the ambient density, the calculation is switched to the dynamic collapse phase.

The settling of solid particles from a jet is a most complicated phenomenon since jet turbulence tends to keep solid particles within the jet while gravitational forces tend to cause them to separate. The OOC model follows the work of Koh and Chang (1973) who used dimensional analysis to show that the dimensionless mass rate of settling is a function of the ratio of the descent velocity of the jet and the settling velocity of the particles, the concentration of each particle class, and the total concentration.

During the dynamic collapse phase the discharged material is assumed to still possess a dynamic character, but its vertical motion is arrested by the density stratification of the sea, and it tends to collapse into its level of neutral buoyancy. In the absence of density stratification, the jet will hit the bottom and collapse there because its density is greater than that of the surrounding fluid. Since, at this point, the jet velocity has become close to that of the ambient, the conservation laws are written with respect to time. The path of a single element of the plume is followed through its history. The element is assumed to have an elliptical cross section. Settling of solids in the dynamic collapse phase is determined as a function of the dimensions, concentration, and settling velocities of individual elements.

For the long-term passive diffusion phase, the plume is assumed to become dynamically passive and subject to turbulent diffusion, advection, and settling of the solid particles. In this mode, a Lagrangian scheme of diffusion was introduced in which the plume was divided into many small Gaussian clouds each of which contains particles from only one class. These small clouds are initially distributed as determined by the dynamic behavior of the jet plume. They are convected, diffused, and settled independently, using a time step of several minutes duration, according to the ambient currents and diffusion coefficients and the particle settling velocity. The result is a tine-varying distribution of small clouds of particles, and from this distribution we can calculate the concentration at any point as the sum of contributions from these small clouds.

Comparison with field data (Brandsma et al. 1980) shows that the model now reproduces several observed features of drilling mud discharges. Additional work is scheduled to consider the primary limitations of the model, i.e., considerations for effects of the turbulent wake of the drill rig and the settling of cohesive or flocculated mud.

Dames & Moore Model

The Dames & Moore model (1978a) consists of two separate sets of programs to predict dispersion of drilling effluents discharged from a vertical submerged pipe in a tidal estuary. The first set of programs was developed to predict the behavior of the cuttings plume, while the second described the spread of the liquid portion of the discharge.

In the cuttings deposition model, the seafloor locations of impact for given particle sizes are calculated from input data on the settling velocity of individual particles, prevailing current conditions, and the configuration (depth, etc.) of the discharge, The current velocity profile is defined at three points and is assumed to vary linearly between these points. Also, more than one particle size may be considered at any one time.

A second program then calculates the fraction of the particles released which land at a given distance for each of the angular sectors. The calculation is based on a depth-averaged frequency of occurrence of the different current condition (i.e., speed and direction) taken over a long period of time. The depth-averaged frequency is taken to be the mean of three frequencies at the different water depths. The particle fall location for each given condition is determined by a method similar to that used in the initial program; however, a uniform speed is assumed to prevail across the whole of the velocity profile After determining the fall locations of the particles for all possible current conditions, the fractions of released particles landing at these locations are determined. This is based on the consideration that these fractions are directly proportional to the frequency of occurrence of the corresponding current conditions. The fractions of particles of all sizes by number as well as by weight are then calculated by summation, taking into account the composition of the original discharge.. Fluxes are evaluated by dividing the weight fractions by the relevant area.

The spread of the mud plume on the surface of the sea is also analyzed on the assumption that it is very slightly buoyant (because of the presence of fresh water) and that it behaves as a surface plume much in the manner of a thermal plume. The program used for the prediction of the dispersion of the mud plume is that of Shirazi and Davis (1974) with minor modifications including a sequence for calculating the Froude number from the initial discharge rate and the current speed.

For the analysis of the mud plume, it is assumed that the current conditions, for the duration of interest, are steady state. In lower Cook Inlet, three specific discharge cases were considered: (1) continuous discharge from normal drilling from shaker only; (2) continuous discharge" from shaker, desander, and desilter; and (3) mud discharge from purging the sand pit.

The analysis by the Shirazi-Davis model is also performed after eliminating the effects related to heat losses and considering a range of input conditions for the plume. An empirical mixing-zone analysis of near-field dilutions is employed to provide the initial concentrations for this model. Based upon field data, it was assumed that the initial mixing-zone concentration was reached at a distance of 150 m (500 ft) from the discharge point. The plume at that point was assumed to be 45 m wide and 11 m deep. The rest of the input data for the model was taken from the field studies; the empirical data related to the turbulence and entrainment, etc. were taken as recommended by Shirazi and Davis (1974).

Although the Dames & Moore model provided results which correlated relatively well with available field data, certain limitations are apparent. For the cuttings plume model, flocculation was not considered. In the fluid plume it should be noted that the intense mixing and complex flow pattern produced by the below-water structure of a drilling rig will vary considerably; consequently, the starting point for modeling (calculations for initial dilutions) will also vary considerably. In addition, the model is designed primarily for continuous discharges and results for instantaneous releases need to be interpreted with caution. A final limitation is that the model does not consider settling of particles contained in the fluids plume.

Krishnappen Model

Krishnappen (unpublished) has modeled the motion of cohesionless dredged material dumped near the surface of a homogeneous stationary body of water. The dredged material is considered to consist of various fractions of uniform size particles, with each fraction exerting an influence on the total behavior of the dredged material in proportion to its negative buoyancy.

The model assumes that the motion of the discharged material includes an initial entrainment phase and a final settling phase. During the entrainment phase the size of the descending cloud increases due to the incorporation of external fluid, and the descent velocity diminishes. The effect of ambient turbulence during this phase is negligible since the dominant force is the particle's negative buoyancy.

In the entrainment phase, the Krishnappen model can evaluate a case where one or more fractions of the main cloud enter the settling phase before the balance of the cloud. The time of this occurrence, the depth at which it occurs, the lateral distance traveled by the cloud at the time of separation, and the behavior of the main cloud after separation are all predicted.

During the settling phase, the vertical downward velocity of the cloud is the same as the fall velocity of individual constituent particles, and the increase in cloud size is solely due to ambient turbulence. A turbulence coefficient (Koh 1971) can be incorporated into this phase to more closely simulate turbulent ambient conditions. Outputs of the settling phase include concentration of the settling cloud at specific points in time, predictions of the aerial coverage and height of the mound formed on the seafloor by settled material, effect of lateral (current) displacement on the distribution of solids, and time required for settling of all fractions. Application of the Krishnappen model is limited by its assumption of a uniform current, lack of bottom encounter, consideration of instantaneous discharges only, and its assumption that the discharged material is cohesionless (Bowers 1976).

Edge-Dysart Model

The Edge-Dysart (1972] model was developed for discharging material as an axisymmetric jet into an infinite fluid of infinite extent. The material is assumed to undergo only a jet discharge phase and a long-term diffusion phase. Furthermore, the model assumes that ambient currents are negligible compared with the jet speed, the discharge flow is steady and turbulent, the fluid is incompressible, fluid velocities are low, changes in density are small, and flow within the jet is of a boundary-layer type.

The jet convective phase terminates when the level of neutral buoyancy is reached. It is assumed that this always occurs far enough above the ocean floor so that there is no bottom encounter. As the material settles from the level of neutral buoyancy, it is transported in horizontal directions in the long-term diffusion model. The scale of turbulent diffusion in the vertical direction is considered to be negligible.

The Edge-Dysart model is similar to that portion of the Koh-Chang model (1973) concerned with disposal by jet discharge. However, the Koh-Chang model, and modifications thereof, contain a much better treatment of the long-term diffusion phase and provide for more detailed tracing of the waste cloud, especially in the dynamic collapse and bottom encounter phases (Johnson 1974).

NORTEC Model

NORTEC (Miller et al. 1980; NORTEC 1981) developed a quantitative modal to characterize the flow, concentration, and deposition associated with below-ice discharge of drilling mud and cuttings in a shallow Arctic sea. At a Reynolds number of 7.5×10^5, a circular jet was formed which, after impinging on the seafloor, spread radially outward as a wall jet. Based upon continuity and momentum considerations and experimental model results, the wall jet was found to increase in height with radius as $r^{1.1}$, maximum velocity as $r^{-1.2}$ and concentration as $r^{-0.5}$.

In the NORTEC model, the *effects* of density stratification, currents, and meteorologic events were not considered important In the shallow ice-covered environment. The primary limitation of the model was in consideration of flocculation which apparently dominates the effluent behavior within a short period (10 to 15 rein) after discharge.

Other Ocean Dispersion Models

Since no mathematical model is available which can predict the behavior of discharges under an array of peculiar ambient conditions, a multifold approach has often been adopted for analysis of mud disposal. Numerous theoretical models have been developed which simulate a particular phase of the disposal process or examine the process under unique environmental conditions.

Various investigators, including Joseph and Sendner, Ozmidov, and Schonfeld (as discussed by Okubo 1962, 1970), have developed theoretical models of turbulent diffusion in the ocean. These studies provide a better understanding of diffusion in the ocean, however, they are of limited use in determining physical fate predictions for a multiphase waste material possessing time-dependent buoyancy and momentum characteristics induced by flocculation and other considerations (Johnson 1974). Schlichting (1968) also provided a detailed model of the wake created behind a solid body, such as a drill rig, and the mechanisms influencing dispersion of discharged material in wakes.

2.2.2 Long-Term Fate of Discharged Materials

As previously indicated in Section 2.1.1. 1, the fluid plume from drilling effluent disposal activities is rapidly diluted so that physical and chemical characteristics of the plume are nearly undetectable from ambient seawater at distances exceeding 1,000 m. At greater distances, advection and dispersion continue to influence the plume so that it becomes undetectable even with the most sophisticated sampling techniques. For this reason, most concern has justifiably been directed toward the long-term fate of the solids plume which is rapidly deposited on the seafloor in the vicinity of the well and on the ultimate fate of finer solids. Finer solids from the upper fluid plume may be transported and deposited in depositional sinks some distance from the source. This process is totally dependent on geographically specific oceanographic conditions such as those covered in Chapters 3 and 4 of this report. Consequently, discussions of long-term effects presented herein are directed toward benthic effects.

In time, cuttings accumulations in the vicinity of the discharge source are dispersed by steady bottom currents and wave-induced surges. The rate of redistribution is determined by such parameters as the cohesive properties of the cuttings, the size of the accumulation, and the exposure of the seafloor to currents and other transport mechanisms. Oetking et al. (no date) found no cuttings pile beneath a platform off Louisiana in 22 m of water where drilling had ceased 15 years before. Shinn (1974) found no cuttings beneath production platforms in 20 m of water 40 km off Galveston, Texas, where drilling had ceased 10 years earlier. No cuttings were evident 3 yr following drilling of C.O.S.T. well G-2 (in about 79 m) on the southern flank of Georges Bank, although substantial amounts of debris from the drilling vessel were seen (R.A. Cooper, personal communication).

Redistribution of cuttings may occur more immediately after deposition than observations made long after cessation of drilling indicate. Underwater surveys of the Tanner Bank disposal site within 10 days of the last discharge (Ecomar, Inc. 1978; Meek and Ray 1980) showed no visible evidence of mud or cuttings accumulation after discharge over 800,000 kg of solids in 85 days. Calculations for potential sediment transport baaed on measured currents and waves indicate that up to 6,000,000 kg of solids could have been transported away from within a 59-m radius of the discharge over the 85-day study period (Meek and Ray 1980).

Size analysis of postdrilling bottom samples at Tanner Bank showed little physical alteration to the seafloor sediments. Trace metal analysis of benthic samples, however, suggests some accumulation from the discharges. Predrilling sediment levels ranged from 8.7 to 156.0 mg/kg (ppm dry weight) for barium, less than 7.0 mg/kg (ppm) for chromium, and from 0.3 to 1.8 mg/kg (ppm) for lead. Postdrilling sediment levels ranged from 173 to 1,680 mg/kg (ppm) for barium, >0.5 to 6.1 mg/kg (ppm) for chromium, and from 0.7 to 9.9 mg/kg (ppm) for lead. It is interesting to note that trace metal levels for sediment trap samples were considerably higher. Barium levels in the sediment traps ranged from 980 to 57,000 mg/kg, chromium varied from 23 to 2,800 mg/kg, and lead ranged from 1 to 3,230 mg/kg. 'The differences observed between the sediment trap (as presented in Section 2.2.1.2) and bottom samples suggest rapid reworking and/or transport of the drilling effluent solids after initial deposition.

Vertical entrainment of cuttings into the seafloor was examined as part of the lower Cook Inlet study (Dames & Moore 1978a, Houghton et al. 1980a). Postdrilling bottom cores were sectioned and screened through a 0.85-mm screen; the portion of the sample greater than 0.85 mm was examined on a grain--by-grain basis for the presence of cuttings. Samples obtained 100, 200, and 400 m from the discharge showed an average cuttings accumulation rate of 30, 10, and 1 gm/m^2 per day, respectively. Mean cutting sizes (for cuttings >0.85 mm) were 3.8, 2.3, and 1.3 mm for the 100-, 200-, and 400-m samples, respectively. Vertical entrainment of cuttings into the bottom sediments was measured to depths of at least 12 cm with largest concentrations occurring at depths of 1 to 7 cm.

Trace metal analysis of these postdischarge bottom samples in the lower Cook Inlet study showed barium levels to be roughly the same as the background levels. Predischarge samples had barium levels ranging from 560 to 660 mg/kg (dry weight) as opposed to values of 640 to 680 mg/kg measured in the postdrilling sampling. As with the Tanner Bank study, a higher barium concentration (760 mg/kg) was measured in the sediment trap.

Tillery and Thomas (1980) found decreasing concentration gradients of barium, cadmium, chromium, copper, lead, and zinc in surficial sediments with increasing distances from some production platforms in the Gulf of Mexico. However, pollutant from the Mississippi River and other nearby platforms tended to mask results. The authors' combination of data from all four compass directions at a given distance from the rig may also have diluted measured impacts if actual effects were focused in a single direction from the rigs by prevailing currents.

Results of monitoring drilling fluid discharges at the C.O.S.T. well Atlantic G-1 in 48 m of water on Georges Bank confirm that drilling mud and associated metals rapidly disperse in shallow water (ENDEco 1976). At roughly the midpoint of the drilling operation weak acid leachable concentrations of barium under the rig ranged from 3.2 to 6.4 mg/kg but were at background level (0.6 mg/kg) within 183 m in the direction of major flow and 91 m in the direction of minor flow. This area (52,547 m^2) is only 0.2 percent of the area assumed under the worst case model discussed above. Chromium sediment concentrations were at background levels within an area of 39,338 m^2. Toward the end of the drilling operation barium levels had dropped and chromium could not be detected as above background levels.

Results of the mid-Atlantic study (Mariani et al. 1980; Ayers et al. 1980a) suggest the possibility of both physical and chemical modifications in the bottom sediments from drilling effluent discharges at much greater distances from the well than reported in any other study. As part of this study pre- and postdrilling bottom samples were analyzed for trace metals (Section 2.3.4), extractable hydrocarbons (oil and grease), and physical properties (grain size analysis and x-ray diffraction) . Drilling discharges caused some localized changes in the grain size distribution and clay mineralogy of the surface sediments as well as changes in the trace metal content of the sediments and benthic organisms. These effects were apparently contained within a 3.2-km (2-mi) radius of the well site.

Much of the apparent increased area of influence can be attributed to the increased dispersion afforded by greater water depth (120 m). However, lower currents and increased water depth would also have resulted in a lower rate of transport of muds and associated metals following initial deposition. This latter effect may be evidenced from the increased percentage of fine particulate (clays) detected as far as 730 m from the well. Mariani et al. (1980) showed no significant increase in clay concentration at their next most distant station (1,600 m); thus, the maximum distance at which clay concentration was elevated could have been anywhere between 730 and 1,600 m from the well. Moreover, these samples were taken using a 15-cm core. Thus, potential changes in the top few centimeters of sediment would be diluted by mixing with deeper sediments where no change would be expected so soon (about 2 weeks) following the completion of the drilling. Based on contours of above-ambient clay concentrations in the sediments presented by Mariani et al., an area of about 500,000 m^2 was affected. The mean percentages of illite, chlorite and kaolinite increased while that of montmorillonite decreased. Increases in the concentrations of lead, barium, nickel, vanadium, and zinc in bottom sediments were detected during the post-drilling survey. Based on the concentrations of nickel and vanadium in drilling discharges, it was unlikely that these increases resulted from the discharges alone (Ayers et al. 1980a). Elevated barium concentrations were not observed in a regular pattern around the rig: but significantly elevated concentrations were evident out to 1,600 m from the well (Mariani et al. 1980). Elevated zinc concentrations were evident as much as 3,200 m from the well; lead concentrations could also have been elevated this far from the well. Sediment concentrations of chromium, the second most abundant metal in the drilling mud, were not elevated over those in the predrilling survey (R. Ayers, Exxon Production Research Company, personal communication). Oil and grease analysis of sediment samples collected during the postdrilling survey showed that concentrations remained below 0.1 percent extractable oil and grease on a dry weight basis (Mariani et al. 1980). Average concentrations of oil and grease for samples collected during the predrilling survey ranged from 0.01 to 0.05 percent, whereas those for the postdrilling survey ranged from 0.02 to 0.07 percent.

Since there was no clear pattern of decreasing metals concentration with distance from the well and since synoptic control stations located beyond the possible influence of the discharges from this and other recent wells in the vicinity were not sampled, two alternative conclusions are possible. First, the influence of discharged drilling fluids could have extended 3,200 m or more from the well. Or secondly, there could have been a general increase in sediment metals concentrations throughout the region that, occurred independently of the drilling operation (the apparent conclusion reached by Mariani et al. [1980]), Because of recognized inadequacies in the methods used for some metals analyses, archived sediment samples *from* the pre- and postdrilling surveys are being reanalyzed using neutron activation (barium, chromium, vanadium) and strong acid digestion (mercury).

2.3 LABORATORY TOXICITY AND SUBLETHAL EFFECTS STUDIES

Scientific testing of the sensitivity of aquatic organisms to materials used in oil and gas drilling began as early as 1951 with the work of Daugherty (1951). Continuing through the early 1970s, investigators used 96-hr bioassay methods primarily with freshwater fish and both whole mud samples and specific mud components (Logan et al. 1973; Lawrence and Scherer 1974). Results of studies conducted prior to 1975 have been summarized by Land (1974). These early works established that materials comprising the major constituents of drilling fluids (barite and bentonite) were *of* relatively low acute toxicity. Minor constituents including bactericide, lubricants, and detergents used to achieve desired fluid performance (section 2.1) were shown to have considerably greater toxicities,

Information from these early acute toxicity studies served well in allowing comparisons of toxicities of various components in relation to each other and to other pollutant discharged into various receiving waters. More recent whole mud toxicity studies also permitted evaluation of actual mixtures that may be discharged into the environment. The observed effects from whole drilling fluids reflect all of the complex chemical and physical interactions of the mud components as well as changes in the mud system due to formation temperatures, pressures, and chemistry. Finally, such tests permit determination of the effects of short-term exposures to various dilutions of mud that can be used to postulate likely acute impacts of actual discharges on receiving water biota.

Prior to 1975 little research had been reported on acute bioassays using marine species, on longer-term tests of sublethal effects (on growth, behavior, reproduction, etc.) *or* on possible uptake and biomagnification of mud components through natural ecosystems. Also lacking was quantitative information on the effects of discharged mud and cuttings on benthic communities.

This section discusses the development of the current data base regarding these important topics. Emphasis is placed on species from, and, studies conducted in, north temperate and sub-Arctic environments which form the basis for impact evaluations on Georges Bank and in lower Cook Inlet.

A variety of laboratory bioassays have been used to assess the acute and sublethal toxicity of drilling fluids. Bioassays are a quick, cost-effective tool to evaluate potential effects of complex physical-chemical characteristics of drilling fluid in fresh water or seawater. However, bioassays cannot be considered as precise predictors of environmental effects. They must be regarded as quantitative estimators of those effects, making interpretation somewhat subjective. The significance of this response to organisms involved is clear, but the state of ecological understanding is such that it remains impossible to predict the ecological consequences of the death of a given percent of the local population of a particular species (USEPA/COE 1977).

Biological effects are a function of the biologically available contaminant concentration and exposure time of the organism. Investigators studying drilling fluids have utilized a number of different test designs, many different types of drilling fluids, and a wide variety of warm-water and cold-water organisms. Comparison of results from even simple acute tests with drilling fluids is extremely difficult because of these parameters and their interactions.

The most variable factors in the literature review of experiments with drilling fluids are the unique, individual characteristics of a drilling fluid within its own general characterization and the methods used to evaluate various fractions of drilling fluids. For comparative purposes this review has identified five different fractions of drilling fluids utilized by investigators. Classification is based on a system initially employed by Neff et al. (1980). These methods are designated in the text and tables as:

1. Layered Solid Phase (LSP). A known volume of drilling fluid is layered over the bottom or added to seawater. Although little or no mixing of the slurry occurs during the test, the water column contains very fine particulate fractions which do not settle out of solution;

2. Suspended Solids Phase (SSP). Known volumes of drilling fluids are added to seawater and the mixture is kept in suspension by aeration or other mechanical means,

3. Suspended Particulate Phase (SPP). One part by volume of drilling fluid is added to nine parts seawater. The drilling fluid-seawater slurry is well mixed and the suspension is allowed to settle for 4 hr before the supernatant (100 percent SPP derived from 10 percent whole mud) is siphoned off for immediate use in bioassays;

4* Mud Aqueous Fraction (MAF). One part by volume of drilling fluid is added to nine parts seawater. The mixture is stirred thoroughly and then allowed to settle for 20 hr. The resulting supernatant (100 percent MAF derived from 10 percent whole mud) is siphoned off and is used immediately in the bioassays. The MAF is similar to the SPP except that longer settling times of MAF allow for a lower concentration of particulate; and

5. Filtered Mud Aqueous Fraction (FMAF). The mud aqueous fraction (MAF) or whole drilling fluid is centrifuged and/or passed through a 0.45-μ filter eliminating all particulates greater than this size.

The LSP and SSP preparations represent the worst-case exposure regimes. The LSP is composed of a layer of dense, settled mud solids on the bottom of the test container and an aqueous phase containing the soluble and finer low-density particulate fractions of the drilling fluid. The SSP mixture provides a greater exposure of suspended paticles in the water column. The test organisms in tests with SSP experience stress both from physical effects of the suspended particulate in solution and potential chemical effects from adsorbed toxicants on particulate and in solution.

In actual field situations one can expect a rapid and reasonably thorough fragmentation of the whole drilling effluent by sedimentation of coarser and heavier particles (Section 2.2). Therefore, several investigators conducted experiments with the soluble fraction or solutions containing particles with diameters of less than 1 μ .

The SSP and MAF preparations lack the dense barite and clay flocculants but do contain high concentration of finer particulate and some of the water soluble components of the drilling fluid. The MAF contains more of the water soluble components than SPP plus only the finest low-density particulate which do not settle out in 20 hours. The FMAF contains only the water soluble fraction of drilling fluids. The ratio of drilling fluid and seawater used in creating the 100-percent stock solutions of SPP, MAF, and FMAF is usually 1:9 giving a 10-percent solution of drilling fluid by volume.

Individual studies of drilling fluids are discussed below. More detailed results of bioassays, test species, and conditions are summarized in Appendix C, Tables C-1 through C--3.

2.3.1 Acute Toxicity Studies

Acute bioassay results have been expressed in different ways by different investigators. The most commonly used value is the LC_{50}-- that concentration lethal to 50 percent of test organisms within the specified test period (usually 96 hr). The concentration at which 50 percent of test organisms exhibit a particular sublethal response is termed the EC_{50}. Table 2-9 describes a simple classification of toxicity and compares the units used to express bioassay results.

TABLE 2-9

CLASSIFICATION OF TOXICITY GRADES AND COMPARISON OF UNITS

Toxicant Classification	LC_{50} Value (mg/liter)	(ppm)	(% by volume)
Practically nontoxic	>10,000	>10,000	>1.0
Slightly toxic	1,000-10,000	1,000-10,000	0.1-1.0
Moderately toxic	100-1,000	?00-1,000	0.01-0.1
Toxic	1-1oo	1-1oo	0.0001-0.01
Very toxic	<1	<1	<0.0001

(a) Source: Sprague (1973) and a joint IMCO/FAO, UNESCO, WMO group of experts on the scientific aspects of marine pollution (1969).

2.3.1.1 Whole Mud Tests

The toxicity of several used, high-density, lignosulfonate drilling fluids from a single exploratory well was determined for lower Cook Inlet fish, crustaceans, and molluscs (Houghton et al. 1980b). Pink salmon fry (Oncorhynchus gorbuscha) were the most sensitive organism tests; 96-hr LC_{50} values ranged from 0.3 percent for well-stirred mixtures (SSP) to 2.9 percent for a minimally-stirred mixture (LSP). Crustaceans including shrimp (Pandalus hypsinotus), mysids (Neomysis integer), amphipods (Eogammarus confervicolus) and isopods (Gnorimosphaeroma oregonensis) were generally more tolerant to higher concentrations of drilling fluid than salmon fry but crustaceans and salmon were nearly equally sensitive to the physical effects of suspended particulate. Ninety-six-hour LC_{50} values for all crustacean experiments ranged from 3.2 percent to >20 percent (32,000 to 200,000 ppm) drilling fluid by volume,

Experiments designed to compare well-mixed (SSP) and minimally-mixed (LSP) solutions of the same drilling fluid had LC_{50} values some 3 to 9 times greater in unstirred solutions which had 1/10 to 1/100 the suspended particulate load. It was concluded that suspended particulate were important contributors to the total observed mortalities but that soluble fractions of the drilling fluids were also contributory factors.

Carls and Rice (1981) exposed Stage I larvae (≤3 days old) of king crab (Paralithodes camtschatica), tanner crab (Chionoecetes bairdi), Dungeness crab (Cancer magister), coonstripe shrimp (Pandalus hypsinotus), dock shrimp (P. danae), and kelp shrimp (Eualus suckleyi) to a LSP and FMAF (prepared from 1:1 mud to seawater dilution) of new and used drilling fluids from Prudhoe Bay, Cook Inlet, and Homer, Alaska. The level of toxicity was dependent on the mud composition, species, and the type of test. The stability of larval response was best after 144 hr so all experiments were conducted over this interval of test time. Their work indicates that the LSP preparations containing some suspended particulate were more toxic to crustacean larvae than the MAF phase of preparations of the same drilling fluids. The 144-hr LC_{50} for the most toxic drilling fluid, a used Cook Inlet drilling fluid, to the species listed above ranged from 0.05 to 0.94 percent for layered/suspended drilling fluid and 0.6 to 6.7 percent for the water-soluble fraction (note that 100 percent MAF is derived from a 50 percent whole mud mixture) . The particulate fraction of the drilling fluids was calculated to be responsible for 80 percent of the observed toxicity and the water-soluble fraction accounted for the remaining 20 percent (based on relative toxicities of whole mud suspensions and water soluble fractions).

Carls and Rice (1981) determined that behavioral observations were a more sensitive indicator of the mud toxicity than mortality. The effective concentrations (EC_{50}) , as determined by the cessation of larval swimming, were measurable earlier than LC_{50}s and occurred at lower exposure concentrations (66 percent of the LC_{50} at 144 hr). variation between mud toxicities was greater than variations between species sensitivity. The 144-hr LC_{50} for FMAF for six new and used drilling fluids exposed to king crab and coonstripe shrimp larvae was 1.8 to 75 percent. Rates of response (changes in swimming behavior, onset of mortality) were slow compared to those elicited by many other pollutants. Carls and Rice concluded that drilling fluids are only slightly toxic to crustacean larvae, and no measurable impact on planktonic and nektonic communities would occur under most natural conditions involving dilution of the effluent.

Nalco Environmental Services (Johnson and LeGore 1976) conducted some acute, static bioassays with pink salmon fry, shrimp, copepods, and mysids exposed to whole drilling fluids and seawater extracts (SPP) of drilling fluids at a Union Oil exploratory oil well in upper Cook Inlet, Alaska. The drilling fluids tested were not toxic to the salmon or shrimp within 96 hr under the conditions tested with toxicant concentrations of ≤ 10 percent (100,000 ppm). Nominal mysid mortalities occurred within 48 hr at concentrations ≥ 7.5 percent. Some copepod mortalities occurred at lower concentrations within .48 hr, but the condition of the test organisms prior to the beginning of the experiment was questionable.

Drilling fluids containing paraformaldehyde at a concentration' of 1.0 lb/bbl drilling fluid were very toxic to copepods and mysids. However, the amount of paraformaldehyde added to the drilling fluid for these experiments was 4 to 10 times that normally used. No significant mysid mortalities were noted in experiments with SPP of drilling fluids containing 0.25 lb/bbl paraformaldehyde. Johnson and LeGore concluded that a 5.6 percent mud concentration is probably not hazardous to mysids and copepods within a 48-hr exposure.

Acute toxicity experiments with seven used drilling fluids and Arctic marine organisms were conducted by Thornberg et al. (1980) in Prudhoe Bay, Alaska. The results of static bioassays with layered solid phase (LSP) of drilling fluids indicated that test organisms varied widely in their responses to exposure to drilling fluids. The 96-hr LC_{50} 'values for isopods (Saduria entomon), snails (Natica clausa, Neptunea sp., and Buccinum sp.) and polychaetes (Melaenis loveni) ranged from 40 to 70 percent (400,000 to 700,000 ppm); mysids (Mysis sp.) <6 to

22 percent, amphipods (Onisimus sp. and Boeckosimus sp.), 22 to 38 percent, broad whitefish (Coregonus nasus), 6 to 37 percent, fourhorn sculpins (Myoxocephalus quadricornis) 4 to 3s percent, arctic cod (Boreogadus saida), 20 to 2S percent; and saffron cod (Eleginus navaga), 17 to 30 percent (170,000 to 300,000 ppm).

Some variations in the toxicity for specific species appeared to be attributable to variations in the drilling fluids used for the tests. For a specific well, the toxicity appeared to increase with increasing depth. These bioassays indicated that sedentary species were less sensitive to drilling fluids than pelagic organisms which have the capability for movement in and/or away from areas potentially affected during disposal (Tornberg et al. 1980).

The toxicity to salmon and saltwater-acclimated rainbow trout and four species of Arctic marine intertidal invertebrates of seven Arctic polymer drilling fluids was determined by the Division of Applied Biology of B.C. Research (1976). Five of the seven drilling fluid samples were toxic to salmonid fish at concentrations less than 4 percent (40,000 ppm) SSP. The most toxic drilling fluid, a weighted polymer, had a 96-hr LC_{50} value of 1.5 percent SSP; the least toxic drilling fluid, a weighted gel XC polymer, had a 96-hr LC_{50} value of 19 percent SSP. The drilling fluids with the greatest and least toxicity to fish also had the greatest and least toxicity, respectively, to clam worms (Nereis vexillosa), soft-shelled clams (Mya arenaria), purple shore crabs (Hemigrapsus nudus) and sand fleas (Orchestia traskiana).

Ninety-six-hour LC_{50}s for invertebrates ranged from 1.0 to greater than 56 percent (10,000 to 560,000 ppm) SSP. For most drilling fluids tested Hemigrapsis and Orchestia were more sensitive than Nereis or Mya. The weighted gel XC polymer drilling fluid was, however, more toxic to the clam Mya than to the other species.

The American Petroleum Institute provided five used drilling fluids to investigators for toxicity work with warm water organisms from the Gulf of Mexico and cold water marine organisms from the Gulf of Maine. A spud mud, density 9.2 lb/gal, a low-density lignosulfonate (LWLS) drilling fluid, density 10.0 lb/gal; a medium-density lignosulfonate (MWLS) drilling fluid density 12.7 lb/gal; a seawater chrome lignosulfonate (SWLS) drilling fluid, density 13.4 lb/gal; and a high-density lignosulfonate (HWLS) drilling fluid, density 17.4 lb/gal were tested. Tests were conducted using separate fractions of drilling fluids, particularly the mud aqueous fraction (MAF) and the suspended particulate fraction (SPP). Neff et al. (1980, 1981) and Carr et al. (1980) tested warm water bivalves, annelids, and crustaceans using all drilling fluids except the LWLA. Gerber et al. (1980) tested cold water organisms using all five muds. The used SWLS mud was the most intensively studied. Acute toxicity of the static MAF, measured as the 96-hr LC_{50}, ranged from 32 percent to >100 percent MAF. These MAF concentrations correspond to 3.2 percent to >10 percent (32,000 ppm to >100,000 ppm) whole drilling fluid.

The most sensitive organisms to the static MAF (media not changed during the 96-hr exposure) were 4-day-old grass shrimp (Palaemonetes pugio) and a marine worm (Dinophilus sp.) (Neff et al. 1981). If the MAF was changed daily during the 96-hr bioassay, its toxicity was about twice as high as the unchanged media tests. In experiments where media were changed, the 96-hr LC_{50} values for the adult marine worm Neanthes arenaceodentata and 1-day-old opossum shrimp (Mysidopsis almyra) were 10 percent MAF [10,000 ppm whole mud) (Neff et al 1981) and 27 percent MAF (27,000 ppm whole mud) (Neff et al. 1980), respectively. Neff (1980) suggests that some of the toxic components of the MAF are lost from the bioassay containers under static conditions, probably by volatilization.

Neff et al. (1980) noted a rapid decrease in the concentration of aromatic hydrocarbons with increasing exposure time in the static experiments. They concluded that this apparently volatile material, which may include both petroleum aromatics and UV-absorbing by-products of lignosulfonate and lignite, appears to contribute significantly to the acute toxicity of the MAF. Data from Neff et al. (1980) show that traces of oils were found in the SWLS drilling fluid, Gerber et al. (1980) measured 6,842 ppm in the same mud.

Few experiments with the MAF of SWLS drilling fluids were conducted by Gerber et al. (1980); however, the 96-hr acute toxicity for representative cold water marine crustaceans, bivalves, polychaetes, and fish was >100 percent MAF (100,000 ppm whole mud).

Generally the MAF of the MWLS drilling fluid was more toxic than the MAF of the other four drilling fluids tested. Postlarvae of the opossum shrimp were one of the most sensitive organisms tested (96-hr LC_{50} = 12.8 percent MAF, Neff et al. 1980). Stage I larvae of the shrimp Pandalus borealis were the only cold water marine organisms which were significantly affected by the same drilling fluid (96-hr LC_{50} = 17 percent MAF, Gerber et al. 1980). Separate chemical analyses of the MWLS mud by Neff et al. *(1980)* and Gerber et al. (1980) indicated that petroleum hydrocarbons were present in significant amounts. Neff et al. (1980) determined that oil was 2 percent by volume and Gerber et al. (1980) found 7,165 ppm (0.7 percent) petroleum hydrocarbons. Thus, petroleum hydrocarbons are probably responsible for the higher toxicity of the MAF of this fluid.

In most cases the MAFs of the used spud mud, the LWLS and HWLS fluids were nontoxic to all species tested from both warm and cold water marine environments. The exceptions include the first zoeae stage of the grass shrimp exposed to high-density drilling fluid (LC_{50} value <18 percent MAF [derived from 18,000 ppm whole mud], Neff et al. 1980) and Stage V larvae of the lobster (Homarus americanus, LC_{50} value <5 percent MAF, Gerber et al. 1980).

Experiments conducted with the FMAF of these lignosulfonate drilling fluids show that the toxicity level of FMAF was nearly the same as the MAF. This indicates that the majority of the toxicity *of* the MAF resides in the soluble components of the drilling fluid and not the fine particulate.

The suspended solids phase (SSP) of the used SWLS drilling fluid was toxic to juvenile brown shrimp (Penaeus aztecus) and postlarvae pink shrimp (P. duorarum). Shrimp exposed to a 10,000 ppm SSP (1.0 percent drilling fluid by volume) for 168 hr had mortalities of 60 percent and 29 percent for brown and pink shrimp, respectively. Neff et al. (1981) conclude that the *SSP* appears to be somewhat more toxic to young penaeid shrimp than the MAF. Physical abrasion of suspended particulate on the drilling fluid varied substantially (O to 95 percent survival) for five species of warm water marine invertebrates (Neff et al. 1981)* There were no surviving adult coquina clams (Donax variabilis) after 96-hr exposure. Other life stages *of* this species and other warm water marine species were more tolerant of the LSP.

Gerber et al. (1960) exposed a variety of cold water marine organisms to the LSP of the low-, medium-, and high-density lignosulfonate drilling fluids and spud mud. The 96-hr LC_{50} values varied from less than 3.2 ml/1 (or a l-mm layer of mud on natural sediment) MWLS for the adult sea scallop (Placopecten magellanicus) to >100 percent (pure mud substrate in container with clean seawater). Most organisms assayed were extremely tolerant (LC_{50} >50 percent) to LSP but notable exceptions were the sea scallop exposed to MWLS, adult lobsters (LC_{50} 29 percent), and male amphipods (LC_{50} 28 percent) exposed to HWLS LSP and adult lobsters (LC_{50} 19 to 25 percent) exposed to LWLS LSP.

Eighteen samples of whole used drilling mud, obtained at different depths from an exploratory well in Mobile Bay, Alabama, were exposed to grass shrimp (Palaemonetes pugio) and mysid (opossum) shrimp (Mysidopsis bahia) by Conklin et al. (1980). Three of the drilling fluids produced intermolt (Stage C) grass shrimp mortalities $\geq$30 percent in 96 hr at concentrations of 1,000 ppm (0.1 percent by volume). The most toxic mud (No. XVIII) produced 100 percent mortality at this concentration. Additional experiments with molting grass shrimp (Stages D_2-D_4) were conducted with the five most toxic drilling fluids and the resulting 96-hr LC_{50} values were in the range of 363 to 739 ppm (0.036 to 0.074 percent). Conklin et al. (1980) report that almost all of the mortalities were molt-related; no control shrimp died. A complete molt cycle for grass shrimp was followed by exposing the shrimp for 10 days to drilling fluid No. XVIII in a continuous flow dosing apparatus. At the highest test concentration (150 ppm) there was 10 percent mortality of molting shrimp. In mysid shrimp life cycle bioassays in which nominal concentrations of 10 to 150 ppm whole drilling mud No. XVIII were administered for 42 days in a flow-through system, an estimated 96-hr LC_{50} of 161 ppm was calculated. The toxicity increased with exposure time and at day 42 lethal concentration was estimated to be 50 ppm.

It is important to note that while these LC_{50} values tended to be two orders of magnitude lower than those reported elsewhere in the literature, the concentrations used in the continuous flow experiments were nominal concentrations. The actual test concentrations were unknown but the authors note that there was a gradual buildup of drilling fluids solids in the test tanks. Thus, exposure levels at which effects occurred were probably considerably greater than the nominal concentrations reported. Moreover, the drilling fluids responsible for this toxicity, while not characterized in terms of composition or chemical characteristics in the paper, were later identified as experimental drilling fluids and very atypical of those used in offshore areas (Neff 1980). Problems encountered during drilling to 23,000 feet (excessive downhole temperatures of 204°C, extensive anhydrite strata, and hydrogen sulfide gas) required a specialized mud system not intended for offshore disposal (M. Jones, IMCO, personal communication),. The components thought to be most hazardous were sodium chromate (Rubinstein et al. 19,80) diesel oil, bactericide, and sodium dichromate (J. Ray, Shell Oil Company, personal communication). Other potentially hazardous materials may also have been utilized to formulate a drilling fluid capable of handling these unusual conditions. Carney and Harris (1975) state that only 0.2 percent of all boreholes drilled in 1974 had temperatures greater than 177°C. The performance of many drilling fluid components is greatly reduced in the presence of high temperatures and other more toxic components must be substituted to maintain mud performance. The drilling fluid utilized in experiments by Conklin et al. (1980) and Rubinstein et al. (1980) were not intended for offshore disposal and were in fact disposed of onshore. The toxicity of these drilling fluids is thus not representative of drilling fluids which are utilized in most offshore drilling operations or are likely to be disposed of offshore. Information gained from this exploratory drilling operation in Mobile Bay, Alabama, has allowed modifications of that mud program to allow offshore disposal for future drilling in the area (M. Jones, IMCO, personal communication).

Seven species of scleractinian corals from the Florida keys were exposed to the SSP of a freshwater ferrochrome lignosulfonate drilling fluid by Thompson and Bright (1980). Montastrea annularis, Agaricia agaricites, and Acropora cervicornis were killed by a 96-hr exposure to 1,000 ppm (0.1 percent) drilling fluid (changed daily in the aquaria to prevent flocculation and settling in the test containers). Acropora cervicornis colonies survived this concentration in a replicate experiment, and the authors attributed this to a possible threshold concentration which was reached in the first experiment but not the second. All corals showed significant ($p < 0.05$) polyp retraction during exposure to 3?6 ppm and 4 of 7 coral species showed significant behavior modifications at 100 ppm. No tests were run to compare these responses to those that would result from similar applications of "inert" sediments, however. Polyps of Dichocoenia stokesii did not react adversely to any drilling fluid concentration tested (Thompson and Bright 1980).

2.3.1.2 Formation Waters

The biological effects of formation waters discharged from offshore or production oil wells have not been addressed in the open literature and are not treated in detail in this report.

Studies of the median toxicity thresholds for 10 species of freshwater fish in brine wastes from a single oil well showed 96-hr LC_{50} values ranging from 4.3 to 11.2 percent of the original brine by volume (Clemens and Jones 1954). Ten different invertebrates were also assayed and the median toxicity thresholds were found to vary between 1.8 to 8.7 percent by volume. The brine contained large amounts of calcium, magnesium, potassium, and sodium as well as chloride ions. Computations by Clemens 'and Jones of hypothetical combinations of chloride-s in the brine indicated sodium chloride to be present in such proportions as to be most toxic. Undoubtedly the brine also contained relatively high quantities of soluble hydrocarbons which have previously been discussed as being important contributions to toxicity.

This study of brine wastes in fresh water may have limited value for comparison with potential biological effects of formation water on marine organisms.

2.3.1.3 Oil Base Drilling Fluids

Oil base drilling fluids account for 5 to 10 percent of the total volume of all drilling fluids utilized in the industry but are used only in applications in which water base fluids do not perform adequately (McMordie 1980). The oil base drilling fluids are very expensive and as such are often reused in other operations. McMordie (1980) estimates the annual replacement volume at less than 40,000 m^3.

Drilling fluids containing oil have been prohibited for offshore disposal since OCS Order No. 7 was issued in August 1969 (prohibition later amended by the Clean Water Act of 1977). Therefore, laboratory studies on the toxicity of oil base drilling fluids have not been recently done.

Cabrera (1966) studied the effects of a diesel base drilling fluid and cuttings on the survival of oysters. He concluded that the survival of oysters was significantly reduced in concentrations over 200 ppm (0.02 percent). In concentrations between 200 and 500 ppm, 50 percent mortality was reached on the seventh day. Thus, oil base muds are substantially higher in toxicity than other water base muds.

2.3.1.4 Drilling Fluid Components

Most research prior to 1975 on drilling fluid toxicity was conducted using drilling fluid components on freshwater organisms. Information on the toxicity of individual pure drilling fluid components is considered of limited utility in evaluating or predicting the toxicity of whole, used drilling fluid discharges to the environments of Georges Bank and lower Cook Inlet, a fact substantiated by Sprague and Logan's ("1979) work on the separate and joint toxicity of drilling fluid components to rainbow trout. The chemical and toxicological properties of drilling fluid components change because the physical and chemical properties of the drilling fluid change during usage (McAuliffe and Palmer 1976).

Information on the toxicity of drilling fluid components is useful to determine which components are most toxic and which ones may contribute most to the toxicity of whole used drilling fluids (Neff 1980). This review evaluates mainly those marine studies dealing with the most toxic or controversial drilling fluid components. Discussion is primarily limited to recent literature. Bioassays in fresh water with freshwater animals cannot be extrapolated to the marine environment since the mechanisms of drilling fluid-mediated toxicity appear to be different in marine and freshwater systems (Neff 1980). An excellent summary of the toxicity of drilling fluid components to freshwater organisms can be found in Land (1974).

Barite, the common mineral form of barium sulfate, is the most extensively used material for increasing the density of drilling fluids. Barite, when exposed to various marine animals and to rainbow trout and sailfin monies in fresh water, has been found to be practically nontoxic (Daugherty 1951; Grantham and Sloan 1975; Beckett et al. 1976). Recently, however, ultrastructural studies on the midgut of shrimp exposed for a 30-day period to 100 or 500 ppm barite-containing media showed that prolonged ingestion of barite causes marked perturbations in the posterior midgut epitheliums of grass shrimp, Palaemonetes pugio (Conklin et al. 1980). These perturbations could be "manifested in the loss of appreciable quantities of mucous and exposure of the delicate microvilli surface to the perpetual abrasive action of ingested barite particles. Investigative studies by these same authors indicate that statocysts, the equilibrium receptors of grass shrimp, may at the time of molting accumluate any particulate material available including barite. The effect of this ingestion process on the physiology of these sense organs is not known.

The toxicities of barite and bentonite were examined by exposing northeastern Pacific shrimp and crab larvae to concentrations of 4 to 200 g/1 (4,000 to 200,000 ppm) barite and of 4 to 100 g/1 (4,000 to 100,000 ppm) bentonite (Carls and Rice 1981). The effective concentration (EC_{50}) which inhibited swimming abilities for Dungeness crab larvae (cancer magister) ranged from 77.6 to 85.6 g/1 (77,600 to 85,600 ppm) with bentonite and was 71.4 g/1 (71,400 ppm) with barite. Dock shrimp larvae (Pandalus danae) were more sensitive with bentonite EC_{50}s ranging from 13.8 to 34.6 g/1 (13,800 to 34,600 ppm) and barite EC_{50}s of 5.4 to 50.4 g/1 (5,400 to 50,400 ppm).

Carls and Rice (1981) compared these toxic concentrations with the concentrations of barite and bentonite in a lower Cook Inlet lignosulfonate drilling fluid. In the whole drilling fluid, bentonite was present at 1 to 3 percent of its toxic level; barite was present in 12 to 63 percent of its toxic level. When reported dilutions of whole mud from actual discharges (e.g. , Houghton et al. 1980a) are applied to the toxicity values of Carls and Rice (1981) the "zone of toxicity" extends only a few meters from the source.

Although ferrochrome and chrome lignosulfonates are known to undergo considerable physical/chemical changes during actual downhole usage in drilling fluids (McAtee and Smith 1969; Liss et al. 1980; Skelly and Dieball 1969), some recent efforts have been made to. evaluate the toxicity of pure lignosulfonate to marine organisms. Carls and Rice (1981) exposed dock shrimp and dungeness crab larvae to ferrochrome lignosulfonate and found 144 hr LC_{50}s of 0.12 g/1 (120 ppm) and 0.21 g/1 (210 ppm), respectively. Chrome lignosulfonate concentrations in drilling fluids range from 3,000 to 60,000 ppm. However, comparison of amounts of lignosulfonate found to be toxic to crustacean larvae and the amounts found in drilling fluids are not strictly valid because of the changes which occur in lignosulfonate contained in drilling fluids during use.

2.3.2 Sublethal (Chronic) Effects

Sublethal indicators of stress in organisms following exposure to various fractions of drilling fluids have been studied by several investigators. Gerber et al. (1980) assayed organisms which survived the acute toxicity tests for the levels of the energy metabolism enzymes, glucose-6-phosphate dehydrogenase (G6PdH) and aspartate aminotransferase (AAT). This assay procedure has previously been used extensively by researchers at NMFS (Calabrese et al. 1975; Gould et al. 1976; MacInnes et al. 1977, Dawson et al. 1977) to determine sublethal effects of heavy metals. The enzyme activities of several invertebrates exposed to MAF or whole mud preparations were significantly different from control organisms. However, levels of G6PdH and AAT in some species increased relative to the controls while the same enzymes in other species decreased relative to controls. The investigators believe that these enzymes are useful as indicators of sublethal stress but they also indicate that enzyme systems in invertebrates are not well understood and thus definite cause and effect relationships are difficult to define.

Energy flux measurements such as filtration, respiration, and excretion have been used as chronic stress indicators in mussels (Widdows and Bayne 1971, Bayne et al. 1977; Gilfillan and Vandermeulin 1978). Gerber et al. (1980} attempted to apply this method on mussels exposed to MAF of drilling fluids for 96 hr. They concluded that except for the use of respiration rates, this approach was probably not a good indicator of sublethal stress induced by short-term exposures. Respiration rates in control mussels were significantly different from treatment mussels exposed to 33 to 100 percent MAF (33 to 10 percent drilling fluid by volume).

The secretion of byssus threads in mussels was used as another indicator of sublethal stress. Mussels (<u>Modiolus modiolus</u>) exposed to a 3 percent LSP HWLS drilling fluid for 14 days secreted few byssus threads and exhibited a reduction in pumping rate while mussels exposed to a 1 percent fraction displayed near normal behavior and by the end of 1 week had secreted numerous byssus threads (Houghton et al. 1980b).

Long-term effects of sublethal stress were demonstrated by reduced growth rates in mussels exposed to 50,000 ppm suspended mud for 30 days (Gerber et al. 1980). The growth rate of mussels for the control and exposed group was similar for days 1 to 10, but growth rate decreased in treated mussels for the remainder of the exposure. At the conclusion of the experiment the mean size of the exposed mussels was significantly smaller ($p < 0.05$) than the controls.

Derby and Atema (1980) Investigated the sublethal influence of Mobile Bay drilling muds on the primary chemosensory neurons in walking legs of the lobster, <u>Homarus americanus</u>. Effects of whole drilling fluids were examined using extracellular neurophysiological recording techniques. Exposure of legs for 3 to 5 min to 10 mg/l drilling fluid suspended in seawater altered responses to food odors of 30 percent of the chemoreceptors examined; similar exposure to 100 mg/l drilling mud resulted in interference with 44 percent of all receptors studied. The investigators concluded that although behavioral assays have demonstrated that feeding behavior is altered following exposure to drilling fluids and petroleum fractions, there is no conclusive proof for a causal relationship between chemoreceptor interference and behavioral deficits.

Krone and Biggs (1980) exposed Madracis decactis corals to suspensions of 1,00 ppm drilling fluid enriched ("spiked") with 0, 3, or 10 ppm ferrochrome lignosulfonate for 17 days. Corals exposed to drilling fluid treatments had increased rates of respiration and excretion relative to control organisms for the first week and for days 10 to 13 of the experiment. Ammonium excretion was significantly greater ($F<0.10$) in FCLS-stressed corals than in uncontaminated corals but no significant difference was found in respiration rates. Respiration, excretion, and polyp activity returned to normal levels within 48 hr after corals were removed from the drilling fluid-contaminated environments. All corals exposed to FCLS reacted by reducing their degree of polyp expansion. However, FCLS added in excess to a drilling fluid is probably more biologically available than that normally present in and complexed with a used whole mud, making these results difficult. to apply to a "real world" situation.

A continuous flow, suspended sediment, dosing apparatus was used by Rubinstein et al. 1980 to expose mysids, oysters, polychaetes, and macrofauna to sublethal concentrations of drilling fluids. The drilling fluid used for these experiments was the same atypical Mobile Bay mud utilized by Conklin et al. (1980) (described in Section 2.3.1.1). These drilling fluids were known to be toxic and were not intended for offshore disposal (J. Ray, Shell oil Company, personal communication).

Three normal concentrations of drilling fluids (10 ppm, 30 ppm, and 100 ppm) were continuously infused into test aquaria. The results (Rubinstein et al. 1980) indicate that 2- to 4-day old mysids Mysidopsis bahia were not actually affected at any concentration; maximum mysid mortality of 17 percent occurred at 30 and 100 ppm nominal concentration after 10 days exposure. Lugworms (Arenicola cristata) were severely affected by the same concentrations: 75 percent mortality at 100 ppm, 64 percent mortality at 30 ppm, and 33 percent mortality at 10 ppm. The time duration of exposure was not indicated. Oyster shell growth was significantly inhibited ($p <0.01$) at concentrations of 30 and 100 ppm. Difference in the rates. of shell deposition between treatments became more pronounced with time. Rubinstein et al. (1980) suggest that this reduced shell growth may result from a possible accumulation of metabolize or xenobiotic or from corresponding differences in turbidity in test aquaria.

These studies used a continuous flow of suspended drilling fluid particulate at nominal concentrations of 10, 30, and 100 ppm. However, a gradual buildup of drilling fluids was reported in test aquaria (Rubinstein et al. 1980). Accumulation of about 12 mm (0.5 in) of drilling mud solids was present in the bottom of the test chamber receiving the 100 ppm continuous inflow at the end of the test. Therefore, the final concentrations of drilling fluids were undoubtedly much higher than the initial nominal values. The reported exposure levels were the minimum initial drilling fluid concentrations to which the organisms were exposed and the concentrations of drilling fluids at which the above-mentioned effects occurred are unknown but much higher than the nominal values.

2.3.2.1 Colonization Studies

The effects of drilling fluid on development of estuarine macrobenthic communities were assessed by comparing number and species of animals settling from planktonic larvae and growing in uncontaminated and drilling-mud contaminated aquaria (Tagatz et al. 1978). A continuous flow of unfiltered ambient seawater entered aquaria containing sand only, 1 part mud and 10 parts sand, 1 part mud 5 parts sand, or sand covered by 0.2 cm mud. After 8 weeks exposure sediments were sieved, and collected organisms were identified.

The numerically dominant phyla were Annelida, Mollusca, Arthropoda, and Coelenterata. The abundance of animals was affected by the drilling fluid with total numbers of animals significantly less ($\alpha=0.05$) in treated aquaria. The numbers of species were significantly different ($\alpha=0.05$) from controls in aquaria containing a layer of drilling fluid over sand. Annelids and coelenterates were most seriously affected in all treatments. Arthropods, particularly Corophium, were significantly affected by the layer of drilling fluid but not by other treatments. The number of molluscs was reduced in aquaria with mud cover but not significantly so. Tagatz et al. (1978) concluded that drilling fluids do adversely affect benthic colonization by planktonic larvae. Furthermore, concentrations of drilling fluids in disposal sites similar to the concentrations of these experiments could upset the benthic community stability by reducing recruitment of organisms and altering the food webs.

Tagatz and Tobia (1978), in another investigation of similar design, evaluated the impact of barite on the development of estuarine communities. The effects of barite on populations of settling planktonic larvae were similar to those found for drilling fluids. Annelids, particularly Armandia sp., were most affected by barite and by drilling fluids . A 5-mm cover of barite affected colonization more than did mixtures of barite and sand. The abundance of molluscs was reduced by a pure layer of barite while other treatments (barite-sand mixtures) had little effect. Numbers of coelenterates were fewer in all treatments with barite than controls, whereas a decreased abundance of the arthropod Corophium acherusicum occurred only in the barite-layered test.

Cantelmo et al. (1979) exposed planktonic meiofauna to various concentrations of barite, both layered and mixed in sand. Trends noted in this study were similar to those of Tagatz et al. (1978, 1980), and Tagatz and Tobia (1978). Specifically, a marked decrease in meiofaunal density was evident in aquaria which had sand under a layer of barite. In contrast to the other studies, meiofaunal densities in aquaria containing 1:10 or 1:3 mixtures of barite and sand were greater than in the control aquaria containing only sand.

Biocides, minor constituents in drilling fluids, were assayed in yet another series of experiments with the colonization of planktonic larvae. Metered concentrations of Aldacide[R] (a paraformaldehyde-type biocide) and three chlorophenol-type biocides (pentachlorophenol [PCP], Dowicide^R G-ST, and Surflo^R B-33 were added to seawater which flowed continuously through aquaria containing sand.

Aldicide^R and Surflo^R B-33 were tested simultaneously for 7 weeks. The results indicate that numbers of animals exposed to 41 and 810 ppb Surflo^R B-33 were significantly reduced, but no reduction occurred in aquaria with Aldacide^R at concentrations of 15 and 300 ppb. Species abundance was not affected by Aldacide^R but Surflo^R at $19 ppm did significantly reduce species diversity.

Pentachlorophenol (7-622 ppb) and Dowicide^R G-ST (2-183 ppb of NaPCP and other chlorophenols, active ingredients) also reduced the numbers of animals. Molluscs were particularly affected at 7 g/PCP/l and 18 g/l of the active ingredient of Dowicide^R G-ST. Numbers of annelids were significantly reduced at 76 g PCP/l and 183 g/l Dowicide^R. The highest concentration of Dowicide^R also decreased numbers of arthropods. For the biocides tested, Aldacide^R and paraformaldehyde were least harmful to colonizing macrofauna. Surflo^R B-33 and Dowicide^R G-ST (chlorophenols) were considerably more toxic to more organisms. Note that pentachlorophenols are no longer permitted in drilling muds discharged offshore.

2.3.3 Discussion of Laboratory Studies

A bioassay may be defined as a test in which the quantity or strength of material is determined by the reaction of a living organism to it (Sprague 1973). The methods used to identify toxic effects may encompass several different overlapping categories. Methods employed by investigators reviewed in Sections 2.3.1 and 2.3.2 included static or continuous flow acute toxicity experiments conducted for 48 to 144 hr and sublethal or chronic experiments measuring growth, swimming performance, behavior, or reproductive success over periods of up to 42 days.

The experimental techniques utilized in the study of drilling fluids included separation of various physical phases in an attempt to identify where the most toxic fractions of the fluids reside. Physical fractions identified as the layered solids phase, suspended solids phase, suspended particulate phase, mud aqueous fraction, and the filtered mud aqueous fraction were evaluated. Generally, the chemical toxicity of the drilling fluid as measured by the toxic effect of the soluble components [filtered mud aqueous phase) was found to vary with the organism and drilling fluid tested. In most cases the toxicity increased when suspended particulate fractions were present. The most conservative estimate of toxicity can probably be best determined by exposing the test organisms to whole drilling fluids kept in suspension. However, undue agitation throughout a test will maintain particles in suspension that would settle out in most environments, thus creating an unrealistic exposure situation; e.g., to mechanical or abrasive effects.

There is some evidence that the toxicity of the drilling fluids increases with the length of exposure. Since acute lethal action may continue beyond 4 days, it would be desirable to employ longer-term tests in order to determine threshold levels. However, longer-term exposures may be unrealistic in terms of actual exposures achievable under natural conditions except in the case of mud impacts on benthos.

Sublethal effects of drilling fluids have been investigated by measuring various physiological parameters in mud-exposed organisms. In some cases where effects have been demonstrated, the significance of the findings is difficult to evaluate in terms of real world effects on organism or population fitness. The measurement of enzyme activities and chemoreceptors is an avenue of research which should be extended but a greater understanding of enzyme kinetics and responses to drilling fluids is needed before meaningful interpretations can be made. Information obtained from micro- and macrofaunal colonization studies together with growth information on organisms in higher trophic levels could provide a valuable baseline of data to make predictions of sublethal environmental effects.

Considerable controversy exists about the application of continuous flow bioassay techniques in drilling fluid research. A well done, continuous flow bioassay has some clear advantages over static bioassays in many toxicant studies. However, drilling fluids are dense mixtures with many components that coagulate or settle out and do not work satisfactorily in a continous flow device. Investigators conducting experiments which have evaluated drilling fluids using continuous flow systems have had no capability to measure the actual exposure concentrations since there is a buildup of drilling fluids in the test containers. Continuous flow bioassays may be a valuable tool to evaluate soluble phases of drilling fluids, but large volumes of soluble mixtures of drilling fluids and seawater would be difficult to obtain. In most drilling fluid research, a static test, with dilutions of known accuracy, is superior to a continuous flow test of uncertain actual concentrations. The toxicity data accumulated for drilling fluids also indicates that measured toxicity increases with daily changes of the media in test containers. This suggests that a volatile component of some muds is lost during exposure to air.

Colonization experiments conducted with a layer of drilling fluids on the bottom of the test container with fresh seawater continuously flowing through the system may be the best application of a flow through system in drilling fluid research. Although exposure concentrations other than nominal concentrations cannot be measured, there is some valid comparison with real world situations. For added realism, whole drilling fluids could be dumped through a water column and only those materials settling out in a specified time period used in the tests to simulate drilling fluid components lost in the upper plume. As the experiment proceeds, the drilling fluid concentration decreases, mimicking the resuspension and transport of drilling fluids from disposal areas. Data on levels of trace metals and petroleum hydrocarbons in various drilling fluid-sediment mixtures should be determined to aid in evaluating possible effects in the environment.

Bioassays have been conducted on both drilling fluid components and whole drilling fluids. Most components when tested individually have been shown to be more toxic to marine organisms than when several components homogeneously mixed in drilling fluids have been assayed using similar animals. The toxicities of components change when mixed together and with temperature and pressure changes during down-hole use. This is due to neutralization reactions between components and adsorption of soluble components on clay particles present in the drilling fluid (Ayers 1980).

Research on the toxicity of components has been useful in establishing the relative toxicities of those components used in drilling fluids. moderately toxic to practically nontoxic. Chlorinated phenol-type biocides have been banned from the outer continental shelf (Federal Register, Vol. 44, No. 129, July 3, 1979).

Very few studies have measured hydrocarbons as a potential toxic component in drilling fluids. In experiments conducted by Neff et al. (1980, 1981) and Gerber et al. (1980) there was evidence that the more toxic, medium-density, lignosulfonate drilling fluids and seawater, chrome, lignosulfonate drilling fluids contained hydrocarbon, probably diesel oil.

Hydrocarbons may be added purposely to water base drilling fluids to increase drilling rate and improve hole stability (Section 2.1.5). The addition of hydrocarbons to 'form water base emulsion drilling fluids improves lubrication of the drill bit teeth and bearings, and drill pipe and drill collars inside the casing. The concentrations of lubricants used will obviously vary with the problem; however, normal use rates are approximately 0.2 to 6.0 lb/bbl (PESA 1980).

The toxicity of hydrocarbons to aquatic organisms is well known and has been reported in a vast literature. Larval crustaceans, identified in this review as the group of marine organisms most sensitive to drilling fluids, are extremely sensitive to hydrocarbons. Rice et al. (1981) determined EC_{50} values for four species of crab and shrimp larvae to range from 0.8 ppm to 2.1 ppm. This range is approximately 3 to 5 orders of magnitude below the toxicity of the FMAF of drilling fluids for the same species (Carls and Rice 1981).

Thus, it is recommended that hydrocrabons be monitored in drilling fluid fractions used in bioassays. Neff and Anderson (1995) have developed a method for measuring hexane-extractable aromatic hydrocarbons (as total naphthalenes) in the mud aqueous fractions of drilling fluids. This technique is not specific for petroleum-derived aromatics but also measures nonpolar, W-absorbing aromatics such as byproducts of lignosulfonates and other organic materials in the drilling fluid.

Most investigators of the effects of drilling fluids to marine organisms evaluated low-, medium-, or high-density lignosulfonate freshwater- or seawater-based drilling fluids. Ninety-five percent of all drilling fluids used in offshore drilling are of this type (Ayers et al. 1980a). Other identified drilling fluids were characterized as polymer drilling fluids and many others were not identified at all. Comparisons of results from even simple acute static tests with drilling fluids are extremely difficult to make because there is often insufficient information available to adequately characterize the drilling fluid.

In addition to the basic composition of the drilling fluid, the point in time when the drilling fluid was collected from a particular well is important. The chemical and physical properties of the drilling fluid are altered by high temperatures and pressures as the well-hole becomes deeper. In general the toxicities of drilling fluids to marine organisms have been found to increase with the depth of the well because of the material added to achieve desired properties.

Variations in drilling fluid characteristics and variations in response to drilling fluids are difficult to evaluate between organisms of the same species and between species of many phylogenetic groups. Test organisms representing various lift stages from Cook Inlet, the North Atlantic, the Beaufort Sea, and the Gulf of Mexico have been used in bioassays. It can be concluded that drilling fluids were most toxic to crustacean larvae, particularly molting crustacean larvae (see Table 2-10). The level of toxicity was dependent upon the mud composition, species, and the type of bioassay. For most drilling fluids tested crustacean larvae are approximately an order of magnitude more sensitive than are fish or adult crustaceans. In general, whole mud 96-hr LC_{50}s for adult marine organisms are in the parts per thousand or parts per hundred (percent) by volume range (Table 2-10 and Appendix C).

The major findings of this literature review of laboratory assays are:

1. Laboratory toxicity studies are important indicators in assessing the impact of drilling discharges, but they alone cannot be used to predict environmental impact. The concentrations of drilling fluids found to be toxic to most marine organisms after an exposure time of 96 hr in laboratory tests far exceed drilling fluid concentrations and exposure times likely to be experienced by organisms in most environments.

2. Most used drilling fluids typical of those used in offshore exploration for oil and gas are not likely to cause acute damage to marine organisms. Ninety-six hour LC_{50} values range frOm 400 ppm mud added (moderately toxic) to >700,000 ppm (practically nontoxic). The most toxic drilling fluid" evaluated to date had a 42-day, LC_{50} value for opossum shrimp of 50 ppm whole mud. It is estimated that dilution ratios of 100:1 for most drilling fluids and 20,000:1 for the most toxic drilling fluid evaluated would reduce the concentrations in the receiving water below acutely toxic levels.

3* Sensitivity of organisms to drilling fluids varies significantly between life stages of organisms of the same species and between phylogenetic groups. The most sensitive group of organisms comprises molting larvae of crustaceans and is 10 to 100 times more sensitive than fish. The 96-hr LC_{50} values for any species generally do not vary over 1 to 2 orders of magnitude using a variety of drilling muds.

4. In most drilling fluid research, a static test, with dilutions of known accuracy, is superior to a continuous flow test.

TABLE 2-10

DRILLING FLUID TOXICITY AS A FUNCTION OF PHYLOGENY AND DRILLING FLUID FRACTIONS (FRESHWATER BASE MUDS)

Taxon	Organism/ Life Stage	96-hr LC_{50} Values[a]
Mollusca	Snails	
	adult	70-100% LSP, >10% MAF
	Clams	
	adults	49-1000 LSP, 8.6 to >10% MAF
	juveniles	>10% MAF
	Mussels	
	adults	>100 MAF
	Scallop	
	adults	0.32% LSP
Annelida	Polychaetes	
	adults	49 to >700 LSP, 2.3 to 56% SSP, 1.0 to >100 MAF, 4.5 to >100 FMAF
	juveniles	9.6% MAF, >100 FMAF
Arthropoda	Isopods	
	adults	53 to >60% LSP, >70 SSP, >10% MAF
	Amphipods	
	adults	22.1 to >100% LSP, >7% SSP
	Mysids	
	adults	<6 to 21.50 LSP, 3.4 to >56% SSP
	molting	0.16% SSP
	Lobster	
	adult	1.9 to 2.5$ MAF
	Stage V	0.5% MAF
	Shrimp	
	adult	3.2 to 71% LSP, >1.5% SSP, 9.0 to >100 MAF
	juvenile	3.2% SPP, 1.3 to 11.3% MAF
	larvae	0.05 to 0.44% LSP, 1.2 to 1.3% SPP, 1.7 to >100 MAF, 0.15 to 5.50 FMAF (144 hr)
	molting larvae	0.04 to 0.07% LSP
	Crabs	
	adult	89% LSP, 5.3 to >100% SSP, >100 MAF
	larvae	0.20 to 0.94% LSP, 0.07 to 1.670 FMAF (144 hr)
Chordata	Fish	
	fry	2.9% LSP, 0.3 to 1.9% SSP
	juvenile	5 to 40% LSP, 1.5 to >250 SSP, >10% MAF

(a) 96-hr LC_{50}s expressed as percent of whole drilling fluid added to seawater.

5. Sublethal bioassays using low concentrations of drilling fluids which are carefully monitored in test containers are valuable tools in predicting chronic effects of drilling fluids, but interactions between organisms and their biotic and abiotic environments are often ignored or difficult to evaluate.

6. Sublethal (chronic) bioassays have shown reduced growth rates of mussels and oysters exposed to drilling fluids at test concentrations generally higher than those that would occur in the open environment. The significance of these results is difficult to evaluate in terms of potentially intermittent discharges of drilling fluids to the environment. Drilling fluids have been found to adversely affect the development of estuarine macrobenthic communities. This conclusion is based on the reduced colonization of planktonic larvae in substrates contaminated by drilling fluid compared to control substrates and, in part, implies that benthic community stability may be altered by drilling mud contamination through reduced recruitment and alterations of the food web.

7. Information on the toxicity of drilling fluid components is considered to be of limited utility in evaluating or predicting the toxicity of whole, used drilling fluids discharged to the benthic environments of Georges Bank and lower Cook Inlet because of the difficulty in achieving realistic exposures. However, the information reviewed is useful in evaluating the significance of doses received by pelagic organisms.

8. Although hydrocarbons are not considered to be a component of most drilling fluids, hydrocarbons have been identified as being contained in various lubricants and in emulsions. Many marine organisms are very sensitive to hydrocarbons and it is recommended that hydrocarbon levels be measured in drilling fluids utilized for bioassays of potential ocean discharges.

9. The objectives of any laboratory test program must be clearly defined prior to establishment of specific methodology to be employed.

2.3.4 Bioaccumulation and Effects of Trace Elements

2.3.4.1 Background

Concern about heavy metals and trace elements are spurred by such extreme problems as bioaccumulation of mercury in fish and/or man, and the resultant "Minamata" and "mad hatter" diseases. The problem of heavy metals contamination has two aspects. The first concern is an acute problem--the damage to tissues resulting from direct exposure to metals either in solution or in particulate form. Although a considerable body of information exists on the effects of heavy metals in aqueous solutions (e.g., Vernberg et al. 1977; Giam 1977), very little is known of the bioavailability and acute effects of heavy metals in particulate form. The second concern is a chronic problem--bioaccumulation and biomagnification of heavy metals and consequent reductions in fitness and reproductive potential through several levels of the food web. Again, although data exist on these effects for aqueous solutions, little is known about the effects of heavy metals in particulate form on faunal assemblages such as those that are the object of this study.

In addition to the obvious chromium in the ferrochrome lignosulfonate, trace metals are present as contaminants in many components used in the drilling process. Barite is the primary source of most of these metals, but barites from different sources differ greatly in quantities of individual metals present in them (Kramer et al. 1980). Metals occur predominantly in sulfide minerals contained in the barites. Pipe dope used to lubricate pipe threads may be the major source of lead from the drilling process (Ray and Meek 1980). While solubilities in seawater of metals from individual components may be significant, presence of other materials used in the complex drilling muds mixture (e.g., bentonite, attapulgite) have been shown to efficiently scavenge some metals from solution (Kramer et al. 1980, Liss et al. 1980). The elements that have received the greatest study to date are arsenic (As), barium (Ba), cadmium (Cd), chromium (Cr), copper (Cu), lead (Pb), mercury (Hg), nickel (Ni), vanadium (V), and zinc (Zn). All of these elements have been shown to have elevated concentrations in surficial sediments near one or more offshore petroleum platforms (Anderson and Schwarzer 1979, Crippen et al. 1980; Holmes and Barnes 1977; Mariani et al. 1980, McDermott-Ehrlich et al. 1978, Tillery and Thomas 1980).

2.3.4.2 Literature Review

The widespread use of barite and ferrochrome lignosulfonate (FCLS) in drilling muds has focused particular attention on the constituents barium and chromium. Liss et al. (1980) investigated the uptake of these metals by the sea scallop Placopecten magellanicus during laboratory exposures both to drilling fluids and to FCLS alone. They found that, over a 4-wk exposure to a I.O-g/l suspension of attapulgite-based synthetic mud (equivalent to 0.074 g/l FCLS), the mean chromium concentration in the kidney increased significantly from 1.7 to 4.4 mg/dry kg ($P=0.05$). However, no significant uptake was observed in the slow adductor muscle. A similar result was obtained with a used, low-density, lignosulfonate drilling fluid. Exposure to suspensions of ferrochrome lignosulfonate alone (0.1 and 0.3 g/l) resulted in approximately 6-fold elevations in the kidney chromium concentration. Considerably greater increases of barium occurred during the exposure to the suspension of synthetic mud containing 0.55 g barite/l. Mean concentrations in the kidney increased significantly from less than 1.0 mg/dry kg to about 100 mg/dry kg. Although not statistically significant, mean levels of barium also increased several-fold in the slow adductor muscle.

Rubinstein et al. (1980) reported distinct increases in levels of barium, chromium, and lead in soft tissues of the oyster Crassostrea virginica exposed for 100 days to three nominal concentrations of used drilling fluid (10, 30, and 100 μ l/l). Because of the nature of the experimental apparatus, accumulations of heavier mud components in the test containers increased the actual doses above these levels. Average levels of Ba, Cr, and Pb in the whole mud were 1,100 1,400, and 40 mg/dry kg, respectively. Relative to a control value of 1.9 mg/dry kg for Ba, the tissue concentrations for the three exposures increased by factors of about 8, 15, and 30. Corresponding increase factors for chromium (mean control: 0.65 mg/dry kg) were about 5, 6, and 15; for lead (mean control: 1.1 mg/dry kg), these increase factors were about 1.3, 1.2, and 3.

McCulloch et al. (1980) exposed the marsh clam Rangia cuneata to a layered solid phase of used chrome lignosulfonate drilling mud that contained 485 mg Cr/dry kg. After 24 hr the mean concentration of Cr in the whole soft tissues increased to about five times the level (3 mg/dry kg) found in animals exposed to the reference sediment (which contained 20 mg Cr/dry kg). However, about two-thirds of the excess metal was lost after 24 hr of deputation, indicating that most of this short-term accumulation was associated with the gut contents. These authors also exposed this clam to an aqueous (artificial seawater) supernatant (termed the 100-percent mud aqueous fraction) of the used, chrome lignosulfonate drilling mud for 16 days. Mean levels of chromium in the soft tissues increased by almost a factor of 3, reaching a maximum of 18 mg/dry kg. Approximately half of this increased chromium was lost within 24 hr of deputation in clean seawater, no further decrease toward the initial concentration (7 mg/dry kg) was measurable over the next 2 weeks.

Similar results were obtained for both chromium and lead in a shorter experiment in which Rangia was exposed to a 50-percent concentration of the mud aqueous fraction of used mid-weight lignosulfonate drilling mud (whose dry weight concentrations of Cr and Pb were 417 and 915 mg/kg, respectively). Whole body mean concentrations increased by about a factor of 1.5 in 2 to 3 days, and for each metal approximately half of the excess was lost after a 4-day deputation period. Upon exposing spat of the oyster Crassostrea gigas to a 40-percent concentration of this mud (which also contained 605 mg Zn/dry kg), tissue concentrations of Cr increased 2- to 3-fold over the first 2 days, and 4-fold after 14 days. By comparison, levels of lead had increased by only about a factor of 2 after 10 days of exposure, and there was no detectable increase for zinc during this period (McCulloch et al. 1980).

Page et al. (1980) investigated the uptake of chromium by another mollusc, the intertidal mussel Mytilus edulis, from various aqueous extracts or "solutions" of this metal. The initial average concentration of chromium in the soft mussel tissues was 1 mg/dry kg. After a 7-day exposure (at 13°C and pH 7.8) to an aqueous extract containing 1.4 mg Cr/l of a medium-density, lignosulfonate mud containing 396 mg Cr/dry kg, the tissue level had increased by almost a factor of 7 and appeared to be near equilibrium. By comparison, exposure at this temperature and pH to a "solution" of trivalent chromium (Cr^{3+}) containing 0.6 mg Cr/l resulted in a 50-fold increase in the tissue concentration after 7 days. It should be noted that this exposure level is an order-of-magnitude above the predicted equilibrium concentration for dissolved trivalent chromium of 0.045 mg Cr/l, at pH 8 and 250C (Jan and Young 1978). Thus, most of the chromium in this exposure test probably was actually in the particulate state. This mAy well be the case for chromium and the other test metals in the aqueous extracts of drilling muds used in the studies discussed above.

Tornberg *et al.* (1980) exposed arctic amphipods (Onisimus sp. and Boeckosimus sp.) for 20 days to various mixtures (5 to 20 percent by volume) of used, freshwater, XC-polymer drilling fluids and ambient seawater. concentrations (in mg/l) of target metals in the undiluted fluid were Cd: <0.5 to 1.5, Cr: 66 to 176, Cu: 10 to 16; Zn: 49 to 110. Mean concentrations of these metals in control amphipod samples were 0.3, 3.0, 9.7, and 86 mg/dry kg respectively. The greatest uptake of these metals occurred not in the 20-percent mixture, but in the 10-percent mixture for cadmium, chromium, and lead or the 5 percent mixture for zinc) . Relative to the above-mentioned mean control values, the maximum increase factors observed for these metals were approximately 5, 2, 2, and 2, respectively. There was little indication that these factors would be increased by a longer period of exposure and, in fact, some deputation may have occurred after 15 days in organisms still exposed to the test media.

Crippen et al. (1980) examined the relationship between concentrations of mercury, lead, zinc, cadmium, arsenic, and chromium in bottom sediments and infaunal organisms following discharge of drilling fluid into the Beaufort Sea. No correlation was found, and the only suggestion of possible bioaccumulation was for mercury at two stations near the discharge site. There, mean concentrations in the organisms were 0.5 and 0.2 mg/wet kg, compared to a mean value of 0.05 mg/wet kg for the study . In the former case, the 10-fold mean tissue increase factor for the infaunal samples (which included polychaetes, oligochaetes, and pelecypods) occurred at a site where the mean sediment mercury concentration (6.4 mg/dry kg) was approximately 90 times the control value (0.07 mg/dry kg). Only in the case of chromium did the mean concentration for the purged infaunal samples (0.4 mg/wet kg) fall more than 10 percent below the mean value for the unpurged infaunal samples (1.5 mg/wet kg) indicating that little of the measured uptake was the result of ingested metals. Moderately elevated levels (to about twice background levels) of mercury, cadmium, and chromium were found in sediments up to at least 1,800 m downcurrent from the discharge site adjacent to the island, and substantially elevated levels (10 to 20 times background) of these elements plus lead and zinc were found within 50 m of the site. The authors concluded that, in this study, mercury was the best tracer for the drilling fluids used, and that the barite in the fluids was the principal source of all the target metals except chromium (whose major source was the chrome lignosulfonate).

Mariani et al. (1980) compared trace metal concentrations in bottom sediments and organisms around an exploratory drill rig before and after the discharge of about 2,200 metric tons of solids in the Mid-Atlantic Bight. Although dramatic increases occurred in some tissue metal concentrations (Table 2-11), overall they found no simple correlation between concentrations in the sediment and tissue samples. The authors used a weak-acid leaching procedure on the sediments in an effort to measure only the biologically available portion of a metal. In contrast, a strong acid digestion procedure was employed to analyze the metals in the tissue samples. Upon their collection, an effort was made to clean and purge the animals of their associated sediment. However, because of the depth of the study site, most animals did not survive long enough to fully evacuate their digestive systems.

TABLE 2-11

TOTAL HEAVY METALS DISCHARGED(a)
AND METALS SHOWING INCREASES IN TISSUES
OF SPECIFIC MAJOR TAXA BETWEEN PRE- AND POSTDRILLING STUDIES(b)

	Barium	Mercury	Vanadium	Lead	Chromium
Total discharged in mud and cuttings (kg)	413,600	5	58	33	1,378
Ophiuroids	X	X	X	X	
Polychaetes	X	X	X		X
Molluscs	X	X			

Source; Based on (a) Meyers et al. 1980a; and (b) Mariani et al. 1980.

A number of the results reported in this paper are difficult to interpret from the available reports. For example, with a few exceptions there were no major increases in the measured sediment concentrations *of* barium before and after the discharge. Examination of the graphical data indicated that most of the values in both surveys were approximately 2 mg/dry kg, although the highest postdrilling value (42 mg/dry kg) obtained 1.6 km from the drill rig was four times the higher predrilling value (10 mg/dry kg). In contrast, major increases were observed in the tissue concentrations of Ba for the three benthic taxa studied. Typical levels in the molluscs (principally Lucinoma filosa) increased from roughly 2 mg/dry kg to more than 50 mg/dry kg near the drill rig, with a maximum of 320 mg/kg (presumably also on a dry weight basis). For the unidentified polychaetes, Ba values were extremely variable, but post-drilling levels appeared to be at least several times higher than those of the predrilling survey. In the case of the brittle stars (primarily Amphioplus macilentus), typical Ba concentrations increased from 1 to 2 mg/dry kg to roughly 100 to 200 mg/dry kg (with a maximum of 5,100 mg/dry kg).

For chromium, only the distributions in the polychaete tissues were presented. Again, the data were quite variable. However, the highest value occurring in the predrilling survey was 0.6 mg/ dry kg, while the postdrilling values typically were an order-of-magnitude higher, and ranged up to 70 mg/dry kg near the drill rig.

For lead, typical sediment concentrations increased from predrilling levels of roughly 0.5 mg/dry kg (with a maximum value *of* 1.6 mg/dry kg near the drill rig) to postdrilling levels of about 3 mg/dry kg (with a maximum concentration *of* about 7 mg/dry kg near the drill rig). Levels of this metal in the mollusc tissues ranged from <1 to 6 mg/dry kg in the predrilling survey, while four values obtained near the drill rig in the postdrilling survey exceeded 24 mg/dry kg (with a maximum value of 140 mg/dry kg). The lead concentrations obtained for the brittle stars were quite variable, but in general appeared to increase by several factors *after* the drilling.

The only cadmium distributions illustrated were for the brittle star. The maximum value obtained for the predrilling survey was 0.3 mg/dry kg, with all other values being less than 0.1 mg/dry kg. In comparison, the lowest postdrilling value observed was about 0.1 mg/dry kg. All of the other values exceeded 0.2 mg/dry kg, with concentrations near the drill rig ranging up to 9 mg/dry kg.

The highest mercury concentration measured in the predrilling mollusc samples was 0.7 mg/dry kg, while six values above 4 mg/dry kg were obtained in the post-drilling survey within 1,600 m of the drill rig. For the polychaetes, values obtained within 200 m of the drill rig ranged between 0.01 and 0.06 mg/dry kg in the pre-drilling survey and between 0.05 and 0.8 mg/dry kg in the postdrilling survey. The highest value observed (1.9 mg/dry kg) occurred during the latter survey, 1,600 m from the drill rig at the southwest edge of the study area (and in the general direction in which most of the discharge is believed to have been transported) . In the case of the brittle stars, mercury concentrations typically increased by two orders-of-magnitude after the drilling (from a predrilling level of roughly 0.003 mg/dry kg).

The authors state that the increased tissue concentrations of mercury were not associated with the mercury concentrations in the drilling discharge solids, which were reported to be less than 0.05 mg/dry kg by Mariani et al. (1980). The metals analysis values listed by Ayers et al. (1980a, Table 10) for some typical muds discharged during the study include mercury concentrations of <1, 1.9, and 2.2 mg/dry kg for mud discharged on February 22, March 25, and April 27, 1979. Total mercury discharged in 2,160 mt of mud and cuttings solids was reported as 5 kg (Ayers et al. 1980a) for an average concentration of 2.3 mg/kg. This is one possible explanation for the unexpected and very large increases in tissue concentrations of this metal observed in the postdrilling survey.

Also, it should be noted that the use of a 15-cm long sediment core may have greatly reduced the chance of detecting actual relationships between sediment and tissue concentrations of the target trace elements. Because the postdrilling survey was conducted only about 2 weeks after drilling-related operations were terminated, it seems unlikely that the solids discharged in this area near the end of the 6-month operation (and which contained the highest concentration of barite and any associated trace metals) would have been thoroughly mixed 15 cm down in the bottom sediments. If instead they were retained within the top centimeter, any excess metal "signal" from the discharge would have been diluted 15-fold in the 15-cm sediment core sample, making detection very difficult. Uncle r this scenario, animals feeding principally near the sediment-seawater interface would be much more exposed to the target elements in the discharge than would be indicated by the postsurvey distributions in the bottom sediment.

The authors present their own discussions of possible explanations for the remarkable increases in tissue metal concentrations observed during the postdrilling survey. Whatever the merits of these arguments, it appears that this study leaves several important questions unanswered.

A reanalysis of some heavy metals from only the top 3 cm of archived cores from the pre-, post-, and l-yr postdrilling surveys is being done using neutron activation (barium, chromium, and vanadium) and strong acid digestion (mercury) (Menzie, EG&G, personal communication). These analyses will be reported in the future and may help explain some of the unusual results described above.

2.3.4.3 Bioaccumulation Near a Sewage Outfall - A Comparison

Several studies have been conducted on bioaccumulation of most of the metals common in drilling effluents by benthic organism living near the submarine discharge of Los Angeles County municipal wastewater off Pales Verdes Peninsula in southern California. On the average, the surficial sediments in this region are contaminated at least several-fold above natural concentrations. Therefore, in view of the fact that municipal wastewaters, like drilling fluids, contain most of the trace metals in association with the particulate phase, it appears useful to consider the degree of bioaccumulation occurring in this environment.

Young et al. (1975) reported levels of toxic trace elements in liver tissue from a flatfish (Dover sole, Microstomus pacificus) collected during 1971-72 from the outfall and a control zone. Typical sediment contamination factors (outfall zone/control zone) for this study are listed in Table 2-12 along with average concentrations measured in liver samples. These results show that, despite the relatively-high sediment contamination factors measured in this study, no statistically significant elevations of the target metals in livers of the outfall zone specimens were observed.

TABLE 2-12

TRACE METALS IN DOVER SOLE (Microstomus pacificus) COLLECTED OFF LOS ANGELES, CALIFORNIA, 1971 and 1972.

Trace Metal	Sediments(a) Outfall/Control	Flatfish Livers (mg/wet kg) Outfall	Flatfish Livers (mg/wet kg) Control
Arsenic (As)	15	1.3 ± 0.2	3.1 ± 0.7
Cadmium (Cd)	160	0.19 ± 0406	0.58 ± 0.29
Copper (Cu)	23	2.0 ± 0.4	2*2 ± 0*5
Mercury (Hg)	85	0.11 ± 0.02	0.11 ± 0.04
Zinc (Zn)	17	26 ± 3	27 ± 4

(a) Outfall specimens were trawled off Pales Verdes peninsula; control off Santa Catalina Island.

Source: de Goeij et al. 1974.

A similar result was obtained for muscle tissue of five bottom-feeding sportfishes collected from this discharge zone (Young et al. 1978). Overall medium concentrations (mg/wet kg) determined from the five species medians for both the outfall and control categories were as follows: Cd, <0.01 vs. <0.01, Cr, 0.03 vs. 0.02, Cu, 0.15 vs. 0.13, Hg, 0.10 vs 0.22; Ni, 0.06 vs. 0.06, and Zn, 3.6 vs 1.9 ppm. Thus, only for zinc was there any suggestion of muscle tissue contamination in the outfall specimens, and then only by about a factor of 2.

As a part of this 1975-76 study, several invertebrates (sea urchin Strongylocentrotus franciscanus; black abalone Haliotis cracherodii; ridgeback prawn Sicyonia ingentis; yellow crab Cancer anthonyi; and lobster Panulirus interrupts) were also sampled in triplicate from the outfall and control regions, and metal concentrations were measured in the edible tissue. In addition, 6 to 8 purple-hinged rock scallops (Hinnites multirugosus) were obtained from the two regions, and three tissues (adductor muscle, gonad, and digestive gland) were analyzed. The results indicated that, in contrast to the case for the fishes, certain invertebrates from the outfall zone exhibited distinct uptake of specific metals in muscle and gonadal tissues which were cleanly separated from the contaminated sediments or wastewater particulate to which the organisms had been exposed.

The greatest accumulations above natural levels (approximately 10-fold) occurred for chromium in the muscle of two molluscs--the black abalone and the purple-hinged rock scallop. The three muscle tissue wet weight values measured in the outfall abalone (0.9, 1.0, and 2.2 ppm) were all an order of magnitude above those measured in the control specimens (0.04, 0.10, 0.10 ppm). For the scallops, the mean (± std. error) values measured in the outfall (n=8) and island control (n=6) specimens were 0.35 ± 0.05 and 0.05 ± 0.02 ppm, respectively. Distinct chromium contamination of the scallop gonadal and digestive tissues was also observed: corresponding values for the gonads were 2.6 ± 0.3 vs. 0.39 ± 0.05 ppm, and for the digestive gland, 41 ± 8 vs. 2.2 ± 0.4 ppm for test and controls, respectively. Furthermore, silver appeared to be accumulated by the outfall zone scallops over control levels. Comparative values for the adductor muscle, gonad, and digestive gland were 0.026 + 0.008 vs. 0.008 ± 0.003, 0.080 ± 0.013 vs. 0.018 ± 0.006, and 2.3 ± 0.5 vs. 0.31 ± 0.06 ppm, respectively. Corresponding values for copper were 0.41 ± 0.1 vs. 0.16 ± 0.04, 3.2 ± 0.2 VS. 2.2 ± 0.5, and 190 ± 40 vs. 64 ± 15 ppm, respectively. Zinc levels appeared to be elevated only in the gonadal tissue of the outfall scallops; the comparative values were 46 ± 6 vs. 20 ± 6 ppm. Finally, the nickel values measured in the muscle of yellow crab from the outfall zone (0.22, 0.26, 0.51 ppm) were well above the available control values (<0.04, <0.05 ppm).

Relatively low concentrations of total mercury were measured in the edible tissue (muscle except for sea urchin gonads) of the outfall and control zone invertebrates. The corresponding median concentrations for sea urchin, abalone, scallop, prawn, crab, and lobster were 0.006 vs. 0.024, 0.011 VS. 0.009, 0.056 VS. 0.024, 0.080 vs. 0.046, 0.034 vs. 0.071, and 0.28 vs 0.25 ppm, respectively. As was the case for the fishes, none of these median concentrations exceeded the 0.5 ppm (now 1.0 ppm) limit established by the U.S. Food and Drug Administration.

Few reports are available on the effects of exposure to or ingestion of elevated levels of the heavy metals. Benayoun et al. (1974) reported concentration of cadmium by the euphausiid *Meganyctiphanes norvigica* from feeding on ^{109}Cd-labelled food. Complete deputation required about 100 days. Cunningham and Tripp (1975a,b) reported increased concentrations of cadmium in the oyster *Crassostrea gigas* which had been fed ^{203}Hg-labelled algal cells. During deputation, concentrations of mercury decreased in gill and digestive tissue but remained constant in the mantle and increased in the gonad and muscle. Nimmo et al. (1977) observed up to 10-fold increases in cadmium in grass shrimp (*Palaemonetes pugio*) after feeding them Cd-labelled brine shrimp for 14 days. Increases ranged from 352 μg Cd/kg whole weight in shrimp fed brine shrimp with 27 mg Cd/kg whole weight to nearly 5,000 μg Cd/kg whole weight in shrimp fed brine shrimp with 182 mg Cd/kg whole weight. No grass shrimp died during the feeding studies. In addition, this study indicated that brine shrimp, exposed only to cadmium in solution, concentrated the metal much more efficiently than grass shrimp, exposed to cadmium only in food. Nimmo et al. postulated that cadmium levels would have to be 15,000 times higher in food than in water to attain equivalent whole-body cadmium residues.

Capuzzo and Sassner (1977) investigated the effects of particulate uptake chromium on filtration rates and metabolic activity of *Mytilus edulis* and *Mya arenaria*. The artificial sediments were prepared from clay suspensions of bentonite and kaolite aerated with 1.4 mg $CrCl_3$/g clay for 1 week. They found that concentrations of chromium above 0.15 mg/g clay caused reductions in filtration rates and disturbed ciliary activity in *Mytilus* and *Mya* when natural sediments were used. Dissolved and particulate chromium affected *Mytilus* whereas only dissolved chromium affected *Mya*. It is also clear from their data that dissolved chromium has a considerably greater effect on respiration and filtration rates than does particulate chromium. However, accumulation was observed in muscle, mantle, gill, and visceral tissues after exposure to both types of chromium. The concentrations of chromium in the sediment examined in this study are generally several orders of magnitude higher than would be observed around drilling rigs (see Section 2.5.2).

2.3.4.4 Discussion

The drilling fluids laboratory and field studies discussed above indicate the potential for bioaccumulation of barium many times above control levels by invertebrates. The increase factor of 30 observed by Rubinstein et al. (1980) for oyster soft tissues exposed to nominal 100 μ l/l used drilling fluid in the laboratory is consistent with the more than 25-fold increases in tissue concentrations reported by Mariani et al. (1980) for molluscs collected during the postdrilling survey near the target platform in the Mid-Atlantic Bight. The 100-fold increases reported Mariani et al. for the brittle star (with a maximum increase factor of about 2,500 to 5,000) are considerably higher than those usually observed for trace elements in other marine pollution surveys. In addition, the highest level observed (5,100 mg/dry kg) is more than 100 times the maximum sediment concentration (43 mg/dry kg) Obtained in the postdrilling survey. Thus, it would seem important to determine if and how such increases in tissue concentrations affect the organism.

The laboratory studies on chromium uptake generally showed increases above control tissue concentrations by factors as great as 15, measured in the oyster tissues exposed to 100 1/1 (nominally) of used drilling fluid (Rubinstein et al. 1980). These values are similar to those observed in benthic organisms around the Los Angeles County muncipal wastewater outfall, and to the increase factors typically seen for the polychaetes in the Mid-Atlantic Bight study.

For lead, laboratory tests yielded increases of only 2 to 3 times control values (Rubinstein et al. 1980; McCulloch et al. 1980), while somewhat higher values were noted by Mariani et al. (1980) in molluscs collected near the Mid-Atlantic Bight platform. In comparison, the digestive gland of rock scallops collected near the Los Angeles outfall contained only twice control levels of this metal (Young and Jan 1979). Thus, from these studies lead does not appear to be as strongly bioaccumulated as some of the other metals discharged to the marine environment along with drilling fluids or municipal wastewater. However, lead is a ubiquitous laboratory contaminant, and such increase factors could be significantly underestimating actual values if the "control" levels are elevated due to contamination during sample collection, preparation, and analysis.

The five-fold increase in tissue cadmium concentrations observed in the amphipods exposed to a 10-percent mixture of used drilling fluid (Tornberg et al. 1980) is similar to the eight-fold increase measured in digestive gland of mussels (Mytilus californianus) collected inshore of the Los Angeles County outfall diffusers (Young and Alexander 1977). In comparison, the data of Mariani et al. (1980) indicate at least two-fold increases to be typical for brittle stars collected during the postdrilling phase of the Mid-Atlantic Bight survey, (with estimated increase factors -ranging up to 90 near the platform).

Unfortunately, none of the laboratory studies on bioaccumulation of metals from drilling fluids covered in this survey included mercury analyses. However, as discussed above, Crippen et al. (1980) did observe a 10-fold elevation of mercury in one sample of infaunal organisms collected near the Beaufort Sea well, and Mariani et al. (1980) reported striking (10- to 100-fold) elevations of this metal in postdrilling samples of molluscs, polychaete worms, and brittle stars around the platform in the Mid-Atlantic Bight study. These elevations are considerably greater than those found in benthic invertebrates collected near the Los Angeles County outfalls, where the surficial sediments contain up to 100 times normal mercury levels (Jan et al. 1977; Eganhouse and Young 1978, Eganhouse et al. 1978). Unfortunately, the physical/chemical states of this accumulated mercury have not yet been established. However, the increase factors and actual concentrations (ranging up to 6 mg/dry kg) for the organisms analyzed are sufficiently high to justify further studies of this toxic metal around drilling discharges.

The laboratory and field study results summarized above clearly show that a number of the potentially toxic trace metals found in drilling fluids are readily bioaccumulated by marine invertebrates. Corresponding results for fishes have not yet been reported. Tillery and Thomas (1980) compared the levels of barium, cadmium, chromium, copper, iron, nickel, lead, zinc, and vanadium in muscle tissue of shrimp (*Penaeus aztecus*) and three rig-associated fish from the vicinity of production platforms in the Gulf of Mexico. In general, metals concentrations were not significantly higher than those in 'similar species collected elsewhere in the Gulf. However, concentrations of copper and iron in sheepshead and spadefish and nickel in sheepshead were elevated over those in controls. This uptake may have been from some rig-associated changes in the environment (discharge of mud and cuttings, shipping, platform corrosion) but because of the potential mobility of the species in question (and "controls" that may also have spent time near other platforms) the results are not conclusive. However, studies conducted around one major municipal wastewater outfall indicate that fish are less likely to accumulate such excess metals. The forms (physical/ chemical states) of these accumulated metals also are unknown.

Despite the growing evidence for bioaccumulation of excess trace metals above normal levels by invertebrates situated near the base of marine food webs, little is known of the physiological or ecological impact of such bioaccumulations. However, recent developments in the field of biochemistry suggest that organisms have natural detoxification systems which afford a measure of protection from unnatural accumulations of certain metals (Young et al. 1979). One such system involves a protein called metallothionein (Brown et al. 1977), which can store excesses of essential metals (such as copper and zinc), and also bind limited quantities of nonessential and toxic metals (such as cadmium). Unfortunately, to date there is little information on the maximum quantities of toxic metal that can be assimilated by tissues of marine organisms before the binding capacity of metallothionein-like proteins is exceeded, and the metals spill over into high molecular weight protein pools where they may poison enzyme systems.

Generally, excess metals concentrations in bottom sediments and organisms have not been shown to be strongly correlated. This may be the result, at least in part, of differences in techniques of mobilizing the target metals from the sediment and tissue matrices in preparation for analysis. In view of the strong association of most trace metals with particulate in the marine environment, it is important that further research be conducted to determine the bioavailability of such particulate-associated metals. Specifically, documentation of the validity of weak-acid leaching techniques sometimes used in such studies should be reported with the results. Results from this leaching technique clearly should not be used to delineate the extent of transport of the discharged particulate.

Concentrations of trace metals in sediment normally range from parts-per-billion (µg/dry kg) to parts-per million (mg/dry kg), while seawater concentrations normally range from parts-per-trillion (rig/l) to parts-per-billion (µg/l). In some cases, levels of a given metal in seawater determined to be toxic in laboratory bioassays are lower than natural sediment concentrations of that metal. Therefore, it is important that elevations of metals in sediments not be confused with seawater bioassay values. Instead, comprehensive toxicity tests with contaminated sediment are needed before meaningful evaluations can be made of results from sediment surveys (i.e., the significance of metals accumulation of sediments).

2.4 FIELD OR IN SITU BIOLOGICAL EFFECTS

Prior to 1970 virtually nothing was published on the actual effects of offshore drilling vessel discharges on benthic or pelagic biological communities. Such effects could result from burial or suffocation, changes in sediment physical properties, or toxicity of some components.

Monaghan et al. (1977) calculated that cuttings from a 3,000-m (10,000-ft) well would occupy a volume of about 200 m^3 (7,000 ft^3) and would weigh some 490 mt (formation density assumed to be 2.5). Ayers et al. (1980a) measured 1,017 m^3 of materials discharged from the solids control equipment during the drilling of a 4,970 m well in the mid-Atlantic shelf. Figures used by BLM {1977) for cuttings volumes produced for typical exploratory (4,600-m) and production (3,000-m) wells are 690 and 540 m^3, respectively. However, these figures are based on uncommonly large well bores (Table 2-4). In addition to formation materials, caked drilling fluids from rig equipment and muds from large volume dumps may accumulate. In 1964, Carlisle et al. reported cuttings accumulations of up to 6 m deep under production rigs off the coast of California. Zingula (1975) reported typical cuttings piles in relatively shallow, low-energy waters in the Gulf of Mexico to be about 1 m in height and 45 to 50 m in diameter when new. Areal shapes were elliptical or in a star-burst pattern depending on currents.

In relatively shallow water such a cuttings pile will be dispersed by storms over a period of years. No cuttings piles persisted under production platforms examined in the Gulf of Mexico where drilling had ceased 10 to IS years earlier (Shinn 1974; Oetking et al. undated). In other, very dynamic environments such as the central portion of lower Cook Inlet, no cuttings piles formed even during drilling (Houghton et al. 1890a). Cooper (1980, NMFS, personal communication) reported no visible cuttings or mud accumulations persisting 3 years after the drilling at the site of a test hole on Georges Bank in 79 m of water. Debris dropped from the rig was clearly visible, however.

Benthic organisms living in areas where cuttings piles form will obviously be displaced or destroyed by burial. Some other interactions of biota with cuttings piles have also been noted. Zingula (1975) observed crabs and gastropod digging in a cuttings pile while groupers and red snappers swam about, apparently undisturbed by chips still falling through the water. However, until very recently there had been little quantitative study of the effects of cuttings and adhering drilling muds or "mud take" on receiving water biota.

Several types of studies recently conducted have examined drilling discharge impacts on biological communities in the receiving waters:

1. In situ bioassays in the vicinity of drilling discharges (e.g., Houghton et al. 1980b).

2* Field studies of colonization and community structure of benthos attached to underwater structures (e.g., Benech et al. 1980).

3* Benthic community analyses in the vicinity of actual discharges (e.g., Lees and Houghton 1980; Menzie et al. 1980).

In addition, most of the laboratory or controlled ecosystem-type experiments described in Section 2.3 provide information that can be extrapolated to the natural environment with varying degrees of uncertainty.

2.4.1 In Situ Bioassays

The only marine *in situ* bioassay studies reported to date from northern waters have apparently been those of Dames & Moore (1978a) reported by Houghton et al. (1980b). In these studies, arrays of flow-through test containers were anchored at 100 and 200 m along the major current axis, and 2,000 m off the major current axis (control), from a semi-submersible drilling vessel operating in lower Cook Inlet. Each array included containers located at the bottom (62 m), near mid-depth (32 m) and near the surface (15 m). Another test container was suspended from the drilling vessel in about 10 m of water. All tests lasted 4 days. No effects related to drilling discharges (including a sand trap discharge and routine continual shaker discharges) were observed in either juvenile pink salmon held in the mid-depth and surface live boxes or in pandalid shrimp and hermit crabs held in the bottom live boxes.

Because of the bimodal nature of currents in lower Cook Inlet (Section 3.1.1), the live box arrays were exposed to the drilling fluid plume for a maximum of 6 hr in each 12-hr tidal cycle. Also, the cages suspended in the water column were probably not at the depth of maximum plume concentration. Nonetheless, the exposure received at the upper live box (100 m from the rig) probably exceeded that which unrestrained pelagic species would be likely to experience (see Section 2.5.1). Because of the strong tidal currents, most of these species tend to move with water masses rather than remaining in the same geographic area. This, in conjunction with the results of the acute bioassays on juvenile pink salmon (Houghton et al. 1980b; Section 2.3.1 this report) and the rapid dilution achieved due to rig-caused turbulence (Houghton et al. 1980a; Section 2.2.1 this report) led to the conclusion that there would be little likelihood of direct mortalities to pelagic species.

The bottom live boxes, particularly those placed at 100 m from the vessel, probably received doses of bottom Impinging discharges (cuttings and the sand trap dump) that quite closely simulated those received by natural sessile species, although for only a small fraction (4 days) of the duration of the drilling operation (3.5 months) . Species used in these tests were motile epifauna, however, and in nature would not be expected to remain in the vicinity of the drilling operation for long periods. It should also be noted that the species tested (*Pandalus hypsinotus* and *Elassochirus gilli*) are more typical of less dynamic bottom areas. Thus, tests in the central portion of lower Cook Inlet subjected them to two stresses: near-bottom currents and abrasion by the sand bedload, and deposition of drilling muds and cuttings. The fact that no mortalities occurred (coupled with results of laboratory bioassays on *P. hypsinotus*, Section 2.3.1) provides a reasonable assurance that no direct mortalities to motile epifauna would occur from short-term exposures to mud and cuttings discharges.

Further studies along these lines would be of limited value because of the need to artificially confine test organisms that, in nature, would be free to move away from the area if conditions were sensed as unfavorable . Furthermore, actual doses received by test organisms are very difficult to evaluate. The levels of toxicity and dilution achieved in actual discharges produce few if any mortalities at distances where live box placement is possible without interfering with drilling operations, at least in dynamic environments such as lower Cook Inlet. Thus, laboratory bioassays, where conditions and doses can be more readily controlled, are certainly preferable for determining acute toxicities of discharges.

In some environments, however, longer term in situ studies might prove useful in assessing impacts on motile species that could be exposed to drilling muds over periods of several months. Large live boxes containing low densities of organisms could be suspended from the drilling vessel or anchored to the bottom under the vessel, for example in the area of cuttings deposition. Test organism densities would have to be low so that they could gather enough food for sustenance from the passing water masses or from the bottom under the cage. Diver monitoring of such tests would be highly desirable. In addition to survival information, data on heavy metal uptake, growth, and gonadal development could be obtained for comparison with similarly detained organisms at control locations.

Hudson and Robbin (1980) exposed Florida Keys coral, Montastraea annularis to a newly prepared freshwater lignosulfonate/lignite drillng fluid by covering the coral heads in situ with four applications of mud in a 7.5-hour period. Growth of these corals was evaluated 6 months after exposure and compared to control corals. Treated corals grew significantly more slowly but at a more uniform rate than untreated ones. These responses to drilling fluids are similar to those of corals growing in areas having high levels of resuspended bottom sediments (Dodge et al. 1974).

Growth rates of this same species of coral were evaluated over a 90-yr period (1888-1979) in specimens collected in the East Flower Garden' Banks of the Texas coast (Hudson and Robbin 1980). The growth rate of M. annularis dropped from a 50-yr average of 8.9 mm to an average of 7.2 mm in 1957. No evidence was found to relate reduced growth rates to drilling operations which took place nearby between 1974 and 1977.

2.4.2 Colonization and Community Structure on Artificial Substrates

The marine organisms subject to the greatest exposure to drilling muds from a deep-water drilling operation comprise the fouling community colonizing underwater parts of semi-submersible drilling vessels. Except in cases where discharges are shunted beneath the horizontal pontoons, these structures may receive continual exposures to relatively undiluted effluents. If, as is common practice, the vessel routinely anchors on a constant heading with respect to prevailing currents, exposures may be prolonged over the duration of several wells, perhaps interspersed with periods of transit, re-anchoring or lay-up when no discharges occur. If the drilling history of the vessel since Its last drydocking is known, these studies of fouling communities on underwater structures chronically exposed to varying levels of drilling effluents can be useful in several ways. Presence or absence, abundance, distribution, size and health factors, and levels of potential tissues contaminants in relation to the exposure gradient are all of interest.

Benech et al. (1980) examined the effects of drilling discharges on several of these factors in the fouling assemblages on a semi-submersible working off of southern California. They measured presence/absence of species in quadrats placed along each of four underwater pontoons. Because of the anchoring orientation with respect to the discharge points, currents, and the sun, each pontoon constituted one of four treatments: exposed (to mud)/lighted, exposed/shaded, unexposed/lighted, unexposed/shaded. Benech et al. used a variety of statistical, classification, and ordination analyses to explore the significance of observed patterns. Community structure was shown to differ between all four pontoons with the two mud-exposed pontoons more closely resembling each other than they did the unexposed pontoons.

A relatively large group of species, mostly motile animals, showed no significant differences in occurrence among pontoons. The ubiquitous mussels (*Mytilus edulis*) and barnacles (*Balanus*) and several species epizoic on them also occurred randomly among the pontoons. Another group of species including five algae and the anemone *Corynactis*, which are sensitive to turbidity and/or sedimentation, were adversely affected by mud exposure. Other species were reduced in occurrence on the mud exposed pontoons due either to feeding impairment, absence of prey species, or habitat modification (silting in of the crevices between barnacles and mussels). A few species responded positively to the mud exposure. These included tube worms (*Diopatra*), for which the mud constituted material for tube construction; erect hydrozoans; the opisthobranch *Hermissenda*, a predator on hydrozoans; and the silt-tolerant anemone *Diadumene* which replaced *Corynactis*. No obvious reason could be found for the increased presence of the hydrozoans. Perhaps because of their erect growth form, they were able to rapidly colonize available substrate where other sessile forms (e.g., algae) were eliminated by the mud. Observable effects were apparently localized within 10 to 15 m from the discharge points with a gradient of decreasing impact with increasing distance from the discharge (Benech et al. 1980).

These studies are useful illustrations of community and species changes on a specific substrate brought about by long-term exposures to mud. However, future similar studies could, with a few minor modifications, provide additional useful information. Certainly a better understanding of effects could be gathered using quantitative measures (counts, cover, weight) in addition to the presence/absence data used by Benech et al. Significant reductions in biomass of the entire assemblage or of individual species may be overlooked by considering merely presence or absence. Additionally, important insight into bioavailability of mud constituents (e.g., heavy metals) in the natural environment under artificially high dose rates would be supplied by analysis of shell and tissue of important assemblage components (e.g. , mussels) . This information would provide a useful adjunct to other laboratory and natural benthic data on bioaccumulation of heavy metals. Finally, examination of differences between assemblages on the upper and lower surface of the pontoons as might provide a measure of the relative importance of chemical effects (probably felt nearly equally on upper and lower pontoon surfaces) and physical effects (e.g., burial, sediment build up) felt only on upper surfaces.

Another type of colonization experiment that has been used very little with respect to drilling effluents is exposure of settling plates. George (1975) observed settling plate colonization in the vicinity of a drilling rig in the Gulf of Mexico (Timbalier Bay) but little information was reported on specific impacts of drilling fluid discharges.

NORTEC (1981) exposed plastic trays containing naturally occurring sediments and clams (Astarte spp. and Liocyma fluctuosa), plexiglass settling plates, and concrete patio blocks at mud disposal test sites in the Beaufort Sea. Gear loss precluded significant results from the clam trays tests. While the mean number of diatom species colonizing plates at the simulated above-ice disposal site was lower than at controls, there were no statistically significant differences in this or other parameters (diversity, evenness, overall abundance) between the two sites. The abundance and species composition of invertebrates colonizing the concrete test blocks differed greatly between controls and the test site even 1 year after the discharge. Harpacticoid copepods and polychaetes, the dominant forms on the control blocks, were absent fran test blocks 3 and 8 months following the discharge. However, part of this difference was attributed to differences in grain size between the control and test sites unrelated to the discharge (NORTEC 1981).

2.4.3 Benthic Impact Studies

Despite the apparent high potential for direct effects, at least locally, on marine benthos from discharge of drilling muds and cuttings, there had been little quantitative field investigation of such impacts prior to 1977. Lack of observation of serious or widespread impacts by those who examined the sea bottom under rigs in the Gulf of Mexico during the early 1970s (e.g., George 1975; Zingula 1975) during the early 1970s probably did little to stimulate quantitative evaluations. The onset of exploratory drilling in productive waters on the OCS of Alaska and the northeastern United States, however, led regulatory agencies to require more detailed assessment of potential impacts of mud and cuttings accumulations on benthos comprising or supporting important fishery resources. Studies in each of these areas are described in some detail below along with limited discussion of studies conducted in other areas.

2.4.3.1 The Lower Cook Inlet Benthic Study

As part of the overall evaluation of the effects of drilling fluids discharged from lower Cook Inlet C.O.S.T. well (Dames & Moore 1978a), the benthic community in the vicinity of the drilling site was sampled before, during, and after the drilling operation (Lees and Houghton 1980). The initial survey was not carefully designed because the investigators were notified of the study only 4 days before the arrival of the drill ship and were instructed that sampling had to be completed before the rig entered the area. Furthermore, the precise anchoring configuration (and hence areas of likely major impact) was not known prior to arrival of the drilling vessel.

The major factor Limiting the statistical strength of conclusions reached in this study was the investigators' inability to precisely locate the same stations in the predrilling survey that were used in subsequent surveys. Because of the bimodality and the strength of currents at the drill site only a rather narrow sector NNE and SSW of the discharge point was expected to receive significant fallout of mud and cuttings. The high degree of patchiness in the benthic community further complicated measurement of the predrilling community in the high impact areas. As a solution for future studies Grassle (personal communication) suggests taking many samples in the expected general impact area (a relatively inexpensive process) and analyzing only those from areas proving to be of greatest interest once the impact has occurred. An alternative approach is to use radial transects with replicate sampling at stations at progressively greater intervals outward along each transect (e.g., Robson et al. 1980; Mariani et al. 1980; Crippen et al. 1980; see following sections).

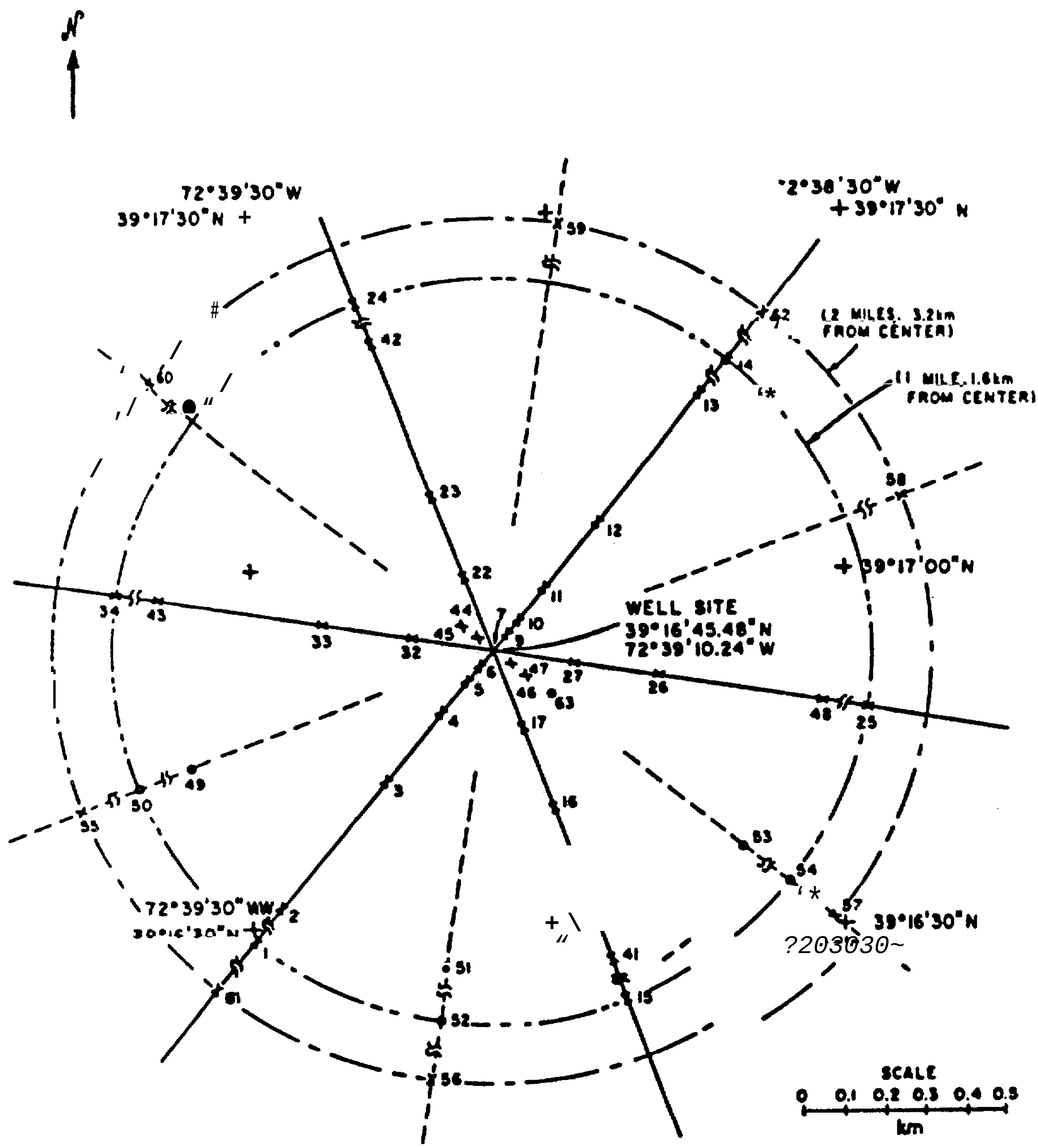
2.4.3.2 Mid-Atlantic Shelf Benthic Study

A similar but more extensive study was conducted in the vicinity of an exploratory well site along the shelf break on the mid-Atlantic shelf east of Atlantic City, NJ, in 1978 and 1979 (Ayers et al. 1980; EG&G 1979; Mariani et al. 1980; Menzie et al. 1980; and Robson et al. 1980). The sampling design selected was, conceived to allow definition of the magnitude and extent of the effects of drilling fluids discharged from the well (Robson et al. 19$0).

Using a systematic sampling design, samples were collected at stations located along six primary axes radiating out from the well site (Figure 2-4). During a predrilling survey, samples were collected and analyzed at 22 stations at distances of approximately 45, 90, 185, 365, 730, and 1,610 m from the well site, including locations both upcurrent and downcurrent as well as offshore and onshore of the well site. Data from the predrilling survey indicated that statistical analyses (probably mainly correlation analysis) would benefit more from analysis of additional stations than additional replicates. Thus, in the post-drilling survey, eight additional stations were sampled and analyzed at 3,220-m from the well; four new stations were also sampled and analyzed on an auxiliary axis oriented perpendicularly to the direction of major current flow for a total of 41 stations in the postdrilling survey.

Seven of the 22 stations analyzed during the predrilling survey were not reoccupied during the postdrilling survey. All of these were located on the primary axes within 100 m of the drill rig. A total of 60 locations was sampled during the study; samples from both surveys were anlyzed at 15 stations.

An oversampling approach was utilized and analyses were conducted on 2 of 6 replicate samples collected at each station (Menzie et al. 1980). In addition, underwater television (UTV) records were made of the megafauna along 10 and 11 transects, respectively, during the pre- and postdrilling surveys.



NOTE : Primary stations are indicated by "x" and secondary stations by "o."

FIGURE 2-4 LOCATIONS OF SAMPLING STATIONS IN THE POSTDRILLING SURVEY OF THE MID-ATLANTIC STUDY (MENZIE ET AL. 1980)

During the postdrilling survey, UTV revealed that sediments in the immediate vicinity (approximately 150-m diameter area) around the well site were comprised of patches of drilling discharges (primarily semi-consolidated, natural subsurface clay materials) which altered the microtopography of the area (Menzie et al. 1980). Grain size analysis (Section 2.2.2) revealed an increased percentage of clay-size particles (probably derived from drilled subsurface clays) out to a distance of at least 800 m from the well site and in the general direction of mean current flow; i.e., to the southwest (Mariani et al. 1980). Increases in the concentration of several trace metals also were detected during the postdrilling survey (Section 2.3.4.2). The authors reported that some of the increases in heavy metals did not appear to correspond to changes that would be expected based on the distribution and chemical composition of drilling fluids and thus may not have resulted from fluids discharges. However, changes in surficial concentrations of clays and heavy metals to which most infaunal organisms would be exposed may have been under-estimated because the sampling methodology resulted in at least a seven-fold dilution of surface sediments (top 2 cm) with underlying sediments (to 15 cm; Chris Wethe, University of Delaware, personal communication). Because of this concern the upper 3 cm of additional archived samples were analyzed for barium, chromium, and vanadium. These data will be presented in the EG&G final report for the mid-Atlantic study.

Data from UTV and benthic surveys revealed changes in the distribution and abundance of epibenthic and infaunal species as well. Overall density of the most abundant epibenthic species, the sea star Astropecten americanus, did not change significantly during the study, but its distribution pattern changed markedly. At the termination of drilling, the sea star's density had increased considerably in the vicinity of the drill rig, probably in response to the increased supply of food items such as mussels that were observed on the sea floor around the rig. These food organisms probably had fallen from the anchor chains and drill rig structure. Fish and crab densities were markedly higher throughout the study area, but especially within 500 m of the rig. Of particular importance were the red hake (Urophycis chuss) and the Jonah crab Cancer borealis. Probable causes for these increases in density were the increased microrelief resulting from cuttings accumulations as well as the increased availability of food items, such as mussels, in close proximity to the drill rig.

In contrast, less motile species (sessile epibenthos and infauna) appeared to decrease in abundance during the study, especially within 500 m of the well site. Sea pens (Stylatula elegans, Menzie, personal communication) were subject to burial by cuttings in the immediate vicinity (i.e., within approximately a 150-m region) of the well site. The density of cerianthid anemones, large burrowing infaunal cnidarians, remained virtually unchanged within 500 m of the drill rig following completion of drilling.

Menzie et al. (1980) reported that community structure varied little in the study area before drilling. Several features suggest that important changes occurred during the study. Species diversity (H'), and species richness (S) values were somewhat lower at the termination of drilling, especially near the well site. This probably reflects the widespread reduction in infaunal densities during the postdrilling survey. In addition, similarity and classification analyses indicated an increase in heterogeneity in the study area between surveys. This too may be partially the result of the overall reduction in density. In the dendrogram for the postdrilling survey, three stations just southwest of the drilling rig showed little similarity to the major station groups or to each other, indicating that the infauna at these stations had become quite different from that in the surrounding areas and was probably affected by the drilling activity. Based on the patchiness in the distribution of the species and in density, Menzie et al. (1980) hypothesized that the variability represented differences between plots in which the infauna had been buried by cuttings and those which had escaped burial or in which recolonization had occurred, but supporting data were not presented. Species that were abundant in the latter patches included the annelids Paraonides lyra, Lumbrineris latreilli, and Tharyx spp., and the amphipods Unicola irrorata, Leptocheirus pinguis, and Byblis serrata. Several of these species previously have been reported to inhabit disturbed areas subjected to deposition, and all are found at the surface of the water-8ediment interface.

Differences in the nature of infaunal assemblages are particularly clear when pre- and postdrilling survey data for densities of major taxa are compared. Pooled densities of annelids, molluscs, echinoderms, and crustaceans were all lower in the postdrilling survey (e.g., Table 2-13).

Beyond the immediate vicinity of the drill rig, densities of annelids, molluscs, and crustaceans displayed significant negative correlations with the clay content of the sediments in the postdrilling study. However, similar correlations between density and barium concentrations in the sediment or tissues were not detected (Section 2.3.4). As reported by Mariani et al. (1980) detectable increases in clay content occurred to at least 730 m and perhaps to nearly 1,600 m downcurrent from the well site (Section 2.2.2). Menzie et al. (1980) concluded that although biological effects may have occurred beyond 800 m it is within this distance that their analyses provided a physical basic (i.e., increased clay content) for relating changes to drilling operation. However, it must be noted that the values for clay content are not representative of the sediment stratum affecting most of the infaunal species.

In summary, this study concluded that the discharge of drilling fluids and cuttings did cause local and at least short-term effects on the fauna in the vicinity of the well site. Increases and/or decreases in abundance were probably related mostly to (1) physical alterations of the substrate, e.g., rapid deposition and burial, increased surface relief or increased clay content of the sediment, as well as (2) effects of predation by hake, crabs, and starfish. No toxic effects were identified.

Additional discussion of these and new data from a one-year postdrilling survey will be provided in a forthcoming final report on this study (C. Menzie, personal communication).

TABLE 2-13

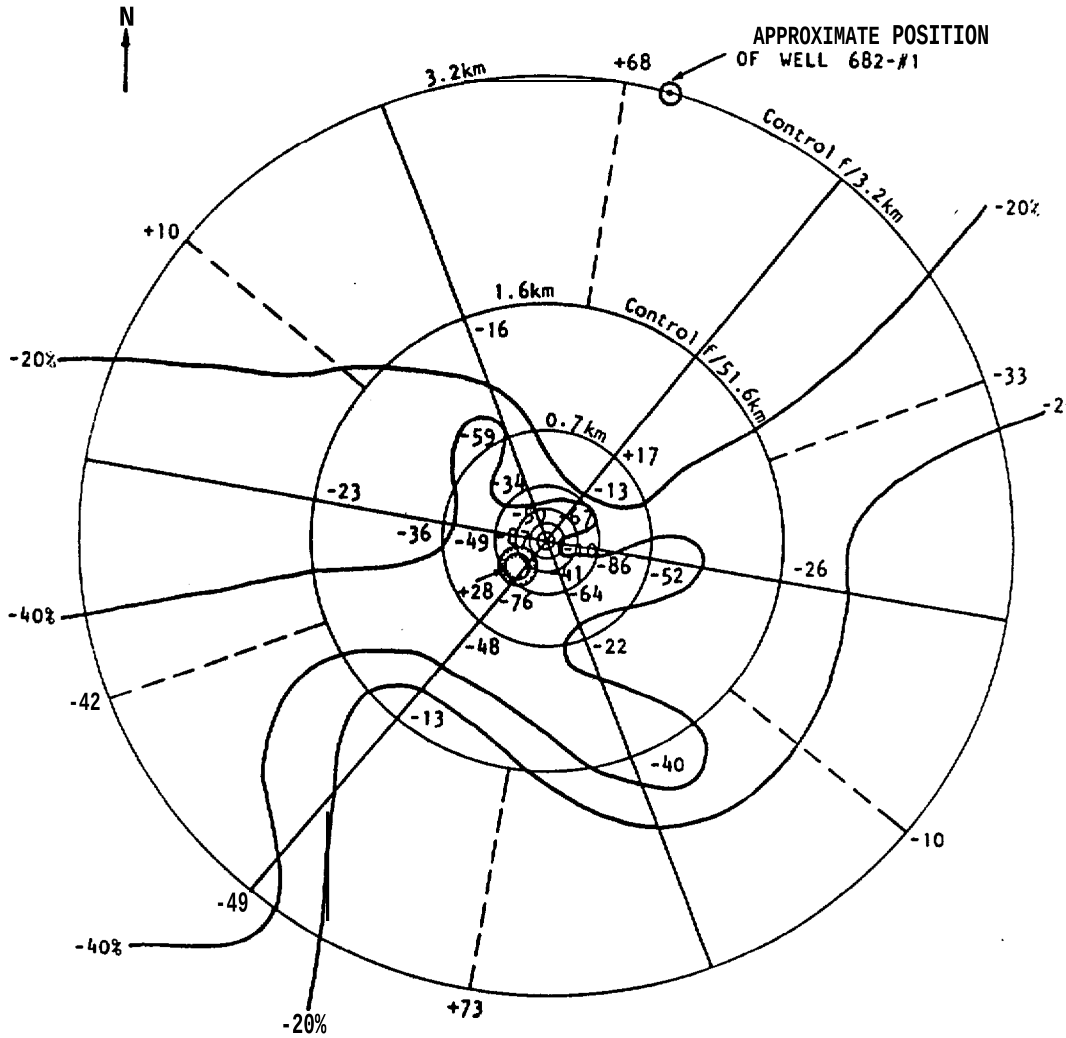
Comparison OF APPROXIMATE DENSITIES[a] OF MAJOR TAXA IN PRE- AND POSTDRILLING SURVEYS ON THE 1.6-KM and 3.2-KM RINGS AT A MID-ATLANTIC EXPLORATORY WELL

	Distance (km)			Pre- to Post- Percent Reduction At	Distance (km)			Pre- to Post- Percent Reduction At
	3.2	1.6	1.6	1.6 km	1.6	1.6	3.2	1.6 km
NE-SW Station	Post- 61	Pre- 1	Post- 1		Pre- 14	Post- 14	Post- 62	
Annelids	900	-4,800	1,010	79	8,200	2,300	1,600	72
Crustaceans	65	360	65	82	330	230	150	30
Molluscs	40	150	35	77	250	130	55	48
Echinoderms	275	700	375	46	1,050	190	660	82
N-S Station	Post- 57+56	Pre- 15	Post- 15		Pre- 24	Post- 24	Post- 59+60	
Annelids	2,400	7,500	1,400	81	9,250	1,800	2,600	81
Crustaceans	140	160	10	94	310	100	195	68
Molluscs	100	150	60	60	300	50	190	83
Echinoderms	420	1,200	175	85	850	370	370	56
E-W Station	Post- 55+60	Pre- 34	Post- 34		Post- 25	Post- 25	Post- 57+58	
Annelids	1,600	8,100	850	90	9,250	1,100	1,250	88
Crustaceans	100	295	30	90	400	20	140	95
Molluscs	65	150	35	77	260	50	60	81
Echinoderms	270	800	260	68	930	250	375	73

(a) Accuracy of densities is limited by scales on figures.
Source: Based on data extracted from Figures 12-19 in Menzie et al. 1980.

Based on our review of the data presented, we agree in general with the findings of Menzie et al. (1980). However, we conclude that the data and analyses discussed do not provide convincing arguments that the effects of drilling fluids did not extend beyond 800 m from the well site. The reasons for these conclusions are described below. Menzie et al. (1980) stated at several points in their paper (pgs. 499, 506 to 512) that abundance had declined during the survey. Our calculations, based on the available data for densities of the major taxa (Table 2 and Figures 9 through 19 of Menzie et al. 1980, as summarized in Table 2-13), indicate that overall density declined, on the average, 80 percent from the pre- to postdrilling surveys at the 1.6-km stations (range of 59 percent at Station 14 to 85 percent at Station 25); decreases of this magnitude seem unusual for a moderately deep-water assemblage between comparable seasons. Postdrilling densities in the close proximity of the rig were also approximately 80 percent lower than predrilling densities. Furthermore, the densities given in these figures for 3.2-km stations are 75 percent lower than predrilling densities at the stations nearest the well site. When comparing predrilling densities for the major taxa at 1.6-km stations with postdrilling densities at the 1.6-km and 3.2-km stations (Table 2-13), postdrilling densities for all 48 comparisons available were from 30 to 95 percent lower. Furthermore, molluscs and crustaceans were well below densities observed at the benchmark stations.

Menzie (personal communication) suggests that the general reduction of infaunal density between the pre- and postdrilling survey even at stations 3,200 m from the well site is probably due to a region-wide population reduction. He further stated that, because of this possibility, comparison between the same stations in different years (use of "temporal controls-) is inappropriate. He indicated that differences in spatial patterns between years might be considered as a basis for concluding the occurrence of impacts. We lack the data to evaluate these patterns, but Menzie also suggested that an appropriate approach is to examine the data for the postdrilling survey alone, using as spatial controls 'outlying stations located upcurrent *of* the well site. . ."; i.e. , "stations to the north generally and to the northeast in particular." In view of this suggestion, we concentrated our analysis on the post-discharge survey based on the mean densities for all organisms presented by Menzie et al. (1980), using northeastern stations (14 and 62) as controls. Based on this guideline, we examined the differences between other stations within 1.6 km of the well site and station 14 (a control), and between other 3.2-km stations and station 62 (a control). We plotted the relative deviation for these differences in Figure 2-5 and assumed that stations with densities at least 20 percent lower than the respective control exhibited an impact. The statistical significance of this assumption is not known and the validity of this approach is compromised by the a posterior selection of control stations. The patchiness of effect mentioned by Menzie et al. is demonstrated by the area about 185 m downcurrent *of* the well site where densities exceeded those of the controls. Nonetheless, all 1.6-km stations had densities lower than the 1.6-km control; 60 percent of these had densities more than 20 percent lower than the control. Among the seven noncontrol 3.2-km stations, 59 percent had densities lower than the control and 47 percent were more than 20 percent lower. If we assume that these differences were caused by the drilling operation, it is clear that this



NOTE : Signed numbers are percent differences from respective controls.

—— Primary Axes
- - - Auxiliary Axes
Scale: 1000m per inch

FIGURE 2-5 DISTRIBUTION OF RELATIVE DENSITY DIFFERENCES FROM THE 1.6-km AND 3.2-km "CONTROL" STATIONS IN THE POSTDRILLING SURVEY OF THE MID-ATLANTIC STUDY influence extended over a considerable area and out past 3.2 km to the southwest.

species-station matrices were not provided, precluding assessment of pre- and postdrilling species composition. Although Menzie (personal communication) states that a high degree of overlap in species composition was present in the two surveys, supporting data are not provided to permit evaluation. Predation of motile epibenthic animals can exert an effect on infaunal density, as pointed out by Menzie et al. (1980). Despite the observed attraction of epibenthos and demersal fish in the immediate vicinity of, and downcurrent from, the well, it seems unlikely that the drilling activity could act as a sufficiently large attractant to account for the observed changes in density. Furthermore, if it does so, it" is a part of the impact of drilling that must be considered.

Sampling design during the postdischarge survey was somewhat inappropriate for clear examination of patterns and possible changes. Seven of the stations closest to the well site in the predrilling survey were not resampled, but were replaced by four new stations. Moreover, although eight stations were sampled on the 3.2-km ring in the post-drilling survey (Figure 2-4), only two were on the same axes as 1.6- or 0.7-km stations, thus confounding straightforward analytical comparison. Then, for graphical purposes for all except the NE-SW axis, the 3.2-km samples from adjacent auxiliary axes (e.g., stations 55 and 60, or 56 and 57) were averaged to provide a comparative value for the principal axes. Two possible problems with this are that (1) the values of the two samples taken on auxiliary axes in the SW quadrant were diluted by pooling them with samples farther removed from the axis of the primary drilling mud plume, and (2) the comparative impact of samples 57 and 60 were exaggerated because they were both used twice (Figure 2-4; Menzie et al. 1980, Figures 10, 12, 15, 17, and 19). Actual values were presented in tabular form and were used in an undefined manner in the statistical (correlation) analyses.

Thus, our conclusions are that the effects of that exploratory well may have been far more extensive than was described by Menzie et al. (1980), possibly extending farther in some directions than the 3.2-km ring. Lack of synoptic controls (Figure 2-5) precludes determination of the extent of observed changes, whether localized and due to the drilling operation or resulting from some geographically widespread phenomenon. However, fluctuations of this magnitude probably are not typical of benthic communities at depths greater than 100 m (Dr. Don Maurer, University of Delaware, personal communication; Dr. Fred Grassle, WHOI, personal communication).

Recent information adds a further complication to the interpretation of these data. Menzie (personal communication, 27 January 1981) brought up the possibility that another well had been completed nearby shortly before this study commenced. G. deHoratiuus (U.S.G.S., Washington D.C., personal communication) confirmed that a well was spudded in Block 684 in March 1978 approximately 3.2 km {2.0 mi) north-northeast of the study well (Figure 2-5). Six other wells were begun between April 1978 and April 1980 in an area 14 to 18 km (9 to 11 mi) northeast of the study well. Quite possibly these wells may "have contributed to the areal extent of apparent reductions relative to controls, particularly to the east-northeast that are seen in Figure 2-5. The proximity of these wells, in the absence of additional data and synoptic control areas, seriously confounds interpretation of these data. It must be noted that analyses of data from the predrilling survey did not provide evidence that nearby drilling operations had affected benthic conditions (e.g. , benthic abundance and community structure, or Ba in sediments) within the 3.2-km diameter around the study well site (C. Menzie, personal communication) . However, the sampling design was not oriented toward that objective.

Finally, based on our experience in lower Cook Inlet, our review of all available literature, and consideration of the quantities of materials involved, it is our opinion that the effects of discharge of drilling fluids from a single well probably could not cause an impact of the magnitude indicated by Figure 2-5. However, the data presented in the available reports do not provide a convincing argument that such an impact did not occur, and, further, these results may well have been compromised by other drilling in the area and analytical methodology. Based on our review of the available data, we cannot discount the possibility that such an impact may, in fact, have occurred, either (1) solely as a result of that single drilling operation, or (2) as a combined effect of the several drilling operations that occurred in the general vicinity, or (3) as a result of exploratory drilling and other disposal activities. Therefore, for the sake of conservatism in our subsequent impact projects (Sections 3.3 and 4.4) we have assumed the possibility of impacts up to 3.2 km downcurrent from a well site in environments similar to that at the mid-Atlantic site. We are hopeful that forthcoming more detailed analyses of data from surveys immediately and 1 year following this drilling operation will more sharply define the geographical extent, ecological consequences, and long-term ramifications of effects of this well and will evaluate the potential interaction of these effects from those with other wells in the vicinity.

2.4.3.3 Beaufort Sea Studies

Crippen et al. (1980) used a graduated radial grid (similar to that subsequently used by Mariani et al. [1980]) to sample sediments and benthos in the vicinity of an artificially constructed gravel island drill site in the MacKenzie River delta. Benthic infauna (from grab samples) showed reduced densities in the vicinity of the island (within 300 m). However, this reduction was attributed primarily to the disturbance during excavation of local bottom sediments to build the island during the previous year and to ongoing sedimentation from the rapid erosion of the island. The primary complication in this study was the inability to separate effects on the benthic community resulting from island construction and erosion from those caused by the drilling fluids discharged.

2.5 GENERIC IMPACT SUMMARY AND INFORMATION NEEDS

This section attempts to summarize the current state of knowledge with respect to the probable and potential impacts of offshore drilling in north temperate and subarctic OCS lease areas. This discussion is based on a synthesis of the entire body of information in Sections 2.1 through 2.4. Areas where information Is incomplete or lacking altogether are identified throughout the discussion (and are summarized in Section 2.5.3).

The effect of any pollutant discharged to the natural environment can be thought of in terms of acute (lethal) and chronic (sublethal) effects acting over varying periods of time. Furthermore, these effects can be either due to chemical or physical properties of the discharges. Finally, the effects can lead directly to mortality or can reduce the organism's fitness (ability to survive and reproduce) in more subtle ways.

The bulk of materials present in drilling fluids are relatively nontoxic chemically but contribute to high suspended solids levels. Other materials present such as heavy metals, biocides, and petroleum hydrocarbons may be highly toxic. They may also accumulate in tissues and be passed to higher trophic levels.

Although volumes and chemistry of mud and cuttings discharged to the marine environment vary widely, for the purpose of this generic discussion total discharge volumes of 300 m^3 of cuttings and 500 m^3 of whole drilling muds are assumed. This represents roughly 800 mt of cuttings and 300 mt of dry mud components. The dry mud components would occupy a volume of some 100 m^3. The trace metals concentrations in drilling muds vary by as much as an order of magnitude between various monitoring studies reported in the literature. For purposes of this generic impact discussion, the concentrations measured in the mid-Atlantic study, which appear to be reasonable and tending toward the higher side of the range of reported values (Ayers et al. 1980a), will be used.

During initial drilling, cuttings will be discharged directly at the seafloor, probably forming a cuttings pile in most environments. Drilling fluids and cuttings discharged in the water column (after the conductor pipe has been set) offshore have been shown to separate into two relatively distinct components (Section 2.2 this report, Ray and Shinn 1975; Ayers et al. 1980a, b). Each of these components or plumes has its primary effects on a different component of the marine biosphere. The upper or near-surface plume, containing liquids, finer silts, and clays with low settling rates, affects drifting or free-swimming (planktonic or nektonic) species of the mid to upper (pelagic) portions of the water column. The lower or bottom-impinging plume, containing the bulk of discharged solids including cuttings, adhering muds, and flocculated clays, affects benthic and demersal species living in, on, or in close association with the bottom. Thus, these two areas of potential impact are treated separately in the following sections.

2.5.1 Pelagic Impacts

All field and modeling studies reported to date have indicated that high rates *of* dilution of drilling fluids (on the order of 10,000:1) occur within a relatively short distance (e.g. , 100 m) of the discharge point (Section 2.1.1.1 this report, Ray and Shinn 1975, Dames & Moore 1978a; Ray and Meek 1980). Under low to moderate discharge rates (10 bbl/hr or less), substantial dilutions (500 to 1,000:1) have been measured within 3 m of the downpipe due to flushing water added to the mud system, "pumping" within the discharge pipe (caused by passing waves) , and initial dilution beyond the pipe mouth (Ray and Meek 1980).

Several investigators have found that all water quality parameters measured (e.g., temperature, salinity, dissolved oxygen, suspended solids, transmittance, trace metals) except suspended solids approach background levels within about 1,000 m of the discharge in areas of relatively low current (Ray and Meek 1980; Ayers et al. 1980a, b) with a gradual settling of the surface plume at greater distances. In an environment of much stronger currents (lower Cook Inlet), a measurable decrease in water transmissivity was reported at distances in excess of 10 km from the discharge point with dilution occurring relatively more slowly beyond the 10,000:1 achieved at 100 m (Houghton et al. 1980a). These reported results include tracking of high volume and high rate discharges approaching the maximum rates (up to about 700 bbl/hr) that occur for short periods infrequently during drilling operations (20 min two to three times per well up to 3 hr once at the end of the well, Table 2-8). Thus, a reasonable scenario that can be used to estimate the dose that could be received by various organisms during high rate discharges is described below.

A 100-percent whole mud discharge (containing 250,000 ppm solids) is diluted 500:1 (to 0.2 percent [2,000 ppm] whole mud; 500 ppm suspended solids) within a few meters downcurrent *of* the downpipe. Within this zone, whole mud concentrations exceeding measured 96-hr LC_{50} values for many species could be experienced for Up to 3 hr by species actively swimming to maintain themselves in the plume. Lawrence and Scherer (1974) found that under certain circumstances, in fresh water, fish may be attracted to a drilling fluid plume. The likelihood of significant numbers of nektonic organisms remaining in this area long enough to suffer mortalities or other irreversible stress is none-the-less remote because of the limited size of the near-field discharge area and the intermittent nature of the high-volume discharges.

In the zone between a few meters and 100 m frau the discharge, concentrations would decline to about 100 ppm whole mud or 25 ppm suspended solids. At 100 to 200 m from the discharge, concentrations of total chromium, after barium the most abundant heavy metal present, would be reduced from 200 $\pm$ ppm in the liquid whole mud to about 20 ppb assuming complete association with the surface plume. The majority of these metals would be in forms that are of limited bioavailability. Within this zone, concentrations exceeding measured 96-hr LC_{50} values for the most sensitive species and the most toxic muds tested to date could be experienced infrequently, again for up to about 3 hr, by active swimmers choosing to maintain themselves in the plume. The likelihood of this occurring is somewhat less remote given the known tendencies of fish to congregate around offshore rigs, but is still very low. The limited duration and frequency of these high volume discharges (Table 2-7) would again make the likelihood of significant mortalities or stress extremely remote.

Beyond 100 m from the discharge, although concentrations will not drop as rapidly, they will be further reduced below 96-hour LC_{50} values for any tests reported to date. Thus, no acute effects are likely in this region.

Routine, near-continuous discharges (from the shale shakers) during drilling are of much lower rates and volumes than those described above. Because of the volume of flushing water entering the system's various components, concentration of suspended solids at exit of the downpipe are on the order of 100 to 1,000 ppm (Houghton et al. 1980a). Thus, organisms remaining within a few meters of the discharge can receive a long-term exposure to concentrations that exceed those found to be lethal to the most sensitive organisms bioassayed to date. This corresponds well with the results of Benech et al. (1980) who found significant alterations in the nature of the rig-fouling community within about 10 m of discharges although they attributed observed effects primarily to smothering (see Section 2.4.2).

Probably few, if any, nektonic organisms would remain in this near-field dilution zone long enough to experience a lethal dose from continuous discharges occasionally interspersed with higher volume discharges. However, in areas with relatively moderate currents such as some parts of Georges Bank, fish congregating around the drilling vessel could experience some degree of sublethal stress unless they actively avoided the plume. Degree of avoidance or attraction of motile organisms to drilling muds (which may be slightly elevated in temperature) has not been adequately explored. In any case, only a negligible fraction of the population of any given species in the region of the drilling activity would be at risk to such sublethal stresses. In the central portion of lower Cook Inlet, with its strong, reversing currents, there is little likelihood of any fish (or other nekton) remaining in the vicinity of a drilling vessel for a significant period of time (more than a few hours or days).

Planktonic organisms would receive a maximum exposure to drilling effluents if entrained in the plume at the downpipe during a bulk discharge. Within a matter of seconds the organisms would go from a concentration of 50 to 100 percent mud (depending on dilution by flushing water) to about 0.2 percent mud. Subsequent dilution to about 100 ppm whole mud would occur over a period of about 3 min with a 0.5 m/see (1 knot) current or 30 min with a 0.05 m/see (0.1 knot) current. Exposure to this rapidly declining dose has not been attempted in laboratory tests. However, based on longer term, constant dose tests (Carls and Rice 1981; Carr et al. 1980), it is possible that the high initial concentration could cause some mortalities of crustacean plankton, including shrimp and crab larvae, if they entered the plume at a highly sensitive stage of ecdysis (molting). Carls and Rice (1981) reported that the most evident immediate response of larval crustaceans upon exposure to high concentrations of whole muds was to reduce swimming activity; however, significant numbers did not cease swimming until exposed to relatively high concentrations for at least 4 hr. Thus, the rate at which larvae lost their ability to swim was slow (*cf.* that seen with some other toxicants, e.g., petroleum hydrocarbons) and they might well have little or no reaction to so brief an exposure. Sensitivity of fish eggs or larvae to drilling fluids have not been reported in the literature but are likely to be no greater than those of larval crustaceans and their exposure would be similarly brief. The percentage of any plankton populations potentially affected would be negligible because of the narrow width and depth of the discharge plume and the brief duration and low frequency of mud dumps of this volume at any well.

Significant bioaccumulation of heavy metals in planktonic or nektonic organisms is not expected due to their high mobility and the nature and duration of the discharges. The lone exception may be found in populations of fish that are attracted to and remain in the vicinity of the drilling vessel for a period of several weeks or months. In some environments fish may browse or otherwise feed on rig-fouling organisms that may contain elevated levels of some metals. These fish could therefore experience some increase in tissue levels of heavy metals although uptake of heavy metals from drilling fluids by fish has not been documented in the literature (Section 2.3.4). The significance of increases in body burden of heavy metals to the organism is poorly understood but is specific to the metal(s) in question. In areas where rig-associated fish are subject to sport fisheries, some fish could contain elevated metals levels that could be due, in part, to drilling discharges. This would be most likely to occur around a production platform where a number of wells may be drilled over a period of several years.

In summary, based on all available information, it appears that the likelihood of significant impacts on pelagic plankton and nekton from drilling mud and cuttings discharges is remote. The potential exists and remains to be explored that some rig-associated fish could incorporate some heavy metals into their tissues.

2.5.2 Benthic Impacts

The degree of impact of drilling fluids and cuttings on benthic and demersal species is highly dependent on a number of local environmental variables (depth, current and wave regimes, substrate type, etc.) and on the nature and volume of the discharges including cutting sizes and the depth of the downpipe. Impacts can be considered to fall into two relatively distinct categories: acute effects of mud toxicity and burial by mud and/or cuttings; and longer term effects of chemical contamination and physical alteration of the sediments.

The extent of the seafloor area where accumulation rates of cuttings and mud are great enough to cause acute stress or mortalities to benthic or demersal organisms (either due to burial or toxic effects) will vary with the factors mentioned in the previous paragraph. Extremes would range from the situation in central lower Cook Inlet, where dynamic conditions precluded formation of any cuttings pile and where cuttings are widely dispersed and entrained vertically into the seabed (Houghton et al. 1980a), to the Gulf of Mexico where cuttings piles typically 1 m in height and some 50 m in diameter are reported (Zingula 1975). Menzie et al. (1980) reported the zone of visible cuttings from the mid-Atlantic C.O.S.T. well was 150 to 170 m across on one axis traversed by underwater television. In very dynamic areas, both in situ bioassays and benthic sampling have shown little evidence of effect on infauna or on epibenthic crustaceans at distances of 100 m or greater from the well. However, even in these very dynamic areas, near complete disruption of benthic communities within 25 to 50 m of the well must be assumed due to seafloor discharge of cuttings during placement of the collector pipe and due to placement of the baseplate, if used. In the Gulf of Mexico situation, fewer motile organisms buried under cuttings piles would surely be killed. However, effects around and beyond the periphery of the piles and rates of recovery have not been well studied. An intermediate situation, similar to that expected over parts of Georges Bank and in deeper parts of lower Cook Inlet, is expected in moderately deep water (100 m and deeper) where currents are moderate to strong. A patchwork pattern of muds and cuttings accumulation is expected to occur and be accompanied by significant reductions in infauna in areas where accumulations are most evident. Physical and chemical changes due to the discharges may be detectable up to 2,000 m downcurrent from the well site.

The sphere of direct Influence may thus range from total mortality for infauna over a 2,000-m^2 area (50-In diameter) to fairly subtle and patchy changes over a much larger area (on the order of 1,000,000 m^2 or greater). In this latter case, changes in infauna may result from direct mortalities due to burial or chemical toxicity, or from inhibition of recruitment because of altered sediment characteristics (e.g. , increases in coarse cuttings near the rig or clay fraction at some distance from the rig). These sources of effects may act synergistically so that in reality it is impossible to identify a single factor as responsible for a measurable impact. In a practical sense, short-term impacts are measurable as changes in species composition, abundance, or biomass. In the short- and long-term, altered species composition and abundance could occur due to inhibited or enhanced larval recruitment to the benthos. Longer-term impacts in the vicinity of a well might be evident as reduced growth or reproductive potential, or increased incidence of morphological or physiological aberrations. These latter types of impacts, should they occur, would be difficult to detect, and would probably only be apparent in species for which substantial morphological and physiological information is available (e.g., sea scallops and lobster). Resultant changes may include increases or decreases in individual species abundance depending on their substrate and chemical preferences and tolerances. Thus, the severity of the impacts is inversely related to the hydrodynamic energy level of the area, but the areal extent of the impacts is directly related to the area's energy level; i.e., in low-energy environments a severe impact will be felt by infauna over a small area, in higher-energy environments lesser impacts (partial mortality, changes in species composition) will occur over larger areas.

Epibenthic fauna (including demersal fish) is unlikely to suffer any direct mortalities. Debris dropped to the bottom (including fouling organisms from the rig and anchor chains) or increased microrelief of bottom topography (due to cuttings or mud accumulations) may tend to increase densities of epibenthos. On the other hand, changes in the physical or chemical nature of the bottom may preclude use of the area for some critical biological activity, for example by increasing the silt content in coarse sediments used for spawning. Local reductions in productivity of infaunal prey organisms will also affect epibenthic species.

Effects described above are those that are likely to occur over a relatively short period--during and within a few weeks or months following drilling activity. Effects resulting from physical alteration of the bottom, e.g., cuttings or mud accumulations that change sea-floor topography and/or grain size, will tend to revert toward their predrilling conditions at a rate directly proportional to the rate at which natural processes are affecting the bottom. In an area such as the central portion of lower Cook Inlet, currents are so strong that no accumulation of mud or cuttings is possible. Cuttings are entrained into sandwaves of approximately similar particle sizes moving along the bottom and finer materials, including muds adhering to cuttings, are picked up by the currents and dispersed widely from the drill site. Within a very short period of time (a few weeks) it is unlikely that mud or cuttings would be detectable at the drill site.

At less dynamic sites, where cuttings and mudcake discharged exceed sizes transportable by normal bottom currents, return to predrilling conditions will occur more slowly. In shallow waters, severe storms will resuspend mud and disperse cuttings, working them into the finer ambient bottom sediments, In deeper waters where little wave surge is felt, biological activity will mix drilling deposits with natural sediments and natural deposition of coastal sediments will continuously dilute cuttings and mud. However, many years may be required before overburden completely isolates the drilling deposits from biogenic reworking.

Presence of cuttings is unlikely to have any significant adverse effect other than very localized burial of some infauna. The 300 m3 of cuttings produced from a typical well, if spread evenly 0.5 cm deep, would cwer an area of 60,000 m^2 (6 ha or 14.8 acres) perhaps killing a majority of infauna present and significantly altering its future character (not necessarily adversely) due to increased coarseness of materials. This assumed area is considerably larger than the largest area of visible cuttings accumulation reported in the literature. Within one to several years the cuttings and their associated impacts would likely be undetectable in most environments due to resuspension and transport and to working of cuttings into the bottom.

Physical effects of drilling muds deposited on the bottom will be short-lived. However, presence of significant mud concentrations (e.g., greater than 10 percent) in surficial sediments could be expected to have significant adverse effects on the existing infaunal community and could inhibit settlement of many types of organisms (e.g., Tagatz et al. 1980).

The persistence of drilling muds in the surficial sediments is again dependent on degree of current and wave surge felt at the bottom, as well as the rate of biogenic activity. This material is expected to be rapidly dispersed (within a period of a few months) by bottom currents, even in the less dynamic areas of lower Cook Inlet and Georges Bank. Nonetheless, mortality or reduced recruitment of key species could occur, affecting benthic species composition for from 1 to several years. A discharge of 500 m^3 of mud solids from an entire 3,000-m well spread evenly 0.5 mm deep would affect an area of 1,000,000 m^2 (100 ha, 50 acres) assuming (very conservatively) that there is no removal of mud from the area during the duration of the well. In reality, in all environments much of the material will be dispersed beyond the limits of detectability before completion of the drilling (e.g., Meek and nay 1980). It can be concluded that, in moderate to low energy environments, accumulations of cuttings and muds on the bottom have the potential to cause relatively severe impacts on infauna up to perhaps 100 to 200 m downcurrent of the discharge and less severe changes in species composition and abundance as far as 1 to 3 km downcurrent.

In addition to these relatively short-term acute, albeit localized, effects, chemicals present in the drilling muds may be ingested by bottom-feeding organisms and become incorporated into their tissues. The heavy metals arsenic, barium, cadmium, chromium, lead, mercury, nickel, vanadium, and zinc may increase up to one to two orders of magnitude above background in sediments very near (within 100 m of) the drilling rigs. Among other variables, the source and metals content of components comprising the mud system in use, as well as the chemistry of the formations being drilled, govern the relative increases in these various metals. At greater distances (to perhaps 1,000 m downcurrent) more abundant chemicals may be increased to perhaps one order of magnitude or less above background.

Quantities of metals discharged in the course of a typical well (e.g., some 1,378 $\pm$ kg chromium, 33 kg lead, Ayers et al. 1980a) would produce concentrations of 1.38 and 0.033 g/m^2 total chromium and total lead, respectively, if spread evenly over 1,000,000 m^2 (very conservatively assuming all metals are in bottom-impinging plume). If uniformly mixed with the top 5 cm of sediment this would result in an elevation of sediment concentration of about 17 mg/kg for total chromium; 0.4 mg/kg for total lead. The value for chromium is on the order of, and the value for lead is an order of magnitude less than, background values (using total digestion) off the northeastern U.S. coast (ERCO 1980).

During the production phase, corrosion products falling from rigs and/or debris in the water may also slightly elevate levels of other metals (iron, nickel) (e.g., Tillery and Thomas 1980). Formation waters discharged during production may contain metals concentrations greater than those in seawater and may contribute to elevated levels in local sediments and biota (e.g., Wheeler et al. 1980). This, coupled with variability in natural background levels of metals and the difficulty in adequately sampling and analyzing low levels of metal in sediments has confused some past assessments of metals contamination in sediments resulting from drilling fluids discharges (see Section 2.3.4).

There is clearly a need for standardized analytical methodologies for metals in sediments and tissues. Of particular utility would be a means of measuring "biologically available" levels of metals in water and sediments. There is also a need for long-term monitoring of metals levels in sediments and local biota to determine the period required for dispersion and deputation processes to bring levels back within the range of natural variability. In very energetic environments this is expected to occur within a few months to a year. Regardless of the rate of the dispersion process and degree of detectability, virtually all additions of metals to the marine environment will remain there until isolated under layers of natural sediments. The only real significance of such additions, however, is in the degree to which they reduce the "fitness" (ability to survive and reproduce) of local organisms or the degree to which they accumulate in the tissues of local organisms and are transmitted through the food web, affecting the "fitness" of the receptor. This is an area of great need for additional and *very* sophisticated study.

The majority of the total metals discharged with drilling fluids and cuttings is in forms that are tightly bound, either in the crystalline structure of rock cuttings, complexed and adsorbed to clays and organic compounds, or in nonreactive oxidized states. These metals may be essentially biologically inert and their presence of little or no biological concern. However, some fraction of metals released is in a biologically available form. Several studies to date have shown tissue levels *of* barium, chromium, lead, and mercury in organisms from the proximity of drilling mud discharges elevated *over* those from control organisms (e.g., Mariani et al. 1980; Crippen et al. 1980). If bottom conditions are such that metals persist in the sediments at some location (either near the discharge or in a nearby depositional area] accumulations in organisms greater than those measured in studies conducted to date (usually within 1 month to 1 year following the completion of drilling) are possible.

At the present time, the significance of heavy metals accumulations in animal tissues is largely unknown as is the relationship, if any, between these metals accumulations and histopathological or physiological changes in the receptors. Although our present ability to interpret the significance of accumulations of metals in animal tissue is limited, it appears that significant effects due to drilling fluid discharges are unlikely beyond 3 km downcurrent of a discharge site.

2.5.3 Additional Study

Examination of existing literature and the development of conservative (worst case) estimates for environmental impacts indicate that, in general, insignificant impacts would result from drilling mud discharges. While conclusions are expected to remain essentially the same with additional information, the following areas of research may be appropriate in order to supplant the assumptions that *were* made. Information needs that are specific to lower Cook Inlet and Georges Bank are covered in Sections 3.4 and 4.5, respectively.

2.5.3.1 Physical and Chemical Fate of Discharges

Although a large degree of success has been achieved in recent years toward describing the physical and chemical behavior of drilling effluent discharges, several aspects of the problem need to be addressed in more detail. Specific areas warranting additional research include definition of the effects of rig-induced turbulence and flocculation of mud solids of the drilling effluent plume.

The lower Cook Inlet study (Dames & Moore 1978a; Houghton et al. 1980a) demonstrated that in currents greater than 5 cm/see, turbulence induced by the submerged portion of a drilling rig is sufficient to produce a wake which dominates the near-field dilution in the upper plume . Consideration of the effects of rig-induced turbulence has also been recognized as a limitation of state-of-the-art computer models (Brandsma et al. 1980) of such discharges.

Flocculation of drilling mud solids upon discharge to the marine environment appears to be important in the behavior and fate of the lower (solids) plume. In studies in the shallow Alaskan Beaufort Sea (Northern Technical Services 1980), flocculation was believed to dominate the behavior of solids within minutes (probably within 10 rein) of bottom encounter. Although the flocculation process was not addressed in any detail in either the lower Cook Inlet (Dames & Moore 1978a) or the Tanner Bank studies (Ecomar, Inc. 1978), Ayers et al. (1980) attribute this process as being a likely explanation of differences between predicted (computer model results) and measured deposition rates and patterns in their recent studies. Although the general mechanisms for flocculation are somewhat understood, more research is warranted to describe the floe size, settling rates, and behavior upon bottom encounter.

2.5.3.2 Biochemical and Biological Implications

In view of the predominant association of anthropogenic inputs of trace metals with particulate, and the tendency for some portion of these to be concentrated on the seafloor rather than being dispersed by currents, it is important to ascertain the degree and nature of availability of such metals to filter- and deposit-feeding organisms. Similarly, improved methods of chemically measuring the biologically available fraction of particulate-associated metals are needed and should be applied in a standardized way to all scientific studies.

The biological (and subsequent ecological) impact of unnatural bioaccumulation of trace metals should be investigated. specifically, there is need to know more about the degree to which such bioaccumulation affects the survival or reproduction of marine organisms. It must be determined whether, and to what degree, the excess metals bioaccumulated from drilling fluids and cuttings by lower organisms are passed through marine food webs. If such biomagnification occurs, the ways in which this affects the health of higher organisms and their predators, Including man, should be determined.

Much needs to be learned about natural detoxification systems for metals and their limits in marine organisms. For example, the protein metallothionein is believed to act as a detoxifying agent for excess concentrations of certain metals (e.g., cadmium) in certain tissues (e.g., the liver). However, it is not yet known how much excess concentration of a given metal can be bound by this protein before "spillover" into the enzyme-containing high-molecular weight protein pool occurs, how such blending is affected by the physical/chemical state of the metal, nor how such limits vary between different kinds of marine organisms. In addition, preliminary evidence suggests that some metals (e.g., lead) may not be bound by metallothionein (D. Brown, personal communication). If this is true, investigation would be appropriate for other metal detoxification systems that have not been discovered. In the next few years, it is possible that our present ideas regarding the relative toxicity of metals may require total re-evaluation.

Further, a number of studies performed during the last decade suggest that hydrocarbons can interfere with the metabolism of metals, altering equilibrium concentrations (Young and Jan 1978; D. Brown, personal communication). Thus, it is possible that organic biocides or petroleum hydrocarbons released with drilling fluid metals may alter the effects thought to be caused by an individual metal. This raises the general question of synergistic effects, not only between metals, but also between different types of contaminants. Obviously, much research effort would be required to address such basic and important questions.

An obvious avenue for exploration of effects of relatively high exposures to drilling fluids, the potential for uptake of contaminants in the natural environment, and possible somatic or genetic impacts lies in investigations of the fouling communities on production platforms during the near-continuous drilling phase. Results could be compared with other rigs or structures where drilling activity has ceased. Rig-associated fish should also be included in such studies.

Long-term colonization studies or applications of dilute mud solutions to existing microcosms *offer* a promising avenue for investigating subtle effects of dilute concentrations of mud. However, care should be taken to avoid conditions leading to misleading conclusions, e.g., build up of mud solids in the test container, unless these conditions are a Part of the experimental objectives of the test. Levels of trace metals and organics (including petroleum hydrocarbons) in the sediments should be documented throughout the tests, and effects of changes in grain-size should be separated from toxic effects of mud components.

Little work has been done on the behavior of marine fish or invertebrates encountering drilling fluid plumes either in the water column or near the bottom. Laboratory investigations (e.g., Lawrence and Scherer 1974), diver observations (e.g., Zingula 1975), and acoustic techniques all hold promise for adding to the available information base.

The sophistication of drilling rig monitoring studies has greatly increased in the last few years but several questions remain unanswered for the deeper water low- to moderate-energy regime case. In theory (Robson et al. 1980) the mid-Atlantic study should have provided an excellent body of information relevant to these situations. However, several aspects of that study are incomplete as of this writing. Reports appearing to date (Mariani et al. 1980; Menzie et al. 1980) do not adequately analyze the available data and do not report other data elements crucial to independent or extended analysis. A reanalysis of these results incorporating the results of a 1-yr postdrilling followup study completed during the summer of 1980 may clarify the significance of impacts of this well.

Simple acute bioassays have been conducted on most major marine species groups at many life stages. Tests on larval fish appear to be lacking from the literature and should be conducted to place their sensitivity relative to other frequently tested groups. Other than this notable exception, further acute bioassays may not be warranted except as a reference for testing possible unique muds prior to discharge.

In all future laboratory and field studies with drilling fluids levels of petroleum hydrocarbons should be investigated along with the standard trace metals upon which much attention has focused. Results of Gerber et al. (1980) and Neff et al. (1980) strongly suggest that diesel oil contamination of muds may be a major factor affecting toxicity.

3. DRILLING EFFLUENT AND EFFECTS IN LOWER COOK INLET

3.1 THE LOWER COOK INLET ENVIRONMENT

3.1.1 Physical Features

3.1.1.1 General

Cook Inlet is a large tidal estuary located on the northwest edge of the Gulf of Alaska in south central Alaska. The axis of the inlet trends NNE to SSW and is approximately 330 km long, increasing in width from 36 km in the north to 83 km in the south. The inlet is geographically divided into the upper and lower portions by the East and West Forelands (Figure 3-l).

The inlet is bordered by lowlands with numerous lakes and major mountain ranges on three sides. Glaciers are abundant throughout most of these mountains, and tributary streams are heavily laden with silt, seasonally contributing heavy sediment loads to the upper inlet. Extensive tidal marshes and mud flats are also common along much of the western and northern margins of the upper inlet.

3.1.1.2 Bathymetry

Bathymetric data for lower Cook Inlet are available from both the U.S. Coast & Geodetic Survey (USC&GS) nautical charts and from the U.S. Geological Survey (USGS). The USGS (1977) data are believed to be one of the best published sources of bathymetric data for the inlet. Additional data are publicly available from the Naval Hydrographic Office or held as proprietary data principally by various oil companies that have conducted seismic investigations on the OCS or state leases.

The bottom topography of Cook Inlet is relatively flat, although numerous shoals and deep channels exist (Figure 3-2). In lower Cook Inlet maximum depths increase from 30 m (16.5 fathoms) just south of the Forelands to over 180 m (100 fathoms) to the east and west of the Barren Islands at the inlet's entrance.

An unusual bathymetric feature of lower Cook Inlet is the occurrence at the head of Stevenson Entrance of a relatively steep slope, the upper limit of which is approximately marked by the 75-m (40-fathom) contour. This feature, referred to as the "ramp," appears to have considerable influence on currents, circulation, and sediment deposition in the lower inlet.

3.1.1.3 Climate

Cook Inlet lies in a relatively mild marine climatic zone, resulting in mild winters and cool summers compared to the interior of Alaska. Air temperatures average from 7 to 16°C in summer and from -7 to -1°C in winter. Relative humidity is moderately high throughout the year, ranging on the average between 70 and 80 percent.

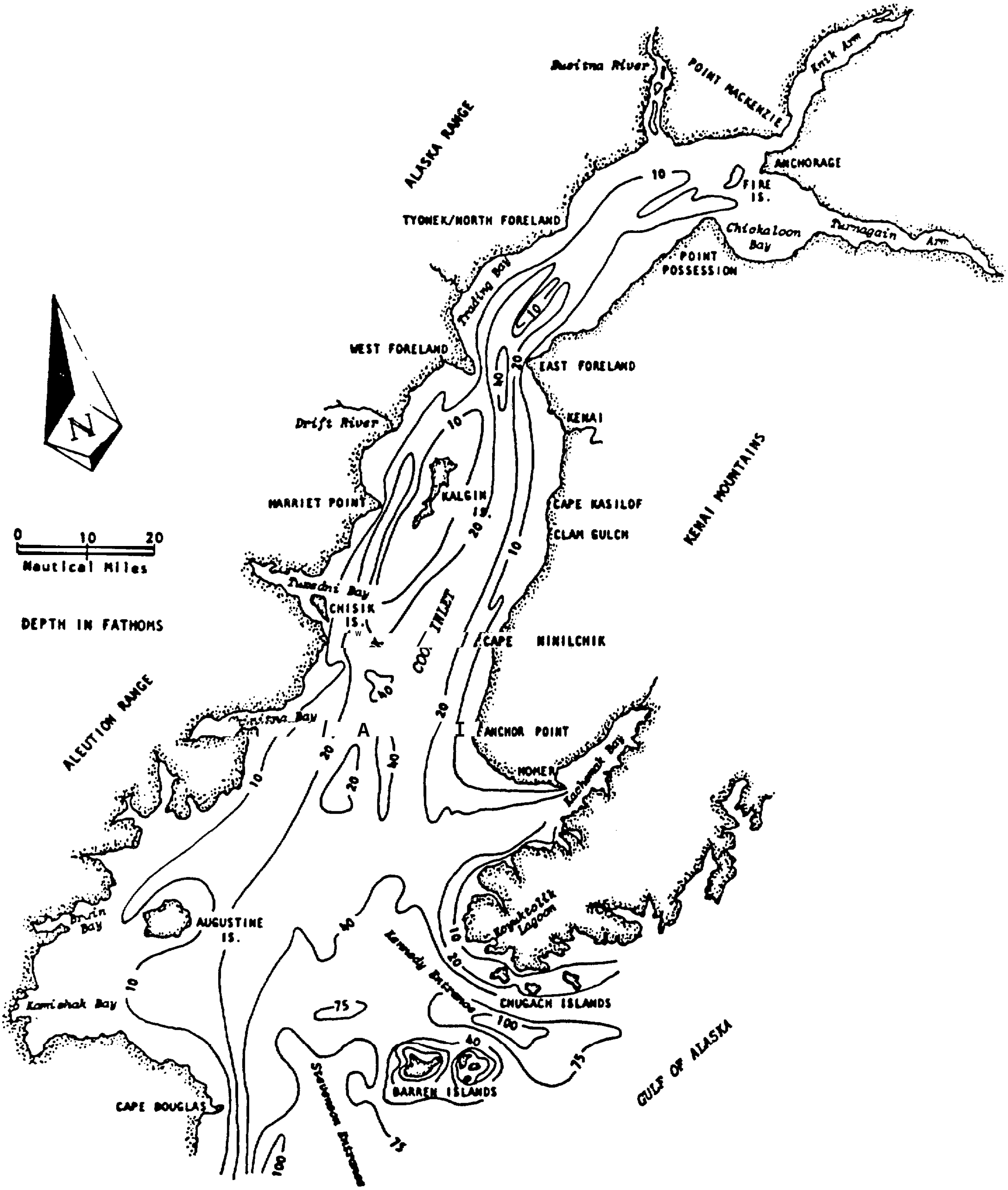


FIGURE 3-1 GENERALIZED BATHYMETRY OF COOK INLET (FROM SHARMA AND BURRELL 1970)

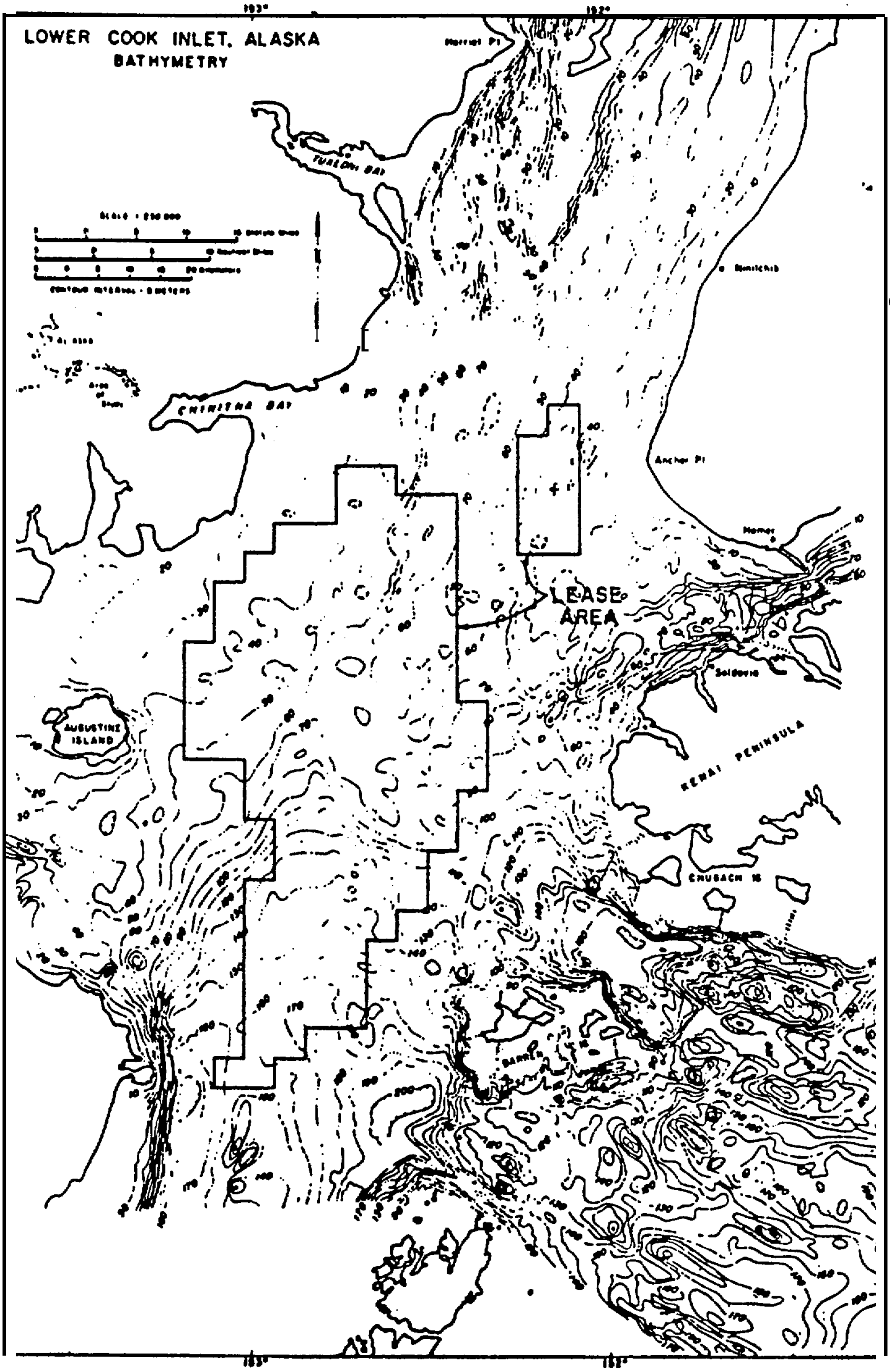


FIGURE 3-2 BATHYMETRIC MAP OF LOWER COOK INLET (FROM BOUMA ET AL. 1978)

The major factors controlling the atmospheric circulation in the region are an elongated east-west trough of low pressure centered in the vicinity of the Aleutian Islands and the positions of the Arctic and North Pacific highs. Orographic influences, however, exert a strong effect on the circulation at any given location in the area. Intense anti-cyclonic conditions, which sporadically bring cold continental air into the area in winter, can result in extremely strong katabatic winds in funneling coastal valleys and mountainous embayments.

Detailed wind speed and direction data for the lower Cook Inlet were collected by NORTEC (1980) for a well site 100 km WSW of Homer. During a November storm, average winds reached 68 knots with gusts to 94 knots, while resulting waves reached 11 m (36 ft). Sixteen other significant wind events (winds >34 knots) occurred from October 1979 through January 1980. Another well approximately 65 km west of Homer reported only two significant wind events during the months of March through June 1980. The maximum winds reported were 36 knots with no gusts.

Data collected by Dames & Moore for a C.O.S.T. well site located 57 km WSW of Homer (Dames & Moore 1978a) indicated lower inlet winds are strongly controlled by orographic effects. Wind speeds at the mid-inlet C.O.S.T. well site were greater than those reported for both Kenai and Homer on the eastern shore. Winds in excess of 30 knots occurred 7 percent of the time at the C.O.S.T. well. Winds came from all three major directions with northeast and southeast predominating.

3.1*1.4 Sea Ice

Snow cover, wind speed, and air temperature are the principal parameters controlling the rate of formation of ice in Cook Inlet. An insulating snow layer of 15 cm is sufficient to halt ice growth (Hutcheon 1972). Ice development in Cook Inlet is also hampered by the occurrence of a number of periods during winter when average daily temperatures are above freezing.

The usual pattern of ice growth in Cook Inlet is for the first ice to form in the upper inlet. The tidal action in the inlet compacts ice in the upper inlet with the incoming tide and flushes it southward with the ebb flow. Ice south of the Forelands is generally open pack with small floes. Pack ice may be found as far south as Kamishak Bay and Cape Douglas along the western margin and Anchor Point on the eastern side of the lower inlet. Large chunks of ice are also set adrift during the breakup of the numerous freshwater rivers which drain into Cook Inlet.

3.1.1.5 Waves

Data compiled and published by the National Climatic Center and the Arctic Environmental Information and Data Center (Brewer et al. 1977) indicate lower Cook Inlet has a moderate wave climate. These sources report wave height at less than 2.5 m from 80 to 98 percent of the time year round. Waves greater than 3.6 m occur 4 to 8 percent of the time; and waves greater than 6 m occur less than 5 percent of the time. It is believed that these data are actually representative of relatively calmer conditions, as most marine operations would avoid adverse weather when possible. Carsola (1975) also investigated wave conditions near the entrance to Kachemak Bay and reported significant wave heights less than 0.6 m (2 ft) occurring approximately 80 percent of the time. Maximum observed significant wave heights were reported to be 2.4 m (8 ft). NORTEC (1980) has documented severe weather and storms causing waves well in excess of 9 m (30 ft), as well as creating a generally confused sea state aggravated by current and tides. Waves of more than 12 m (40 ft) have been reported in the vicinity of the Barren Islands (Ocean Bounty data on file with USGS 1979). Intense westerly winds in excess of 100 knots occasionally funnel through mountain passes in the Kamishak Bay area and create severe sea conditions in the western portion of the lower inlet.

3.1.1.6 Tides

The U.S. Department of Commerce provides daily tide predictions for two stations in Cook Inlet (Seldovia and Anchorage) and corrections for 19 other locations in the inlet. Tides in the inlet are mixed and are characterized by two unequal high and low tides in a period of approximately 25 hr. The normal tidal cycle is completed over about a 12-hr period, although high tide in the upper inlet occurs approximately 4-1/2 hr later than at the mouth.

Tidal data for the upper, middle, and lower portions of cook Inlet can be summarized as follows: mean diurnal tide range varies from 3 m (20 ft) at the mouth to 9 m (30 ft) at the head of the inlet; it varies within the lower portion of the inlet from 5.8 m (19.1 ft) on the east to 5.1 m (16.6 ft) on the west side (Wagner et al, 1969). Extreme tidal ranges produce sea level changes in excess of 12 m (40 ft) at the head of the inlet (Britch 1976).

3.1.1.7 Currents

Currents in Cook Inlet are normally dominated by tidally induced flows . Currents due to wind stress, surface waves, runoff, and ordinary convective and advective processes are more local and of smaller magnitude by comparison (Marine Advisers 1965). Tidally-driven currents reverse direction approximatley every 6 hr in response to the mixed diurnal and semi-diurnal components of change in sea level elevation. Tidal currents are typically 3.8 knots in magnitude at the surface (Wagner et al. 1969) and occasionally reach 6 to 8 knots at topographic narrows (Horrer 1967). There are unconfirmed reports of measured velocities of 11 to 12 knots in localized areas. The high Coriolis force at this latitude, the strong tidal currents, and the inlet geometry produce considerable cross-current turbulence throughout the water column during both ebb and flood tides (Burrell and Hood 1967).

The NOS implemented a tide and current monitoring program for Cook Inlet during the summers of 1973 and 1974, occupying 55 stations throughout the lower inlet. Dames & Moore (1976) estimated average maximum currents by tabulating peak current velocities for all ebb and flood tide conditions (Figure 3-3).

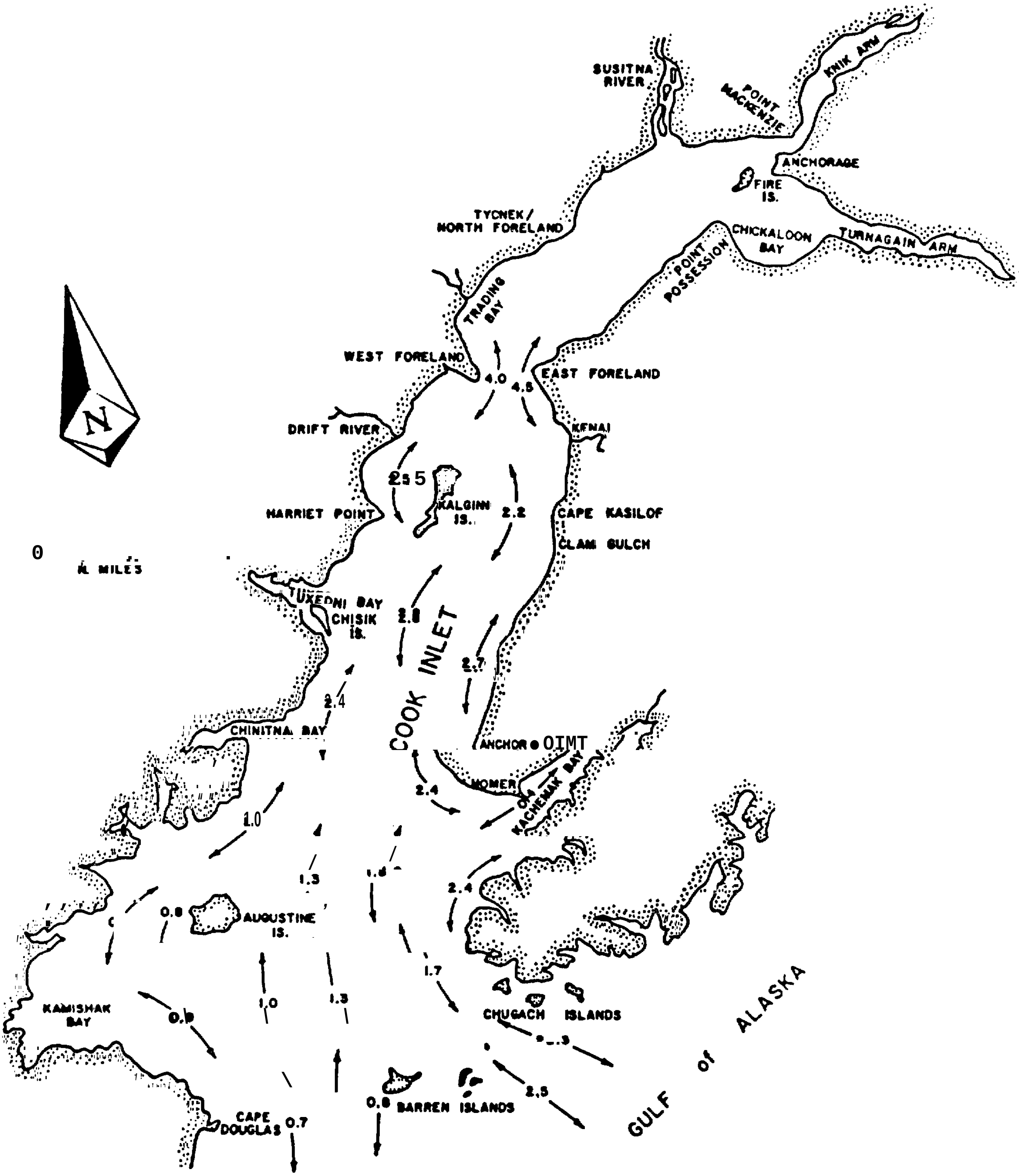


FIGURE 3-3 AVERAGE MAXIMUM SURFACE TIDAL CURRENTS IN LOWER COOK INLET (SPEED IN KNOTS)(FROM DAMES& MOORE 1976)

In conjunction with a study of oceanographic conditions at the lower Cook Inlet C.O.S.T. well, Dames & Moore (1978a) deployed current meter arrays and surface, midwater, and near-bottom drogues. Data from the current meter arrays (Table 3-1) indicate colinear current with maximum surface flood currents flowing in a general NNE to NE direction and ebb flowing in a S to SSW direction. Drogue studies clearly demonstrated this predominantly NNE to SSW tidal flow and also demonstrated the significance of the Coriolis effect by moving through clockwise ellipses in the water column during tide reversals. Near-bottom current meters showed some minor deviations (<20°) in direction of these major current axes and the presence of a third major direction (NE) reflecting local bottom topography.

TABLE 3-1

REPRESENTATIVE CURRENTS AT THE LOWER COOK INLET C.O.S.T. WELL

Depth Below MLLW (meters)	Flood Tide Mean Max. Speed (knots)	Flood Tide Average Direction (° True)	Ebb Tide Mean Max. Speed (knots)	Ebb Tide Average Direction (° True)
14	1.5	35	2.0	225
31	1.2	35	1.3	200
52	100	15	0.8	185

Source: Dames & Moore 1978a.

Examination of tidal data with both the (Lagrangian) drogue and (Eulerian) current meter data indicated currents lag tidal height fluctuations in phase by at least several hours. As an example, during periods of maximum tidal level change, such as the middle of the rising or falling limbs of the tidal cycle, tidal currents are minimal. Conversely, currents reach their maximum speeds approximately 1 hr before either high or low water. This lag in the occurrence of maximum current speed is expected for large embayments with strong tidal currents.

3.1.1.8 Current Circulation Patterns

Large tidal ranges, bathymetry, surface wind patterns, Coriolis effect, water density structure, and shoreline configuration are all important factors governing the complex surface circulation pattern in lower Cook Inlet. Numerous investigators have studied circulation in this region in recent years (Wright 1975; Burbank 1974; Sharma et al. 1974; Gatto 1976). Figure 3-4 depicts the most recent, and perhaps the best, interpretation of surface circulation in lower Cook Inlet. (Most of the available data are for surface circulation; little is known of near-bottom circulation patterns.) Clear oceanic water from the Alaska current enters Cook Inlet through the Kennedy Entrance. As a result of Coriolis forces, intruding Gulf of Alaska waters are diverted offshore and bypass outer Kachemak Bay, flowing northward along the eastern shore of the lower inlet. In the vicinity of Anchor Point a substantial portion of northward-flowing oceanic waters are diverted westward,

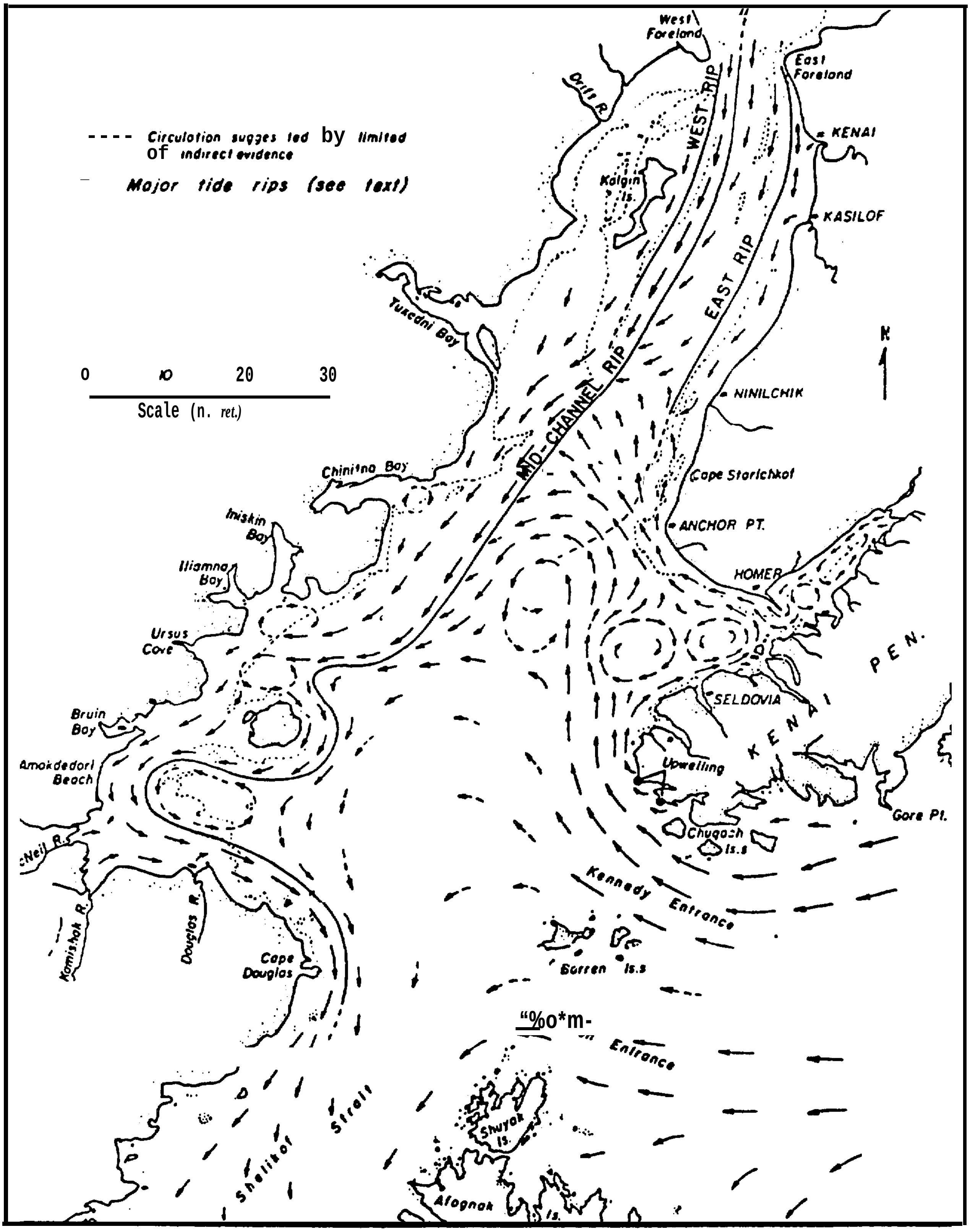


FIGURE 3-4 NET SURFACE CIRCULATION IN LOWER COOK INLET BASED PRIMARILY ON DATA COLLECTED DURING THE SPRING AND SUMMER SEASONS (FROM BURBANK 1977)

producing a counterclockwise gyre in the central lower inlet. A significant amount of the intruding oceanic water continues north and northwest of Anchor Point where it encounters a strong southward flow of turbid, low-salinity water from the upper inlet. The meeting of these two water masses generates a complex series of currents and gyres around Kalgin Island and in other areas of the lower inlet.

Wennekens et al. (1975) discovered a counterclockwise gyre in the waters off the Bluff Point-Homer area, and Gatto (1976) found a back eddy offshore Cape Kasilof. During winter the freshwater input to Cook Inlet is greatly reduced; thus the northward flowing seawater may reach as far north as the Forelands during this season.

Hydrographic surveys of temperature, salinity, and suspended sediment distribution (Matthews and Rosenberg 1969; Kinney et al. 1970, Wright 1970; Sharma et al. 1974) and LANDSAT-1 imagery data (Gatto 1976) indicate ebbing sediment-laden water from the upper inlet flows southward along the western shoreline. A portion of this flow circulates around the west side of Augustine Island into Kamishak Bay. The remainder flows east of Augustine Island past Cape Douglas into Shelikof Strait as a concentrated, warm (at least during summer), low-salinity band (Muench et al. 1978). The NOS current station off Cape Douglas, with a constant 1 to 2 knot southward flow, supports these data.

Dividing the flood and ebb flows are at least three major tidal rips: the west, mid-channel, and east rips. These rips form at frontal zones marking the convergence of water masses and tend to accumulate floating debris. The west and east rips contain relatively small amounts of debris, but the mid-channel rip has been observed to have heavy accumulations including occasional logs and other large debris. The mid-channel rip has also been recognized by some investigators as the approximate division between clear oceanic waters and relatively turbid freshwater outflows (Burbank 1977).

Muench et al. (1978) identified a westerly flow from Kennedy Entrance across the lower inlet toward Cape Douglas paralleling isobaths along the "ramp." This westerly flow is driven in part by the influence of the westerly flowing Alaska Current and in part by the baroclinic field established in coastal waters by inflowing fresh water. This circulation leads to localized upwelling in the central lower inlet and a consequent supply of cold, saline, nutrient-rich water to the surface.

Major alterations in surface transport can be produced by persistent moderate to strong winds. Strong winds have been observed to eliminate the Kachemak Bay gyre systems, and other gyres within the inlet are probably also susceptible. Strong southerly winds persisting longer than 2 to 3 days have been observed to greatly increase northward surface transport in the lower inlet and, as a consequence, generate a strong southward flowing countercurrent at depth (Burbank 1977). Correlation with winds of most regional scale perturbations of lower inlet circulation has, however, been severely inhibited by lack of accurate offshore weather data.

3.1.1.9 Salinity and Temperature

As a coastal embayment, Cook Inlet is subject both to variations in marine source waters and to fluctuations in freshwater inputs from terrestrial drainages. Upper inlet salinities decline rapidly in the summer season to levels Of 6 to 15 ppt near Anchorage due to increased freshwater inflow (Murphy et al. 1972). These values are contrasted to winter salinities exceeding 20 ppt in the upper inlet. Salinities in lower Cook Inlet remain relatively constant at 32 ppt. However, slight summer declines in lower inlet salinities occur and are in part due to the low-salinity coastal current entering Kennedy Entrance from the northern Gulf of Alaska (Muench et al. 1978). As a result of freshwater input, tidal action, the Alaska Current, and Coriolis effect, the water on the eastern side of lower Cook Inlet tends to be more saline than water on the western side. The salinity gradient is more pronounced below the Forelands where intrusion of oceanic waters to north of Anchor Point increases salinities on the eastern side and freshwater discharge from upper Cook Inlet decreases salinities on the western side (Sharma et al. 1974; Burbank 1974).

During winter, water temperatures in the upper inlet cool to near or below 0°C. During spring, freshwater discharge and warmer air temperatures result in warming of the water column and temperatures in the upper inlet can reach 15°C (Murphy et al. 1972). The lower portions of the inlet are affected by the intrusion of oceanic waters that range in temperature from slightly above O* to 10°C. During winter, upper inlet water temperatures typically exceed those in the lower inlet; this trend is reversed in summer. Although smaller seasonal temperature variations are found in lower Cook Inlet, the eastern side of the inlet tends to be cooler than the western side during summer.

Variations in surface salinities and temperatures were also noted to be a function of tidal stage (Gatto 1976). More intense lateral salinity and temperature gradients during the flood tide results from inflows of oceanic waters. On the ebb tide surface waters have mixed, and intense gradients are less apparent.

Several STD vertical profiling stations were occupied by the NOS between May and September 1973, in mid-lower Cook Inlet. These data indicate salinities varied from 32.0 ppt in May to 20.4 ppt in September. Vertical variations between the surface and the bottom averaged 0.5 ppt and ranged from 0.0 to 3.6 ppt. Water temperatures for these same profiles varied from 4°C in May to 11*C in August. Vertical variations in maximum temperature averaged 0.7°C and ranged from 0.0 to 2.0°C in individual profiles; warmer temperatures typically occurred at the surface.

3.1.1.10 Suspended Sediments

Cook Inlet receives large quantities of fine-grained glacial sediments from glacial-fed streams in the Matanuska River system. Discharges from the Susitna River and Knik Arm represent 70 to 80 percent of the total freshwater and suspended sediment flow into Cook Inlet (Burbank 1974). Other sources of sediment include smaller streams and coastal erosion. Suspended sediment is concentrated in the well-mixed northern inlet; it is nearly absent in the water of the east-central and eastern portions of the inlet mouth. Figure 3-5 indicates the generalized surface suspended sediment concentrations in Cook Inlet.

In the upper and lower sections of Cook Inlet, clay and silt-sized particles are kept in suspension by the tidal currents. The circulation patterns in Cook Inlet result in about 80 percent of this fine sediment being transported down the west side of the inlet and into Shelikof Strait where most of it is deposited. Although some deposition occurs in the northern end of the strait, the major area of deposition is in its central portion (Feely et al. 1980). Extreme ranges in suspended sediments vary from 1 to 2 mg/l at the mouth of Cook Inlet (Burbank 1974) to over 2,000 mg/l in Knik Arm (Britch 1976).

3.1.1011 Bottom sediments

Bottom sediments in Cook Inlet vary dramatically from fine glacial silts to cobbles and boulders or rock depending upon bottom current conditions. A general classification modified from that of Sharma and Burrell (1970), Bouma et al. (1978), and BLM (1976) divides the average sediment facies into five components as shown in Figure 3-6.

Facies of coarse or fine sand dominate a large portion of the shoreline and seafloor of Cook Inlet, especially east of the Susitna River, along the shore of the east and west sides of the inlet south of the Forelands and in the central basin of the lower inlet. The deposits in these facies are winnowed Pleistocene-early Holocene gravels, with many of the sand-sized or smaller particles removed and redeposited to the south. In addition, the sediments contain a very thin cover of fine-grained silts and clays which are modern.

Another very important facies, characterized by pebbles, gravel, and boulders, extends south down the middle of the inlet from the mouth of the Susitna River to a line between the northern points of Kachemak and Kamishak Bays. South of this line, patches of this substrate have been observed, especially extending into the sand on the east side and middle of the central basin. Varying amounts of fine sediments fill the interstices of the matrix formed by the sediments in this facies; the amount and fineness varies inversely with the current intensity.

A rock facies appears spordically below the Forelands, especially in association with the pebble-gravel-boulder facies and in shallow water in Kennedy Entrance and in southern Kachemak Bay. Mud is the least common facies and occurs primarily in Kamishak Bay, especially in the numerous embayments and south to southwest of Augustine Island. Mud is also found in Kachemak Bay north of Homer Spit and in the Stevenson Entrance to Cook Inlet.

Hein et al. (1979) state that the clay mineral deposits in the lower Cook Inlet facies are dominated by clay mineral suites from two distinct sources. A chlorite-rich suite from the Copper River dominates the clay mineral fraction in deposits between the Barren Islands and Kachemak Bay. The region to the west and north of Kachemak Bay is dominated by an illite-rich suite contributed by the Susitna River in upper Cook Inlet.

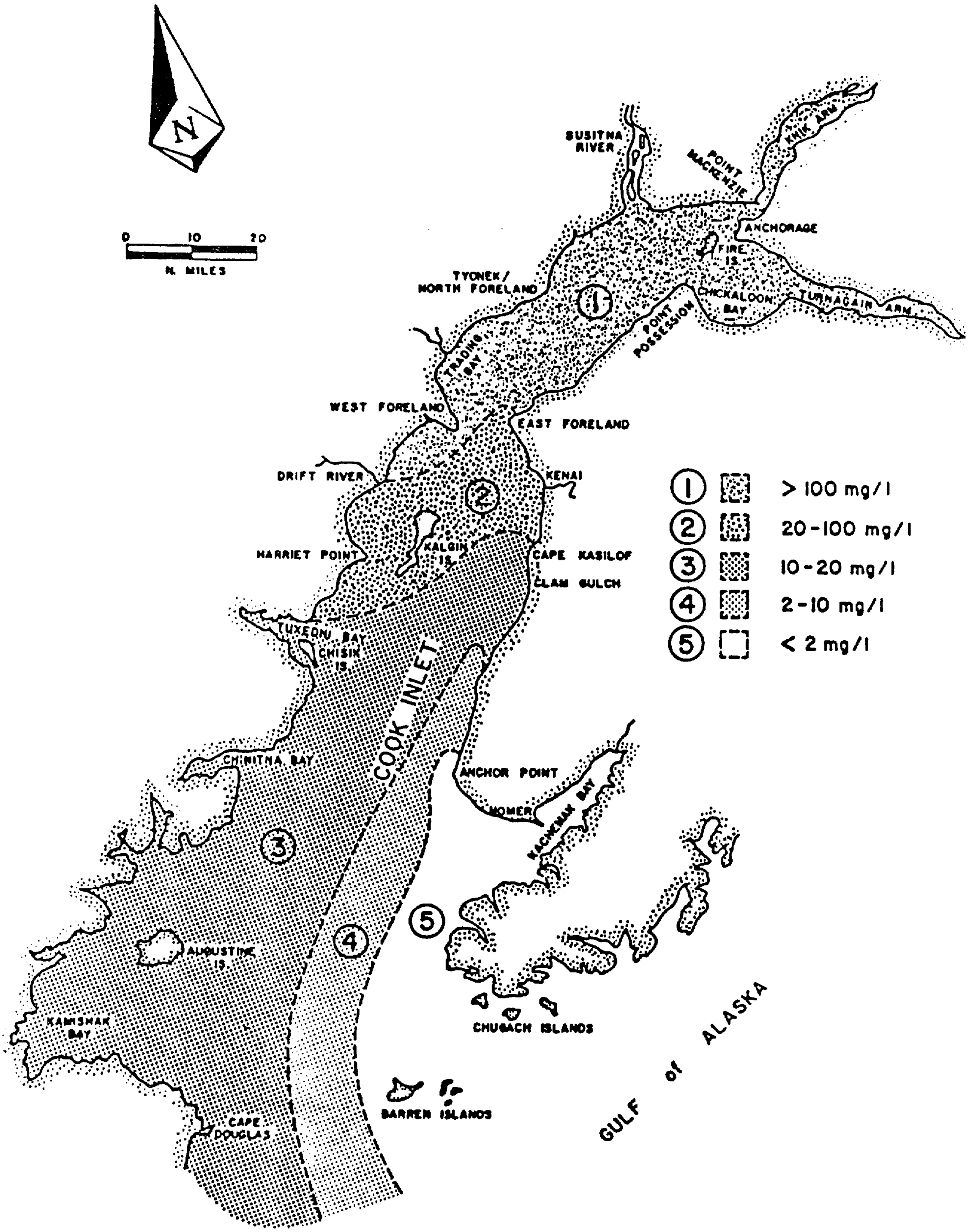
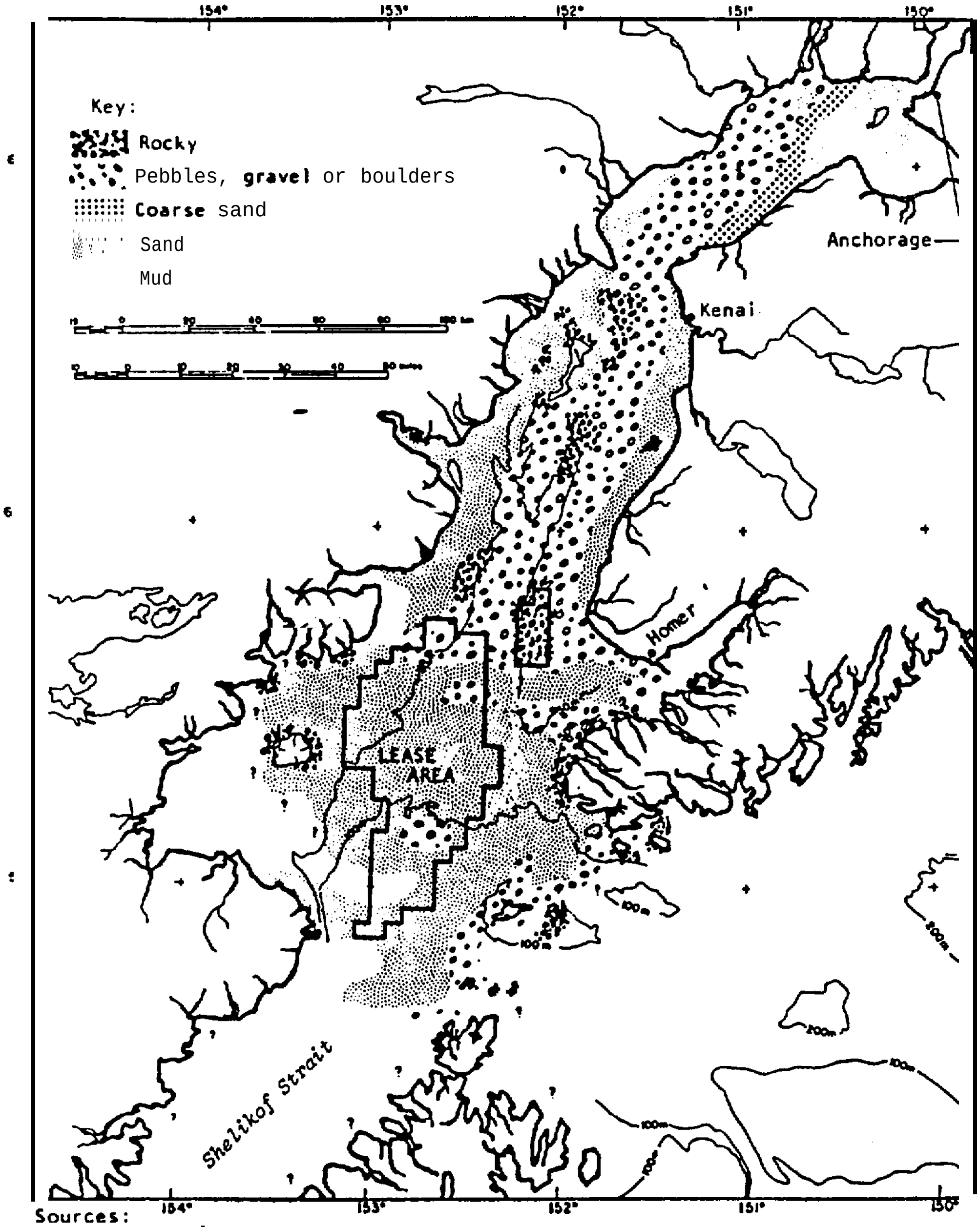


FIGURE 3-5 GENERALIZED SURFACE SUSPENDED SEDIMENT CONCENTRATIONS IN COOK INLET (FROM SHARMA ET AL. 1973)



Sources:
1. Sharma and Burrell 1970
2. Bouma et al. 1978
3. BLM 1976

FIGURE 3-6 BOTTOM SEDIMENT DISTRIBUTION IN COOK INLET

Grain-size analysis conducted in June and July 1976 by the R/V Sounder in lower Cook Inlet indicates that mean grain size decreases from north to south in samples analyzed, while the degree of sediment sorting increases along this gradient. This trend is most likely due to progressive sorting of sediments by current transport and winnowing (Figure 3-7).

Bed conditions in the central portion of lower Cook Inlet are typically sand or gravel waves of three significant size classes. Bouma et al. (1977) distinguished these waves as follows: (1) waves 8 to 15m long and less than 2 m high, (2) waves 50 to 150 m long and 3 to 5 m high, and (3) waves 400 to 1,000 m long and 5 to 10 m high. These sand waves are normally strongly asymmetrical rippled bodies of sand with relatively smooth flanks and sinuous crests.

Although underwater television observations have documented grain motion to 30 cm/sec along sand wave crests and 1 to 5 cm/sec in their troughs, no information is available on the migration of these large sand bodies (Bouma et al. 1977). Variations in asymmetry of the large sand waves and smaller ripples suggest some degree of mobility. The larger bedforms may, in fact, be remnants of higher hydraulic conditions on a geological time scale. Smaller sand ripples are somewhat mobile in the existing flow conditions.

In deeper southern portions of lower Cook Inlet, the bottom is fairly stable as indicated by a considerable attached epifauna of hydroids, bryozoans, and sponges. While clays and silts comprise a large percentage of surficial sediments (40 to 70 percent, Dames & Moore 1978d), these bottom sediments may be periodically disturbed by large storms or other episodic events that create considerable bottom currents (1.5 m/see or greater) even at these depths.

3.1.2 Biological Features

Cook Inlet contains marine biological resources of considerable economic, ecological, social, and aesthetic value. Commercial harvest of fin fish and shellfish is worth approximately $10 million annually to fishermen (Table 3-2) (see also Section 3.1.2.7, Fisheries). This value is more than doubled when total economic stimulus to the region is considered. Saltwater-oriented recreational fishing and hunting is of growing importance while subsistence hunting and fishing are vital to the maintenance of native cultures.

A large proportion of the plant material to support these Important fisheries resources is produced in lower Cook Inlet, especially in its southeastern quadrant (Larrance and Chester 1979; Dames & Moore 1980b). Phytoplankton production is very high in Kennedy Entrance and Kachemak Bay and lower but still important in other portions of lower Cook Inlet. Macrophyte production is also high in Kachemak Bay and Kennedy Entrance but is generally insignificant elsewhere in the inlet.

Because of the migratory nature of most of the commercial species, the fisheries of Cook Inlet probably ●lso benefit substantially from the plant primary production of Shelikof Strait and the Gulf of Alaska. Such

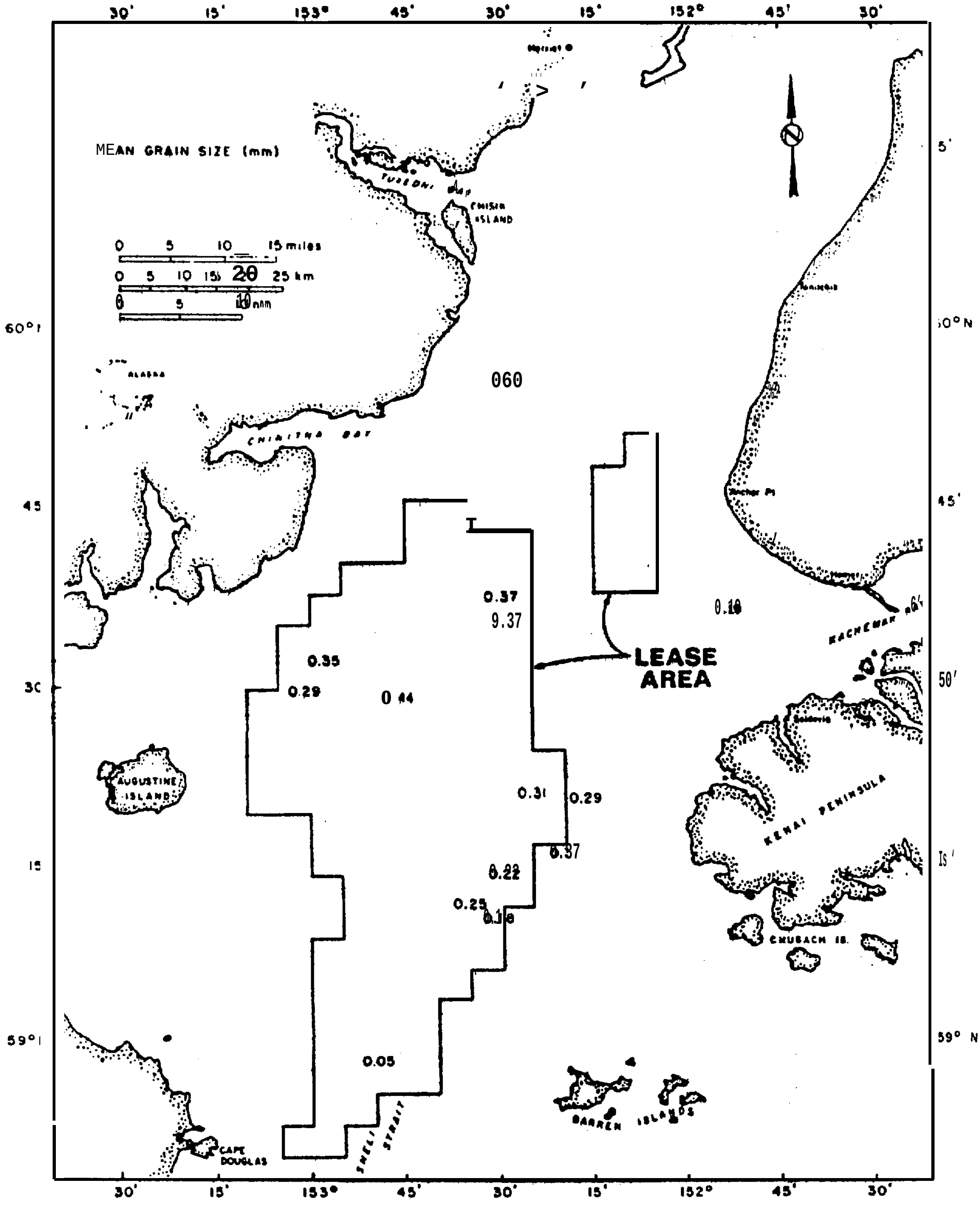


FIGURE 3-7 MEAN SURFICIAL SEDIMENT GRAIN SIZE IN LOWER COOK INLET (FROM DAMES & MOORE 1978a-f/ SHARMA AND BURRELL 1970)

TABLE 3-2

YIELD AND GROSS ESTIMATED VALUE TO FISHERMEN
OF MAJOR FISHERIES IN LOWER COOK INLET, 1978-1980

Fishery/Species	1978 Yield (lb X 10^6)	1978 Value ($ X 10^6)	1979 Yield (lb X 10^6)	1979 Value ($ X 10^6)	1980 Yield (lb x 10^6)	1980 Value ($ x 10^6)
Shrimp						
Trawl	7.185	1.150	4.275	0.962	3.453	1.001
Pot	0.379	0.171	0'.241	0.181	0.741	0.556
Crab						
King(a)	1.181	1.476	1.395	1.339	1.832	1.759
Tanner	5.481	3.015	5.114	2.813	3.846	2.115
Dungeness	1.215	0.851	2.131	1.385	1*661	0.747
Razor Clam	0.045	0.045	.,0.156	0.156	0.132	0.132
octopus	--	--	0.009	0.009	0.008	0.008
Herring(b)	0.959	0.192	0.896	0.180	None	None
Halibut	0.783	1.342	1.044	2.224	Not Available	
Salmon(c)						
King	1.6	0.038	1.3	--	0.4	--
Red	156..4	1.583	66.8	--	66.4	--
Coho	5*9	0.067	1102	--	12.7	--
Pink	353.6	0.470	2,997.5	--	894.8	--
Chum	69.9	0.249	225.1	--	74.9	--
	587.4		3,301.9		1,049.2	
Estimated Value of Total *Salmon* Fishery ($ x 10^6)		2.449		5". 5		1.8
Combined Value of All Fisheries		10.691		14.749		8.118

(a) Preliminary data for 1980.
(b) Value is approximate.
(c) Yield of fish in numbers of fish x 10^3 rather than weight (in pounds).
Sources: Mr. Thomas Schroder, Area Management Biologist, Alaska Department of Fish and Game, Homer, Alaska.
Mr. Richard Meyer, International Halibut Commission, Seattle, Washington.
Bureau of Land Management 1980. Draft Environmental Impact Statement for Proposed OCS Oil and Gas Lease Sale, Lower Cook Inlet and Shelikof Strait, Sale No. 60, Vol. 3, Part 2.

animals as salmon and king crab, for example, migrate seasonally into those areas. In addition, phytoplankton and drifting kelp from the Gulf enter the Cook Inlet system as a consequence of tidal and wind-driven currents.

In turn, the biological productivity of lower Cook Inlet is a major energy source for neighboring ecosystems (Dames & Moore 1977a: 1980b). There are indications that large quantities of drift kelp originating in the lower inlet are carried into the upper inlet where they contribute to the available food base for detritivores (Rick Wright, Governor's Office, State of Alaska, personal communication). There may also be similar transport of materials to deep water areas south of the inlet. The diversity of wildlife in lower Cook Inlet is of considerable aesthetic interest to growing numbers of visitors to the area. Protection of these important resources will be a major consideration during the continued development of the area.

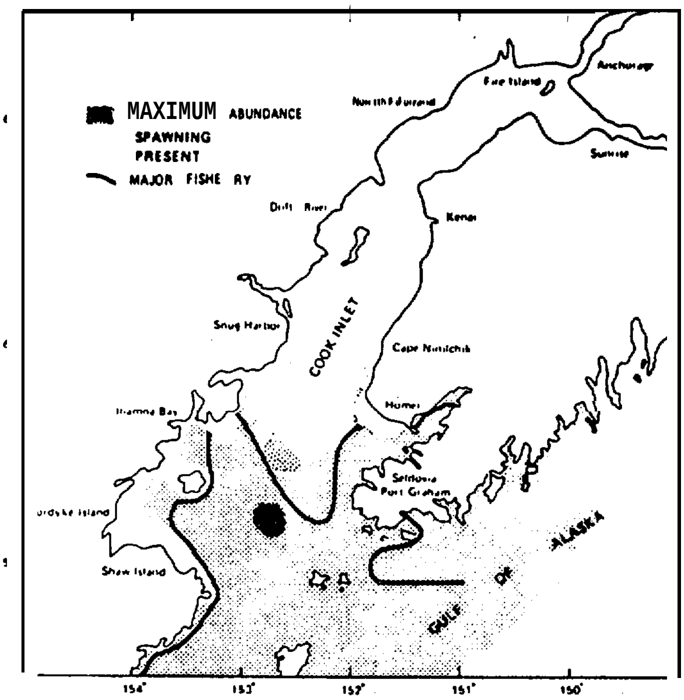
The productive fisheries, on one hand, and plant production, on the other, are linked through broad detritus-based food webs (Feder et al. 1980; Dames & Moore 1980a, b). At the bottom of these food webs are microbial assemblages (Griffiths and Morita 1979). Besides the energy pathways in food webs leading to commercial fisheries, important pathways also lead to other groups 'including marine mammals and birds. The pathways leading to marine mammals and birds are based largely on planktonic herbivores whereas those leading to waterfowl and shorebirds are usually based on detritus-based assemblages.

The lower Cook Inlet lease sale stimulated considerable research on various components of the marine ecosystem of the area. Studies by various agencies and research organizations between 1976 and 1980, while by no means definitive, provide a much greater understanding Of Cook Inlet biological systems than was possible in 1975. Two documents, the "Final Environmental Impact Statement" for the lower Cook Inlet lease (BLM 1976) and the BLM-sponsored "Lower Cook Inlet Synthesis Report" (SAI 1977) have brought together much of the information currently available on the area. Unless otherwise referenced, the information in this section can be found in those two documents.

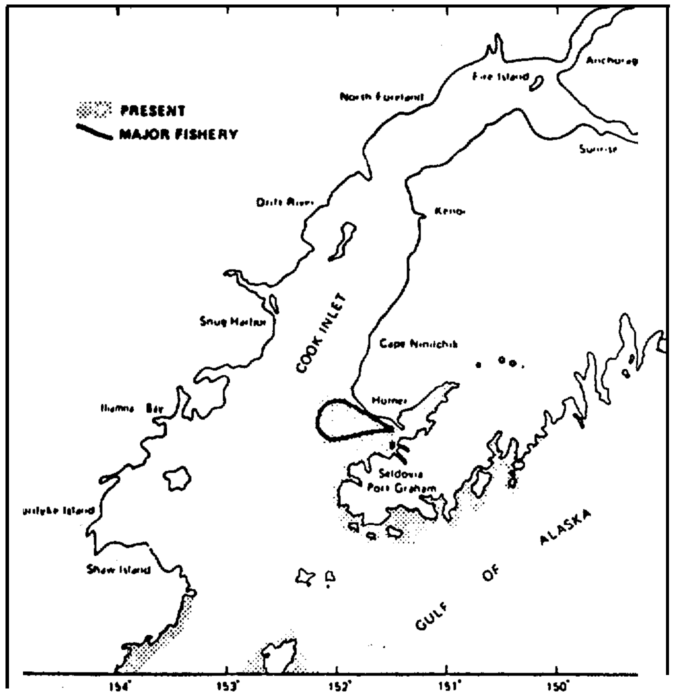
A series of maps (Figures 3-8 through 3-10) based on surveys conducted by Alaska Department of Fish and Game (ADF&G) and National Marine Fisheries Service (NMFS) is presented which summarize known distributions of several commercially important species in lower Cook Inlet. It must be noted that many of the distributions shown are based on very little systematic sampling and that ranges and concentrations of many species extend beyond those shown. Further studies will add to the information available on lower Cook Inlet marine biota.

3.1.2.1 Primary Productivity and Sources of Organic Carbon

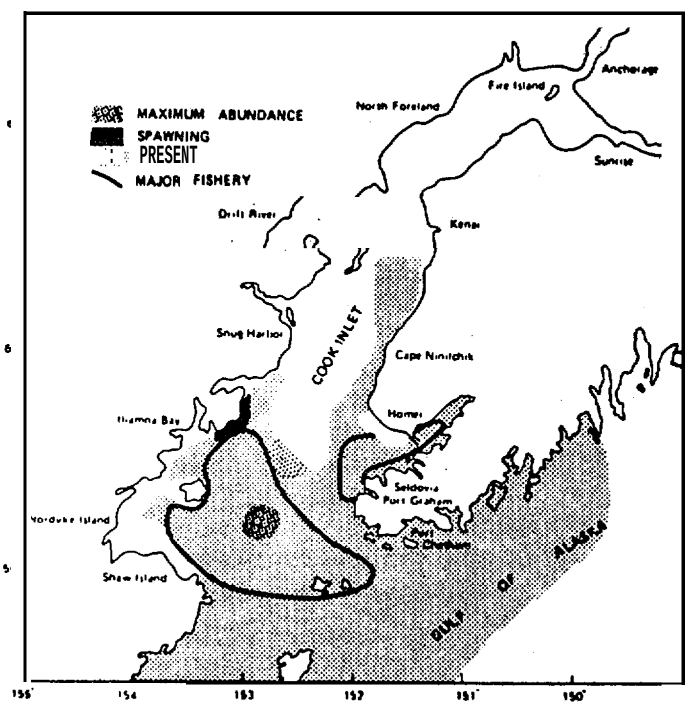
Nutrient-rich oceanic water flowing north through Kennedy Entrance, as shown in *Figure* 3-4, supports high rates of growth by microscopic phytoplankton (primarily microflagellates and diatoms) and large attached kelps in the southeastern part of lower Cook Inlet and in Kachemak Bay. Productivity is far lower in the more turbid waters of the northern and



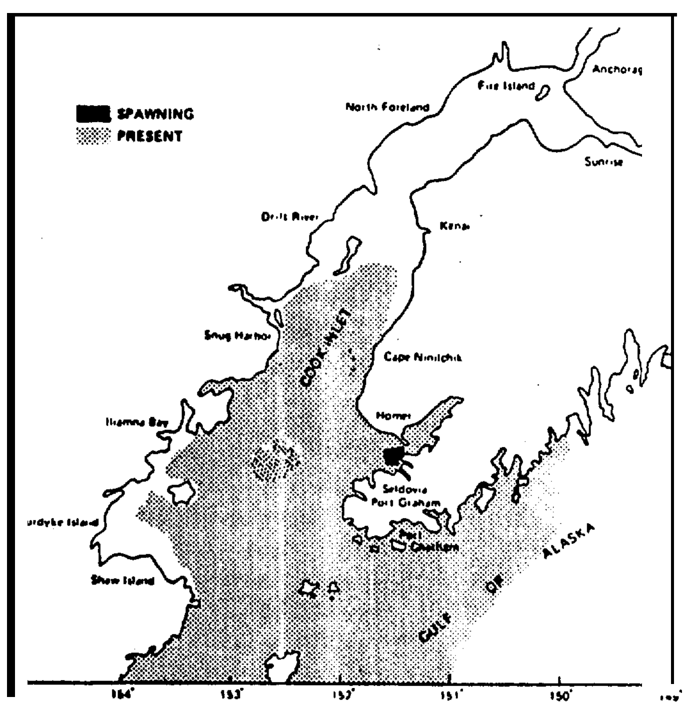
a) KING CRAB (SAI 1977)



b) DUNGENESS CRAB (SAI 1977)

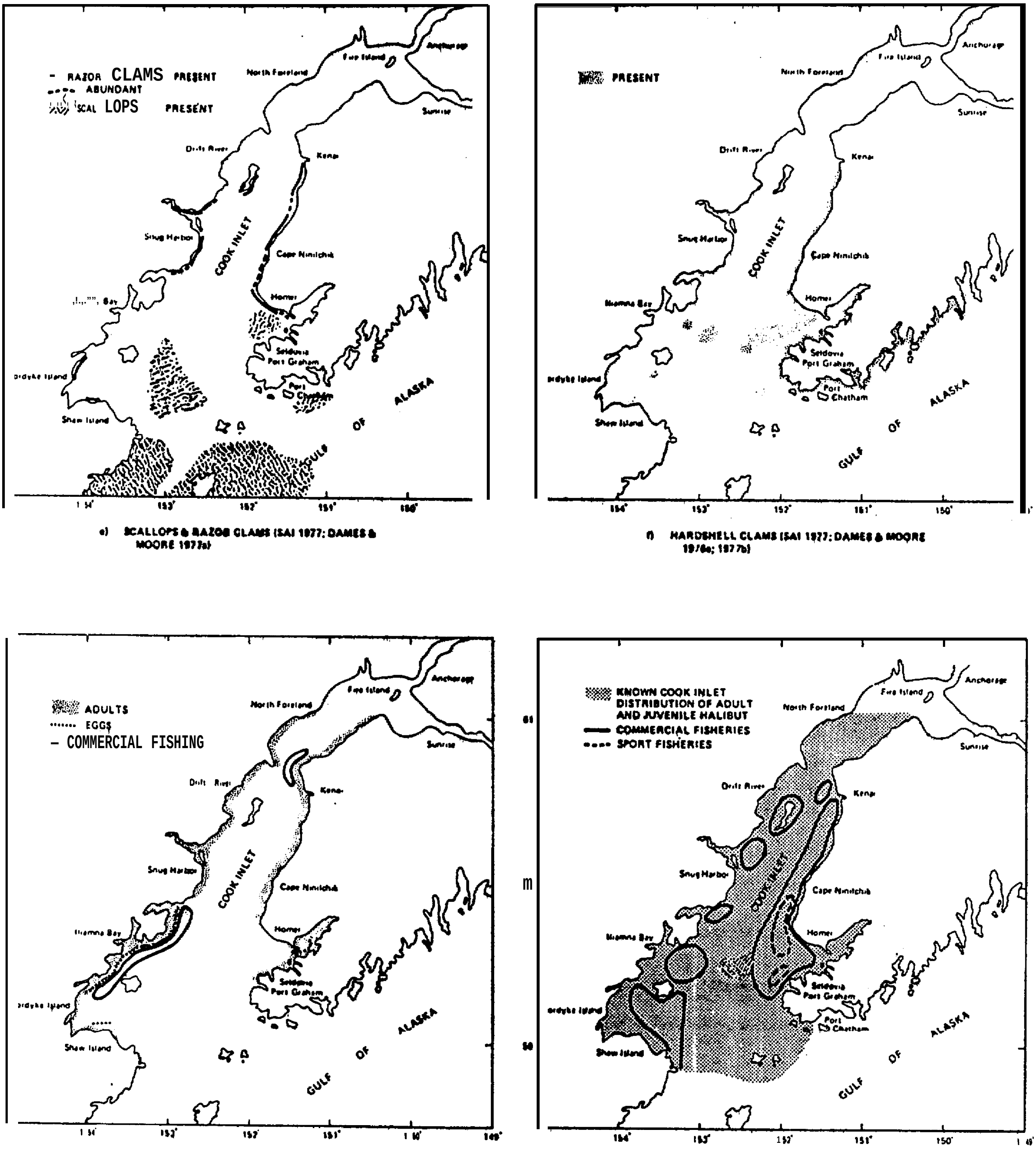


c) TANNER CRAB (SAI 1977; DAMES & MOORE 1977a)



d) KNOWN DISTRIBUTION OF SHRIMP - ALL SPECIES (SAI 1977)

FIGURE 3-8 KNOWN DISTRIBUTION OF CRAB AND SHRIMP IN LOWER COOK INLET



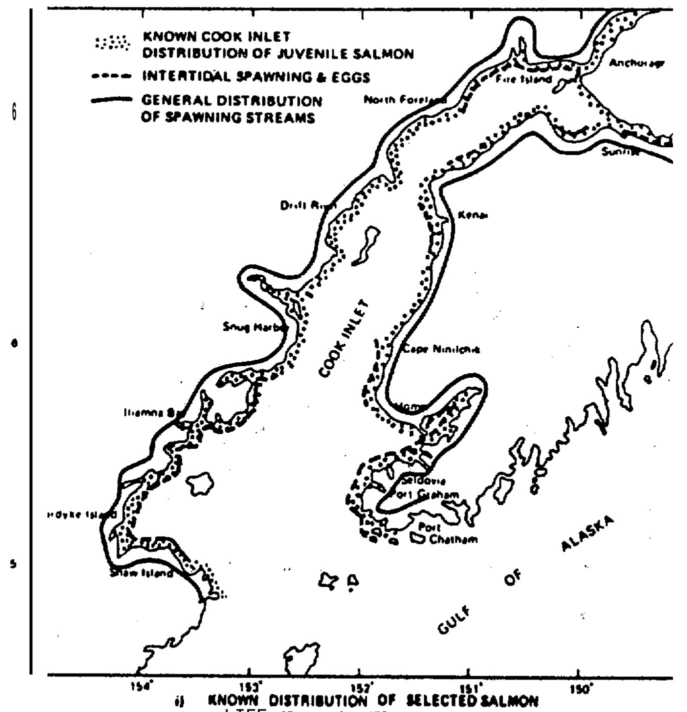
a) SCALLOPS & RAZOR CLAMS (SAI 1977; DAMES & MOORE 1977a)

f) HARDSHELL CLAMS (SAI 1977; DAMES & MOORE 1976a; 1977b)

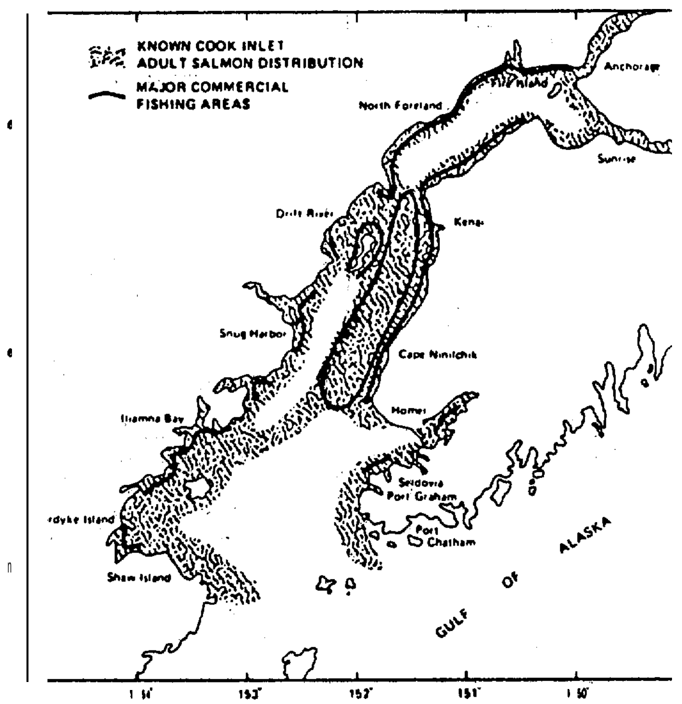
g) SPRING DISTRIBUTION OF HERRING (SAI 1977)

h) SPRING & SUMMER DISTRIBUTION OF HALIBUT (SAI 1977)

FIGURE 3-9 KNOWN DISTRIBUTION OF CLAMS AND SELECTED COMMERCIAL FISH IN LOWER COOK INLET



i) KNOWN DISTRIBUTION OF SELECTED SALMON LIFE STAGES (SAI 1977)



j) KNOWN SPRING & SUMME R DISTRIBUTION OF ADULT SALMON (SAI 1977)

FIGURE 3-10 KNOWN DISTRIBUTION OF SALMON IN LOWER COOK INLET western portions of the inlet (Larrance et al. 1977) although dense growths of attached algae are found locally in some rocky Intertidal and shallow subtidal areas on its southwest side (Dames & Moore 1980b).

The period of peak growth for the kelps appears to be April and May with considerable growth commencing in February and continuing until July (Figure 3-11, Dames & Moore 1980b). The patterns of carbon fixation probably are rather similar to the reported growth patterns but extend later into the summer or fall, as was described by Johnston et al. (1977). Significant carbon fixation probably occurs at least into early fall for the laminarian kelps, whereas tissue production is greatly reduced after June or July. However, the period of peak contribution of carbon (and nitrogen) from kelps to the benthic assemblages of Cook Inlet probably corresponds to the occurrence of fall and winter storms that cause severing of holdfasts and erosion of tissue at the distal ends of attached blades.

The period of peak primary productivity for phytoplankton in lower Cook Inlet appears to be in late May with considerable production occurring from March through August (Figure 3-12; Larrance et al. 1977; Larrance and Chester 1979). The timing of peak productivity varies. considerably among major regions of lower Cook Inlet as a consequence of oceanographic differences (Table 3-3). Peak productivity is dependent upon the physical stratification of the water column. In Cook Inlet, stratification occurs earliest in Kachemak Bay (April and May), so that productivity peaks about 1 month earlier in Kachemak Bay than in Kamishak Bay; peak productivity in the central part of the lower inlet, which seldom stratifies, occurs about 2 to 3 months later than in Kachemak Bay (Table 3-3).

Dominant phytoplankton species varied among the major regions. Microflagellates, the diatoms Chaetoceros and Thalassiosira spp. dominated in Kachemak Bay, Kamishak Bay, and the south part of the lower inlet, whereas the diatom Melosira sulcata was dominant in the central inlet near the Forelands (Larrance et al. 1977).

The importance of the organic contribution of phytoplankton varies widely among major food webs and regions of lower Cook Inlet. Larrance and Chester (1979) concluded that about 12 percent of the carbon fixed by phytoplankton passes to the bottom. Of the material falling to the bottom, "about 83 percent was attributed to grazing and subsequent fecal pellet production." Organic carbon from macrophyte production is probably used almost exclusively by bacteria and benthic animals. Furthermore, it is probable that a great preponderance of the material is used by detritivores rather than herbivores. Terrigenous organic carbon entering Cook Inlet from several major watersheds is another important source of organic carbon.

From the summation of these contributions of organic carbon, we can discern that at least three distinct regions can be defined in lower Cook Inlet on the basis of abundance and seasonal availability of detrital material to the benthos. Kachemak Bay, receiving the organics from high production of both phytoplankton and macrophytes, is characterized by high, fairly stable levels of organic carbon, probably in excess of

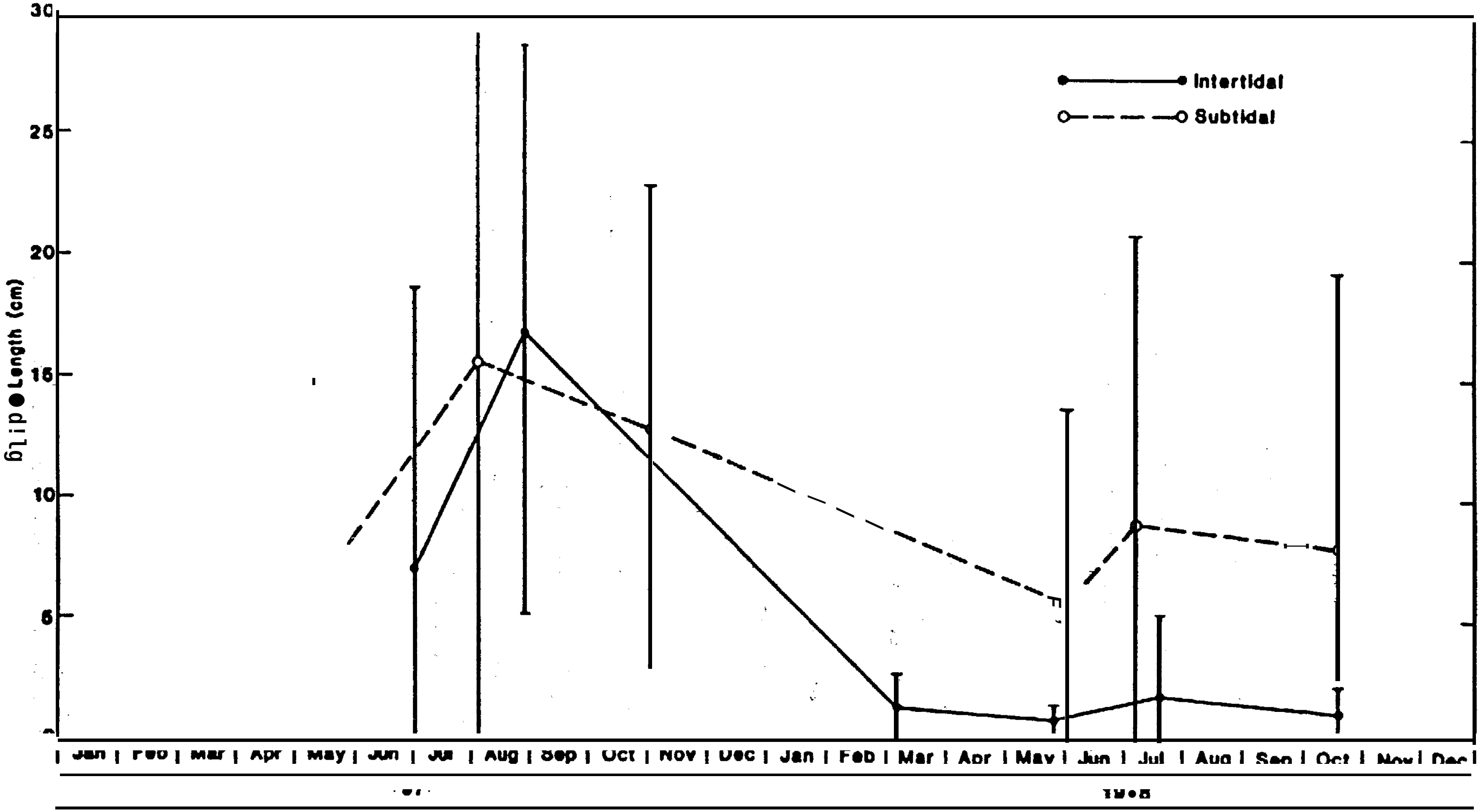


FIGURE 3-11 VARIATION IN MEAN STIPE LENGTH (±s) OF *Laminaria groenlandica* IN INTERTIDAL & SUBTIDAL POPULATIONS AT SELDOVIA POINT IN 1977-1978 (DAMES & MOORE 1980b)

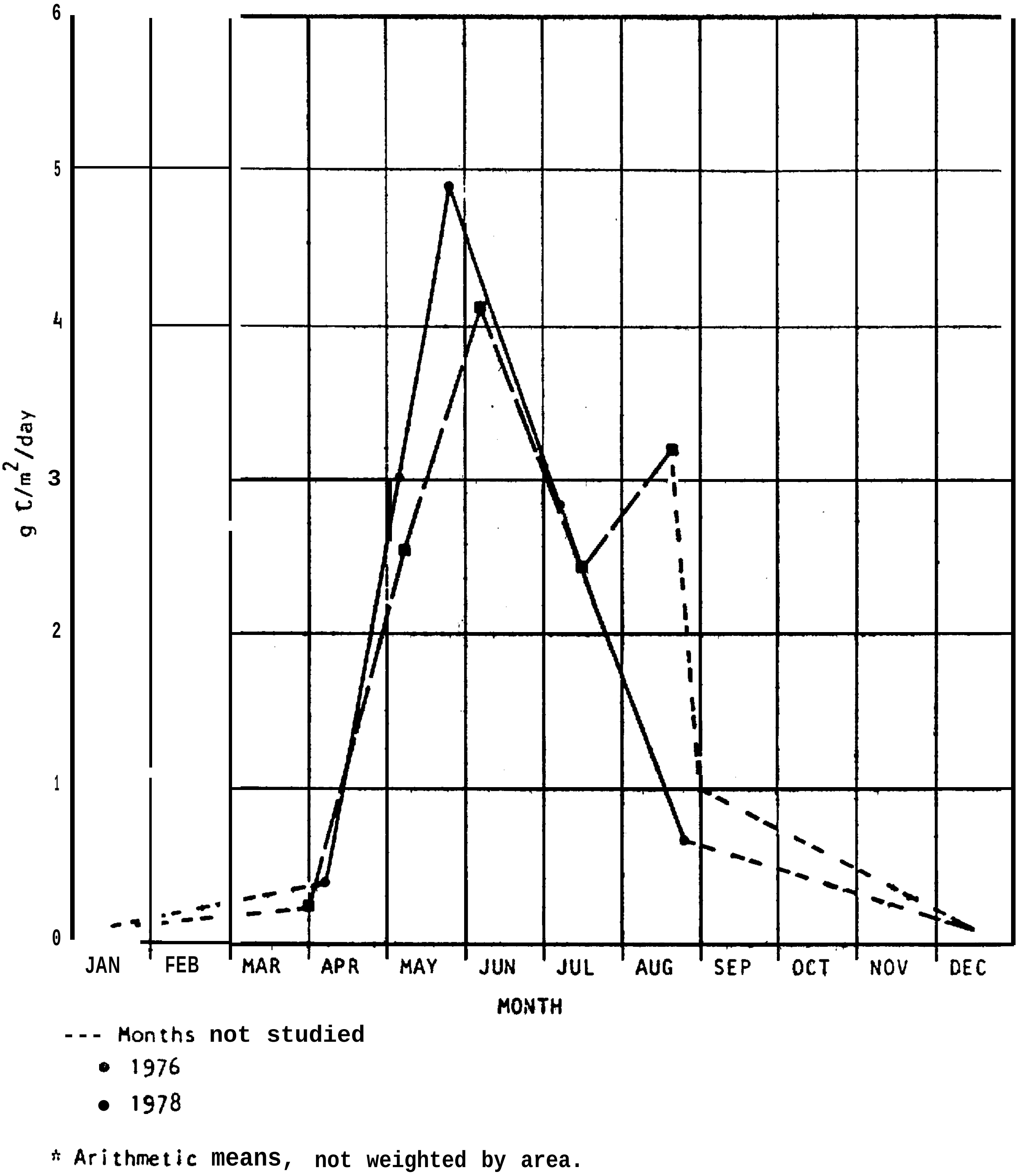


FIGURE 3-12 SEASONAL CHANGES IN AVERAGE* PRIMARY PRODUCTION OF PHYTOPLANKTON IN LOWER COOK INLET (LARRANCE ET AL. 1977; LARRANCE AND CHESTER 1979)

TABLE 3-3

SEASONAL AVERAGES FOR PRIMARY PRODUCTIVITY BY PHYTOPLANKTON IN LOWER COOK INLET IN 1976 AND 1978

	(mg C/m²/day)		
	Kachemak Bay(a)	Central Part of Lower Cook Inlet(b)	Kamishak Bay(c)
24-26 March 1978	283	391	31
Early April 1976	232	--	44
8-12 May 1978	7,035	515	145
Early May 1976	7,699	1,128	--
Late May 1976	4,813	7,522	2,321
7-11 June 1978	4,674	1,200	4,618
13-18 July 1978	3,626	1,819	1,468
Mid-July 1976	2,906	4,307	3,581
14-18 August 1978	2,694	5,256	930
Late August 19?6	920	738	725
Annual Primary Productivity (g C/m²/yr)	545	283	210

(a) Station 6 in 1976 and Station 7 in 1978.
(b) Stations 1 and 2 in 1976 and Station 4 in 1978.
(c) Stations 7 and 8 in 1976 and Station 1 in 1978.
Source: Larrance et al. (1977); Larrance and Chester (1979).

140 g $C/m^2/yr$. Kamishak Bay, with moderate ratesi of phytoplankton production in summer and terrigenous organic input in spring, summer, and fall, is characterized by a moderate quantity of organic carbon, probably somewhat in excess of 40 g $C/m^2/yr$, arriving mainly during spring and summer. The southern portion of the central inlet appears to receive the lowest amount of organics of these three areas. Phytoplankton probably accounts for most of the 17 g $C/m^2/yr$ estimated to impinge on the seafloor during a short period in the summer (Larrance and Chester 1979).

3.1.2.2 Zooplankton

Zooplankton assemblages in Cook Inlet, comprising holoplankton, meroplankton, and ichthyoplankton, are dominated by copepods but also include a wide diversity of other groups. On the whole, the abundance patterns are rather similar to those described above for phytoplankton (Dey and Damkaer 1977), i.e., the abundance levels peaked first in Kachemak Bay in early Hay, and not until mid-July at stations in the open areas of lower Cook Inlet. The abundance level in Kachemak Bay was at least three times higher than in the remainder of lower Cook Inlet. Generally, zooplankton settled volume measurements closely followed phytoplankton primary production (Figure 3-13), reflecting the response of copepods and other grazers to the availability of phytoplankton resources.

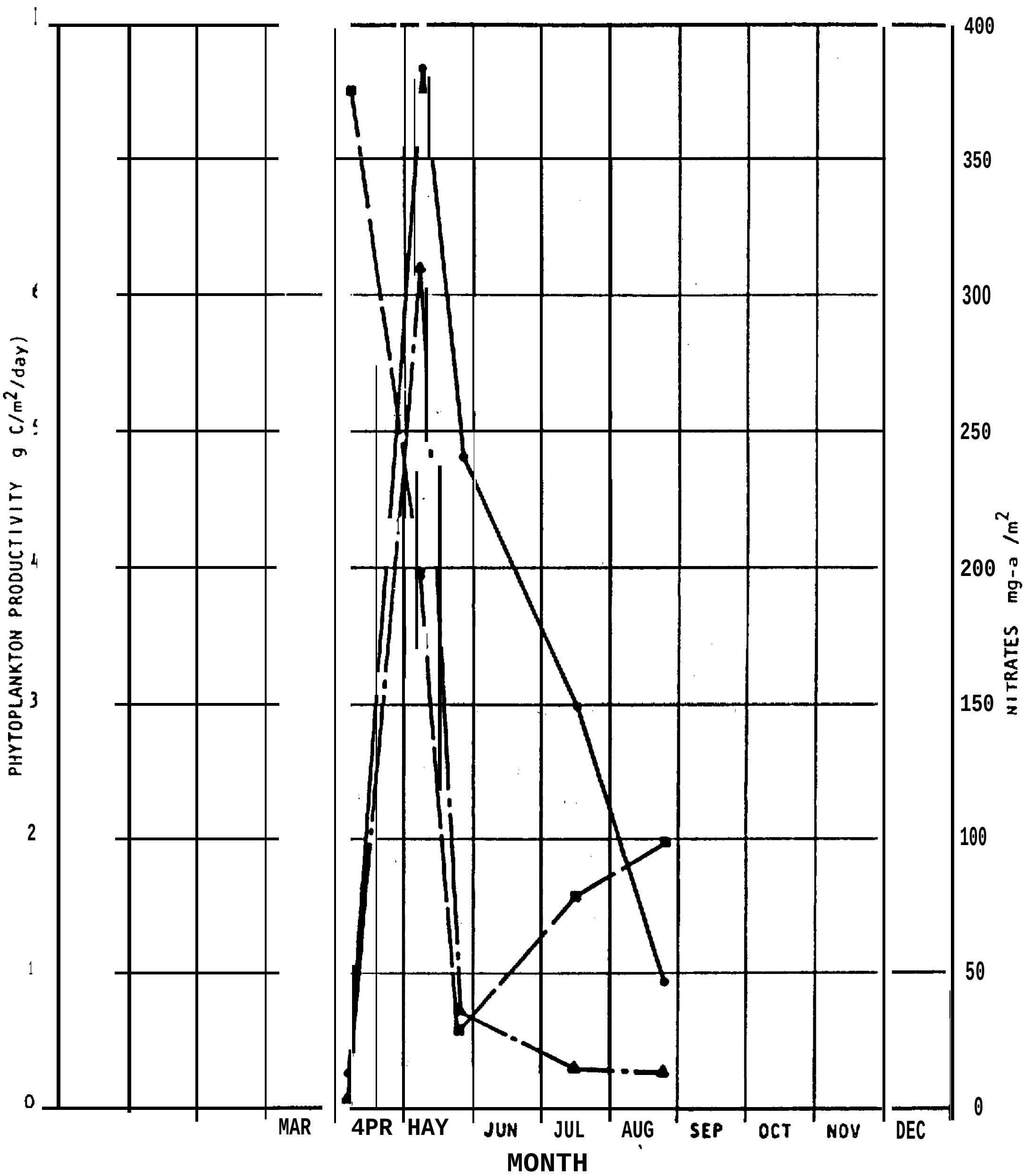
The major holoplanktonic species were copepods such as Pseudocalanus spp., Acartia longiremis and Oithona similis. Also important were euphausiids (krill), herbivores more characteristic of deeper offshore regions, and the chaetognath Sagitta elegans, a predator on copepods.

The major meroplanktonic species were barnacle larvae, represented by nauplii in early April and by less abundant cyprids in early May. Two different generations of barnacle larvae were observed during the summer of 1976. Other important meroplanktonic species, although much less abundant, included crab zoeae (Dey and Damkaer 1977). Haynes (1977) sampled much more intensively in Kachemak Bay and the southeastern quadrant of lower Cook Inlet to examine spatial and temporal distribution patterns of the larval stages of king crab (Paralithodes kamtchatica), pink shrimp (Pandalus borealis), and humpback shrimp (Pandalus goniurus). He reported that king crab larvae were most abundant in the central and southern portion of Kachemak Bay early in the season but the most important area for settling was along the northern shelf of the bay. Studies of postlarval king crab by Sundberg and Clausen {1977) corroborate these findings. Abundance of pink and humpback shrimp were also initially highest in the central and southern portion of the bay, but later stage larvae were most abundant along the southern portion of the bay. Larvae of humpback shrimp were also moderately abundant in the southern portion of the central inlet. Patterns of larval dispersal were similar in 1972 and 1976. English (1977) reported that king crab and shrimp larvae were more common in Kachemak and Kamishak Bays than toward the middle of the inlet.

English (1977), primarily studying ichthyoplankton, reported that because of the generally counterclockwise circulation in the lower inlet, large quantities of fish eggs and larvae seem to collect in Kamishak Bay, which he postulated is of great Importance to refiring of juvenile stages of many fish species which subsequently disperse about the inlet. In addition, he noted that fish larvae, particularly of forage species such as herring, tended to be abundant in the central portion of the southern inlet.

3.1.2.3 Benthos

Many of the economically important organisms in lower Cook Inlet are members of, or dependent on, the benthos, i.e. , assemblages of organisms that live in or on the bottom. Intertidal and shallow subtidal rocky bottoms often support a high biomass and a wide variety of animals in addition to dense algal growths (Dames & Moore 1976; 1980b). Most of these animals filter their food from the passing waters (barnacles and mussels) , graze on attached macro- and microscopic algae (limpets, chitons, sea urchins), are predators (some snails, crabs, and starfish), or scavenge for whatever plant or animal food may be available (several



■ NITRATES
▲ ZOOPLANKTON
• PHYTOPLANKTON

Sources:
1.) For nitrates •nd phytoplankton, Larrance et al. *1977*
2.) For zooplankton, Oey •nd Damkaer 1977

FIGURE 3-13 SEASONAL RELATIONSHIPS BETWEEN NITRATES, PHYTOPLANKTON PRODUCTIVITYAND SETTLED VOLUME OF ZOOPLANKTON IN KACHEMAK BAY IN 1976 types of snails and crabs). Although there is little direct harvest of organisms from rocky nearshore areas in Cook Inlet, these areas are of significance to the productivity of the inlet as a whole. For example, juvenile king and dungeness crab rear in such areas (Figure 3-8a and b) while juvenile salmonids (Figure 3-10i) and other fish may forage there. Herring, important commercially and as a forage fish for salmon, spawn on kelp and epifauna in shallow rocky areas of Kachemak arid Kamishak Bays (Figure 3-9g). Furthermore, as shown above, the seaweed produced there appears to be an important source of food material in the food webs supporting most commercial species, particularly in Kachemak Bay (Section 3.1.2.1).

The benthos of shallow soft-bottom areas of the inlet is somewhat less conspicuous than that on rocky bottoms but it is also of major importance in supporting "useful" species. Clams, amphipods, and polychaetes (sea worms) are often abundant and provide a food resource for larger predators such as king, tanner (Chionoecetes bairdi), and dungeness crab (Cancer magister) and halibut (Hippoglossus elassodon). Razor clams (Siliqua spp.), a genus of great recreational importance and commercial potential, are abundant on exposed sandy beaches on both sides of the inlet (Figure 3-9e). Hard-shelled clams (butter and littleneck; Veneridae) are abundant in gravelly substrates in Kachemak and other bays on the outer Kenai Peninsula (Figure 3-9f). Another hard-shelled clam (the "pinkneck," Spisula polynyma) is found on exposed razor clam beaches as well as on deeper sandy bottoms. The soft-shelled clams, Mya spp., although not widely utilized at present, are very abundant In silty muds or upper bays on both sides of the inlet.

Few examinations of the noncommercial benthos have been made in deeper areas of lower Cook Inlet but the assemblages appear similar to those living on similar substrates at shallower depths, except for the absence of algae in deeper areas. These faunal assemblages comprise several strongly distinctive components. Each poses its own peculiar sampling problems, is sampled by different methods, and imposes specific limitations on interpretation.

The main elements include:

(1) small infauna which live in the upper few centimeters of soft sediment;

(2) large infauna which generally live down to at least 30 cm in soft sediment;

(3) sedentary epifauna which live at or extend above the water substrate interface;

(4) mobile epifauna which move readily across soft or hard substrates.

Benthic assemblages strongly reflect the sedimentary regime of the area In which they occur. The several major geological facies reported have been described by Orlando (in press), who also illustrated the known distribution of these facies. Description of the benthic assemblages associated with these geological facies has been quite piecemeal and is very incomplete and inadequate for our purposes. The following description are based primarily on Dames & Moore (1976; 1977a, b; 1978a, b, c, d, e, f; 1979; 1980a, b); Driskell (1977); and Feder et al. (1981). Only the substrate types considered to be most vulnerable to drilling impacts are considered here.

Sand Habitats

Sandy sea bottoms, generally indicative of fairly high hydrodynamic energy levels (Shepard 1963; Bascom 1964), are distributed widely throughout lower Cook Inlet. Sand beaches in lower Cook Inlet are generally located below MLLW and are' frequently associated with steep gravel beaches that occur above MLLW. Additionally, large tracts of sand habitat are distributed subtidally 'throughout the central part of Cook Inlet south of Kalgin Island (Sharma and Burrell 1970; Bouma et al. 1978) in the northern and eastern parts of Kamishak Bay, and in the central northwestern parts of Kachemak Bay (Driskell 1977; Bouma et al. 1978), and in many smaller exposed bays (Dames & Moore 1977b; 1979).

Sand substrates are relatively unstable habitats for biota. Surficial grains are easily resuspended and are very abrasive when in suspension. Currents or surges form different sizes and types of bedforms . The surface grains of these are transported laterally and, in passage, either deeply bury or uncover tubicolous or less active burrowing species. The consequence of this instability is that resident assemblages do not have sufficient time to develop a high degree of complexity . In the central part of lower Cook Inlet, however, the currents, although strong, are reversed during every tidal cycle. Thus , the net rate of sand migration may be minimal and successful types of animals frequently swim and/or burrow there actively.

Biological assemblages on sand beaches in lower Cook Inlet, although better developed than axposed gravel beach assemblages, also have limited species richness and biomass. Whole wet weight ranges from about 1 g/m^2 to about 34 g/m^2 and average about 16 g/m^2 (Dames & Moore 1977a; 1979; 1980b). Because of similarities in hydrodynamic activity, substrate characteristics, and other features among sand habitats, the biotas in intertidal and subtidal areas in lower Cook Inlet often exhibit fairly strong similarities (e.g., Lees and Houghton 1980). However, subtidal environments lack such characteristic intertidal stresses as emersion and extremes in temperature and salinity. This, in turn, increases the stability of subtidal habitats and permits the fauna in most areas to attain a higher level of development. Some of the dominant benthic species in the subtidal sand habitats in lower Cook Inlet include the worms Polygordius sp., Spiophanes bombyx, Scolelepis sp., Scoloplos armiger, Ophelia limacina, and Nephtys spp., the sea pen Ptilosarcus gurneyi, the clams Liocyma (=Venus) fluctuosa, Spisula polynyma, and Tellina nuculoides, the sand dollar Echinarachnius parma, and the gammarid amphipod Paraphoxus milleri (Dames & Moore 1978a, b; Lees and Houghton 1980). This assemblage is closely related to one described by Thorson (1957) for benthic assemblages on sand at shallow to moderate depths in east Greenland, Peter the Great Bay, and the Arctic ocean.

The infaunal assemblage observed in a mixed sand-clay habitat about 18 km west of the C.O.S.T. well differed dramatically from that described above the current-swept sand. The sediments are primarily a well-sorted silty sand overlain by a veneer of gray clay up to 5 cm thick. The tidal currents wash the sand into bedform about 0.5 m to 1 m high (Dames & Moore 1978c). Important epifauna included sea pens and sand dollars. Dominant members of the infauna include the polychaetes Myriochele oculata, Magelona sp., Lumbrineris zonata, Scoloplos, and Euclymene sp., the small clams Psephidia lordi, Nucula tenuis, and Macoma obliqua. Except for the sea pens, sand dollars, and Scoloplos, species also found in the current-swept sand habitats near the C.O.S.T. well were uncommon. H. Feder, personal communication, 1978) described infaunal assemblages dominated by polychaetes, suspension- and deposit-feeding clams (e.g., Astarte spp., the cockle Clinocardium ciliatum and Yoldia myalis) in muddy sand sediments near Kamishak Bay. Important motile epifaunal forms included tanner crabs, hermit crabs (Paguridae), and the predatory snails Natica spp., Oenopota spp. and Boreotrophon pacificus.

Similar faunal assemblages were reported from sand and silty sand habitats with sand waves up to 2 m high in the central part of outer Kachemak Bay, except that Axinopsida serricata replaces Liocyma as the dominant clam (Driskell 1977).

Mud Habitats

Mud habitats appear to be primarily distributed in completely or partially protected areas such as embayments (Hayes et al. 1977) or deep water (Dames & Moore 1978d). However, large muddy areas are found in locations exposed to moderate tidal currents or to wave action (Dames & Moore 1977a).

Because muddy sediments in lower Cook Inlet are usually relatively stable and occur in rather protected locations, the biological assemblages attain a fairly high level of development. Furthermore, the relationship between sediment particle size, organic carbon and nitrogen, and bacteria, can often enhance standing stocks of large consumer organisms. As mean particle size decreases, the organic content in the sediment and the density of bacteria increase (Dale 1974; Griffiths and Morita 1979). Thus, mud habitats generally have high concentrations of food materials for detritivore assemblages. The general species composition of a specific detritivore assemblage is strongly influenced by the stability of the sediment and the hydrodynamic activity level, i.e., whether organics and bacteria are resuspended, thus permitting development of suspension-feeding assemblages, or remain deposited, requiring development of deposit-feeding assemblages.

The assemblages dominated by suspension feeders usually have highest standing stocks (D. Lees, Dames & Moore, personal observation). In most cases, the mud flat fauna is strongly dominated by clams; worms are usually of subordinate importance (Newell 1970).

Several reports describe assemblages associated with subtidal mud habitats but the patterns are not clear. In Stevenson Entrance, where sediments range from moderately well-sorted, coarse sandy silt to fine silty sand and where the sediment surface features are limited to small ripple marks, bottom currents are probably light (Dames & Moore 1978d). The infauna is dominated by the suspension-feeding clams Axinopsida serricata and Psephidia lordi; the deposit-feeding clams Nucula tenuis, Nuculana, and Macoma calcarea; the deposit-feeding polychaetes Decamastus gracilis, Myriochele heeri, M. oculata, and Magelona sp.; and the suspension-feeding polychaete Spiochaetopterus costarum (Dames & Moore 1978d). Other notable species are the tusk shell Dentalium and the solenogaster Chaetoderma, both deposit feeders. Exploratory fishing by BCF and underwater television transects by Dames & Moore (1978d) disclosed substantial populations of tanner crabs and pink and side-stripe shrimp on this sediment type in the southern part of lower Cook Inlet.

In the trough in outer Kachemak Bay, sediments range from anoxic clay to sandy silt (Driskell 1977). Sediment surface conditions indicate that currents range from still to light. The molluscan fauna was dominated by Axinopsida, Nucula, M. calcarea, and Nuculana. The polychaete fauna was dominated by the deposit-feeding families Maldanidae and Orbiniidae. Sedentary epifaunal organisms are generally sparse in such habitats, but large motile forms such as tanner or king crab, pandalid shrimp, and demersal fishes are frequently very abundant and probably constitute major predators. The deposit-feeding organisms that dominate such substrates are usually fairly small, probably as a consequence of the energy requirements of burrowing for food and the high predation rates.

Semi-Protected Sand-Gravel-Cobble or Shell Debris Habitats

Mixed habitats are widely recognized as generally supporting greater species diversity and productivity than any of the component habitat types (Hedgpeth 1957; Houghton 1973). This situation also exists for the protected intertidal and shallow subtidal sand-gravel-cobble habitats in lower Cook Inlet found sporadically along the shores of fjords and bays. Similar habitats are also found in numerous deeper subtidal locations, especially along the northern platform of Kachemak Bay and west of Anchor point. The substrates are, a complex mixture of clay, silt, sand, gravel, cobble, and shell hash. The associated faunas differ dramatically with the varying proportions of sediment constituents, degree of submergence, current, and surge exposure. Generally, clams dominate but, because of the broad admixture of Substrates, components of both rock and soft bottom biotas coexist. Consequently, it is common to observe kelps, herbivores, infaunal and epifaunal suspension feeders, and deposit feeders, as well as a broad variety of predators and scavengers, On mixed substrates. In short, these areas, particularly subtidally, support some of the most complex and productive benthic assemblages known in lower Cook Inlet (Dames & Moore 1977a; 1980b). It is also in this habitat type that fauna often exert their greatest influence over the sedimentary regime, particularly through the action of mussels.

From very low intertidal levels out to depths of at least 44 m, the large sea mussel Modiolus modiolus lives buried almost completely in the interstices between cobbles and gravel, consolidating the cobble matrix with byssus threads. Densities approach 150 individuals/m^2 (Dames &

Moore 1980b) and wet tissue weights of over 4 kg/m^2 have been reported (Dames & Moore 1976; 1977a; 1980b). Some of these submerged mussel beds constitute the most complex biotas yet observed in this habitat. At the substrate surface, in depths shallow enough to support seaweeds, substantial stands of kelp (e.g., Nereocystis luetkeana, Alaria spp., Laminaria spp., and Agarum cribrosum) grow on the cobbles. Sea urchins, limpets, and chitons graze on the seaweeds. Dense assemblages of epifaunal suspension feeders (e.g., serpulid worms, sea anemones, barnacles, sea cucumbers, brittle stars, sponges, tunicates, bryozoans, and hydroids) live on or among the rocks, competing intensely for space with foliose and encrusting coralline algae. Living in the upper stratum of the substrate are the sea mussels, and filling in the spaces between them are dense beds of sabellid worms. Below this upper stratum, butter clams, soft-shell clams (M. truncata) and Macoma obliqua frequently attain densities of up to 20 mature individuals per m^2. In addition, moderate densities of worm and sipunculid species burrow in the sediments. At the surface, feeding on this abundance of animal tissue are numerous predators, e.g. , snails (at least 10 species), starfish (17 species), crabs (at least 10 species), polychaetes, and fish (at least 20 species of each) (Dames & Moore 1976).

Another case of increased richness in the mixed environment was reported from a mixed mud-sand-gravel substrate at about 140-m depths in the middle of lower Cook Inlet (Dames & Moore 1978e). The faunal assemblage here was much richer than that in sand habitats to the north (Dames & Moore 1978a, b, c) and a mud habitat to the south (Dames & Moore 1978d). The increased richness was largely a consequence of the epifauna attached to the gravel and cobbles, especially hydroids, bryozoans, and sponges. Dominant infaunal forms included the polychaetes Myriochele oculata and Magelona sp. and the clams Axinopsida serricata and Psephidia lordi, all important species in the previously described sand-mud substrates. Exploratory fishing trawls in this area by BCF discovered large populations of tanner and king crab, as well as pink, side-stripe, and humpback shrimp.

In areas with optimum current and growth conditions, the resulting high productivity of clams eventually produces a sufficient quantity of shell material to influence the nature of the surficial sediments. Such shell-hash habitats have been reported between 12 and 34 m on the north shelf of Kachemak Bay and between 29 and 65 m on the south side of the bay (Driskell 1977), as well as between 33 and 42 m off Anchor Point (Dines & Moore 1978f). The clams probably are important to a number of commercial species. The juvenile king crab sanctuary, established by the Alaska Department of Fish & Game in Kachemak Bay, is in one such area. Exploratory trawling by BCF found large numbers of Pacific halibut and king crab in some of these areas, as well as large populations of the "football" sea cucumber Cucumaria fallax and the sea urchin Strongylocentrotus drobachiensis.

3.1.2.4 Fish Assemblages

Fish assemblages are major consumers in the biological systems of lower Cook Inlet; in addition, they support several large fisheries.

Major changes in fish abundance, spatial distribution, and size structure are apparent in the inlet seasonally (BCF 1958, 1963, 1968; Blackburn 1977; Blackburn et al. 1979; Rosenthal and Lees 1979). In terms of fish abundance, the major families include Ammodytidae, Clupeidae, Cottidae, Gadidae, Hexagrammidae, Osmeridae, Pleuronectidae, Salmonidae, and Trichodontidae. Geographic distribution of many species in these families is strongly influenced by a common temporal pattern; most species move out of nearshore areas in the late summer and fall and remain in offshore areas until spring. Thus, feeding efforts are concentrated in deeper water regions during the winter and expand into inshore areas in the spring and summer. It is not yet clear which species of fish remain in Cook Inlet in the winter and which migrate completely out Into the Gulf of Alaska. The most notable of the families that move into inshore waters in spring include the Ammodytidae, Clupeidae, Cottidae, Hexagrammidae, Osmeridae, Pleuronectidae and Salmonidae. Generally, the inshore areas are used by many species in these groups as nursery grounds for larvae and juveniles during summer months.

The fish assemblages of lower Cook Inlet are moderately complex and quite dynamic. For ease of discussion, they will be separated into three nonexclusive categories, i.e. , forage, pelagic, and demersal fish.

Forage Fish

This category includes small schooling bait fish such as Pacific sand lance (Ammodytes hexapterus), Pacific herring (Clupea harengus pallasii), capelin (Mallotus villosus), long fin and surf smelts (Spirinchus thaleichthys and Hypomesus pretiosus). These species constitute very important food of larger predatory species such as salmon and various marine birds and mammals. All of the species listed have strong dependencies on both pelagic and benthic habitats; they feed mainly on zooplankton but they spawn in both intertidal and subtidal soft and hard substrates. All range widely in large schools throughout lower Cook Inlet.

Pelagic Fish

The main fishes in this category are juvenile and adult salmonids. These anadromous species (steelhead, Salmo gairdneri, and Pacific salmon, Oncorhynchus spp.) are found in inshore waters of the inlet primarily in spring and summer months. Juveniles mainly feed on small planktonic and epibenthic crustaceans in the inshore waters in spring and summer and migrate into offshore waters by fall. Adults use inlet waters, especially inshore regions, as migration routes from offshore and Gulf of Alaska waters to spawning streams and rivers. However, they probably feed heavily on large epibenthic and planktonic crustaceans and forage fish for a large part of their oceanic migration. Winter distribution of Cook Inlet salmonids is poorly understood.

Demersal Fish

This category of fishes, closely associated with the bottom, comprises a broad variety of species including true cod (gadids), flatfish (pleuronectids), sculpins (cottids), greenling (hexagrammids), and rockfish (scorpaenids). The primary food types for most of these species are benthic invertebrates such as crabs, snails, clams, and polychaetes. The fact that they are heavily dependent upon the condition of diverse groups of infaunal and epifaunal species is part of the reason they constitute the most likely group of fishes to be affected by drilling fluid and cuttings discharges. Moderate-sized epifaunal crustaceans such as shrimp, hermit crabs, and "small spider crabs appear particularly important food items to many species (Blackburn et al. 1979; Rosenthal and Lees 1979). Generally, adults of most demersal species move into inshore waters in the spring and summer. However, adult gadids usually remain in deeper water than the other demersal groups during those periods. In most cases, the juveniles of demersal species are found in much shallower water than the adults. However, juveniles for both greenling and rockfish are pelagic during their early stages.

Demersal fish assemblages in lower Cook Inlet vary fairly consistently by substrate and, to a lesser extent by depth. Rock habitats in lower Cook Inlet are characterized by several species of rockfish (Sebastes), greenling (Hexagrammos), sculpins (e.g., Myoxocephalus spp., Hemilepidotus spp. , and Artedius spp.), searchers (Bathymaster spp. and Ronquilus jordani), and the rock sole (Lepidopsetta bilineata). Pacific halibut (Hippoglossus elassodon) are most commonly associated with rubble or shell debris substrates, at least during the spring and summer. Juveniles of several pelagic or forage species also aggregate around rock habitats (e.g., salmonids, herring, and sand lance), and juvenile Pacific tomcod (Microgadus proximus) are common around kelp beds in summer (Rosenthal and Lees 1979).

Flatfish generally appear to dominate on soft substrates. Starry flounder (Platichthys stellatus) are characteristic of shallow muddy habitats. Butter, yellow fin, and sand sole (Isopsetta isolepis, Limanda aspera, and Psettichthys melanosticus) are common on sandy substrates. The Pacific staghorn sculpin (Leptocottus armatus) is common in shallow water on most substrates, especially near stream or river mouths (Blackburn et al. 1979). The gadids (cod) are generally common on soft substrate in deeper water, especially in areas where shrimp are found such as deeper portions of Kachemak Bay and the central and southern parts of lower Cook Inlet (Blackburn 1977). Sablefish Anoplopoma fimbria) are only common on soft substrates in the southern parts of lower Cook Inlet (BCF 1958; 1963; 1968).

3.1.2.5 Bird Assemblages

The three major types of seabirds in lower Cook Inlet are marine birds such as alcids and gulls, waterfowl such as scoters and eiders, and shorebirds such as sandpipers. Birds are an important component of the marine ecosystem of Cook Inlet and one that is highly vulnerable to the direct and indirect impacts of human activities. Cook Inlet is important to various species for several different reasons; among these are feeding (summer and/or winter), breeding areas, migration routes, and overwintering habitat. Relative abundance patterns for various bird groups, seasons, and geographic areas are indicated in Table 3-4.

TABLE 3-4

RELATIVE SEASONAL ABUNDANCE OF THE FIVE MAJOR BIRD GROUPS IN INSHORE AND INTERTIDAL HABITATS COMPARED AMONG REGIONS OF LOWER COOK INLET

Region	Bird Group	Winter	Spring	Summer	Fall
		Numbers counted during coastal surveys in:			
Kennedy Entrance (Region 4)	Waterfowl (all anatids)	3,539	1,218	167	1,258
	Gulls	229	720	4,361	2,031
	Shorebirds	154	135	2	52
	Alcids	19	1	53	14
	Cormorants	241	460	882	974
Kachemak Bay (Region 3)	Waterfowl	8,016	14,104	11,813	9,801
	Gulls	1,185	4,307	4,895	8,237
	Shorebirds	748	5,395	96	48
	Alcids	212	167	54	3
	Cormorants	5	218	14	585
Kamishak Bay (Region 2)	Waterfowl	1,286	7,720	9,883	1,791
	Gulls	0	2,316	1,803	516
	Shorebirds	0	6,111	188	1,223
	Alcids	0	0	98	1
	Cormorants	7	50	202	120
Kalgin Island Area (Region 5)	Waterfowl	144	9,686	4,710	9,061
	Gulls	4	27,843	9,604	5,668
	Shorebirds	3,375	4,304	50	98
	Alcids	0	4	5,626	0
	Cormorants	0	85	138	3

Source: Based on preliminary unpublished aerial census data frcm 1976 by D. Erikson and P. Arneson, ADF&G, Anchorage, Table 3-8 in SAI (1977) Lower Cook Inlet synthesis report.

3.1.2.6 Marine Mammals

The four major taxa of marine mammals occurring in lower Cook Inlet are sea otters, pinnipeds, toothed whales, and baleen whales. The distribution patterns of these groups are basically independent of each other. Geographic distribution patterns exhibit marked seasonality. The species which reside year-round in Cook Inlet are the sea otter, the harbor seal, the Steller sea lion, and the belukha whale. All except the sea otter are almost strictly piscivorous.

Sea otters have been observed mainly in the southern half of lower Cook Inlet (i.e., Kamishak and Kachemak Bays and Kennedy Entrance).

Of the two pinniped species found in lower Cook Inlet, harbor seals are far more widely distributed and, except in the vicinity of the Barren Islands, more abundant than Steller sea lions. The toothed whales include the belukha and killer whales. Belukhas occur primarily in the southern part of the inlet in the winter and in the northern part of the inlet in the summer. Killer whales have not been observed north of Kachemak Bay but do range into inner Kachemak Bay occasionally. Baleen whales regularly occurring in the inlet include the minke, grey, and sei whales Only the minke whale routinely penetrates into the inlet as far north as Kachemak Bay. Harbor porpoises range throughout the lower inlet and are particularly common in protected inshore waters such as Kachemak Bay. Dan porpoises are primarily encountered in more exposed areas such as Kennedy Entrance and probably do not range much north of Kamishak Bay.

3.1.2.7 Fisheries

Lower Cook Inlet supports moderately large, diverse commercial fisheries and has potential for some utilization of additional species. The crab fishery is the most valuable resource, and tanner crab are consistently the most important species. The salmon fishery is next in importance, followed by a very stable pandalid shrimp fishery in Kachemak Bay.

Each fishery is concentrated in a different general area. The trawl shrimp fishery is concentrated in the deeper portions of outer Kachemak Bay, on soft substrates. In contrast, the pot shrimp fishery is concentrated on rock and soft substrates along the slopes of deep bays on the south side of Kachemak Bay.

Although the king and tanner crab are distributed over a large part of lower Cook Inlet and the area of maximum abundance for the two species seems to be quite similar, there are some differences in the location of major crab fishing efforts (Figure 3-8). Tanner crab are most heavily fished in Kachemak Bay and outer Kamishak Bay, and fishing does not extend south of the Barren Islands (Figure 3-8c). Major effort for king crab is also concentrated in Kachemak and Kamishak Bays, but efforts also extend more generally throughout the southern part of the lower inlet and south of the Barren Islands into Shelikof Strait and the Gulf of Alaska (Figure 3-8a). Although Dungeness crab are fished generally along the outer Kenai peninsula from Kachemak Bay into the Gulf of Alaska, maximum effort is expended along the northern shelf of Kachemak Bay (Figure 3-8b).

Pacific herring occur along the shores of both sides of lower Cook Inlet and in Kachemak Bay, but the major harvest effort occurs in Kamishak Bay, especially in its northwestern corner (Figure 3-9g) . Halibut are distributed generally throughout lower Cook Inlet, but commercial fishing is concentrated in the entrances of major embayments such as Kachemak or Kamishak Bays and along the eastern side of the inlet. In addition, a major sportfishery for halibut is located in Kachemak Bay, especially on the large platform extending into the entrance of Kachemak Bay from its northern shelf (Figure 3-9h).

Five species of salmon occur throughout lower Cook Inlet and are also fished commercially and for sport. The largest proportion of the fish are caught in set or drift gill nets between Anchor Point and the Forelands and along the southern shore of outer Kachemak Bay. Sportfishing is largely concentrated in Kachemak Bay and along the east side of the lower inlet (Figure 3-10).

Small quantities of razor clams and octopus are harvested for bait in the halibut fishery. The razor clam harvest occurs primarily on sandy beaches along the west side of the lower inlet, especially at Polly Creek and Chinitna Bay (Figure 3-9e). The octopus fishery is very new and is currently concentrated along the south side of Kachemak Bay, especially in the vicinity of Seldovia.

In addition, marginally harvestable quantities of weathervane scallops have been located in deep water between Augustine Island and the Barren Islands (BCF 1968) and in outer Kachemak Say (Driskell 1977) (Figure 3-9e). Also, benthic surveys have indicated the presence of large populations of hardshell clams in severs areas in lower Cook Inlet (Figure 3-9f) (H. Feder, personal communicant on, 1978; Driskell 1977).

3.1.2.8 Basic Food Webs in Lower Cook Inlet

"Trophodynamics" refers to the transfer or flow of energy through a food chain and to the efficiency in conversion of energy to biomass from lower to higher trophic levels. Energy pathways in a foQd chain can be illustrated by drawing arrows from lower to higher trophic levels (e.g. from prey organisms to predators); the resulting diagram is referred to as a "food web."

Based on the behavior of discharged drilling fluids described in Section 2.2, it appears clear that neither drilled cuttings nor muds will be carried from the present lease areas into inshore areas in detectable concentrations. We have therefore limited our discussion of food webs to offshore areas in lower Cook Inlet.

Offshore food webs can be fairly cleanly separated into pelagic and benthic components, largely on the basis of the nature of the food resources driving them. The pelagic food web (Figure 3-14) is supported mostly by carbon from phytoplankton whereas the benthic food web (Figure 3-15) is supported largely by carbon in organic debris In or at the sea floor. This detrital material is derived from macrophytes and terrestrial debris as well as from phytoplankton. The pelagic and benthic food webs are further described in the following paragraphs.

The Pelagic Food Web

The pelagic food web, very heavily dependent upon phytoplankton productivity, is fairly simple and generally hierarchical. The producer (first) level is phytoplankton. The primary consumer level comprises herbivores such as copepods, cladocerans, and a wide variety of adult and larval invertebrates that feed directly on phytoplankton cells. Second-level consumers, including invertebrates (e.g., chaetognaths and medusae), larval fish of many species, and adult forage fish, feed largely on the primary consumers. Third-level consumers are generally marine birds and adult fishes that feed on forage fish. The fishes include demersal species such as Pacific halibut, Pacific cod, and walleyed pollock as well as pelagic species such as salmonids. Higher order consumers usually feed on two or more lower levels of consumers. For example, killer whales feed on sea lions, salmon, and herring, and thus their diet includes basically three trophic levels.

The major pelagic pathways are probably those linking herring and sand lance to man, sea lions, and marine birds. However, Larrance and Chester (1979) found that about 11 percent of the carbon fixed by phytoplankton was lost to benthic systems in the form of detritus. Thus, considering additional losses to benthic or demersal predators, a substantial proportion of the energy from pelagic food webs is transferred to benthic food webs.

The major mechanism for accumulation of toxicants in the food web is ingestion. In view of the transitory nature of the major source of nutrition (phytoplankton), the opportunity for food web accumulation (biomagnification) of toxicants from drilling fluids appears low.

The Benthic Food Web

The benthic food web is based heavily on organic debris derived from phytoplankton, macrophytes, and terrigenous detritus. These materials have usually been triturated to a small particle size by previous ingestion or abrasion and are colonized by bacteria. The organic aggregates are often flocculated and occur with fine sediments which are also colonized by bacteria. Generally, these materials are in close contact with the substrate, either being mixed with sediment or having been resuspended.

The invertebrate animals feeding on these nutrient resources (detritivores) usually ingest large quantities of the organic-bacteria-sediment aggregate to obtain their nutrition. As a consequence, deposits of the muds, heavy metals, and complex organic compounds that may be associated with drilling fluids would ultimately be assimilated by the low-level consumers in the areas of deposition. Menzie et al. (1980) and Mariani et al. (1980) have documented this conclusion for several infaunal species in the vicinity of an exploratory well site in the mid-Atlantic Ocean lease area.

The organisms included in the benthic food web for lower Cook Inlet comprise species or major taxa that were indicated to be dominant consumers in terms of biomass by Feder et al. (1980); Blackburn et al. (1979), or in the BCF exploratory trawling records. Those taxa that are circled in Figure 3-15 were dominant at their particular trophic levels. Drilling fluids and associated heavy metals would enter this food web mainly in association with the organic debris resource as part of the food materials for clams, polychaetes, and small crustaceans such as gammarid amphipods, isopods, and benthic mysids. These types of organisms, as well as organic debris, are major components of the diet of most of the higher order consumers in the central portion of lower Cook Inlet where exploratory and production drilling would take place. As indicated in Figure 3-15, the more important higher-level consumers are medium- to large-sized decapod crustaceans (pandalid and crangonid shrimps and king, tanner, and Dungeness crabs), flatfish (esp. Pacific halibut), and gadids (esp. walleye pollock).

Based on the BCF exploratory trawls in the central basin of Cook Inlet, the most frequently encountered and abundant large, motile epibenthic animals were by far crustaceans, followed by echinoderms and fish. Invertebrates far exceeded fish as dominant consumers in this area (Table 3-5), and two commercial species were in the top five species. In fact, echinoderms were the only noncommercial species in the top 12 species collected in these trawls. Trawl data reported in Blackburn (1977) did not reflect catches of shrimp or echinoderms, but the otherwise most abundant species were very similar, including tanner and king crab, halibut, and walleye pollock as well as several flatfish.

TABLE 3-5

SUMMARY OF CATCH DATA
FROM EXPLORATORY TRAWL SURVEYS IN LOWER COOK INLET

Animals		Frequency of	Average Biomass/
Common Name	Scientific Name	Occurrence	1-hrt (lb)
Pink shrimp	Pandalus borealis	23	77.5
Sea urchin	Strongylocentrotus drobachiensis	13	20.4
Starfish	Asteroidea	4	11.4
Brittle star	Ophiuroidea	3	11*0
Tanner crab	Chionoecetes bairdi	19	10.9
Sea cucumber	Cucumaria fallax	11	9.1
Sidestripe shrimp	Pandalopsis dispar	6	9.0
Turbot?	Pleuronectidoe	10	6.3
King crab	Paralithodes kamtschatica	9	6.2
Pacific halibut	Hippoglossus elassodon	8	6.2
Walleye pollock	Theragra chalcogramma	9	5*0
Humpback shrimp	Pandalus goniurus	5	3.0

Source: BCF 1958; 1963; 1968.

Determination of the most important pathways in this food web, and thus the pathways that would be most influenced by adverse effects of the heavy metals and toxic substances associated with drilling fluids, is quite imprecise based on the present state of knowledge available from lower Cook Inlet. Furthermore, the relative importance of these pathways undoubtedly varies over the long term with changes in the availability of various prey and predator species. However, the lower consumer groups are sufficiently broad to allow for such variations; and the higher groups appear, based on commercial fishing records and trawling records, to be sufficiently abundant and stable to permit designation of three major pathways and tentative specification of the one in which substances associated with drilling fluids would be most highly concentrated. The pathway in which substances associated with drilling fluids would be most concentrated is probably that including the tanner crab and leading to Pacific halibut and man. Others of high importance are those linking Pacific halibut to (1) king crab, (2) pandalid shrimp, and (3) walleye pollock.

Tanner crab feed on nearly all important taxa at lower consumer levels and are also one of the most abundant higher-level consumers in the area contacted by drilling fluids. A broad variety of the important low-level consumers are also fed upon by walleye pollock. Pacific halibut are in a particularly crucial position; most of the important low- or intermediate-level consumers are important components of the diet of halibut, a species that apparently feeds opportunistically on a broad variety of organisms so that its diet strongly reflects abundance patterns of benthic organisms of suitable size. The dietary patterns of man strongly overlap with those of the halibut, and thus man's position in the trophic web may be as crucial as that of the halibut. However, unless areas of deposition become extensive and the duration of the problem is prolonged, the relative importance of animals containing substances associated with drilling fluids would be quite small in any of the populations of consumer species.

3.2 IMPACTS ON THE PELAGIC ENVIRONMENT

To date there have been nine wells drilled in the lower Cook Inlet OCS lease area including the C.O.S.T. well and eight exploratory wells. None of this exploration has reported any results to suggest that recoverable quantities of hydrocarbons may be found. Additional exploratory wells may be drilled in the next few years, but no firm plans to do so are apparent. Since the likelihood of a commercial discovery appears slim at this time, the BLM (1976) development scenario is very likely invalid. This scenario calls for 84 exploratory wells and 520 production wells *from* 23 platforms. The total estimated cuttings discharge for this scenario is 160,650 m^3 (210,000 yd^3), and the total estimated whole mud discharge is 27,350 m3 (172,000 bbl).

Because of the very dynamic nature *of* the currents in lower Cook Inlet, impacts on the pelagic environment can be considered on the basis of a single well. There would be little chance for interaction of impacts even if several wells were being drilled simultaneously.

3.2.1 Initial Dilution and Dispersion

The upper plume of the drilling discharge, consisting of wash water, liquid fractions of the drilling mud, dissolved components (including trace metals), and fine-grained suspended sediments (primarily micron- and submicron-sized bentonite clay particles), would come in contact with the pelagic community. Considering the ambient conditions of lower Cook Inlet (Section 3.1.1) and the work of Dames & Moore (1978), it Is likely that dilutions of 10^4, ,.5, and 10^6 can be achieved at distances of 100, 2,000, and 10,000 to 20,000 m, respectively, downstream of the drilling operation. Given these dilutions as well as characteristics of the drilling fluids, increases in trace metal levels would be in the parts per billion range (with the possible exception of barium), and increases in suspended sediment concentrations would be less than 50 mg/l at a distance of 100 m from the discharge. At 2,000 m from the discharge, barium would likely be the only trace metal detectable in the water column; increases in suspended sediment concentrations would be limited to less than 5 mg/l (Section 2.5.1). At distances of several kilometers, increases in any trace metal level would not be detectable using conventional sampling and analytical techniques; effects of the plume on turbidity would likewise be difficult to detect.

3.2.2 Ultimate Fate

Currents and ambient and/or induced turbulence in lower Cook Inlet would tend to maintain the micron-sized and smaller clay particles in suspension virtually indefinitely. However, flocculation of some of these particles with each other and with other suspended sediments could accelerate settling somewhat. Particles that do settle may be resuspended during peak flows on each tide change until they are moved to areas where near-bottom currents are below the critical velocities for resuspension. Burbank (1977) and others suggest that gross circulation would eventually carry the suspended and dissolved components of the effluent to the western side of lower Cook Inlet where they would subsequently be carried into Shelikof Strait. Investigations by Feely et al. (1980) indicate that 80 percent of the fine-grained particles entering Cook Inlet (such as in the size range of bentonite clay) are not deposited in the inlet. Rather they leave Cook Inlet through Stevenson Entrance and may subsequently be deposited in northern and (mainly) central Shelikof Strait (R. Feeley, personal communications).

3.2.3 Biological Effects

The high dilution rates experienced in the upper plume as described above and by Houghton et al. (1980a) should effectively preclude significant biological effects on pelagic organisms in lower Cook Inlet. As described in Section 2.5.1, few, if any, fish or macroinvertebrate species would be expected to remain in close association with a drilling rig in the lease areas of lower Cook Inlet. Small schools of adult salmon (probably coho, Oncorhynchus kisutch) were casually observed passing the rig drilling the C.O.S.T. well in lower Cook Inlet, but little tendency to delay was noted (D. Beyer, personal communication). Other pelagic schooling fishes (herring, smelt) would not be able to withstand the currents in most of the inlet to remain near a drilling vessel for more than a few minutes. If strong swimming fish, such as adult salmon, reacted positively to the turbidity of the discharge or the shading of the drilling rig and chose to remain in the plume in the immediate vicinity of the point of discharge, they could be exposed for up to 3 hr (once per well) to doses approaching the 96-hr LC_{50} during the infrequent high volume discharges. However, the likelihood that significant numbers of fish would both encounter the drill rig and choose to maintain themselves in the plume during a bulk mud discharge is believed to be negligible.

The maximum drilling fluid dose received by planktonic organisms would be similar to that described for bulk discharges in Section 2.5.1, ranging from 50 to 100 percent down to about 0.2 percent (2,000 ppm) whole mud within a few seconds and then to about 100 ppm whole mud within about 3 min (assuming a 50 cm/sec current). As described in Section 2.5.1, this dose would not have a significant impact on any planktonic populations.

Thus, it is extremely unlikely that drilling fluid discharges from one or many wells would have any significant impact on pelagic assemblages in lower Cook Inlet. Because of the limited exposures that pelagic organisms (both plankton and nekton) would have to drilling fluids discharged in lower Cook Inlet lease areas, no critical pathways have been defined.

3.3 IMPACTS ON THE BENTHIC ENVIRONMENT

3.3.1 Initial Deposition

Studies on lower Cook Inlet (Houghton et al. 1980a) and in more quiescent environments (Ecomar, Inc. 1978; Ayers et al. 1980a) document that mud and cuttings contained in the lower plume (see Section 2.2.1) can accumulate on (or in) the seafloor. Initial depositional patterns will vary substantially from well to well depending on the water depth, ambient currents, discharge rate, and volume, as well as the physical-chemical properties of the discharge materials.

Although the interaction between these factors does not allow accurate prediction of deposition rates for all cases, field investigations for exploratory drilling operations (Dames & Moore 1978a; Ayers et al. 1980a) suggest that deposition rates in the order of 10 to 50 $g/m^2/day$ would be conservative estimates for a distance of 50 to 150 m from the discharge point. Therefore, assuming a well duration of 90 days, the total amount of solids (cuttings and some mud) accumulation in less dynamic deeper areas of the southern inlet would be in the order of 0.9 to 4.5 kg/m^2 or roughly equivalent to 0.4 to 2.2 mm deposition on the seafloor. This would also equate to about 1 to 5 g solids/kg sediment, assuming mixing with the top 5 cm of sediment. For the assumed total solids discharge from a well (800 m^3, section 2.5), this would cover an area of 2,000,000 m^2 (if evenly spread 0.4 mm deep) to 365,000 m^2 (if spread 2.2 mm deep) assuming, very conservatively, no solids transport from the area during the drilling. The disparity between these theoretical areas and the area where these fluxes have been measured (150 m radius = 70,700 m^2) is indicative of the conservatism of this assumption. Also, since it is normal drilling practice with exploratory wells to allow the return flow of cuttings and mud, if used, to discharge directly from the annulus at the seafloor prior to setting the conductor pipe, larger accumulations within 50 m of the well are likely during the first 50 to 100 m of the drilling.

Once the conductor pipe has been set, discharge of all mud and cuttings occurs through a down pipe located near the sea surface. In central and northern portions of lower Cook Inlet, routine cuttings discharges during drilling would not be expected to accumulate to depths affecting biota because of the strong and shifting currents in the area, and because only limited quantities of mud would be carried with them to the seafloor. Most cuttings are carried to the seafloor. However, the loose boundary hydraulics of the seafloor result In rapid horizontal dispersion and some vertical mixing into the seafloor. Bulk discharges of mud and/or cuttings, especially if occurring during a period of slack current, could locally accumulate in available crevices, animal burrows, and depressions over a small area around the point of initial bottom contact. Accumulations above the existing seabed would not remain through more than a few tide cycles. Currents would transport these materials away from the initial impact zone with some of them being redeposited in depressions down-current of the dump site.

3.3.2 Ultimate Fate

From the time of their initial deposition, mud and cuttings accumulation on the seafloor will be continuously reworked by currents and, in shallower waters, by wave particle motions. Finer fractions of the accumulated mud and cuttings (such as bentonite clay adhering to cuttings) will be resuspended and transported along the seafloor. Larger-grained materials (primarily cuttings) will, however, become entrained in the bottom sediments. Dames & Moore (1978) measured cuttings (particles greater than 0.85 mm diameter) accumulations of 30.0, 10.2, and 0.8 $g/m^2/day$ in a sandy bottom at distances of 100, 200, and 400 m, respectively, from the discharge point on the lower Cook Inlet C.O.S.T. well. It was also noted that, although vertical entrainment in the seafloor sediments had occurred, most cuttings had remained within the upper 10 cm. Although cuttings discharged in lower Cook Inlet would be continuously reworked along with the natural sediments, it is unlikely that coarser-grained materials would be transported any significant distance from the drilling site except in areas with hard bottoms.

In the dynamic sandy bottom common throughout central and north-central areas of lower Cook Inlet, it is believed that long-term trace metals contributions from drilling effluent discharges would result primarily from metals contained in the cuttings rather than in the drilling mud. Information is not available regarding trace metals levels for various geologic formations occurring offshore in lower Cook Inlet.

Portions of the lease area, such as off Anchor Point, exhibit hard bottoms characterized by gravel and cobbles. In these regions seafloor irregularities (probably on the order of several centimeters in height) may locally trap mud components and cuttings until either extreme currents or storm events can rework the natural bed materials. It is believed that mud would ultimately be transported to deeper waters and out of the inlet, whereas the cuttings would become entrained in sandy sediments adjacent to the hard bottom areas or between cobbles within the area through action of near-bottom currents and bioturbation.

More quiescent areas are found at greater depths in the southern portion of the lease area. Here, seafloor sediments consist of sandy silts and may be relatively stable. In these areas, reworking of the bottom sediments may occur primarily as a result of major storm activity or other sporadic episodes of unknown cause when currents throughout the water column may exceed 1.5 m/see (3 knots). Consequently, finer portions of the drilling mud may remain in the vicinity of potential drilling sites for longer periods of time (a year or less), but coarser particles (cuttings) may not be as deeply entrained into the seafloor sediments in these areas as in the more dyamic sandy bottoms of lower Cook Inlet.

3.3.3 Biological Effects

3.3.3.1 Short-Term Effects

In the very dynamic central and north-central portions of lower Cook Inlet where no visible accumulations of cuttings or mud are expected, only very insignificant effects, if any, would occur in the benthic or epibenthic assemblages. The rapid transport and dilution of drilling muds from the drill site would preclude significant toxic effects induced by metals or hydrocarbons closer to the site, and dynamic boundary conditions at the seafloor would rapidly reduce concentrations of mud and cuttings. Since associated heavy metals or hydrocarbons would be unlikely to increase sediment metals levels significantly above ambient, metals or hydrocarbon accumulations by local organisms would remain generally within their natural ranges.

Since most of the bottom sediments in these areas include some coarse sand and fine gravel, the quantity of coarse cuttings worked into the sediment would be unlikely to significantly alter the stability of the bottom or its suitability for any species. Larger pieces of inorganic debris discarded or lost over the side could be expected to attract a considerable fouling community, provide a collecting point for organic debris, and hence create a focal point for epibenthic predators and scavengers (e.g., crab, shrimp). Organic debris knocked from the fouling assemblages on the vessel or its anchor chains would be carried away by the currents and would not result in long-term attraction of scavengers to the drill site (as was reported in the mid-Atlantic by Menzie et al. 1980). However, Dames & Moore (1978a) did report that disturbances of the seafloor caused by anchoring activities resulted in a temporary increase in predators (e.g., king crab and flatfish), apparently attracted by infaunal organisms that had been unearthed and/or damaged by movement of anchors and chains.

In the shallower northeast corner of the lower Cook Inlet lease area off Anchor Point, the hydrodynamic regime is no less rigorous than that in the central portion of the lease area. However, presence of gravel, cobble, and rocky outcropping and their associated fauna may significantly alter the likely impacts of drilling mud and cuttings discharges from those described above for the central region. Tidal currents will likely remove mud and most cuttings on each tide. However, dense assemblages of attached epifauna such as bryozoans, hydroids, and sponges could be directly affected by burial during bulk discharges. Shallowly buried mussels (Modiolus modiolus) might survive up to several days of burial until currents uncover them by removing the mud. Although generally tolerant of intermittently turbid waters, other epifaunal forms such as snails, sea urchins, and starfish would likely be killed by more than a day or two of complete burial. cuttings and mud accumulations in crevices and depressions amongst the cobbles, in shell "hash," or between individuals in the mussel beds found there could be expected to cause at least some mortalities to small infaunal polychaetes and bivalves inhabiting underlying natural sediments. Mortalities could result either from smothering or from chemical toxicity to organisms forced into direct contact with the muds; however, bioassay studies in lower Cook Inlet suggest that the toxicity of the muds is low (Houghton et al. 1980b; Carls and Rice 1981). Filling of the interstices between boulders or between mussel shells could also deprive smaller epifaunal crustaceans of critical microhabitat providing them protection from the strong currents in the area. Presence of mud in these spaces during certain times of the year would alter the recruitment success of many species which could influence local species composition for a year or more (e.g. Tagatz et al. 1980).

In the deeper waters near the ocean entrances to Cook Inlet, short-term effects of mud and cuttings discharges would be similar in many ways to those described above for the northeastern sector. However, the feature that might allow accumulation of visible cuttings and mud deposits is the reduced energy regime of the near-bottom environment rather than roughness. The relative importance of deposit-feeding infauna is far greater in the deeper water area although a substantial sessile epifauna (hydroids, bryozoans, sponges, polychaetes, etc.) is still present, attached to bits of gravel and shell (Dames & Moore 1978d). Mortalities to less motile epifauna and infauna would be expected where accumulations of a few millimeters or more of mud and cuttings occurred. If a high percentage of mud solids persisted in or on sediments near the well, changes in the success of larval recruitment would be expected. Mud and cuttings accumulations and associated effects would be expected to occur patchily over a relatively small area (e.g. , Menzie et al. 1980)--perhaps 1,000,000 m^2 (section 2.5.2)--and might persist for as much as a year following completion of drilling.

3.3.3.2 Long-Term Effects

In the dynamic central and north-central portions of lower Cook Inlet, drilling of one or many wells would not have a measurable long-term effect on local marine benthos. The greatest potential for long-term impacts would be in depositional areas (the "ultimate sinks") probably in deeper water to the south, especially in Shelikof Strait. Because of the bimodal tidal patterns in the inlet and the extreme dilution expected before ultimate deposition, levels of mud, associated heavy metals, hydrocarbons, and other potential toxicants resulting from the maximum development scenario would be undetectable by humans and inconsequential to marine life within a few months of completion of drilling.

Mud and/or cuttings accumulated and retained in crevices and depressions in the hard bottom areas of the northeast portion of the lease area off Anchor Point would be steadily and rapidly winnowed from the crevices and dispersed by currents and wave surge. The speed at which this process occurs is difficult to estimate. However, it is possible that some of the largest or most firmly compacted materials would require a period of weeks to disperse. During this period infauna in underlying sediments could be affected due to smothering, chemical toxicity, changes in sediment grain size, and resulting changes in recruitment success. The degree of change could range from partial mortality over a limited area, to minor changes in species composition over a somewhat larger area, to no measurable effect. Although mortalities of epifauna due to burial could occur in a limited area, substrate would be available for recolonization within a few weeks of the end of drilling as currents cleaned any accumulated mud from the upper surfaces of cobbles.

During the period while currents were transporting and dispersing muds from the bottom in the vicinity of the drill site, local organisms and organisms downcurrent of the site would be exposed to small increases in levels of some trace metals or petroleum hydrocarbons, with the metals being primarily associated with very fine particles. Levels in the near-bottom water column would be well below those causing acute toxicity. However, as these particles are transported near the bottom they may be taken up by the primarily filter-feeding sessile epifauna.

Since the area is not depositional, and the bottom tends to be hard, there are relatively few deposit feeders. However, uptake by the organisms (primarily polychaetes and ophiuroids) of small quantities of trace metals or hydrocarbons from mud-contaminated sediments is likely. Measurable increases in trace metal levels in various organs of both suspension and deposit feeders would be possible within a few hundred meters of the drill site. Beyond that distance some local increases may occur, but generally metal and hydrocarbons would be well within the range of natural background levels and therefore not detectable.

As discussed in Section 2.3.4, the significance of increased metals levels in organism tissues is poorly understood and highly variable depending on the metal in question. Effects on higher trophic levels of eating metals-contaminated prey are also poorly documented, but biomagnification appears unlikely for two reasons. First, there is little historic evidence of biomagnification of trace metals (other than mercury, Section 2.3.4). Second, most predators on the infauna or sessile epifauna of this area are relatively mobile and, even if many wells were drilled in the area, would be likely to spend only a small fraction of the time feeding in contaminated (vs. uncontaminated) areas.

The critical pathway with respect to species of direct importance to man might be the clam/mussel --> king crab --> man linkage (Figure 3-15). If metals levels near the bottom were elevated for a sufficient period of time, and if Flustrella (an erect bryozoan) or other prey species assimilated significant quantities of any of these metals, and if eating contaminated prey had any direct harmful effect on juvenile king crab, then an adverse economic effect on local fisheries could result from a large-scale drilling program in this area. However, none of the above hypotheses is known to be true, and there is no reason to assume that all three are true. Moreover, net circulation patterns should tend to move resuspended muds north away from the most important king crab nursery areas around the northern entrance to Kachemak Bay (Section 3.1.2). Nonetheless, given the importance of this area to juvenile king crab, examination of the sensitivity of king crab prey species to drilling muds and the effects on crab of feeding on mud-exposed food items would be a reasonable prerequisite for a major production drilling program in this area . Another similar potential critical pathway would be through Pacific halibut, also a commercially important predator on suspension and deposit feeders of the northeast portion of the lease area.

In the less dynamic southern portions of the lower inlet, detectable levels of mud *or* mud-associated contaminants might persist near a well site as long a year or more. Therefore, it would be highly probable that recruitment success of many species would be reduced in this localized area (perhaps as large as 1,000,000 m2. Exposures of sessile benthos to trace metal or hydrocarbon contaminants could be longer than would occur elsewhere *in* the inlet providing a greater opportunity for uptake of heavy metals or petroleum hydrocarbons. Again, the significance of possible uptake of heavy metals by benthic organisms on these organisms or on their predators cannot be fully evaluated. However, based on available information, it seems clear that the area of bottom where measurable uptake could occur would be limited (perhaps 1,000,000 m^2 per well (Section 2.5.2). As discussed above, the effects of this uptake *on* organism fitness is a major unknown.

If all the drilling mud (27,350 m3) produced by the now highly unlikely BLM development scenario were spread evenly over the bottom in the probable ultimate sink of Shelikof Strait (9,800 km^2 of depths of 90-160 m), they would form a layer about 3μ thick. *Given* that the average colloidal bentonite particle is some 2μ in diameter this layer would be equivalent of 1.5 particles thick. Levels of trace metals and hydrocarbons would be undetectable as would associated biological effects.

3.4. ADDITIONAL AREAS FOR RESEARCH

Unless there is a significant discovery in one of the few exploratory wells that may be drilled in lower Cook Inlet OCS lease areas, there is no need for additional data to analyze the impacts of drilling fluid and cuttings discharges. The large central area of the inlet is ideally suited for the dispersion and dissipation of these types of effluents so that no significant impacts are likely even from a large-scale drilling program. This conclusion cannot necessarily be applied to state lease areas on either side of the inlet, some of which are in very sensitive ecological areas with totally different biological and hydrodynamic characteristics. Nor can it be applied without qualification to the OCS Sale 60 area in Shelikof Strait.

The information needs listed below are primarily for areas where further investigation would be fruitful in refining our ability to evaluate impacts of large-scale drilling activities in the OCS area of lower Cook Inlet. These information needs include:

1. Evaluation of the potential *for* movement of suspended drilling muds into depositional regions such as the southern portion of Kamishak Bay (south *of* Mt. Augustine), the central portion of southern Cook Inlet, and northern and central Shelikof Strait. The latter are believed to be the primary areas in which drilling muds will (or have been) deposited.

2. Investigation of the potential effects of ultimate storage of drilling fluids in depositional regimes of lower Cook Inlet and Shelikof Strait. This would also be desirable in the event of drilling in those areas pursuant to Sale 60 in lower Cook Inlet and Shelikof Strait. This should include long-term bioassays for sublethal impacts of low concentrations of drilling fluids on benthic deposit feeders and animals with exposed tissues such as sea pens, and polychaetes and sea cucumbers, and feeding experiments with commercially important predators on benthos (e.g. crabs, halibut, etc.) to determine transferability of metals through the food chain.

3 A more complete assessment of benthic assemblages and food webs in deep-waters depositional areas in the central portion of southern Cook Inlet (north of Barren Islands and Stevenson Entrance) and in northern and central Shelikof Strait. At present, virtually no information is available for Shelikof Strait.

4. Investigation of the distribution of corals in Kennedy and Stevenson Entrances, around the Barren Islands, and in northern and central Shelikof Strait. Numerous types of corals (hydro-corals, Pennatulacea, Gorgonacea and Alcyonacea have been reported from nearby areas, but appropriate investigations have not been conducted in southcentral Alaska.

4. DRILLING EFFLUENT FATE AND EFFECTS ON GEORGES BANK

Concern about the ultimate fate and biological effects of drilling effluents on the Georges Bank ecosystem has been widely expressed by a broad spectrum of interested parties. Effects on the rich and highly productive Georges Bank fisheries are of principal concern. It is generally recognized that the effects of a single exploratory drilling operation are limited to a small area. However, there is great concern over the potential, cumulative effects of drilling fluids resulting from the drilling of numerous wells should the fluids and associated pollutants accumulate in significant concentrations for a significant period of time in specific depositional areas.

It has been hypothesized that drilling effluents from oil and gas operations will have relatively short residence times on Georges Bank. The current regime is likely to transport the bulk of these effluents off the bank and into three potential sinks which include the southern portion of the Gulf of Maine, the "Mud Patch" on the continental shelf off Rhode Island, and the canyon heads along the southern flank of Georges Bank.

Elements of the Georges Bank environment which are pertinent to the examination of drilling effluent fate and effects are first presented (Section 4.1) to provide a background for the physical and biological analyses which follow. The most probable drilling scenario is then developed to provide dimensions for the proposed action (Section 4.2). Dispersion of effluents in the water column and resulting biological effects on the pelagic environment are discussed in Section 4.3. Conceptual models of the deposition and transport of the drilling effluents are then presented along with discussion of potential critical pathways and biological effects on the benthic community (Section 4.4). Simplifying but conservative assumptions are applied when possible to establish upper limit conditions on effluent effects. Further refinement of deposition estimates is not pursued if evaluation of such upper limit effects does not reveal any significant impact on the receiving environment. Chapter 4 concludes with a discussion of the relevance and applicability of available data and potential areas for future research on Georges Bank (Section 4.5).

4.1 THE GEORGES BANK ENVIRONMENT

4.1.1 Physical Features

The water adjacent to the east coast of the United States in the northeast Atlantic can be divided into four regimes--the shelf water, the slope water, the Gulf Stream, and ocean water (Figure 4-1). The slope water may at times extend into the seaward portion of the shelf water. The Gulf Stream forms a narrow current regime about 90 km wide and runs seaward of the shelf water.

Georges Bank is bounded by the Great South Channel, the Gulf of Maine, the Northeast Channel, and the continental shelf/slope break where some of the major east coast canyons can be found. Labrador Sea water occasionally intrudes into the Georges Bank area and affects the

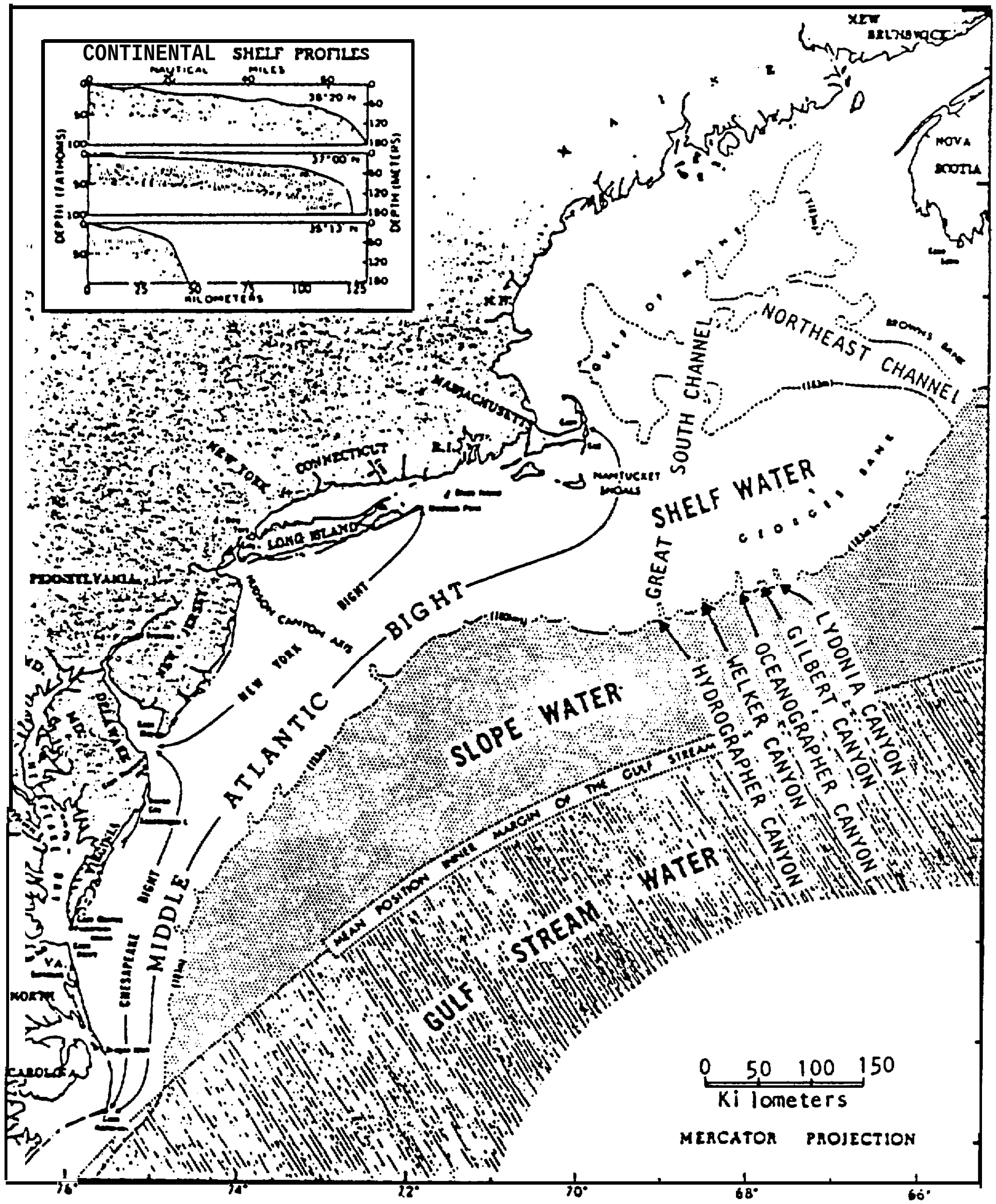


FIGURE 4-1 EAST COAST WATER MASSES (BLM 1979)

hydrographic properties of the surface layer. At greater depths, the Western Boundary Undercurrent flows southwestward into the slope water along the continental rise to cross under the Gulf Stream at Cape Hatteras.

An extensive data base was reviewed in an attempt to develop a summary of the physical oceanographic conditions of the Georges Bank environment. This information was developed from BLM (1977, 1979) TRIGOM (1974), Gusey (1977), CNA (1977), and numerous more recent references.

4.1.1.1 Temperature and Salinity

The temperature and salinity distributions of the northeastern continental shelf were first discussed by Bigelow (1927, 1933) and Bigelow and Sears (1935). Colton and Stoddard (1972) developed maps of temperature distribution, and Colton et al. (1968) published charts on salinity distribution. Their results have been summarized in TRIGOM (1974). The National Marine Fisheries Service (NMFS) has conducted surveys for spring and fall sea surface temperature and salinity conditions from 1972 to 1977 (Pawlowski and Wright 1978). Their results have shown temperature and salinity distributions and ranges similar to those obtained from the earlier studies.

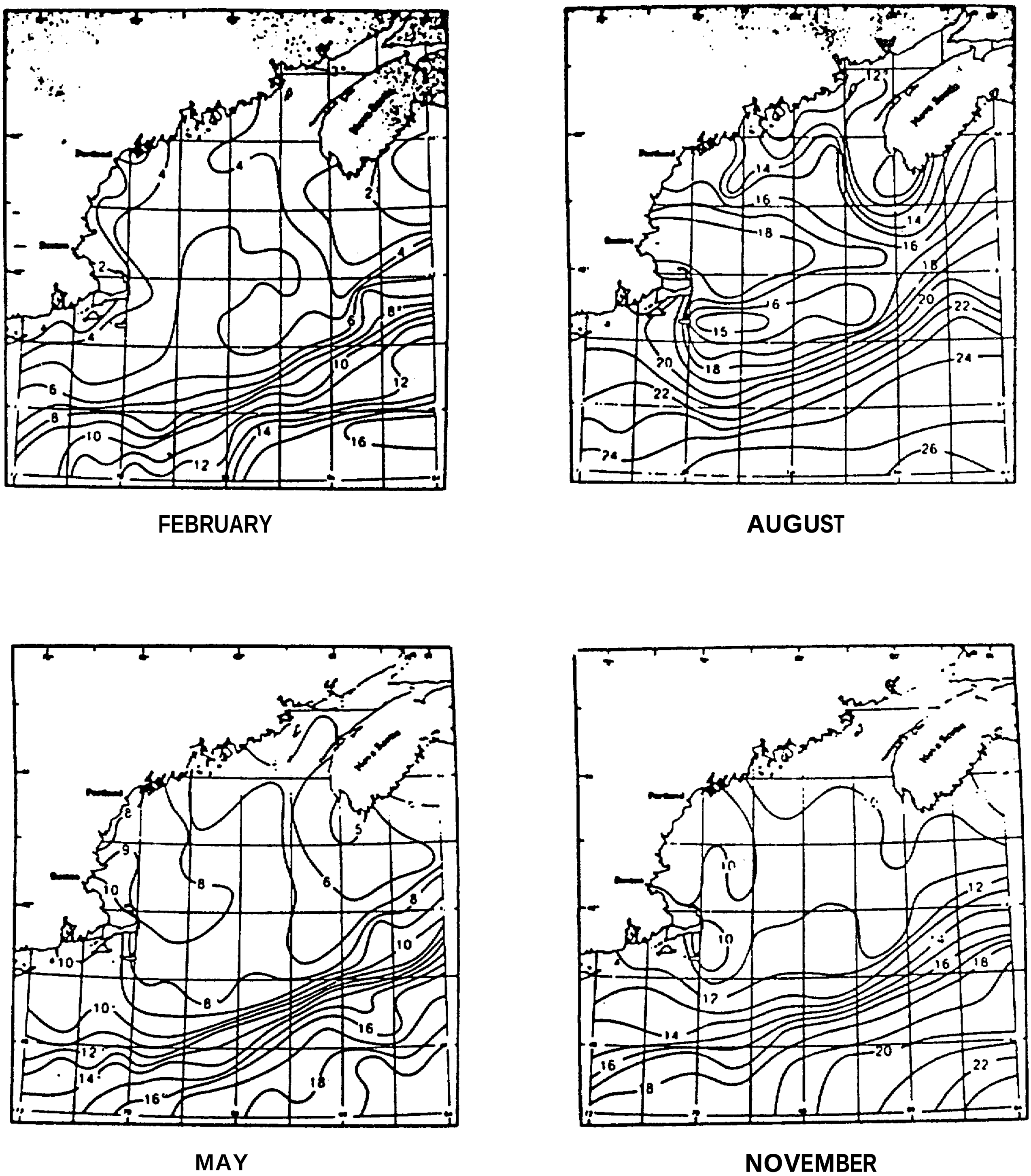
Temperature

An annual cycle of seasonal temperature variations has been observed thoughout the area (Colton and Stoddard 1972) and is discussed in detail by BLM (1977). Pawlowski and Wright' (1978) have also indicated a strong seasonal trend in temperature distribution. In late spring, thermoclines start to develop and become progressively stronger by summer. Intense water column stratification occurs in August and September, especially in areas of deep water where tidal mixing is weak. In shoal areas such as Georges Bank and Nantucket Shoals, tidal mixing limits the formation of intense vertical thermal stratification. By winter, temperature distribution in the water column becomes relatively homogeneous, though weak stratification may occur in the deep slope water. Colton and Stoddard (1972) showed a wide range in surface temperature from the offshore region to coastal areas (Figure 4-2).

Bottom temperature usually varies with depth, and isotherms closely parallel the contours of the coast and shoals (Colton and Stoddard 1972). The occurrence of a bottom pool of cool water along the southern flank of the bank between the 60- and 100-m isobaths has been observed. Temperatures are generally less than 10°C, and the pool is surrounded by warmer water masses. This is a persistent feature throughout the summer.

Salinity

Sea-surface salinity in the region does not show the same strong seasonal effects as the temperature distribution (Pawlowski and Wright 1978) . A relatively large, homogeneous salinity field over the Gulf of Maine-Georges Bank area is bounded by sharp gradients. An eastern gradient at the Scotian Shelf break separates the more saline Gulf of



Adapted from TRIGOM (1974)

NOMINAL SCALE 1:6,000,000

FIGURE 4-2 AVERAGE MONTHLY TEMPERATURE AT THE SURFACE (COLTON AND STODDARD 1972)

Maine water from the Scotian Shelf water. A southern gradient at the shelf/slope front was also observed (Colton et al. 1968).

In late spring, increased freshwater discharges result in salinity stratification in the upper layers of coastal waters. Stratification tends to increase through September due to the distribution of lower salinity water throughout the Gulf by currents (TRIGOM 1974). Stratification in shoaling areas such as Georges Bank is much less intense than in the deep water area of the Gulf of Maine and the south-lying shelf/slope boundary.

The continental shelf/slope region of Georges Bank has been characterized by the existence of a persistent temperature/salinity front. The Georges Bank shelf/slope water front is similar in structure and continuous with the front at the continental shelf/slope region of the Mid-Atlantic Bight. The front appears to remain between the 1,000- and 100-m isobaths (Wright 1976; Ingham 1976). Pawlowski and Wright (1978) noted that there are distinct gradients where known water masses and geographical barriers meet. Such gradients also appear along the northern edge of Georges Bank, the Northeast Channel, and the Nantucket Shoals-Great South Channel area. The shelf/slope front continuously forms the southern boundary of the study area.

4.1.1.2 Circulation

Studies of the general circulation patterns in the northeast Atlantic by Bigelow (1927), Bumpus and Lauzier (1965), and Bumpus (1973, 1976) have generally confirmed a residual counterclockwise circulation in the Gulf of Maine and a clockwise circulation in the Georges Bank area at speeds of approximately 10 cm/sec (Figure 4-3). South of Nova Scotia, flow is northwestward into the Gulf of Maine or diverges eastward into the Bay of Fundy. Southwestward flow occurs across Nantucket Shoals south of Cape Cod. An oblong, counterclockwise, eddy-like circulation exists seaward of the Georges Bank gyre with a southwestward moving limb located closer to the continental shelf.

These studies, however, have not concluded complete closure of the Georges Bank gyre. A seasonally varying circulation pattern has been presented. The Georges Bank gyre is strongest in summer (Bumpus and Lauzier 1965) with a southerly offshore component on the eastern edge. In winter, the near-surface flow is offshore. The southern, eastward moving limb of the Gulf of Maine eddy crosses the northern limb of the Georges Bank eddy in spring but slows by early summer. During fall and winter, the southern limb dissipates into a southerly drift across Georges Bank as the eddy withdraws into the northern corner of the Gulf of Maine.

Fixed location current meter measurements were conducted on Georges Bank and the adjacent shelf in several field studies from 1975 to 1979 by scientific groups including USGS, WHOI, EG&G, and NEFC (Butman et al. 1980). These current meter measurements have collected data of near-surface currents typically at depths of 10 to 15 m and subsurface currents at greater depths. Figure 4-4 shows the results of these studies.

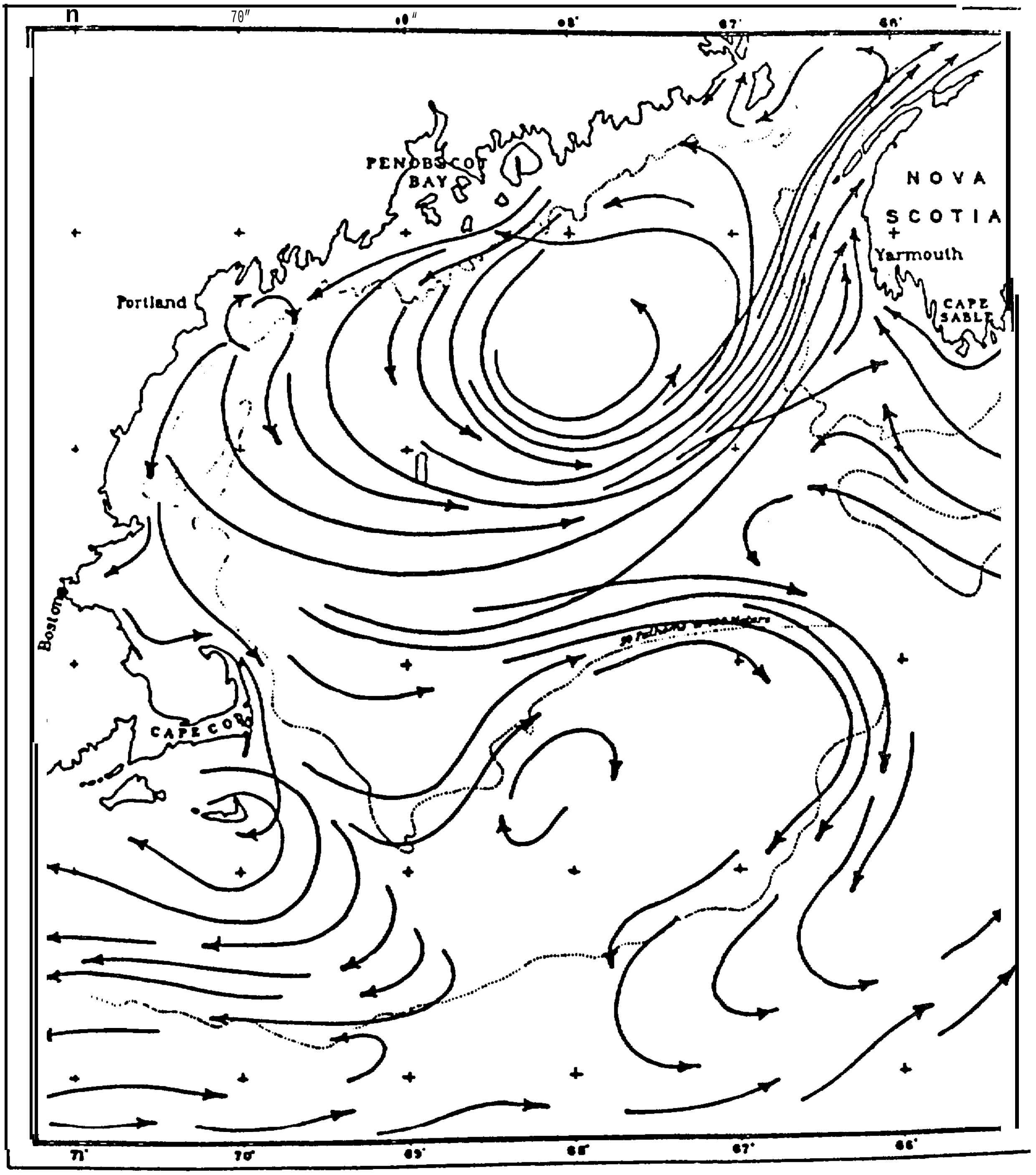


FIGURE 4-3 **THE MEAN CIRCULATION IN GEORGES BANK AND ADJACENT AREAS (ADAPTED FROM BIGELOW 1927)**

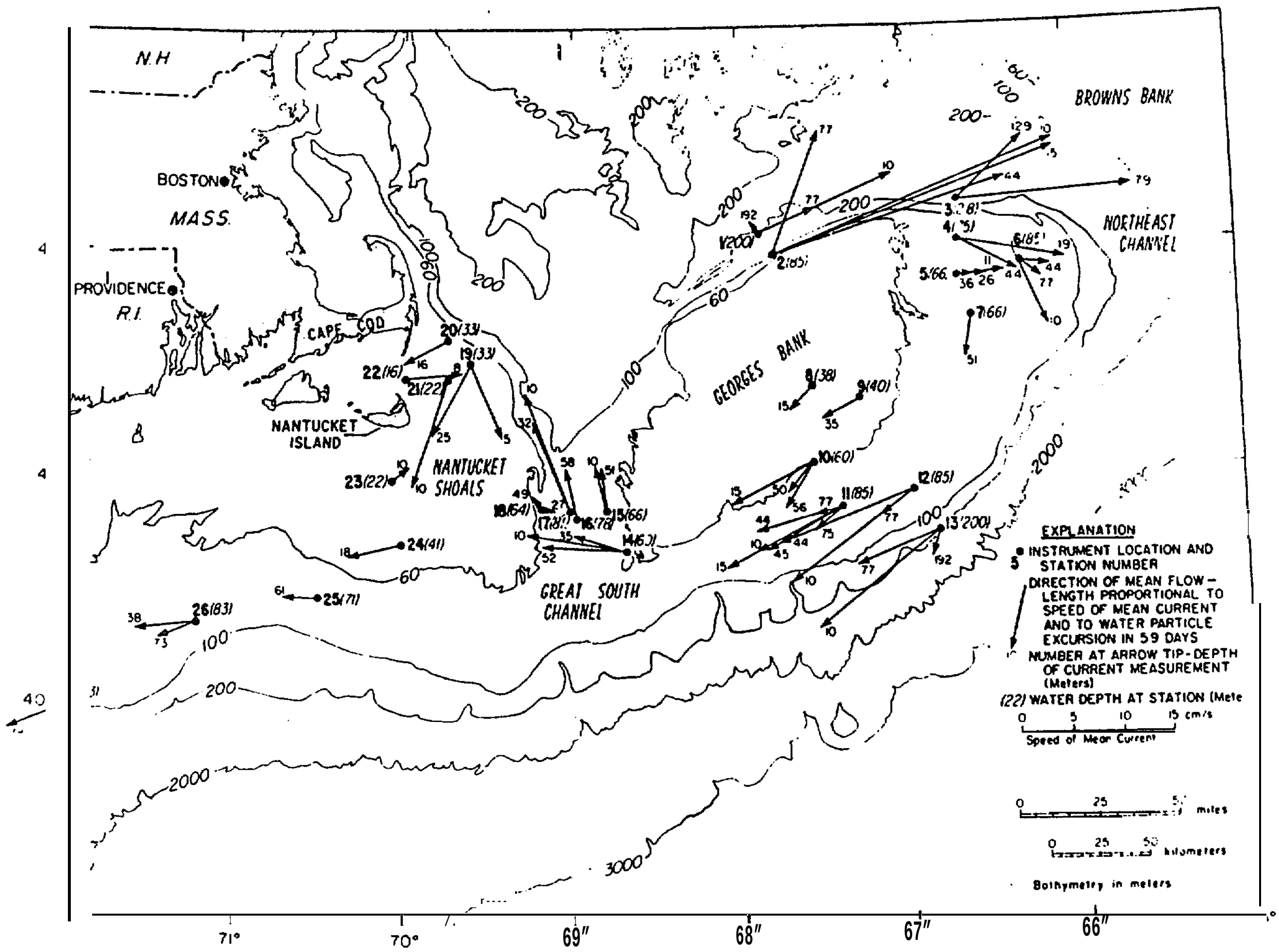


FIGURE 4-4 MEAN EULERIAN CURRENTS (BUTMAN ET AL. 1980)

Northern Flank Circulation

A near-surface, northeastward moving jet with steady current speed of about 30 cm/sec has been observed in water depth of 85 m along the steep northern flank of the Georges Bank, generally following the local isobaths. This speed persists throughout the water column and was also detected at 44 m from the surface. The speed of near-bottom currents decreases to approximately 15 cm/see, and an off-bank component was detected. Off the steep northern flank, water depth increases toward the Gulf of Maine basin, and observed current speeds decrease. Current speeds of 16 cm/sec in a northeastward direction were detected in the near-surface flows. The near-bottom current velocity ranges from 2 to 5 cm/sec and possesses an onshore component. The fast-moving jet current was hypothesized to be confined to a bank 10 to 20 km wide along the steep, northern flank (Butman et al. 1980). However, the question of the horizontal position of the jet is not fully resolved. The axis of the jet is probably associated with the density front on the northern flank of the Bank and is subject to fluctuations in response to external forces (Magnell et al. 1980).

Toward the northeastern corner of the bank, current velocity weakens and direction is southeastward in the near-surface flows with speeds of 8 to 12 cm/sec. Velocity ranges from 2 to 7 cm/sec in subsurface to near-bottom flows, and directions are southeastward, eastward, and southward. Stronger southward components have been detected in both near-surface and subsurface flows at current meter locations relatively south on the eastern edge of the bank, suggesting a southward flowing direction around the bank. However, strong eastward flowing currents were detected in deep waters of the northeastern corner following local isobaths. Current speed ranges from 10 to 15 cm/sec at mid-depths in water 218 m deep with an off-bank component in the deeper subsurface flow.

Southern Flank Circulation

Current-meter data for the southeastern corner of Georges Bank are lacking. Along the southern flank of Georges Bank, mean current direction is southwestward along isobaths. Near-surface flows are typically 10 to 15 cm/sec. Current speed increases with increasing distance offshore and slightly offshore components are detectable. At mid-depth, velocity ranges from 8 to 15 cm/sec and possess an onshore component. Offshore components are again detectable in near-bottom flows, and speed is generally less than 5 cm/sec at 8 to 10 m above the bottom. Data collected at a station located in water depth of 85 m demonstrated that the mean subsurface flow in all seasons is toward the west roughly parallel with the local isobaths on the southern flank of the bank.

Western Flank Circulation

Flow is consistently toward north and northwest at 5 to 10 cm/sec at all depths on the eastern side of Great South Channel. Current magnitude slightly decreases from near-surface to near-bottom depths. Stronger northward components were detected at locations relatively north along the eastern side of the channel. The current direction just south of the channel at 60 m deep was northwestward with a westward component. At that location, current magnitude is comparable to flows on the southern flank of the bank along the same isobath.

Southward and southwestward flows at 5 to 10 cm/sec at all depths were detected across Nantucket Shoals. Between Monomoy Island and Nantucket Island, an eastward drift toward Nantucket Shoals was detected. Limeburner (1977), Limeburner et al. (1980) have shown a consistent mean southward and southwestward flow from the Gulf of Maine and Nantucket Sound over most of Nantucket Shoals. A consistent westward subsurface mean drift was detected in the mid and outer shelf south of Cape Cod at speeds of less than 10 cm/sec. Beardsley et al. (1976) have shown a consistent westward subsurface mean flow of 5 to 10 cm/sec along the mid and outer shelf of the Mid-Atlantic Bight. Residual drift detected on the crest of Georges Bank is weak in the south and southwestward direction.

Butman et al. (1980) reported the results of an aircraft-tracked surface drifter in the top 1 m of water depth and a satellite-tracked near-surface drifter drogued at 10 m from the surface. Figures 4-5 and 4-6 show the mean Lagrangian near-surface currents and drifter trajectories at 10 m, respectively. It should be noted, however, that drifter buoy data may include minor bias in water particle trajectory results. This is due to the drifter floats' inability to follow vertical water motions and to wind and wave influences on the surface buoy.

Results of surface drifters show northeastward flow along isobaths on the steep slopes of northern Georges Bank. Slightly onshore components away from the bank occur in deeper waters off the bank. Lagrangian 10-m drifters show similar northeastward, strong jet-like flow along isobaths as shown by Eulerian current meter data. At the northeastern corner of the bank, results of 1O-UI drifters indicated that flow is eastward and changes to southeastward toward the eastern edge of Georges Bank. Surface drifters indicated inflow into the Gulf of Maine area south of Browns Bank on the eastern side of the Northeast Channel. Both surface (l-m) and near-surface (10-m) drifters show slightly offshore southerly components on the southern bank of Georges Bank. This offshore flow component was most evident in the December 1978 deployment (Figure 4-6). In the Great South Channel area, a 10-m drifter indicated northward to northeastward flow on the eastern side of the channel and southward flow in the western side near Nantucket Shoals. Surface drifters, however, showed no consistent inflow into the Great South Channel.

Drifter trajectories at 10 m (Figure 4-6) clearly indicate a complete loop around Georges Bank in August 1979; this drifter eventually crossed the shelf break and drifted into the deep offshore waters. A drifter deployed in winter 1978 followed the eastern edge of the bank before it drifted offshore on the southern flank. Drifters crossing the Great South Channel were observed in a May 1979 deployment. Bi-directional flow along the Great South Channel was evident from the June 1979 drifters. These results also showed inflow into the Gulf of Maine at locations northeast of the Great South Channel. These drifters eventually rejoined flows around Georges Bank.

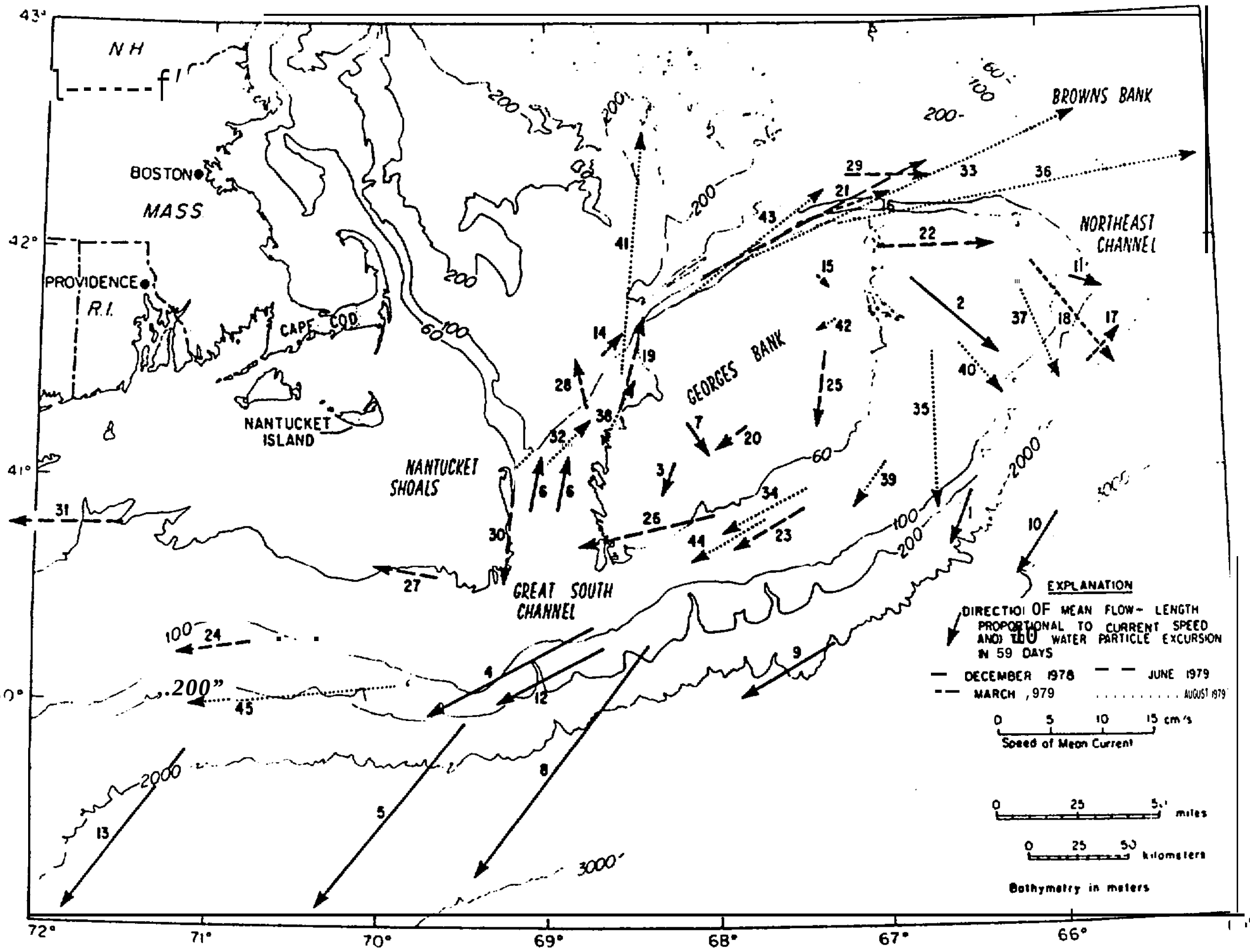


FIGURE 4-5 MEAN LAGRANGIAN NEAR-SURFACE CURRENTS 10 m FROM THE SURFACE (BUTMAN ET AL. 1980)

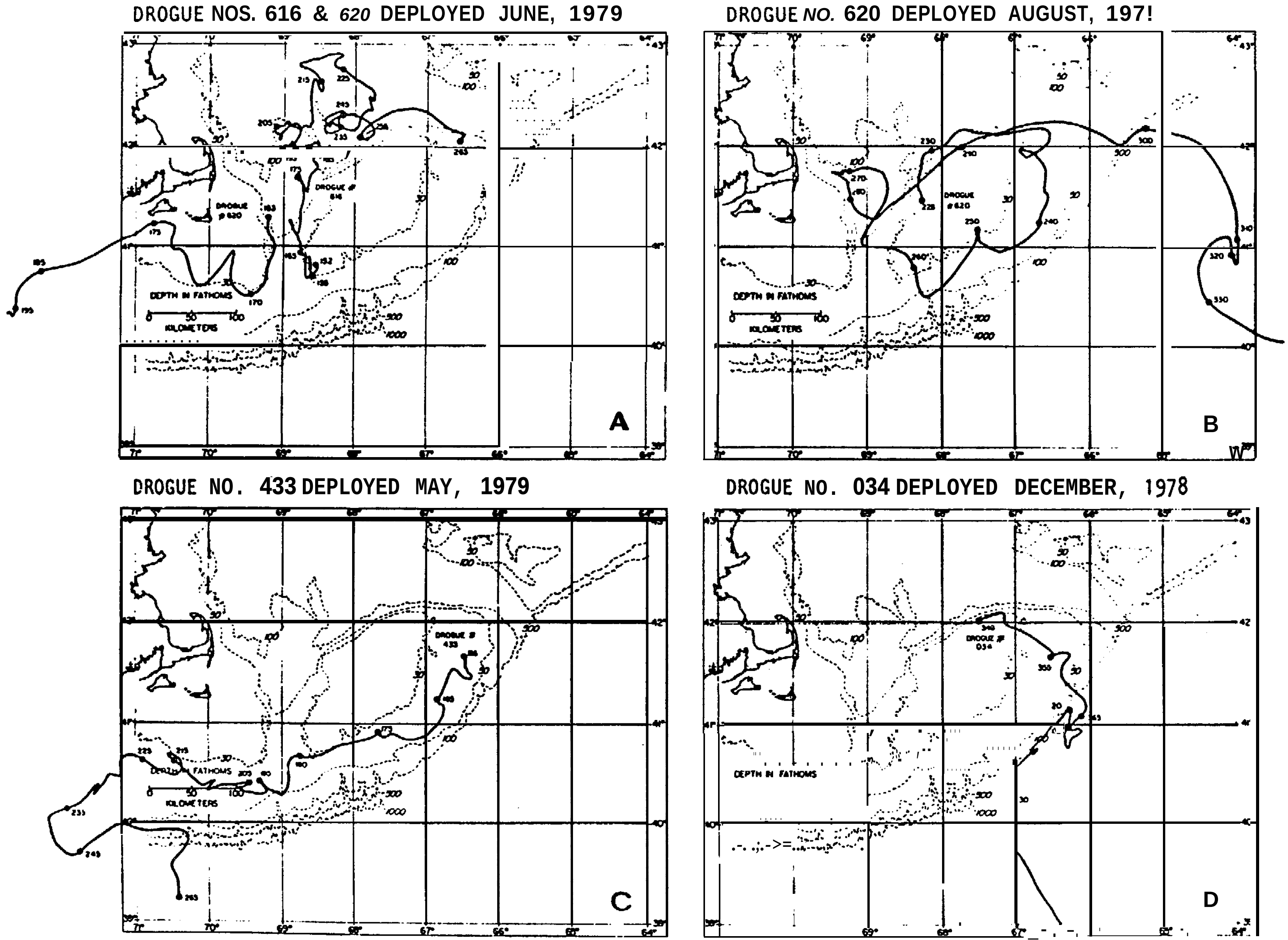


FIGURE 4-6 NEAR-SURFACE DRIFTER TRAJECTORIES 10 m FROM THE SURFACE (BUTMAN ET AL. 1980)

Current Measurement Summary

Eulerian current meter and Lagrangian drifter measurements have shown the following principal features of the circulation pattern in Georges Bank area: the clockwise long-term residual flow; the high-speed, northeastward flow on the steep northern flank; the southwestward current on the southern flank with near-surface offshore components; the weak flows on the crest; the weak southward and southeastward flow in the eastern area of the bank; and the northward flow on the eastern side of the Great South Channel. However, deviations from the general, aforementioned, flow pattern have been noted in surface (l-m) drifter data, e.g., flow into Gulf of Maine occurs south of Browns Bank, and there is absence of consistent inflow into the Great South Channel.

The consistency in the results of the mean Eulerian current measurements and the 10-m drifters have suggested a long-term, intermittently-closed, clockwise gyre subsurface circulation around the shallow center of Georges Bank, although seasonal variations may exist in the strength of this circulation. In the tidally-mixed region with depths shallower than 60 m, water may recirculate, i.e., the subsurface central core of the Georges Bank gyre may be partially closed (Butman et al. 1980). The gyre is by no means a permanently closed feature as reflected by the offbank flow components in the deep water areas around the bank and the variability in the 10-m drifter trajectories. The circuit time of a water particle moving around a 60-m isobath was estimated to be approximately 2 months and perhaps longer in depths shallower than 60 m. Results of a diffusion model (Butman et al. 1980) suggested that the average residence time on Georges Bank is 2 to 3 months during the summer and less than 1 month during the winter.

The Gulf Stream

The Gulf Stream is characterized by multiple currents and counter currents. over the years there have been increasing observations of meandering, anticyclonic, Gulf Stream eddies which bring warm, saline Gulf Stream water onto the slope region. Flagg (1979) reported a large clockwise-rotating eddy detected from the Gulf Stream south of Nova Scotia in late summer 1977. Data describing the eddy were collected in November 1977 when it affected the southwestern portion of Georges Bank. The hydrographic data indicate that the eddy displaced the shelf/slope front by 50 to 100 km onshore and offshore, that there was a permanent exchange of between 350 and 450 km^3 of water between the eddy and Georges Bank, and that the entrainment of bank water extended to approximately the 100-m depth. Current data show that the eddy had surface currents in excess of 100 cm/see, with little decrease in velocity for at least the upper 500 m. Moored instruments on the bank showed the passage of the eddy as a shoreward movement, followed by an offshore movement of the shelf/slope front. After the passage of the eddy, alongshore oscillations with 4- to 5-day periods were evident in the current records. Hydrographic and current meter evidence suggests that when an eddy moves quickly along the shelf break, the region of greatest shelf/eddy interaction is confined to the immediate vicinity of the eddy and to the wake region to the east.

The Western Boundary Undercurrent

The Western Boundary Undercurrent (WBUC) is a persistent, deepwater flow that carries water of Norwegian Sea origin through the slope water region and beyond to the south. It flows inshore of the Gulf Stream at a slower speed and carries less quantity of water than the Gulf Stream. Speeds are on the order of 10 cm/sec but range as high as 47 cm/sec (Zimmerman 1971; Richardson 1973). The highest velocity occurs closest to the continental slope. The cold water mass of WBUC and its characteristics have been used to trace the current beyond Cape Hatteras (Barrett 1965) as far as the Greater Antilles Outer Ridge north of Puerto Rico Trench (Tucholke et al. 1973). Most observations of this current are in water depths ranging from 3,580 to 5,000 m, but it has also been observed in depths as shallow as 1,000 m. The current appears to shift positions north and south from time to time (Schmitz et al. 1970).

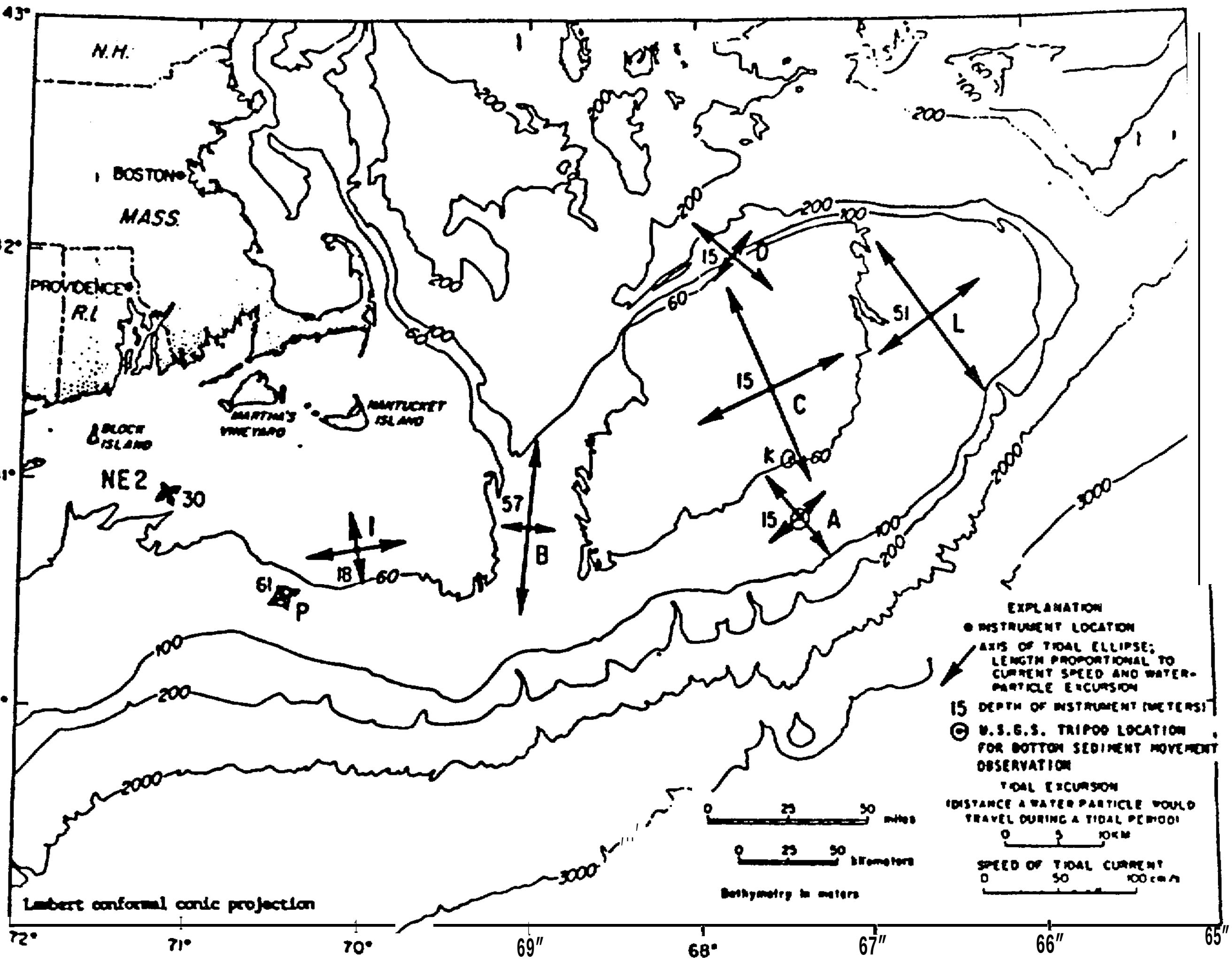
The Northeast Channel Flow

Studies conducted in recent years by the NMFS and USGS, and by the ICNAF since 1975 (data unpublished) show that a shelf/slope front exists persistently inside the Northeast Channel below 100 m with a significant gradient above 100 m (Pawlowski and Wright 1978). Above this gradient, data show that waters characteristic of the Scotian Shelf are common, suggesting a southwesterly flow from Browns Bank across the Northeast Channel onto the northeast corner of Georges Bank and the shelf/slope front as a seasonal characteristic. Below 100 m of water, net inflow into the Gulf of Maine along the Northeast Channel occurs in summer and winter, and a period of low transport occurs in spring (Ramp et al. 1980) as indicated by data collected at three current meter moorings set along a SW-NE transect across the channel with a sill depth of 230 m. At the southwest-most current meter location closest to George Bank, however, persistent outflow was detected below 100 m of water.

4*1.1.3 Tidal and Low-Frequency Currents

Tides and tidal currents in the Georges Bank and the adjacent areas are semi-diurnal in nature exhibiting two cycles in one tidal day (24.84 hr). The tidal current data are shown on Figure 4-7 and presented on Table 4-1.

Tidal current intensity is generally weaker in the deep waters of the Gulf of Maine Basin than in the shoaling areas of Georges Bank. Current meter moorings set in water depths between 50 to 250 m on northern Georges Bank (Schlitz and Trites 1979) have indicated that the perimeter of the tidal ellipses described by the rotary velocity vector on the bank were about four times larger than over the deeper water off the bank. Magnell et al. (1980) also found that the near-bottom tidal amplitude is about 20 to 22 cm/sec and that the tidal currents at 77 m at a 200-m water depth are weak and variable compared to the tidal current velocities found at the same depth at an instrument located 10 km away. Tidal currents diminish in magnitude substantially over short distances off the steep northern flank of Georges Bank (R. Schlitz 1980, personal communication). Tidal currents also decrease in intensity southwestward along the bank toward the west. In the mid and outer continental shelf



Note: The data shown were collected at stations A, B, C, D, I,L,P and NE 2.
The measurements were not made simultaneously.

FIGURE 4-7 MAGNITUDE AND ORIENTATION OF SEMIDIURMAL TIDAL CURRENTS ON GEORGES 8ANK AND THE ADJACENT SHELF AREA (AARON ET AL. 1980; BUTMAN 1980)

TABLE 4-1

TIDAL CURRENT INTENSITY

Location (Water depth, m)	Instrument Depth (m)	Semi-Diurnal Tidal Current Amplitude (cm/see)	Source of Data
Crest of Georges Bank (38)	15	75	(a)
Northern Flank (85)	15	35	(a)
Eastern Edge (66)	51	60	(a)
Southern Flank (85)	15	35	(a)
Great South Channel (78)	57	55	(a)
Nantucket Shoals (41) (71)	18, 61	35, 10	(a)
Mid-Atlantic Bight (80)	74	12	(b)

Sources:
(a) Aaron et al. 1980.
(b) Butman *et al.* 1980.

region south of Cape Cod, near-bottom tidal strength diminishes to less than 10 cm/sec at a site located in 71-m water depth. The same order of magnitude of near-bottom tidal intensity was also observed at a location on the continental shelf of Mid-Atlantic Bight in the 80-m water depth (Butman et al. 1980).

A study conducted by Magnell et al. (1980) on the tidal and low-frequency currents *on* the northern slope of Georges Bank has disclosed the stiking relationship between these two natural forces. The steady high-velocity northeastward jet flow was somewhat an unexpected phenomenon when it was first observed from *current meter measurements* This flow magnitude was not observed either in the deep waters of Gulf of Maine or in the shoal waters of Georges Bank. This study has found that the velocity of the jet along the 100-m isobath is proportional to the amplitude of the local tidal current. The near-bottom cross-isobath flow is also proportional to the tidal current amplitude for the long-shelf velocity fluctuation component in the frequency band containing wind-driven energy. The low-frequency current and the jet circulation are believed to be connected with the large-scale response of the Gulf of Maine flow system.

4.1.1.4 Potential Pathways and Exits from Georges Bank

At present, because of the many unresolved questions concerning the dynamics and circulation on Georges Bank and in adjacent areas, it is difficult to arrive at a quantitative and rigorous evaluation of the exact nature of flow pathways and exits of drilling discharges from the bank area. Furthermore, drilling effluents vary widely *in* their physical characteristics and may therefore follow several flowpaths to different exits depending on the location of the discharge and the time *of* its occurrence. Low-frequency current oscillations resulting from storm events and the like can produce substantial deviations from the mean circulation pattern (Butman 1980). In spite of these complications, potential flow pathways and exits can be approximately identified with some distinction between deep and shallow water discharge locations based on the mean circulation pattern. Data presented in Section 4.1.1.2 suggest that the mean circulation consists of an intermittently closed, clockwise gyre centered around the shallower center of the bank. This average circulation dominates the near-surface to subsurface flows for waters 10 m or more below the surface. Offshore flows can occur in the surface layer.

Exits out of the Georges Bank flow system for near-surface and subsurface flows are discussed separately in the following paragraphs. The near-surface flow system is more likely to be associated with the transport of the fine to colloidal solids fractions as well as liquid fractions of the effluents. The subsurface flow system is more likely to be associated with the transport of resuspended solid fractions.

Near-Surface Flow System

Four potential exit locations can be identified in the near-surface flow system (Figure 4-8). These locations are the northwestern corner of Georges Bank on the eastern side of Great South Channel (hereafter called the NW exit location), the eastern edge of Georges Bank adjacent to Northeast Channel (E exit location), the southern flank of Georges Bank (S exit location), and southwestern corner of the bank adjacent to Great South Channel (SW exit location).

At the NW exit location there is northward flow occurring on the eastern side of Great South Channel. Near-surface drifter data indicated inflow into the Gulf of Maine region at that location (Figure 4-6). Once a particle enters the Gulf of Maine area, it may settle, due to the change of tidal strength, from the high energy of Georges Bank to the relatively low energy of the Gulf of Maine, or it may possibly become a part of the Gulf of Maine gyre system if it remains in the water column. However, Figure 4-6 also shows that a particle may return back into the Georges Bank flow system. Greater understanding of the interaction between the Gulf of Maine flow system and the northeastern flow component of the Georges Bank gyre, especially the hypothesized "crossing mechanism" of these two flow systems, would provide more insight into these phenomena.

In the vicinity of the E exit location, an off-bank eastward flowing component occurs at the northeastern corner of the bank. Although near-surface current meter data have been extremely limited, there has been some indication of a seasonally-varying southwestern form of Scotian Shelf water across the Northeast Channel, affecting areas of the northeast corner of the bank and shelf slope break. Near-surface drifter data (Figure 4-6) also indicate flow out of Georges Bank system on the eastern side of the bank; the subsequent flow path is in the direction of the deep slope water regime. However, current meter data are also lacking for the southeastern corner of the bank, so that the tendency toward off-bank flow into the slope water has not been fully verified at that location.

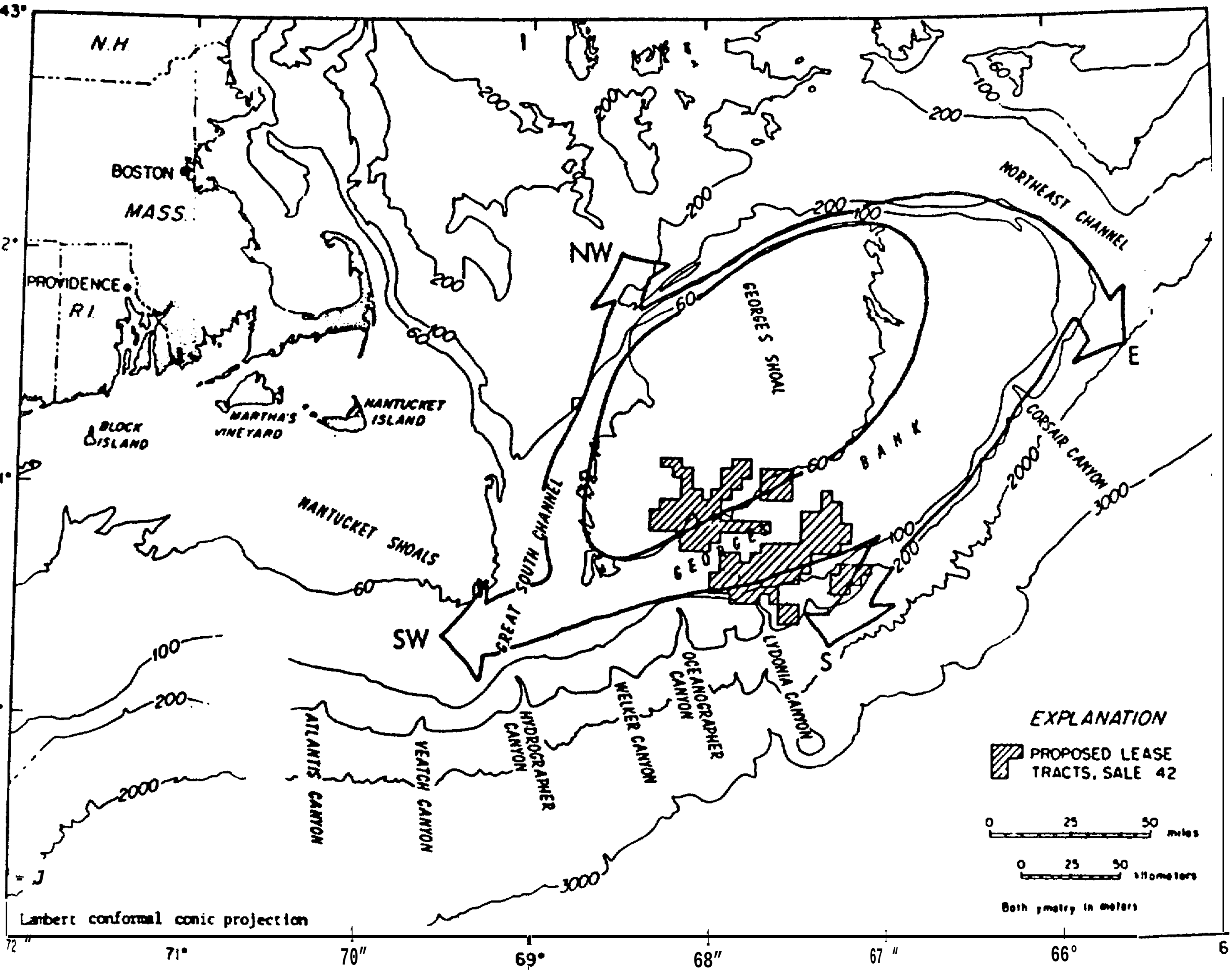


FIGURE 4-8 POTENTIAL PATHWAYS AND EXITS FROM GEORGES BANK FLOW SYSTEM IN NEAR-SURFACE FLOWS (10 -15 m BELOW THE SURFACE)

Slight offshore components have been observed in near-surface Eulerian current measurements made at locations on the southern flank of the bank. Near-surface drifter data substantiated this observation. The offshore component tends to be more developed in deeper water (depths greater than 100 m) than in shallower water. Subsequently, after exiting out of the Georges Bank system at the S exit location, flow can either be moving off the continental slope into the deep water or in the direction of the canyons.

At the SW exit location, strong westward flowing component has been observed from both the Eulerian current meter deployment and drifter trajectories. Flow crosses the Great South Channel and becomes a part of shelf transport in the direction of either the mid-Atlantic or canyon areas.

Subsurface Flow System

Four potential exit locations can also be identified in the subsurface flow system (Figure 4-9). They are the deeper water areas of the steep northern flank, (hereafter called the N exit location); the northeastern corner of Georges Bank (NE exit location); the southern flank of the bank (S exit location); and the southwestern corner adjacent to Great South Channel (SW exit location).

At the northern flank of the bank, strong northeastward flowing jet occurs with off-bank components into the Gulf of Maine indicating that this is a potential exit location (N) of the Georges Bank flow system. Tidal and mean current magnitude diminish substantially as water depth increases off the steep slope. Particles introduced into the Gulf of Maine may settle as the current magnitude decreases, or may be trapped in the Gulf of Maine gyre system.

The strong northeastward jet flow continues toward the northeast corner of the bank where off-bank components have also been observed. Additional evidence for a subsurface NE exit into the Gulf of Maine is found in flow observations in the Northeast Channel. Northward flow components through the Northeast Channel have been observed at depths greater than 100 m from the surface. The convergence of the northeast flow along the northern flank of the bank and the northern flow in the Northeast Channel suggest an off-bank flow into the Gulf of Maine at this location.

Subsurface flow along the southern flank of the bank is mainly along local isobaths. However, weak offshore components have been observed at near-bottom depths suggesting it is a possible exit location (S) of the subsurface flow system particularly for near-bottom flows of the Georges Bank system. Subsequently, flow may be in the offshore direction toward the slope water regime or toward the canyon area, depending on the exact location of exit.

Another possible exit location (SW) is the southwestern corner of the bank where there have been observations indicating cross-Great South Channel flows in the direction of the mid-Atlantic as shelf transport.

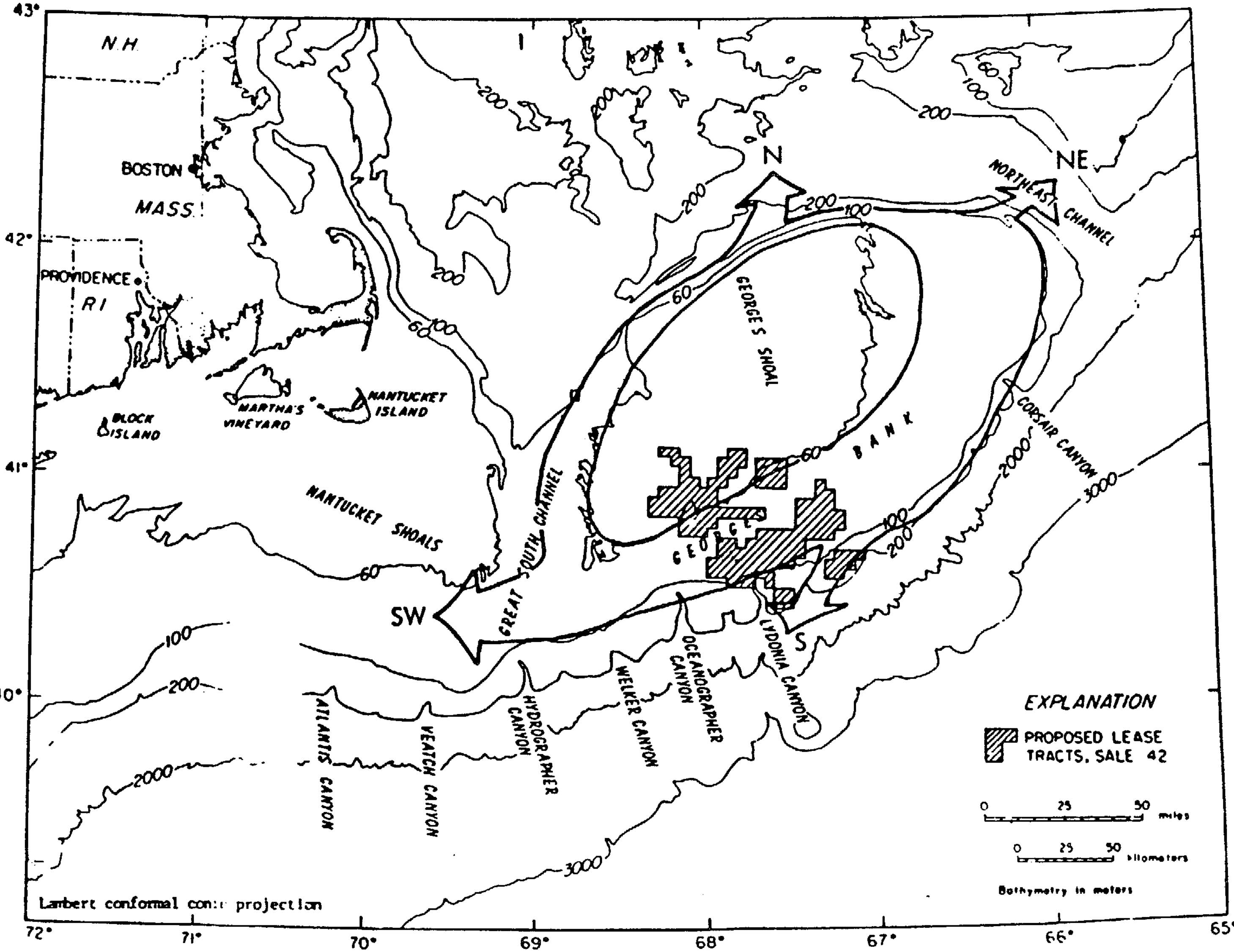


FIGURE 4-9 POTENTIAL PATHWAYS AND EXITS FROM GEORGES BANK FLOW SYSTEM IN SUBSURFACE FLOWS (GREATER THAN 15 m BELOW THE SURFACE)

Table 4-2 summarizes the preceding discussion of the near-surface and subsurface flow systems of Georges Bank and provides a generalized picture of the potential exits and flow pathways.

4.1.1.5 Sediments and Sediment Transport

Georges Bank sediments have been investigated to map the major geographic features of sediment type and distribution (Schlee and Pratt 1970; Wigley 1961a). Wigley (1961a) described the distributions of several sediment parameters. The geographic distributions of sediment grades, predominant fractions, organic matter, and mollusc shell fragments are shown on Figures 4-10 and 4-11.

Sand, the principal sediment grade on Georges Bank, covers 75 percent of the area (Figure 4-10A). Gravel covers a significant portion of the northeastern bank and smaller patches occur in small areas of Great South Channel and on the north-central part of the bank. Small areas of silt and clay occur in deep water northwest of the bank. A plot of predominant sediment fractions (dominant fraction in each sample) gives greater resolution to the distribution of sediments (Figure 4-10B). Only sand fractions are given in this presentation. They show that most of the sandy sediments are composed of medium to fine sand fractions. Fine sands occur primarily from 30 to 100 fathoms on the southwest part of the bank and along the northern and southeastern edges of the bank.

The organic content of sediments on Georges Bank ranges from 0 to 3.4 percent by weight (Figure 4-11A). The highest values are associated with the silt and clay sediments in deep water northwest of the bank. Most of the bank from its center to the Great South Channel (medium to fine sand) is characterized by 0.1 to 0.5 percent organic content.

Mollusc shell fragments, of importance to tube-building polychaete worms, accounted for up to 25 percent of the samples by weight and were most prevalent (5 to 25 percent) in' a broad band extending from north to south along the eastern edge of the bank (Figure 4-11B). This corresponds with the occurrence of sea scallops (Placopecten magellanicus) (Wigley 1961a).

Since 1976 USGS has deployed tripod systems to measure bottom sediment in the Georges Bank Region (Butman 1980). Principal findings from these studies are that the southern flank of Georges Bank can be broadly divided into three major zones according to their physical oceanographic conditions and observed bottom sediment mobility. These include the well-mixed zone in depths shallower than 50 to 60 m where fine-sandy bottom sediments are frequently reworked and fine materials winnowed by the tidal currents and winter storms. This is characterized by observations made at Tripod Location K. Bottom tidal currents of 25 to 40 cm/sec have been observed during nonstorm seasons. Silty and clayey (less than 10 percent) bottom sediment are reworked primarily by winter storms in the intermediate zone with depths of 60 to 100 m. Bottom currents of 20 to 30 cm/sec were detected at Tripod Location A during storm seasons. In areas with water depths greater than 100 m to the shelf edges, tidal currents are weak and unable to initiate sediment

TABLE 4-2

POTENTIAL EXIT LOCATIONS OF THE GEORGES BANK FLOW SYSTEM AND FLOW PATHWAYS

(A) Near-Surface Flows (10-15 m from the surface)				(B) Subsurface Flows (> 15 m from the surface)			
Location of Exit	Supporting[a] Data for the Location of Exit	Subsequent Flow Pathway	Data Gap or Recommendation For Further Study	Location of Exit	Supporting[a] Data for the Location of Exit	Subsequent Flow Pathway	Data Gap or Recommendation for Further Study
Northwestern Corner (NW)	A.2	(1) Gulf of Maine gyre	Dynamics and interaction of the Gulf of Maine and Georges Bank flow system, and mechanism of their "crossing" phenomenon	northern flank (N)	A.1	(1) Gulf of Maine gyre	Same as (A)
Eastern Edge (E)	A.1 A.2 C	(1) Slope water and slope transport into deep ocean water	(1) Near-surface flows in northeast channel (2) Mean current at south-eastern corner of the bank (3) Flow in the slope water regime	Northeastern Corner (NE)	A.1 B	(1) Gulf of Maine gyre	(1) Subsurface flow in northeast channel in depths less than 100 m from the surface
Southern Flank (S)	A.1 A.2	(1) Slope water and slope transport into deep ocean water (2) Canyon area	(1) Flow in the slope water regime	southern Flank (S)	A.2	(1) Slope water and slope transport into deep ocean water (2) Canyon area	Same as (A)
Southwestern Corner (SW)	A.1 A.2	(1) Crosses Great South Channel in the direction of Mid-Atlantic shelf transport (2) Canyon area	(1) Flow dynamics in the vicinity of the canyon head	Southern Corner (SW)	A.2	(1) Crosses Great South Channel as shelf transport (2) Canyon area	Same as (A)

(a) Sources:
A : Butman et al. 1980.
A.1 - Eulerian current data
A.2 = Lagrangian drifter data
B : Ramp et al. 1980.
C : Wright 1980.

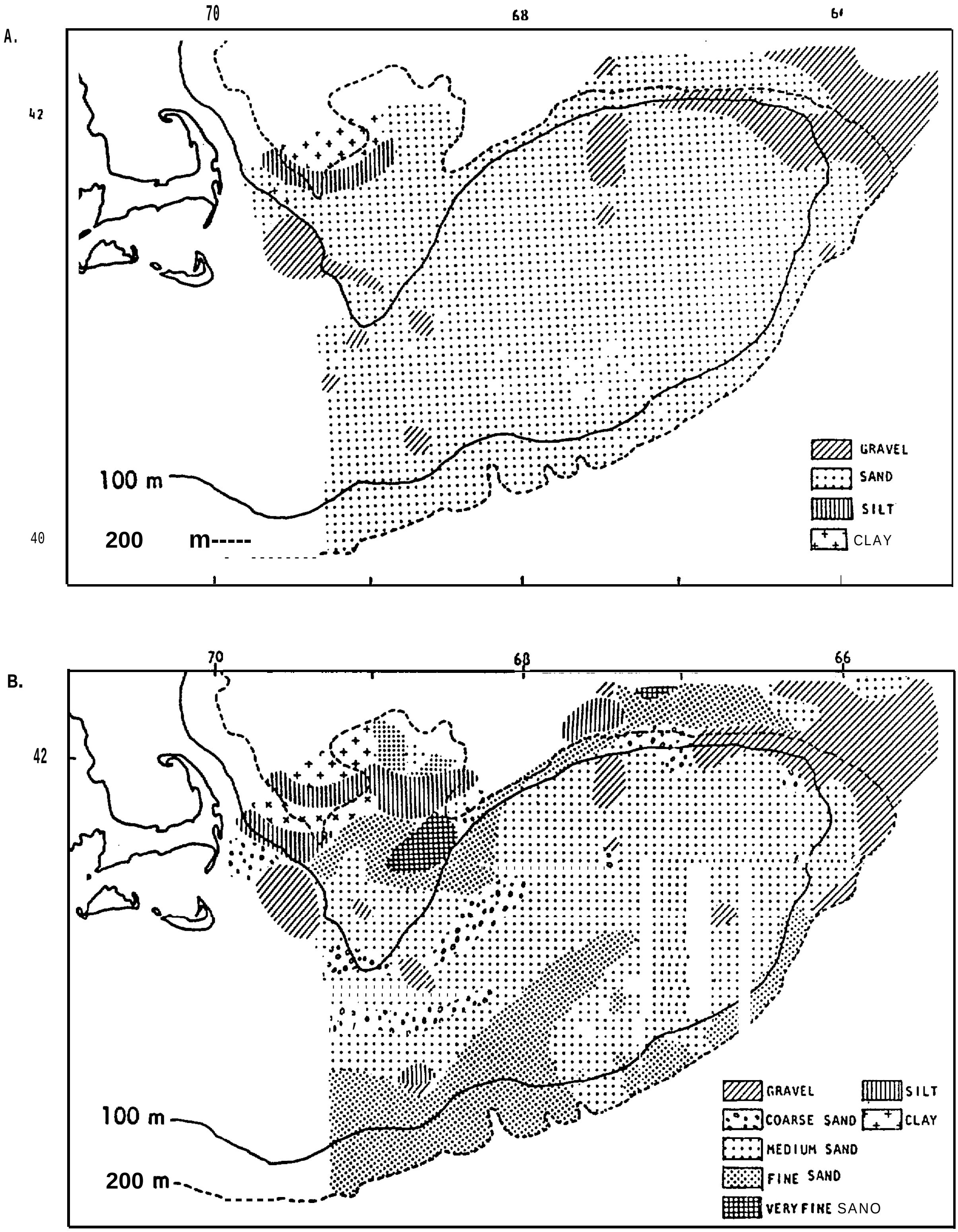


FIGURE 4-10 GEOGRAPHIC DISTRIBUTION OF SEDIMENT GRADES (A) AND PREDOMINANT FRACTIONS (B) (WIGLEY 1961a)

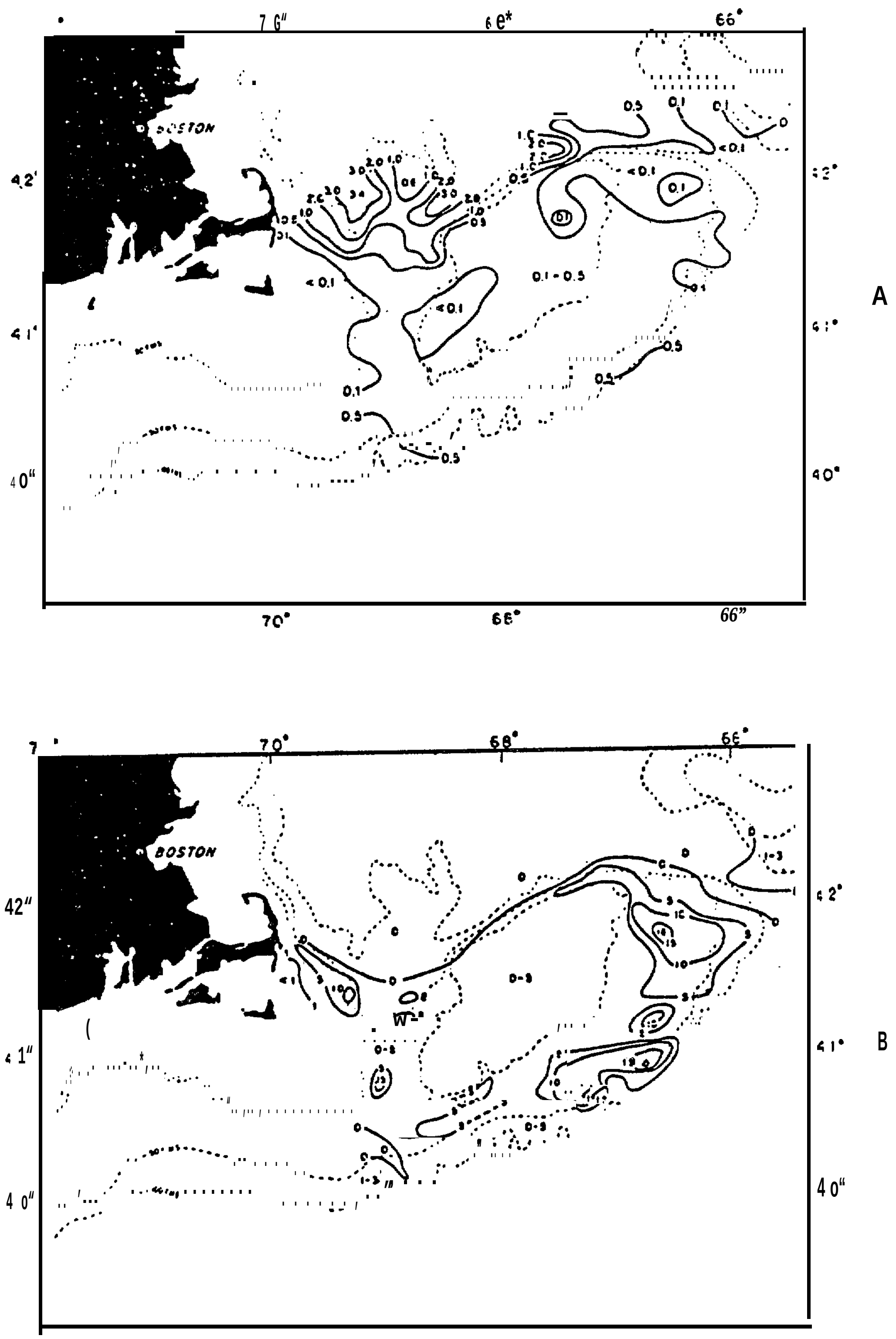


FIGURE 4-11 QUANTITATIVE GEOGRAPHIC DISTRIBUTION OF SEDIMENT ORGANIC MATTER (A) AND MOLLUSC SHELL FRAGMENTS (B) IN PERCENTAGE WEIGHTS (WIGLEY 1961a)

movement. Observations made at Tripod Location P have indicated the importance of winter storms in reworking the silty and clayey bottom sediments. At this location, bottom currents are typically less than 15 cm/sec during nonstorm seasons. Reworking of sandy bottom sediments were also observed at tripod locations in the Mid-Atlantic Bight during winter storms (Butman et al. 1980) where typical tidal amplitude is less than 15 cm/sec during nonstorm seasons.

The effect of storm-generated low-frequency currents on bottom sediments movements in the Georges Bank and adjacent areas has been clearly demonstrated. These current data in Figure 4-12 have been low filtered to remove the tidal and higher-frequency fluctuations, thus representing net water movements (Butman et al. 1980). Low-frequency currents on the crest are weaker than those on the northern and southern flanks of Georges Bank. Typical long-shelf, low-frequency particle excursions are on the order of 10 km near-bottom and 20 to 26 km near-surface. The along-shore component is stronger than the cross-shelf component over most regions in the study area except at areas with deep water depths in Great South Channel and the northeast corner of Georges Bank. In the Mid-Atlantic Bight, the typical low-frequency current excursion is 20 to 30 km long-shelf and 5 to 10 km cross-shelf (Butman et al. 1980).

There is indirect evidence that silts and sands are transferred across the shelf edge onto the upper slope from temporary deposits on the continental shelf. Stanley et al. (1972) terms this feature "offshelf spillover" or "shelf-edge bypassing." Southard and Stanley (1976) distinguish between several modes of spillover. The major ones are (1) entrapment of bedload moving in a stream by a submarine canyon incised into the shelf; and (2) termination at the shelf edge of a sand stream directed normally or obliquely off shelf.

Entrapment of silt, sand, and gravel by canyon heads is a well known mode of shelf-edge bypassing of coarse sediment. This spillover mechanism is prevalent on both wide and narrow outer margins. Typically a sand stream controlled by some pattern of shelf currents is intercepted by a canyon without any effect on the current itself (Southard and Stanley 1976). Figure 4-13 shows a simplified general model of sediment dispersal on the outer continental margin emphasizing offshelf transport of coarse material through canyons.

Lateral dispersion of suspended material is wholly dependent on the movement of the water mass in which the material is contained. In this aspect the transport of fine-grained suspended material is similar to the transport of coarse-grained materials discussed above. However, because of the low gravitational settling velocities of fine-grained materials, their transport into deeper waters is controlled largely by salinity and/or temperature differences within the water column. Figure 4-14 illustrates four models for the transport of suspended particulate from the shelf break to the outer margin.

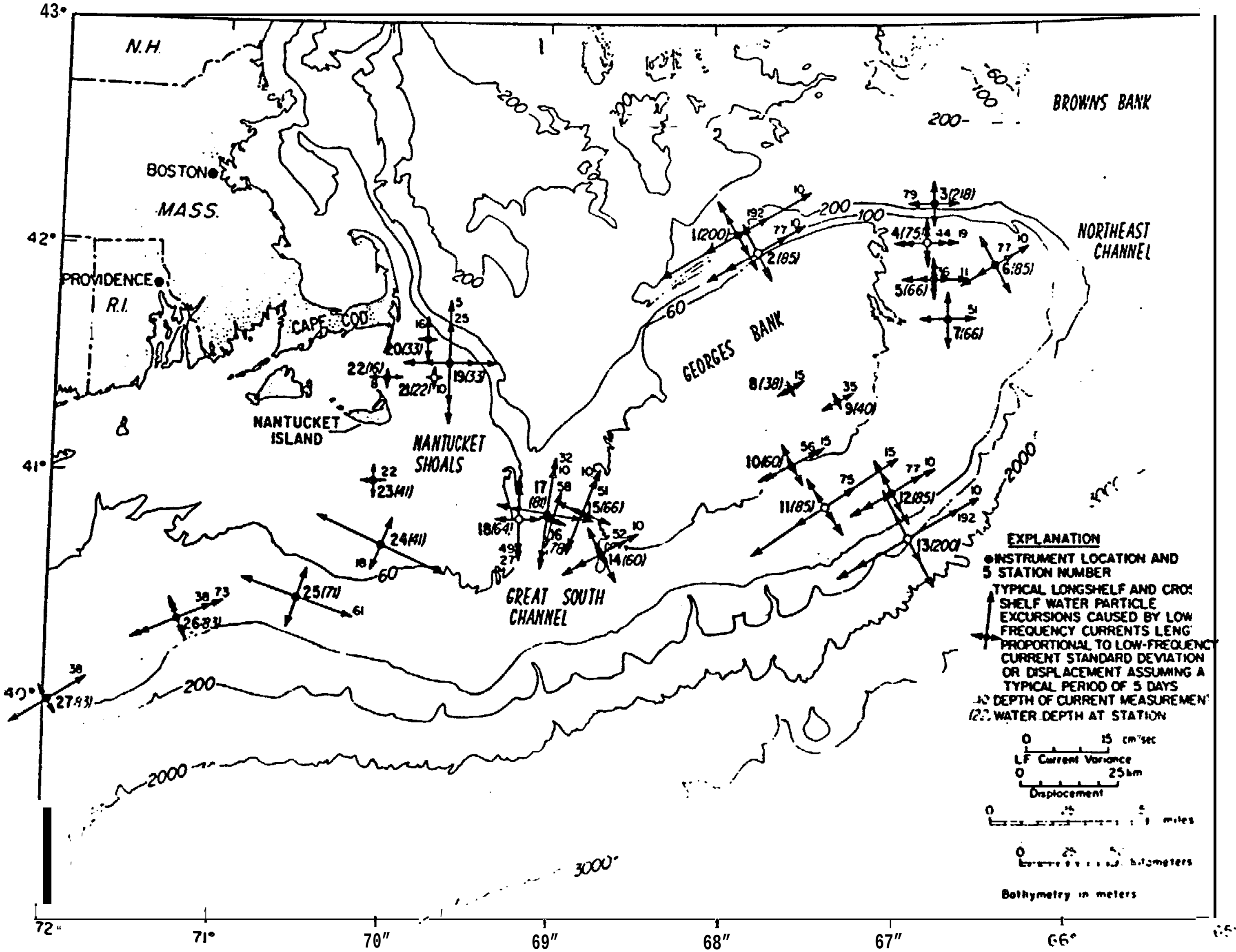


FIGURE 4-12 LOW FREQUENCY CURRENT STANDARD DEVIATION
(BUTMAN ET AL. 1980)

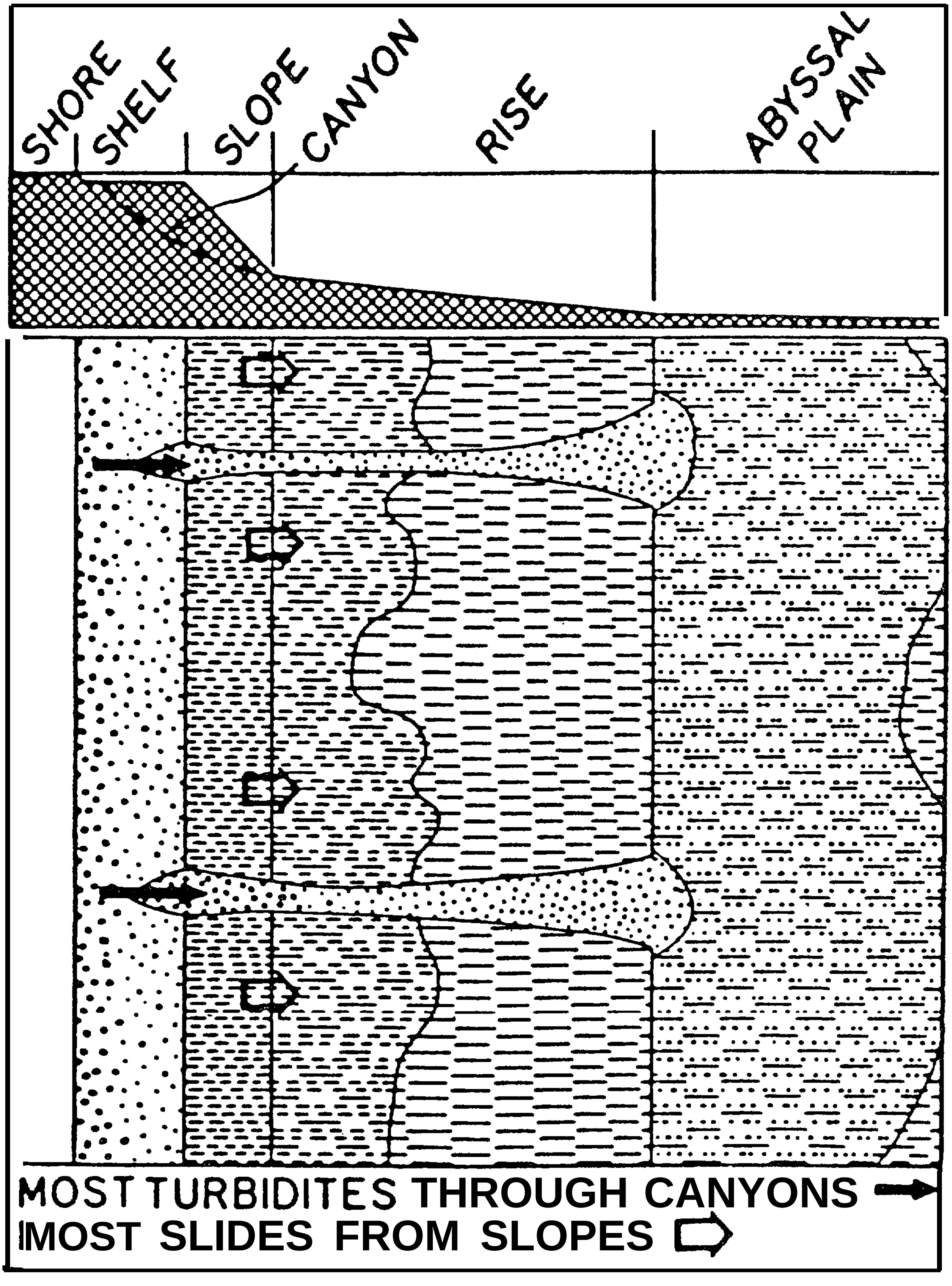
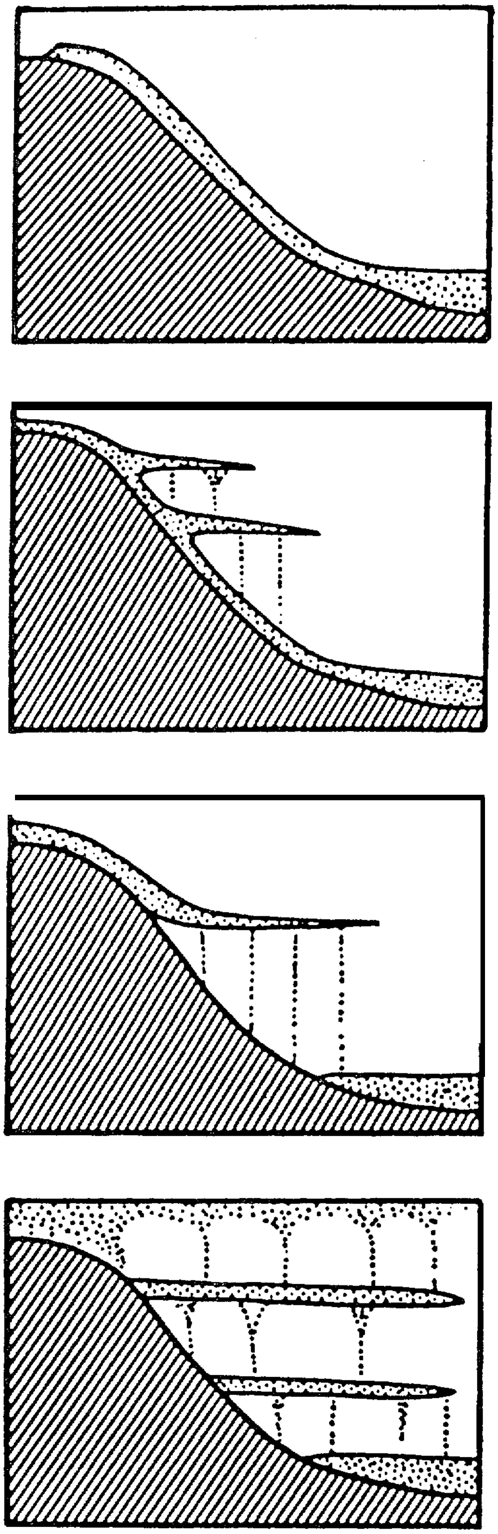


FIGURE 4-13 SCHEMATIC SEDIMENT FACIES AND DISPERSAL ON OUTER CONTINENTAL MARGIN (EMERY 1969)



Excess density flow

Detachment from bottom turbid layer

Cascading

Single particle settling,
accumulation at density interface
and renewed settling

FIGURE 4-14 SCHEMATIC MODELS FOR TRANSPORT OF SUSPENDED MATERIAL FROM THE CONTINENTAL SHELF (PIERCE 1976)

4.1.1.6 Sea and Swell

Thompson and Harris (1972) calculated a wave height distribution function for the Gulf of Maine using data gathered from shipboard observations. Waves greater than 7 m occur only 0.1 percent of the time, those greater than 1 m occur 50 percent of the time, whereas those greater than 0.5 m occur 81) percent of the time. Emery and Uchupi (1972) reported that other data sources agree with Thompson and Harris only for the lower wave heights. Wave data gathered by Neu (1970-1972) indicated that wave heights over Georges Bank and Browns Bank are higher than those within the Gulf of Maine. The I-yr maximum over Georges Bank is 11 to 12 m. The 100-yr wave height for this area is projected at 19 m.

The monthly percent frequency of sea states in the offshore and inshore areas of the North Atlantic region is presented in Table 4-3 (BLM 1977). These data facilitate interpretation of the seasonal trends in sea states, though they should not be considered to accurately predict the sea state of the area.

The extreme wave heights estimated by the U.S. Department of Commerce (1973) for return periods of 2, 5, 10, 25, and 50 years are 15, 20, 24, 27, and 30 m, respectively. The major wave approaching directions are southerly and southwesterly occurring principally in summer. In autumn and winter months, waves approaching from the north and northwest occur more frequently than from other directions.

TABLE 4-3

CUMULATIVE WAVE HEIGHT PROBABILITY DISTRIBUTIONS NEAR GEORGES BANK(a)

	Wave Height (less than or equal to in m)					Number of
	0.6	1.2	1.8	2.7	3.7	Observations
January	11.4	31.7	52.1	78.2	88.7	964
February	14.1	34.0	52.5	79.4	90.5	659
Mar ch	25.0	47.3	66.2	86.7	95.7	2,122
Apr i 1	31.2	57.1	74.9	90.2	97.0	1,376
May	48.8	72.1	84.5	95.0	98.9	2,015
June	48.9	78.5	90.2	98.4	99.6	2,175
July	54.6	80.5	92.8	99.0	99.8	2,160
August	44.6	74.0	90.0	97.8	99.5	1,070
September	33.4	62.2	79.9	93.7	98.4	951
October	26.9	51.5	70.0	90.8	96.5	998
November	17.3	40.8	62.0	86.7	94.3	773
December	14.2	37*1	58.3	81.6	92.0	713

(a) Cumulative probabilities are in percent and are for the region from 40°N to 41°N and 58°W to 69°W.

Source: Naval Weather Service Detachment 1976; presented in BLM 1977.

Ward et al. (1977) generated extreme wave statistics for the Baltimore Canyon and Georges Bank areas using hindcasting techniques for the most severe historical hurricanes. A total of 36 storm events from 1900 to 1975 were used. The maximum and significant hurricane wave heights for Georges Bank are provided in Table 4-4. Ward et al. (1977) also calculated the cumulative probability distribution of wave heights for the Georges Bank area and computed the wave statistics for severe winter storms over Georges Bank (Evans 1971)* The results indicate that winter storm waves exceed hurricane-generated waves (CNA 1977).

TABLE 4-4

HURRICANE WAVE HEIGHTS FOR GEORGES BANK

R_H	Sites 1		2		3		4		5	
	H_s	H_m	H_s	H_m	H_s	H_m	H_s	H_m	H_s	H_m
25	34	62	33	61	32	60	31	58	29	54
50	39	72	37	70	37	68	35	65	32	60
100	43	81	41	78	40	75	39	72	35	66

'H = return period (years)
H_s = significant wave height (feet)
H_m = maximum wave height (feet)
Source: Ward et al. 1977 (adapted from CNA 1977).

9.1.1.7 Canyon Dynamics

The topography of the southwestern portion of Georges Bank at the continental shelf/slope boundary is characterized by a series of submarine canyons. Canyons from Georqes Bank to the New York Bight exhibit similar dynamic 'and sedimentological phenomena (Hotchkiss 1980, personal communication). Geological investigation of Hudson Canyon has identified three distinct zones of sediment distribution in the canyon floor differing with depth. Large-grained sediments in shallow parts of the canyon head area grade toward a layer of mud from 400 to about 1,000 m deep and a very deep bottom layer of sandy sediments disturbed only by occasional strong current surges.

Three types of currents can exist in the canyon area and are believed to be responsible for sediment motion: the oscillatory up- and down-canyon flows, the low-speed turbidity currents, and storm-generated currents (Shepard et al. 1979; Hotchkiss 1980). The normal continuous up- and down-canyon current can potentially transport very fine-particle sediments. Turbidity currents and storm-generated currents are believed to be the major mechanism of transporting materials over great distances down-canyon (Hotchkiss 1980). The periods of alternating up- and down-canyon flows appear to be closely related to both the depth of water and range of tide. In the west coast submarine canyons, approximately synchronous up- and down-canyon flows were observed at near-bottom and mid-depths to heights of 30 to 90 m above the floor; they occurred at the proximity of the canyon head with a net down-canyon flow facilitated by gravity (Shepard et al. 1979). Turbidity currents carry large quantities of sediment flow in the down-canyon direction. These catastrophic turbidity currents have not been strictly observed in the east coast canyons. However, milder surges (i.e., sediment-bearing flows with peak speeds of 50 to 70 cm/sec [Hotchkiss 1980] resembling the low-speed turbidity currents) have been described by Shepard et al. (1979). The difference between these storm-generated currents occurring in the east coast canyon and the low-speed turbidity currents is their duration: 16 hr for down-canyon storm-related flows (Hotchkiss 1980) with a maximum speed of 60 cm/see, compared to a few hours (usually 1 or 2) for the low-speed turbidity currents.

In the east coast canyons off Georges Bank, data were collected from a study in Hydrographer Canyon at three locations with axial depths of 348, 512, and 713 m near the canyon head area (Shepard et al. 1979). The data indicated that the long-term net flow was down-canyon at the shallow and deep stations, whereas the middle station had a net flow up-canyon at 3 m above the bottom. At the shallow station, net flow is cross-canyon with equal up- and down-canyon flows. The velocities of the flows at the shallow stations peaked at 52 cm/sec in the down-canyon direction, and the up-canyon flow in the middle station showed velocities in excess of 40 cm/sec. These are among the fastest currents of any of the Shepard et al. (1979) surveys. However, still higher up- and down-canyon velocities have been observed from deep-diving vehicles (B.C. Heezen, personal communication in Shepard et al. 1979). Figure 4-15 shows the superposition of the time-velocity curves for the 348- and the 512-m depths in Hydrographer Canyon. The later peak times for the shallower station indicate *up-canyon* advance of internal waves. The record also clearly shows the continuous, high velocity character of the flows.

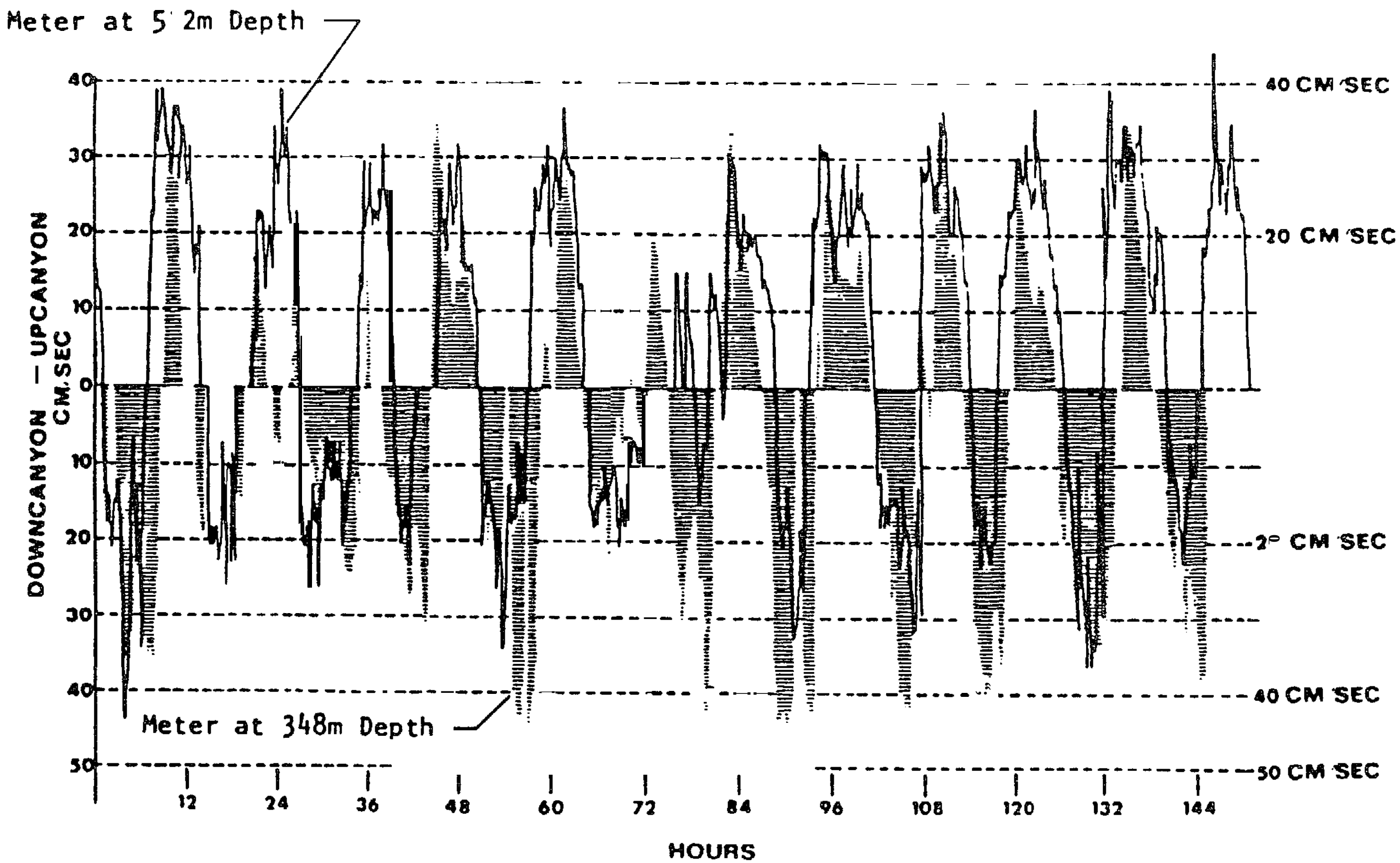
Shepard et al. (1979) proposed that normal alternating currents are caused by the landward-propagating internal waves. Some of these waves found on adjacent continental shelf are of tidal period. Shepard et al. further indicate that data collected in Hudson Canyon showed long-term net down-canyon flows at two stations in depths of 223 and 1,222 m, and up-canyon or cross-canyon at a deep station in depth of 765 m. All current meters were deployed 3 m above bottom.

Hotchkiss's (1980) study on hydrographic properties of Hudson Canyon has reached the following conclusions:

1. Concentration of internal waves and tides in the canyon head probably cause sediment movement and suspended mud in the canyon head area.

2. The direction of internal wave energy propagation is up-canyon, away from the sea.

3. Oscillatory currents in the canyon are of two origins: internal tides produced at the edge of the canyon and more frequent internal waves trapped in the canyon as they enter it.



Note Current meters are at 3 m above bot om.

FIGURE 4-15 IME-VELOCITY FOR HYDROGRAPHER CANYON (SHEPARD ET AL.

4* However, an internal wave field in the canyon does not produce large enough velocities and energy to move large quantities of sediment significantly.

5. They are, nonetheless, strong enough to induce erosion of the canyon floor at its head.

6. Consequently, storm-generated down-canyon currents are believed to be-playing a more important role in sediment transport than the oscillatory flows related to the internal wave field in the canyon area.

Other mechanisms also influence sediment movement in submarine canyons. These include gravity-controlled and biologic processes (Kelling and Stanley 1976). The gravity-controlled processes are:

1. Sliding and slumping where cohesive materials yield and move under gravitational influence in a more or less coherent manner.

2. Slow creep of cohesive or cohesionless material as a variant of the slump or slide.

3. Mass flow where the internal coherence of the material is essentially lost.

4. Grain flow as a category of mass flow where the energy sustaining the sediment in motion derives from grain-to-grain interactions.

5* Fluidized flow where the supportive energy is derived from excess pore pressures in a cohesionless sediment-fluid system.

6. Debris flow as a category of mass flow where there is generally a wide range of grain sizes and the larger particles are supported by a clay-water mixture that possesses finite cohesion or strength.

7. Turbidity flow (current) where the solid material is essentially supported by turbulence within the flow which is generated by the downslope motion of the flow.

The quantitative importance of the group of biologically controlled processes cannot be defined accurately but organisms appear to play some part in the initiation and maintenance of critical sediment paths such as submarine canyons, and may, therefore, have a role or considerable importance in outer margin sedimentation (Kelling and Stanley 1976). These processes include:

1. Biogenic activity.

   a. Surface grazing and ingesting infauna process sediment and eject it as fecal pellets which not only modifies the original sediment textures and structures, but also significantly alters the geotechnical properties.

b. Burrowing and benthic organism activity in muddy sediments may provide substantial increments of suspended sediments on a local basis.

c. Mounding with local exceedance of critical angles for sand motion may result in sediment motion downslope.

d. Burrowing significantly alters sediment structure, packing, texture, and porosity/permeability so that the internal shear strength and load capacity of the deposit is changed, and shear failure and slumping are promoted. Such a process is likely to be most important in the vicinity of submarine canyons, where the sedimentary fill is generally regarded as unstable.

2. Biologic erosion where boring organisms act as erosive agents, even in the solid rock of canyon walls. Similar observations have been made in some of the canyons off Georges Bank (Dillon and Zimmerman 1970, in Kelling and Stanley 1976) where the steepness of canyon walls appears to be maintained by periodic collapse of surficial sediment through burrowing rather than boring.

4.1.1.8 Water Quality

Dissolved oxygen level shows annual degree of saturation greater than 90 percent in surface waters (Colton et al. 1968). In deeper water (100 to 200 m), values range from 56 to 94 percent.

Riley (1941) investigated the concentration of nutrients, particularly of the surface phosphates and nitrates. He also estimated the nitrogen/phosphorus (N/P) ratio in the surface water, which was 4:1 in April and 11:1 in September (normal ocean waters have 15:1 ratios]. The low N/P ratio is characteristic of shallow areas where there is intense tidal mixing and nutrients from the bottom are rapidly regenerated into the water column. In general, maximum surface phosphate concentrations greater than 1.0 μg-at/l, are found in winter due to vertical mixing, and minimum concentrations occur in summer, attributable to phytoplankton uptake of phosphate with decreased vertical mixing. However, the monthly variations in surface phosphate levels show an increase in May and July, probably attributable to zooplankton excretion. Nitrate concentration increases with depth at all times of the year. Nitrate concentrations are relatively low over Georges Bank in mid-summer, and a general gradient exists in surface nitrate concentrations with decreasing magnitudes In the offshore direction.

Spencer and Sachs (1970) reported an average suspended matter level of about 0.56 mg/kg of seawater for the area. Recently, surveys conducted for BLM on Georges Bank have provided more information on the level of total suspended matter. Hausknecht (1979) reported on the distribution of total suspended matter (TSM) on Georges Bank; highest concentrations occur in winter and spring, with maximum values of 0.96 mg/l. Levels in the Gulf of Maine and slope water were lower (0.06 to 0.52 mg/l). Total particulate concentration shows a decrease in magnitude away from the shoaling areas of Georges Bank into the deeper waters (Milliman et al. 1980).

ERCO (1978) reported that concentrations of particulate trace metals in the water column were generally higher during the winter and spring over Georges Bank. On the southern flank of Georges Bank, iron concentrations ranging from 1 to 9 $\mu g/l$ over a period of about 1 yr have been observed. Significant seasonal and depth variation was apparent. The primary source of iron in the water column is considered to be the resuspension of aluminosilicate sediments.

Generally, total particulate lead and copper concentrations showed near-shore enrichment, with highest levels observed during the summer. In the southeastern part of Georges Bank, lead concentrations ranged from 8 to 311 nanograms/liter (rig/l). The highest levels were observed in the summer. Values in near-bottom samples were generally lower than these in the near-surface samples. In the same area, copper concentrations ranged from 16 to 62 rig/l, exhibiting no significant seasonal variations. Near-surface values were generally higher than those near-bottom. Concentrations of other trace metals in the southeastern part of Georges Bank were as follows: nickel, 1-38 rig/l; zinc, 100-12,300 rig/l; chromium, 2-227 rig/l; and cadmium, 100-4,300 rig/l. No consistent seasonal patterns were detected.

Hydrocarbons in the marine environment may be due to natural processes, such as biosynthesis, or to petroleum discharge by tankers and other vessels (McLeod et al. 1980). ERCO (1978) analyzed near-surface and near-bottom samples from two benchmark stations (18 and 26) in the vicinity of the drilling area. Total particulate hydrocarbon concentrations ranged from 0.03 to 1.49 $\mu g/l$. No consistent seasonal or depth pattern was observed. Concentrations of total dissolved hydrocarbons ranged from 0.2 to 38.9 $\mu g/l$. The highest values, ranging from 16.4 to 38.9 $\mu g/l$, were observed in the winter, whereas the lowest values, ranging from 0.2 to 0.3 $\mu g/l$, were observed in the fall. No consistent depth patterns were observed. Concentrations of total surface film hydrocarbons in samples collected at the same stations during spring and summer ranged from 3.7 to 20.0 $\mu g/l$.

4.1.2 Biological Features

The richness of Georges Bank fisheries is widely recognized and has been the subject. of extensive scientific study in the last few years due to the increasing fishing pressure, the decline of stocks, and the need to assess the effects of proposed petroleum exploration activities on fishery resources. A review of the literature, including the regional overview prepared by the Research Institute of the Gulf of Maine (TRIGOM 1974) and BLM (1977) studies suggests that the richness of the fisheries is due in part to the following:

- The location of Georges Bank near the convergence of the southerly flowing Labrador Current and the northeasterly flowing Gulf Stream, with the attendant upwelling of nutrient-laden bottom waters.

- continuous vertical mixing of waters over the bank due to its shallowness and the influence of wind and currents (Riley and Bumpus 1946; TRIGOM 1974), resulting in rapid replenishment of water column nutrients.

- The high level of mixing and nutrients which support a rich pelagic food chain (phytoplankton, zooplankton, pelagic fishes, and other nekton).

- The high benthic diversity related to four types of surficial sediments which form a complex mosaic of bottom types (Drapeau 1973; Schlee and Pratt 1970; Wigley 1961a).

- Productive benthic macroinvertebrate populations over the bank, which tend to be high to the northeast and in the Great South Channel areas and moderate to low elsewhere (Wigley 1965).

- A positive correlation between high groundfish production and benthic macroinvertebrate population biomass, with the biomass serving as the food supply for groundfish (Wigley 1965).

This section presents regional and site-specific descriptions of marine biological resources of Georges Bank, the "Mud Patch," and canyons along the southern flank of Georges Bank. These resources have been the subject of numerous field investigations that broadly characterize the distribution, abundance, and use of resident species. Some investigations have focused on particular aspects of a species' ecology. In most instances, the voluminous data base is not readily available for use in preparing a site-specific description. The Northeast Fisheries Center (NEFC) of the National Marine Fisheries Service (NMFS) was especially helpful in providing access to its central data files.

4.1.2.1 Phytoplankton

A number of reports discuss the major factors that affect phytoplankton composition and abundance in the Georges Bank area (BLM 1977, TRIGOM 1974). Detailed investigations of Gulf of Maine and Georges Bank phytoplankton conducted by Riley (1941) and Sears (1941) as well as those reported by Bigelow et al. (1940) and Lillick (1940), provide a substantial data baseline for Georges Bank.

Diatoms constitute the bulk of the phytoplankton community on Georges Bank (Riley 1941; Sears 1941), although dinoflagellates are seasonally dominant (Lillick 1940). The phytoplankton community on Georges Bank exhibits a marked seasonal variation in species composition and abundance (TRIGOM 1974). In December, neritic diatoms and a mixture of dinoflagellates dominate the phytoplankton (Lillick 1940). During the mid-winter minimum, (January) production is low (50 mg C/m^2/day; Riley 1941). In late February to early March when the diatom spring bloom occurs, total phytoplankton production averages 190 mg C/m^2/day (Riley 1941). The bloom continues through April, attaining an average production of 950 mg C/m^2/day.

Riley's (1941) data for phytoplankton density on the bank (Table 4-5) show that plant density is highest over the shallow portions (less than 50 m) of the bank and falls off sharply in depths greater than 150 m. Riley (1941) felt that his data indicated a spring bloom-summer depression-fall bloom pattern of primary productivity. However, more recent investigations (Cohen and Wright 1979) based on the results of 11 cruises (1975-1978) suggest there is no summer depression of production.

TABLE 4-5

AVERAGE PHYTOPLANKTON PIGMENT DENSITIES ON GEORGES BANK[a]
1939-1940

Survey	Bottom Depth (m)					
	—50	51-100	101-150	151-200	201-250	>251
September 1939	11,800	9,100	5,300	8,600	3,300	3,300
January 1940	--	2,300	--	2,300	1,200	2,500
March 1940	32,700	11,200	--	3,600	4,500	7,400
April 1940	40,700	41,100	27,500	--	4,000	43,700
May 1940	22,800	11,000	3,900	--	10,800	--
June 1940	13,200	8,600	6,400	1,200	--	2,400
Average	24,200	13,900	10,800	3,900	4,800	3,900[b]

(a) Data are plant pigment densities in Harvey Units per m^2 averaged over 1-, 10-, and 30-m depths at each station.
(b) Average calculated with April measurements deleted; April measurements are obvious outlying values.
Source: Riley 1941, Table VII.

Cohen and Wright (1979) also proposed that the *extremely* high phytoplankton production of Georges Bank (400-500 g $C/m^2/yr$) is due to its unique topography and hydrography. The north and south frontal zones at depths of 150 m or more consist of nutrient-rich oceanic waters that are regularly transported into shallower areas through upwelling processes. Intense vertical mixing of these nutrient-laden waters supports the high level of phytoplankton production over most of the bank.

4.1.2.2 Zooplankton

Zooplankton comprise the first level of pelagic consumers in the marine food chain and, in turn, are of considerable importance as food for other planktonic and nektonic organisms. Three broad categories of planktonic organisms are holoplankton, hypoplankton, and meroplankton. Holoplanktonic organisms spend their entire lives in the floating state and include such animals as copepods, amphipods, ostracods, and euphausiids. Hypoplankton live Intermittently on the seafloor and in the water column and include some mysids, amphipods, and cumaceans.

Meroplankton include temporary members of the plankton and consist mainly of the eggs and larve of invertebrates and fishes. It has been hypothesized that the amount of zooplankton available as food to larval fish (ichthyoplankton) is a primary determinant of the number of fish that recruit as juveniles to the fish stocks on Georges Bank (Dube et al. 1977).

Copepods comprised at least 75 percent of the organisms sampled (Sherman et al. 1978). Various combinations of four copepod species, viz. Calanus finmarchicus, Pseudocalanus minutus, Centropages typicus and C. hamatus, represented at least 91 percent of the organisms sampled during six MARMAP surveys conducted in 1977. Other copepods of occasional importance were Metridia lucens (up to 3 percent) and Oithona similis (up to 6 percent). Calanus finmarchicus and P. minutus were abundant during the summer-fall period. Peak abundance-for C. typicus and C. hamatus was during early fall. These seasonal and year-to-year patterns summarized by Sherman et al. (1978) show that the zooplankton community on Georges Bank is characterized by substantial long-term variation of species dominance and abundance.

The geographic variation of zooplankton on Georges Bank was described by Dube et al. (1977) based on the results of MARMAP surveys conducted during the winters of 1975 and 1976. The winter period, when zooplankton populations are low, may be critical to larval fish survivorship. Comparisons of distributional abundance of the four dominant copepod species (Dube et al. 1977) show the geographic variation from year to year is substantial. Therefore, it is difficult to predict the abundance of a given species in a particular locality of the bank.

4.1.2.3 Ichthyoplankton

Georges Bank is one of the more important fish spawning areas in the northwestern Atlantic along with the southern Gulf of Maine and the coastal areas of Massachusetts, Rhode Island, and Connecticut (TRIGOM 1974). The bank is a known spawning ground for at least 26 fish species (BLM 1977), and the ichthyoplankton (pelagic eggs and larvae) of 29 species have been collected on the bank (Marak and Colton 1961, Marak et al. 1962a,b; Colton and Byron 1977). Species that use the bank extensively for spawning are listed in Table 4-6.

The spawning characteristics of these fishes were summarized by TRIGOM (1974) and their spawning times (Table 4-6) and locations by Colton et al. (1979). Estimates of spawning area and season are based on the occurrence of eggs and early-stage larvae. Fish eggs and larvae of some species may be found over the bank throughout the year. Many of the species are demersal spawners whose planktonic eggs float near the surface. An important exception is the Atlantic herring, a pelagic species that spawns in dense aggregations over predominantly gravel bottom, the demersal eggs adhere to one another and to the bottom, forming extensive, thick mats over the substrate (Drapeau 1973).

Georges Bank ichthyoplankton were sampled by the Bureau of Commercial Fisheries (BCF), now the NMFS, between 1953 and 1956 (Marak et al. 1961; 1962a,b). Colton and Bryon (1977) summarized the results from more

TABLE 4-6

PRINCIPAL SPAWNING TIMES OF FISHES ON GEORGES BANK

Family/Species	Common Name	Area	J	F	M	A	M	J	J	A	S	O	N	D
Clupeidae														
Clupea harengus harengus	Atlantic herring										—	•	•	
Gadidae														
Brosme brosme	tusk					•	•	—	—					
Enchelyopus cimbrius	Fourbeard rockling					—	•	•	—					
Gadus morhua	Atlantic cod		—	—	—	—								
Melanogrammus aeglefinus	Haddock			•	•	—								
Merluccius bilinearis	Silver hake	NE						—	•	•	—	—		
		S					•	•	—	—	—	—		
Urophycis chuss	Red hake						—	•	•	—	—			
Labridae														
Tautogolabrus adspersus	Cunner	S					•	•	- -	- -				
Cottidae														
Myoxocephalus octodecemspinosus	Longhorn sculpin		•	- -									—	•
Ammodytidae														
Ammodytes sp.	Sand lance		•	•	—	- -								—
Stromateidae														
Peprilus triacanthus	Butterfish	Sw					•	•	•	—				
Bothidae														
Citharichthys arctifrons	Gulf Stream flounder	Sw						- -	- -	- -	- -			
Scophthalmus aquosus	Windowpane						- -	- -	- -	- -				
Pleuronectidae														
Glyptocephalus cynoglossus	Witch flounder						•	•	—	—				
Hippoglossoides platessoides	American plaice			—	•	•	—							
Limanda ferruginea	Yellowtail flounder				—	•	•	—	—					
Pseudopleuronectes americanus	Winter flounder				- -	- -	- -	- -						

(a) ———— known spawning season
— — — uncertain spawning season
. . . . peak spawning
NE, S, SW specific areas on Georges Bank.
Source: Colton et al. 1979; Table 1, p. 913-914.

recent extensive surveys conducted from September 1971 to February 1975 under the auspices of the International Commission for the Northwst Atlantic Fisheries (ICNAF).

BCF (Marak et al. 1961; 1962a,b) conducted three to five surveys per year in the Gulf of Maine, Browns Bank, and Georges Bank. Ninety samples were taken on the bank during 12 cruises; of these, 20 samples were taken in the area in which most of the exploratory drilling will occur. The data are summarized in Table 4-7. Egg and larval densities (number per tow) were averaged for stations within the area of proposed drilling and and for stations elsewhere on the bank to facilitate assessment of potential impacts on spawning and ichthyoplankton. The dates of the 12 cruises overlap to a limited extent, but can be reasonably considered as representative of four sequential sampling periods. The comparatively low number of samples relative to the size of Georges Bank and the lack of sample replication preclude any extensive statistical treatment of the data.

Only eight species were present in the ichthyoplankton early in the year (February-March) followed by a steady increase to 24 species through the last survey period (May-June) (Table 4-7). This pattern is consistent with principal spawning times of fishes on Georges Bank (Table 4-6). The total number of species present in samples taken from the area of proposed exploratory drilling was generally less than that of samples taken from other areas of the bank; however, more samples were taken from the other areas, so that a greater number of species would be expected, Haddock and cod eggs and larvae were numerically dominant from February to mid-May (Table 4-7). Eggs and larvae accounted for up to 90 percent of the samples, with no obvious or consistent difference in relative abundance or density between the drilling area and other portions of the bank. In the mid-May to June period, the relative abundance of haddock and cod declined considerably.

A few additional species were numerically important during one or more sampling periods. American plaice were present in appreciable numbers from February to April. Sand lance were most abundant on the bank in March-April and were more abundant outside the area of proposed drilling. Yellowtail flounder first appeared in the plankton during March-April and became increasingly numerous through the May-June period when they comprised 30 to 48 percent of the samples. Silver hake were collected only during May-June and made up 9 and 23 percent of samples outside and within the drilling area, respectively, suggesting that silver hake reproduction was substantially higher in the lease area.

Atlantic herring larvae were present in very low densities and were almost exclusively taken from stations outside the area of proposed drilling. The low densities are consistent with an October-November peak spawning period (Table 4-6) not covered during the BCF surveys. The heaviest concentrations of herring larvae are normally over the northeastern portion of the bank (Parnkratov and Sigajev 1973) above 41°43'N (Graham and Chenoweth 1973).

The ICNAF program focused on larval herring so surveys were scheduled to coincide with the anticipated months of high larval abundance (September to February) (Colton and Byron 1977). The data are summarized

TABLE 4-7

SPECIES COMPOSITION AND RELATIVE DENSITIES OF ICHTHYOPLANKTON IN SURFACE WATERS OVER GEORGES BANK AND NEAR LEASE BLOCKS

	Cruise Nos. 57, 71 February-March				Cruise Nos. 46, 58, 72 Plarch-April				Cruise Nos. 48, 60, 73 April-May				Cruise Nos. 50, 61, 75, 76 May-June			
	Georges Bank (n)[a] = 11)		Near Blocks (n = 3)		Georges Bank (n = 17)		Near Blocks (n - 5)		George. Bank (n = 23)		Near Blocks (n - 7)		Georges Bank (n = 191		Near Blocks (n - 5)	
	E[b]	L[b]	E	L	E	L	E	L	E	L	E	L	E	L	E	L
Haddock-Cod	42.7		7.0		32.5		63.0		16.1		7.4		2.0			
Haddock		44.5		4.0		31.9		67.6		20.4		14.0		5.4		30.2
Cod		12.1		0.7		12.6		15.2		1.8		6.6		2.6		
American plaice	3.3	2.4		5.0	1.5	2.1	8.4	6.0	0.6	0.7	0.1	1.6		0.3		
American eel		0.9				0.1						0.6				
Pollock		2.0				1.5		1.0		0.3				0.4		
Sand lance		0.3				16.9		2.2		0.6				0.05		
Atlantic herring		1.0				3.6		0.2		3.7				0.2		
Atlantic wolffish		0.1														
Yellowtail flounder						0.5		0.2	1.0	2.0	3.9	4.9	9.4	17.2		38.8
Longhorn sculpin						0.1						0.3				
Cusk									6.0	3.3			3.3	1.3	2.8	
Fourbeard rockling									2.3	1.7			1.8	1.8		
Witch flounder										0.04		0.1	0.7	1.6		0.4
White hake										0.4				0.4		1.6
Squirrel hake										0.04		0.1	0.4	0.4	2.0	9.2
Silver hake													1.9	3.4	12.2	17.4
Redfish																0.2
Striped mullet																0.4
Banded rudderfish														0.1		
Lanternf ish														0.2		
Atlantic mackerel													0.3	0.3		0.4
Rough scad														0.05		
Butterfish																0.2
Northern searobin																0.4
Shanny														0.1		
Cunner															0.2	0.4
Puffer														0.05		
Unidentif ied						0.06							0.4	0.3	4.0	7.8
Total Number of Taxa	2	8	1	3	2	9	2	7	5	12	3	8	8	19	4	12
Total Average Number Individual	46.0	63.3	7.0	9.7	34.0	69.4	71.4	92.4	26.0	35.0	11.4	28.2	20.2	36.2	21.2	107.4
Total Ichthyoplankton		109.3		16.7		103.4		163.8		61.0		39.6		56.4		128.6

(a) n - number of tows.
(b) Relative average densities of eggs (E) and larvae (L) per tow.
Sources: Marak et al. 1961; 1962a, b.

to characterize larval fish densities in the general area of proposed exploratory drilling compared with those for the rest of Georges Bank (delimited by the 200-m depth contour and Great South Channel to the west) (Table 4-8).

Larval densities were highest in the September-October period and declined significantly in November-December to a level maintained in February. As is typical of ichthyoplankton samples, variation among samples and areas was very high, reflecting the extreme patchiness of species distribution. For this reason, detailed statistical comparisons are not warranted, but general comparisons indicate differences in larval densities between the lease area and other portions of Georges Bank.

4.1.2.4 Benthic Invertebrates

Much of the impetus for investigation of the benthic invertebrate fauna of Georges Bank stems from a need to understand the abundance, distribution, and variation of the organisms preyed upon by many groundfish species. Bottom sediment composition has been broadly documented as a major determinant of these factors. Most of the previous and ongoing investigations of these organisms have been conducted by R.L. Wigley and R.B. Theroux of the NEFC. The large volume of material acquired has not been completely processed. However, several publications (Wigley 1961a,b, 1965; 1968) have described the broad features of bottom sediment and invertebrate distribution, and Wigley (1965) found a strong positive correlation between groundfish and benthic invertebrate abundances. In 1976, BLM initiated a multi-year benchmark study on Georges Bank, conducted by the Energy Resources Company (ERCO). Forty-two stations were sampled during 4 seasons over 1 year, after which the study was terminated. Some of the benthic invertebrate data from two of the surveys are available.

The major components of the Georges Bank benthic macroinvertebrate fauna collected by grab samples (organisms retained on a l-mm sieve) have been described by Wigley (1961a, 1965, 1968). Based on early data, he stated that Georges Bank supported an average of 1,690 specimens with an average total wet weight of 156.6 g/m^2 of sediment. Crustaceans (primarily amphipods) made up 66 percent of the specimens but, due to their small size, constituted only 5 percent of the biomass (wet weight) (Table 4-9). Molluscs (snails, clams, etc.) and echinoderms (sand dollars and starfish) each accounted for only 3 percent of the individuals, but 41 and 31 percent of the biomass, respectively. Annelids (worms) were moderately abundant but contributed little to the total biomass (6 percent). Coelenterates (anemones) and ascidians (tuncates) were the main components of the miscellaneous group, representing 8 percent of the specimens and 17 percent of the biomass. The common benthic macroinvertebrate genera or species that typically occur on the four principal bottom types (sand, silty sand, gravel and mud) of Georges Bank are listed in Table 4-10 (Wigley 1968).

The geographic distribution of benthic invertebrate biomass (wet weight) reported by Wigley (1961a; 1965) indicates that the biomass of benthic invertebrates was high (greater than 100 g/m^2) in three general areas of the bank: northeast, south-central, and western (Figure 4-16).

TABLE 4-8

SPECIES COMPOSITION AND AVERAGE LARVAL FISH DENSITIES OVER GEORGES BANK AND NEAR LEASE BLOCKS

	Average Larval Fish Densities (No. /m^3) (a)					
	Cruise Nos. 71-4 September-October		Cruise Nos. 71-7, 72-9 73-9, 74-13 November-December		Cruise Nos. 74-2, 75-2 February	
Taxa	Georges Bank (n[b] = 33)	Near Blocks (n = 9)	Georges Bank (n = 1,30)	"Near Blocks (n = 43)	Georges Bank (n = 57)	Near Blocks (n = 14)
Atlantic herring	42.8 ± 135.1	1.3 ± 2.5	24.8 ± 52.2	14.8 ± 50.8	2.7 + 6.7	1.9 ± 3.6
Red hake	14.5 ± 29.4	4.3 ± 12.5	0.01 ± 0.05	0.02 ± 0.06		
Silver hake	24.8 ± 56.5	60.0 ± 126.8	0.05 + 0.22	0.04 ± 0*14		
Butterfish	0.1 ± 0.4	0*3 ± 0.9				
Myctophidae	2.2 ± 7.3	41.9 ± 37.9	0.1 ± 0,.9	0.3 ± 0.6		
Gulf Stream flounder	0*1 ± 0.3	0.02 ± 0.07				
Pollock			0.6 ± 2.4	0.08 ± 0.40	2.1 ± 3.5	2.5 ± 4.3
Atlantic cod			3.3 ± 8.6	0.8 ± 2.9	1.1 ± 2.1	1.3 + 2.3
Paralepididae			0.04 ± 0.31	0.3 ± 0.8		
Sand lance					19.3 ± 56.9	17.3 ± 48.0
Haddock					0.2 ± 0.6	0.3 ± 0.6
Total *Number of Taxa*	7	7	7	7	5	5
Average No. Larvae/m^3	85.4	108.1	28.9	16.3	25.4	23.3

(a) Data are expressed as mean ±1 standard deviation.
(b) n = number of tows.
Source: Colton and Byron 1977.

TABLE 4-9

SUMMARY OF THE AVERAGE COMPOSITION OF GEORGES BANK BENTHIC FAUNA

Taxonomic Group	Specimens (per m²)		Wet Weight	
	Number	Percentage	g/m^2	Percentage
Crustacea	1,113	66	8.2	5
Mollusca	54	3	64.6	41
Echinodermata	47	3	48.4	31
Annelida	334	20	9.2	6
Miscellaneous	142	8	26.2	17
Total	1,690	100	156.6	100

Source: Wigley 1961a.

The latter area comprised a number of small patches whereas the northeast and south-central areas were of large size. Areas with moderate levels of biomass (50-100 g/m^2) were adjacent to all high biomass areas. More than 50 percent of the bank supported a low biomass (less than 50 g/m^2). The south-central area of high biomass appears to be in the general vicinity of the lease area.

Wigley (1961a) observed that the total number of individuals and biomass on the bank was highest in the coarse sediments and lowest in fine sediments. The highest biomass (1,300 g/m^2) was on gravel and sand-gravel bottoms, largely due to the presence of beds of the northern horse mussel (Modiolus modiolus). Sediments dominated by the sand fraction supported a biomass of 14 to 154 g/m^3, and sediments dominated by silt or clay fractions supported the lowest biomass. The number of organisms associated with the various sediment types was similar to the patterns for biomass, though the greatest organism densities were found in sandy sediments. However, based on analysis of more recent samples, it appears that Wigley's estimates were very conservative and the biomass-sediment relationship that he reported may be inaccurate. This will become apparent in the following section.

Benthic Invertebrates in the Lease Area

Since the benchmark and earlier samples have yet to be completely processed, wet weight, expressed as g/m^2 of bottom, is the most useful estimate now available for characterizing the geographic variation of the benthic invertebrates on Georges Bank. Unfortunately, the lack of sample replication and the acquisition of samples during different seasons and years contributes to variation among samples that may inaccurately reflect the true standing crop on an area of bottom. Nevertheless, the broad patterns available may be useful in assessing the impacts of proposed drilling operations.

TABLE 4-10

COMMON ORGANISMS ASSOCIATED WITH PRINCIPAL BOTTOM TYPES ON GEORGES BANK

Bottom Type	Organism: Scientific Name	Organism: Common Name	Typical Locality of Occurrence
Sand Fauna	Crustacea		Central Georges Bank, often moderating shallow water
	Chiriodotea	isopod	
	Crangon septemspinosis	sand shrimp	
	Haustoriidae, Phoxocephalidae	amphipods, beach fleas	
	Leptocuma	cumacean	
	Pagurus acadianus	hermit crab	
	Annelida		
	Clymenella	polychaete worm	
	Goniadella	polychaete worm	
	Ophelia	polychaete worm	
	Mollusca		
	Astarte castanea	bivalve, chestnut astarte	
	Lunatia heros	gastropod, snail	
	Nassarius trivitattus	gastropod, snail	
	Spisula solidissima	surf clam	
	Echinodermata		
	Echinarachnius parma	sand dollar	
Silty Sand Fauna	Coelenterata		Southern margin of George Bank, deeper water
	Cerianthus	tube anemone	
	Crustacea		
	Ampelisca compressa	amphipod	
	Ampelisca vadorum	amphipod	
	Diastylis	cumacean	
	Dichelopandalus	shrimp	
	Edotea	isopod	

Source: Wigley 1968.

TABLE 4-10 (continued)

COMMON ORGANISMS ASSOCIATED WITH PRINCIPAL BOTTOM TYPES ON GEORGES BANK

Bottom Type	Organism: Scientific Name	Organism: Common Name	Typical Locality of Occurrence
Silty Sand Fauna (continued)	Annelida		
	Harmothoe	polychaete worm	
	Nephtys	polychaete worm	
	Scalibregma	polychaete worm	
	Mollusca		
	Arctics islandica	ocean quahog	
	Colus pygmaeus	gastropod, pygmy distaff shell	
	Crenella	bivalve	
	Nucula	bivalve	
	Venericardia	bivalve	
	Echinodermata		
	Amphilimna	brittle star	
	Amphioplus	brittle star	
	Thyone scabra	burrowing sea cucumber	
Gravel Fauna	Porifera		Northeastern Georges Bank, parts of Great South Channel, generally shallow water
	Clyona	sponge	
	Myxilla	sponge	
	Plymastia	sponge	
	Coelenterata		
	Bougainvillea	hydroid	
	Eudendrium	hydroid	
	Gersemia	soft coral	
	Paragorgia	coral	
	Sertularia	hydroid	
	Tubularia	hydroid	
	Crustacea		
	Balanus crenatus	barnacle	
	Balanus hameri	barnacle	
	Hyas	toad crab	

TABLE 4-10 (continued)

COMMON ORGANISMS ASSOCIATED WITH PRINCIPAL BOTTOM TYPES ON GEORGES BANK

Bottom Type	Organism: Scientific Name	Organism: Common Name	Typical Locality of Occurrence
Gravel Fauna (continued)	Annelida		
	Chone	polychaete worm	
	Serpula	polychate worm	
	Spirorbis	polychaete worm	
	Brachiopoda		
	Terebratulina	lampshell	
	Mollusca		
	Anemia	bivalve	
	Dendronotus	nudibranch	
	Doris	nudibranch	
	Modiolus modiolus	bivalve	
	Musculus	bivalve	
	Neptunea	gastropod, snail	
	Placopecten magellanicus	bivalve, scallop	
	Echinodermata		
	Crossaster	starfish	
	Ophiacantha	brittle star	
	Ophiopholis	brittle star	
	Solaster	starfish	
	Urochordata		
	Amaroucium	tunicate	
	Ascidia	tunicate	
	Boltenia	tunicate	

TABLE 4-10 (continued)

COMMON ORGANISMS ASSOCIATED WITH PRINCIPAL BOTTOM TYPES ON GEORGES BANK

Bottom Type	Organism: Scientific Name	Organism: Common Name	Typical Locality of Occurrence
Muddy Basin Fauna	Crustacea		Deepwater between fishing banks
	Calocaris	shrimp	
	Geryon	crab	
	Haploops tubicola	amphipod	
	Munnopsis typica	isopod	
	Pandalus	shrimp	
	Annelida		
	Amphitrite	polychaete worm	
	Leanira	polychaete worm	
	Onuphis	polychaete worm	
	Sternaspis	polychaete worm	
	Mollusca		
	Cadulus	scaphopod, tusk shell	
	Dentalium	scaphopod, tusk shell	
	Modiolaria discors	bivalve	
	Scaphander	gastropod, snail	
	Echinodermata		
	Amphiura otteri	brittle star	
	Brisaster fragilis	heart urchin	
	Ctenodiscus crispatus	mud star	
	Ophiura robusta	brittle star	
	Ophiura sarsi	brittle star	
	Urochordata		
	Polycarpa fibrosa	tunicate	

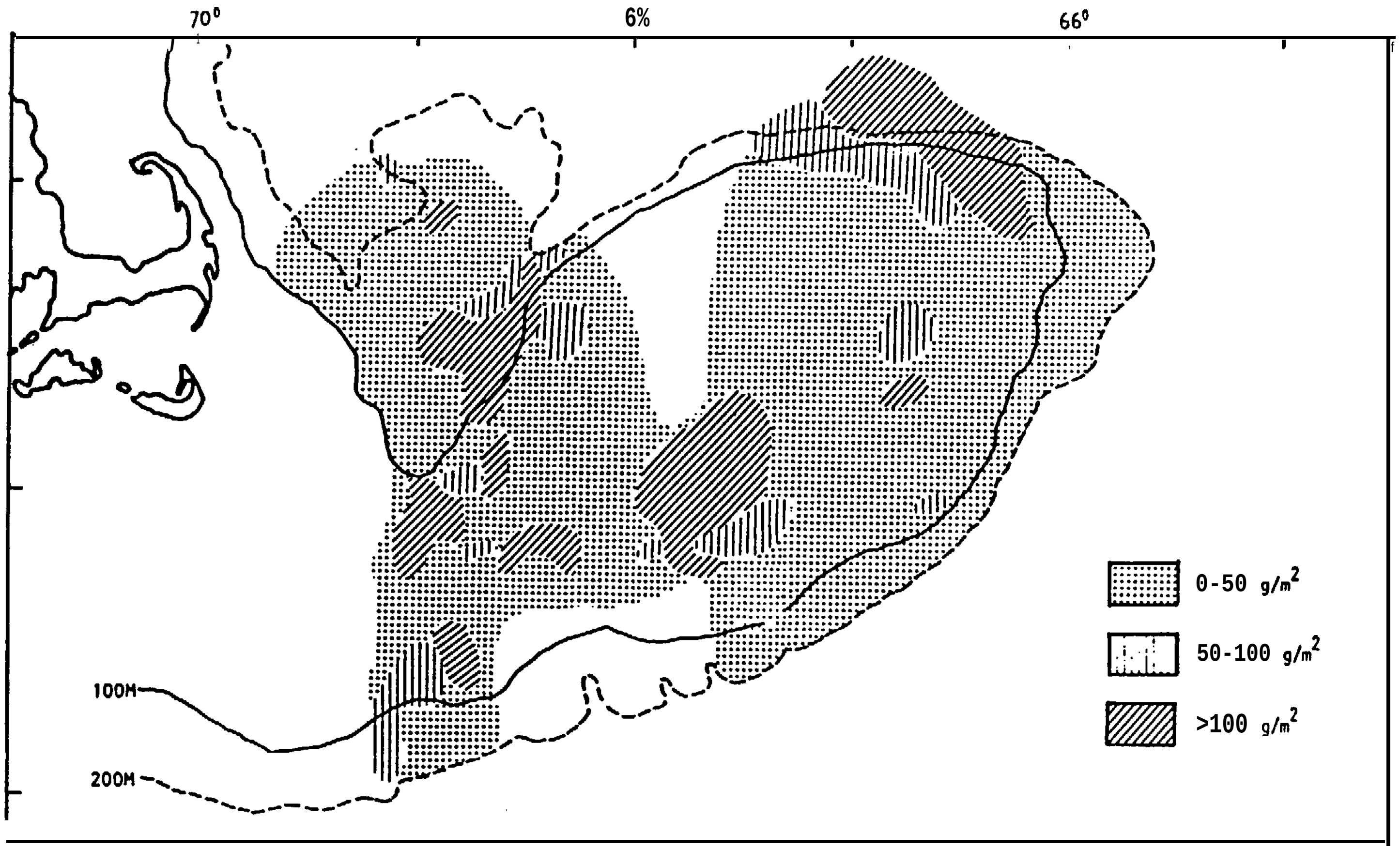


FIGURE 4-16 GEOGRAPHIC DISTRIBUTION OF THE BENTHOS IN TERMS OF WET WEIGHT PER m² (ADAPTED FROM WIGLEY 1961o)

The biomass of benthic invertebrates in the general lease area averaged 2,392 g/m^2, with an average of 22,846 $organisms/m^2$ of sediment (Table 4-11, Wigley 1968). Compared to an average of 157 g and 1,690 $specimens/m^3$ for Georges Bank as a whole (Table 4-9), this area is apparently very productive. However, the area is far from uniform in abundance of benthic invertebrates, with wet $weights/m^2$ ranging from 0.35 to 26,149 g and the number of $specimens/m^2$ ranging from 41 to 255,140. The distribution of wet weights appears to be largely related to water depth and associated sediment parameters such as grain size (Figure 4-17). At depths greater than 100 m, biomass was generally less than 30 g/m^2. From 75 to 100 m, wet weight ranged from 33 to 1,200 g/m^2. In water 50 to 75 m deep the biomass generally ranged from 50 to 26,000 g/m^2.

The geographic distribution of biomass in the area is shown on Figure 4-18. Two areas of very high biomass (more than 5,000 g/m^2) are evident. One area is in the vicinity of 41°00'N by 67°30'W; the other area is to the west in the vicinity of 40°45'N between 68°15' and 68°30'W. Areas of moderately high biomass (500 to 5,000 g/m^2) are adjacent to the areas of very high biomass. Most of the central portion of the area supported moderately high to moderately low biomass (50 to 500 g/m^2). Few localities shallower than 100 m, and all below this depth, supported a biomass less than 50 g/m^2.

Four stations in the two areas characterized by very high biomass were each deed.nated by members of one taxonomic group. Stations 38 and 42 (Table 4-11) produced the highest biomass of the stations shown on Figure 4-18, 96 to 97 percent of which was contributed by bivalves (clams, mussels, or scallops). Station 188 produced the third highest biomass and was dominated by tunicates (98 percent). Station 43 was the only location at which replicate samples (10) were taken, and it produced the fourth highest biomass (average value). Twenty-two to 99 percent of the biomass at Station 43 was echinoids; in all likelihood these organisms were sand dollars. Bivalves and echinoids are dominant throughout the samples, though other taxa frequently account for 50 percent or more of the sample biomass from a given locality or depth. For example, anemones were found in 9 of 12 samples from 48 to 68 m and occurred very sporadically in deeper water.

Distribution of Shellfish Stocks

The most important shellfish fisheries on Georges Bank are for Atlantic sea scallops and for lobster. Fisheries for surf clam and ocean quahog are of much lesser importance on the bank. The red crab resource in deeper slope areas has yet to be exploited to a significant extent.

Sea scallops (*Placopecten magellanicus*) occur primarily on firm sand or gravel bottoms (Bourne 1964). On Georges Bank they are most commonly found between the 40- and 100-m depth contours and in the northeast portion of Georges Bank where 581 square nautical miles were characterized by scallop densities in excess of 200/10,000 m^2 (Merrill and Posgay 1964; Figure 4-19). The commercial landings for the New England states (Gusey 1977) indicate that scallops were quite abundant during the period covered by Figure 4-19 (Figure 4-20). subsequently,

TABLE 4-11

TOTAL WET WEIGHT AND NUMBER OF SPECIMENS /m^2 OF SEDIMENT FROM LOCALITIES IN THE VICINITY OF PROPOSED EXPLORATORY DRILLING ACTIVITIES

Station	Latitude	Longitude	Depth (m)	Vessel	Cruise No.	Date	Sampling Gear	Total Weight (g/m 2)	Total Number of Specimens (no. /m^2)
1121	41°16'N	67° 16'W	57	Gosnold	22	August 1963	Campbell[b]	2,587.68	470
43[a]	41°10'N	67°28'W	4a	Albatross IV	65-11	August 196S	Smith-Mc Intyre[c]	8,539.10	50,020
68	41°06'N	68°00'W	44	Albatross 111	101	August 1957	Smith-Mc Intyre	13.00	2,870
64	41°04'N	67°28'W	60	Albatross III	101	August 1957	Smith-McIntyre	1,839.60	24.730
42	41°01'N	67°32'W	66	Albatross IV	65-11	August 1965	Smith-McIntyre	24,063.50	14,630
1120	41°00'N	67° 16'W	74	Gosnold	22	August 1963	Campbel l	179.15	749
03	40°59'N	67°28'W	60	Albatross III	101	August 1957	Smi th-McIntyre	2,090.40	29,760
1123	40°59'N	67°00'W	74	Gos nold	22	August 1963	Campbel l	1,326.74	1,621
70	40"57"94	67 52*W	51	Albatross 111	101	August 1957	Smith-McIntyre	2,878.70	11,010
37	40°52'N	68°28'W	35	Albatross IV	6S-11	August 1965	Smith-McIntyre	578.50	23,540
72	40°49'N	67°49'W	66	Albatross 111	101	August 1957	Smith-McIntyre	590.30	38,900
81	40°48'N	67°23'W	81	Albatross 111	101	August 1957	Smith-McIntyre	140.10	32,440
104	40°48*N	68°06'W	66	Albatross III	101	August 1957	Smith-McIntyre	95.20	6,450
186	40°48'N	68°19'W	57	Albatross 111	101	August 1957	Smith-McIntyre	1,892.10	17,850
188	40°48'N	68°32'W	53	Albatross III	101	August 1957	Smith-McIntyre	15,214.80	74,040
176	40°47'N	67°12'W	95	Albatross 111	101	August 1957	Smith-McIntyre	145.30	20,680
178	40°46'N	67°25'W	84	Albatross 111	101	August 1957	Smith-McIntyre	261.20	20,980
180	40°46'N	67°37'W	75	Albatross 111	101	August 1957	Smith-McIntyre	1,309.10	255,140
18 1	40°46'N	67°45'W	68	Albatross 111	101	August 1957	Smith-McIntyre	997.40	84,830
182	40°46'N	67°52'W	70	Albatross III	101	August 1957	Smith-McIntyre	55.90	12, 180
38	40°46'N	68° 16'W	55	Albatross IV	6S-11	August 1965	Smith-McIntyre	26,146.90	22,580
41	40°44'N	67° 37'W	80	Albatross IV	65-11	August 1965	Smith-McIntyre	507.60	2,160
1114	40°40'N	67°45'W	79	Gosnold	22	August 1963	Campbel 1	81.13	4,931
1113	40°40'N	68°00'W	86	Gosnold	22	August 1963	Campbe 11	34.60	918
1119	40°39'N	67°00'W	214	Gosnold	22	August 1963	Campbel 1	36.00	1.786
1118	40°39'N	67° 15'W	111	Gosnold	22	August 1963	Campbell	9.85	790
79	40°37'N	67°28'W	86	Albatross 111	101	August 1957	Smith-McIntyre	516.10	94,180
39	40°35'N	67 55*W	90	Albatross IV	6S-11	August 1965	Smith-McIntyre	991.10	23,430
76	40°32'N	67°33'W	121	Albatross III	101	August 1957	Smith-McIntyre	15.30	7,540
1117	40°31'N	67° 16*W	235	Gosnold	22	August 1963	Campbe 11	4.46	656
1115	40°30'N	67 45*W	124	Gosnold	22	August 1963	Campbel 1	10.77	3.223
1059	40°30'N	68°29'W	94	Gosnold	13	May 1963	Campbell	33.03	1,777
1112	40°29'N	68°00'W	123	Gosnold	22	August 1963	Campbel 1	7.96	1,754
1116	40°21'N	67°48'W	3a 2	Gosnold	22	August 1963	Campbell	15.54	336
1083	40°21'N	68°15'W	144	Gosnold	13	May 1963	Campbell	0.35	81
10 64	40°20'N	68°01'W	154	Gosnold	13	May 1963	Campbe 11	a.49	41
1060	40°19'N	68°30'W	123	Gosnold	13	May 1963	Campbe 11	31.28	1,616
1062	40°11'N	68°13'W	426	Gosnold	13	May 1963	Campbe 11	19.78	177
1061	40°11'N	68°29'W	507	Gosnold	13	May 1963	Campbell	10.38	t 18
Mean								2,392.04	22,846

(a) Values are the average of 10 replicate samples.
(b) Sample area of 0.56 m^2.
(c) Sample area of 0.1 m^2.
Source: Wigley 1968.

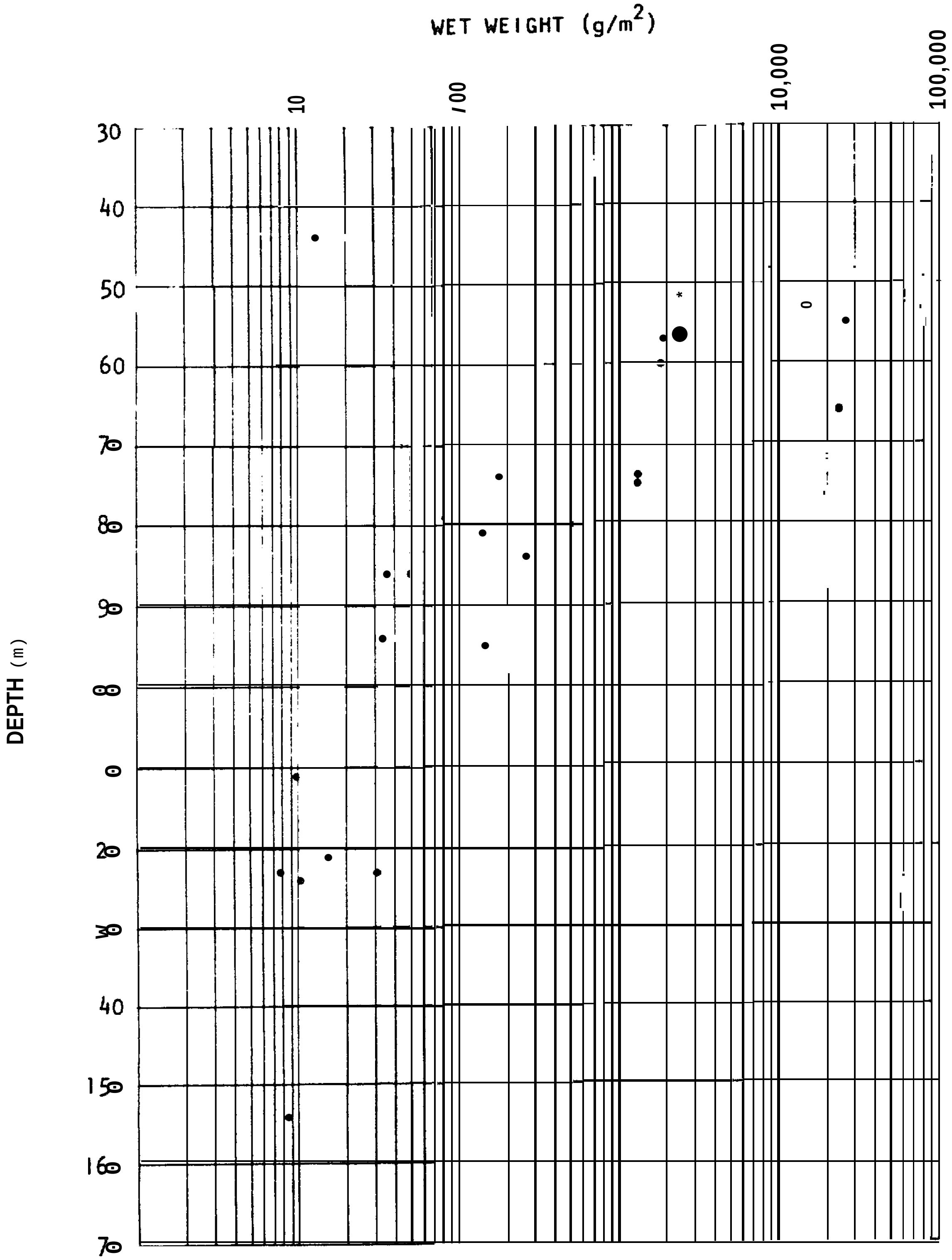


FIGURE 4-17 WET WEIGHT (g/m²) OF BENTHIC INVERTEBRATES AS A FUNCTION OF WATER DEPTH (m) IN REGION OF PROPOSED EXPLORATORY DRILLING

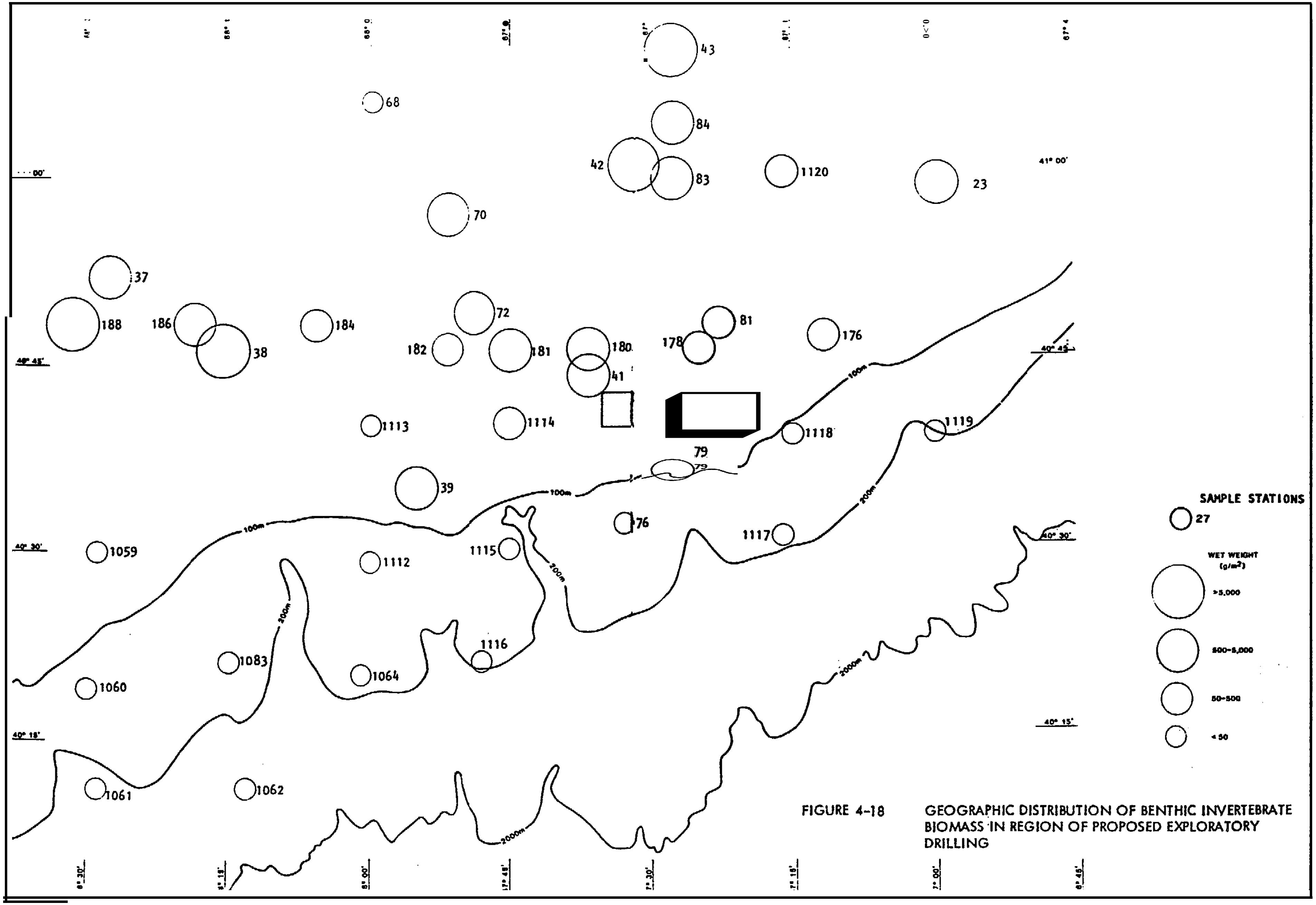
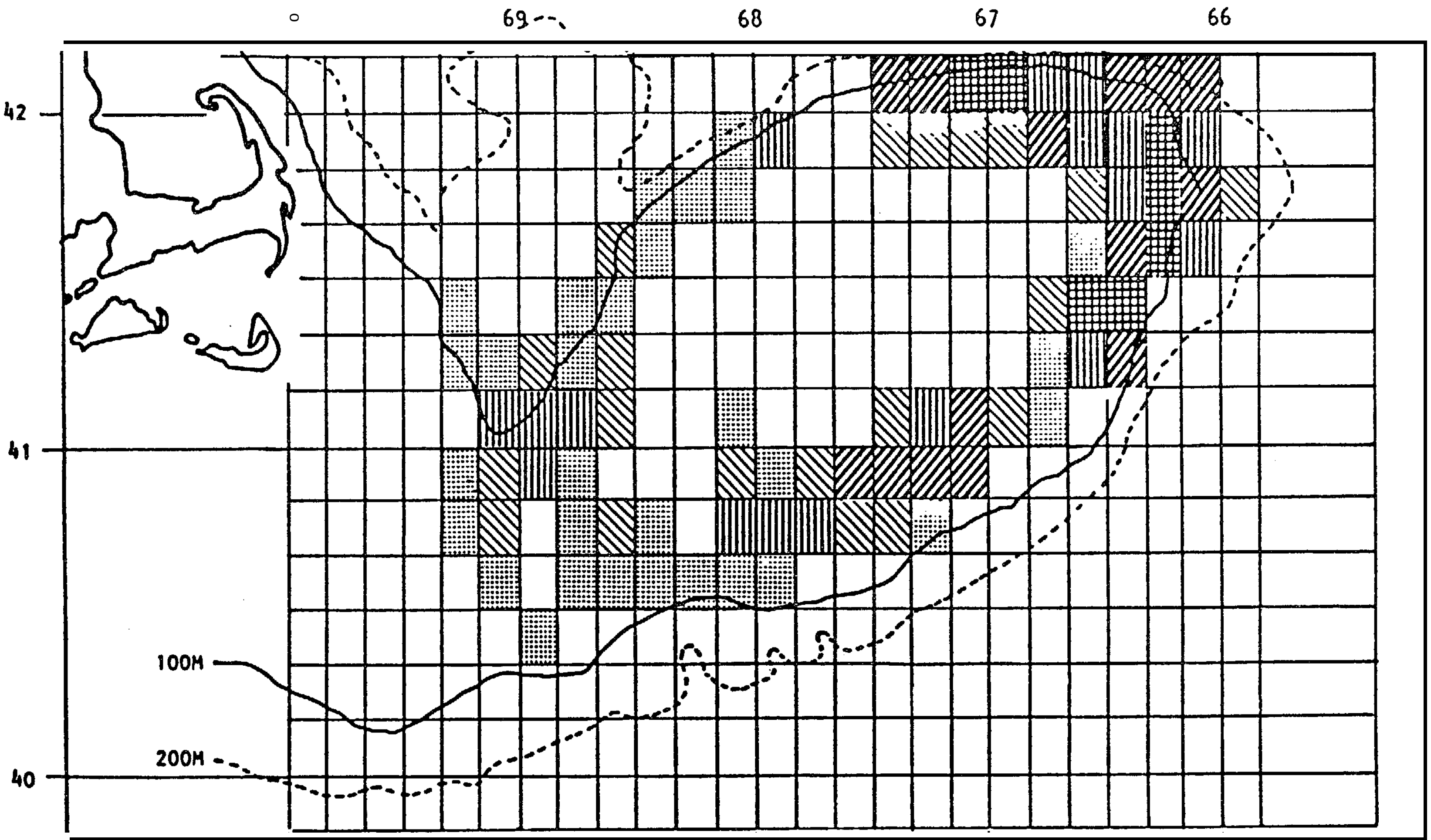


FIGURE 4-18 GEOGRAPHIC DISTRIBUTION OF BENTHIC INVERTEBRATE BIOMASS IN REGION OF PROPOSED EXPLORATORY DRILLING



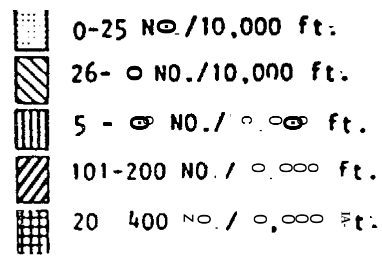


FIGURE 4-19 DENSITY AND DISTRIBUTION OF SEA SCALLOP ON GEORGES BANK BASED ON RESULTS OF RESEARCH CRUISES, 1958-1963 (ADAPTED FROM MERRILL AND POSGAY 1964)

FIGURE 4-20 SEA SCALLOP LANDINGS IN THE NEW ENGLAND STATES, 1951-1974 (ADAPTED FROM GUSEY 1977)

catches have declined from a high of about 23,000 lb in 1961 to a low of about 4,000 lb in 1974. The stock has recovered somewhat in recent years as the domestic and Canadian fleets landed record catches (more than 15,000 mt) in 1977 through 1979 (Brown 1980).

A limited amount of information is available from the published literature on the status of surf clam (Spisula solidissima) and ocean quahog (Arctics islandica) stocks on Georges Bank (Ropes 1978; Merrill and Ropes 1969). The low frequency of occurrence of these two species on Georges Bank suggests that commercial concentrations are very limited. Specific density data for the bank have not been encountered in the literature.

Red crabs (Geryon quinquedens) support a small fishery in southern New England, operating primarily out of New Bedford, Massachusetts and Point Judith, Rhode Island. However, Wigley et al. (1975) reporting on the results of NMFS quantitative surveys on eastern Georges Bank at depths from 229 to 1,646 m, stated:

> "... red crabs were common from offshore Maryland to western Georges Bank, but rather sparse in the Georges Bank region. Bathymetrically, crabs were scarce in relatively shallow waters, most common at intermediate depths, and moderately sparse to absent in deep water."

It thus appears the lease area is not of great importance to the fishery, and will not be in the future.

The American lobster, Homarus americanus, ranging along the east coast of North America from North Carolina to Labrador (Cooper and Uzmann 1977), is most abundant from New York to Nova Scotia. The lobster fishery is normally discussed in terms of inshore and offshore stocks; the latter is of primary concern regarding petroleum development on Georges Bank. The offshore lobster population occurs along the upper slope and outer continental shelf between Delaware Bay and eastern Georges Bank, at depths of roughly 110 to 450 m. The area of occurrence is 8 to 16 km wide and 644 km long. Massachusetts CZM (1980) shows the prime lobster pot grounds. The lobster pot fishery in coastal areas peaked in 1960 at 29 million pounds and has since declined. This decline has been offset by increased fishing of the offshore stocks which from 1968 to 1974 averaged over 20 percent of the U.S. catch. The U.S. landings have stabilized at about 30 million pounds per year (Cooper and Uzmann 1977).

Lobster habitats on the outer continental shelf and upper slope include featureless mud/silt substrates, boulder fields on sand substrate, gently sloping mud-clay substrates, and semi-consolidated clay or vertical or very steep walls with narrow ledges of clay or bedrock in heads of the canyons (Cooper and Uzmann 1977).

presently very little quantitative distribution data exist for offshore lobster stocks (Cooper, NMFS, NEFC, Woods Hole, personal communication, May 16, 1980). Cooper and Uzmann (1977) estimated that the average density of lobster on the open shelf and upper slope was

0.001 individual or 0.085 g/m^2, and at the heads of submarine canyon areas the average density was 0.05 lobsters or 4 25 g/m^2. These estimates were made during the June-August period when 30 to 50 percent of the offshore population migrates into shoal waters.

Benthic Invertebrates in the Mud Patch

Species composition and distribution of benthic macroinvertebrate assemblages for the Middle Atlantic Bight from Cape Cod to Cape Hatteras have been described by Wigley and Theroux (1976). Approximately 31 stations were sampled within the area known as the "Mud Patch" using methods similar to those described above for Georges Bank.

Bottom sediment distribution in the southern New England region is shown in Figure 4-21 where the Mud Patch is enclosed by a heavy line. The region covers an area of about 13,000 km^2 between roughly 60 to 200 m depths (Twichell et al. 1980). Sediments in the Mud Patch comprise 30 percent or more silt and clay, and it is readily apparent that this large area of fine sediments is anomalous for its depth range compared to the remainder of the Middle Atlantic Bight (see Section 4.1.1).

The distribution of organic carbon (percent weight) in the sediments of the Middle Atlantic Bight is shown in Figure 4-22 where the Mud Patch is enclosed by heavy lines. Organic carbon content of sediments normally increases with decreased sediment particle size (i.e., silt and clay fractions). Accordingly, the organic carbon content of sediments in the Mud Patch is higher than in surrounding areas characterized by coarser sediments at comparable depth (Figure 4-22).

Given the unusual occurrence of a large area of fine sediments at comparatively shallow depths (60 to 200 m) on the shelf, the benthic macroinvertebrate fauna could be a rather unique component of the Middle Atlantic Bight ecosystem (Figure 4-23). Within the Mud Patch density is generally high (1,000 to 4,999 individuals/m^2 of bottom), but large areas of adjacent bottom to the north (shallower) and east support generally higher densities (Figure 4-23). Macroinvertebrate biomass within the Mud Patch is moderately low over about two-thirds of the area and fairly high over the remainder (Figure 4-24). Biomass distribution in the Mud Patch does not appear to be substantially different from other areas of the bight at similar depth. In general, however, the coarser-grained sediments in the southern New England area support greater biomass than finer sediments (Wigley and Theroux 1976). The data definitely suggest that biomass and density in the Mud Patch are not high or particularly different from other macroinvertebrate relationships.

Macroinvertebrate identification was done at phyletic, class, or ordinal level so that only a very general description of taxonomic composition is possible. Annelids, crustaceans, molluscs, and echinoderms comprised 29, 29, 20, and 17 percent, respectively, of the average number of individuals (Table 4-12).

Relative Importance of the macroinvertebrates in the mud patch by mean biomass data differs significantly from the description based on numbers of individuals (Table 4-13). Echinoderms, annelids, and molluscs constituted 34, 25, and 21 percent, respectively, of the biomass.

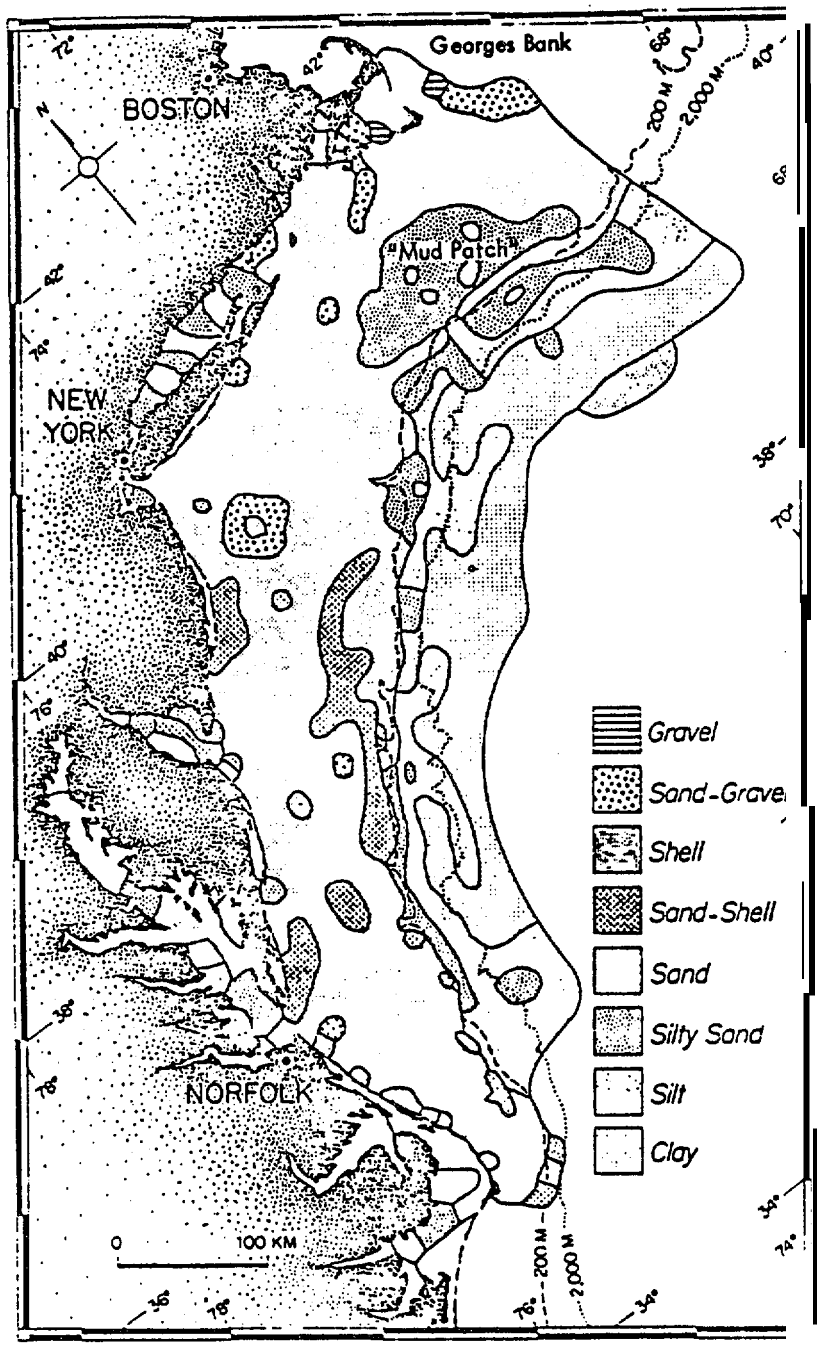


FIGURE 4.21 GEOGRAPHIC DISTRIBUTION OF BOTTOM SEDIMENT TYPES I-N THE MIDDLE ATLANTIC BIGHT REGION (WIGLEY AND THEROUX 1976)

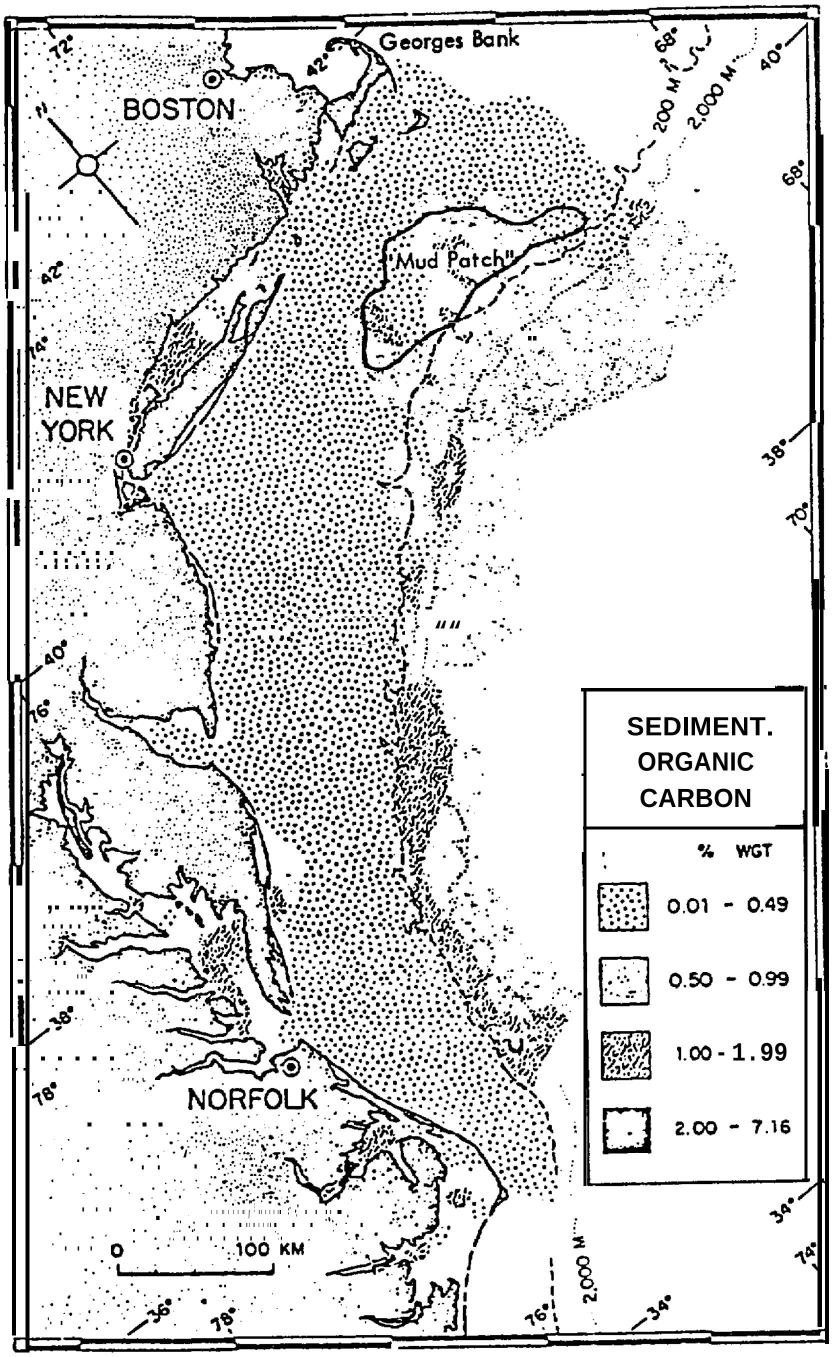


FIGURE 4-22 GEOGRAPHIC DISTRIBUTION OF SEDIMENT ORGANIC CARBON IN THE MIDDLE ATLANTIC BIGHT REGION (WIGLEY AND THEROUX 1976)

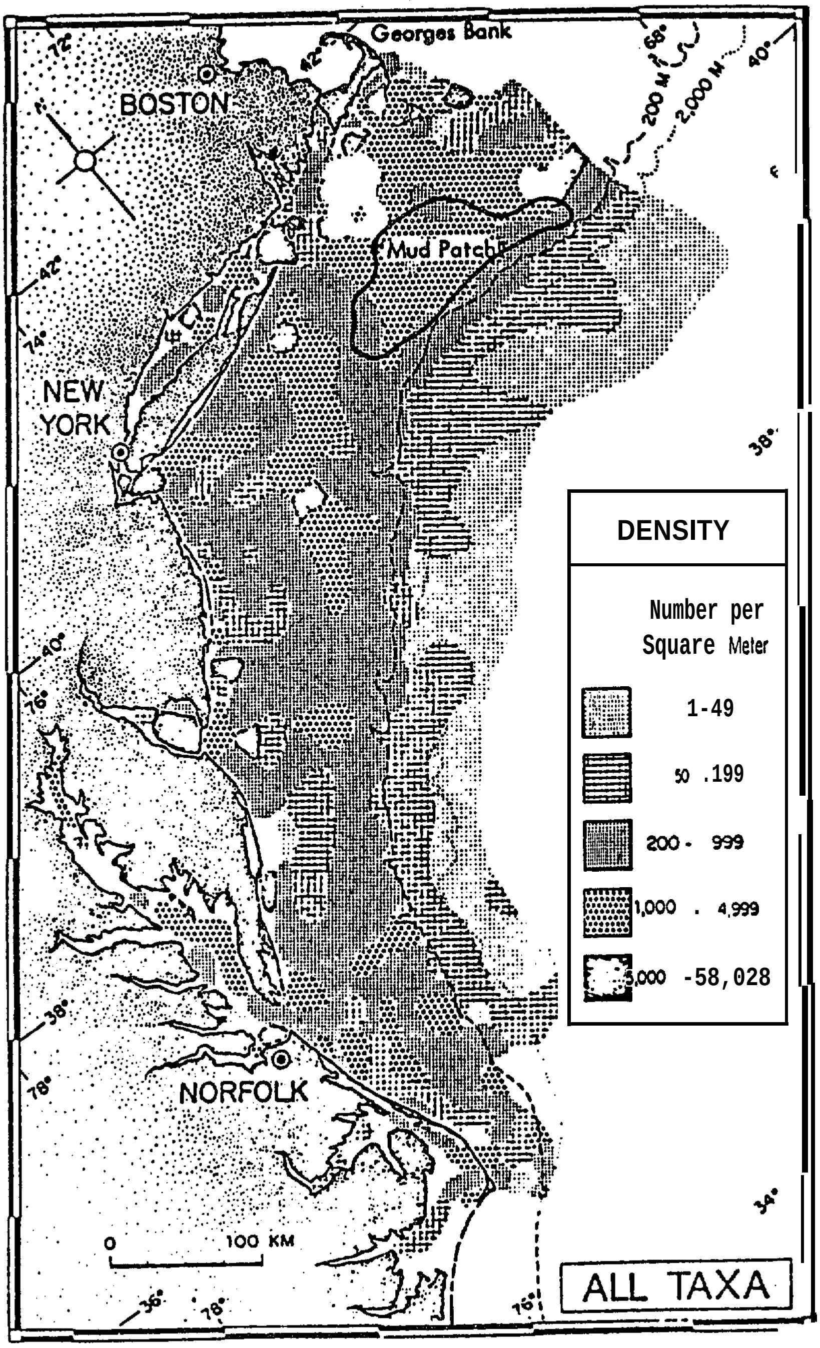


FIGURE 4-23 GEOGRAPHIC DISTRIBUTION OF THE DENSITY OF ALL TAXONOMIC GROUPS COMBINED, EXPRESSED AS NUMBER OF INDIVIDUALS PER SQUARE METER OF BOTTOM (WIGLEY AND THEROUX 1976)

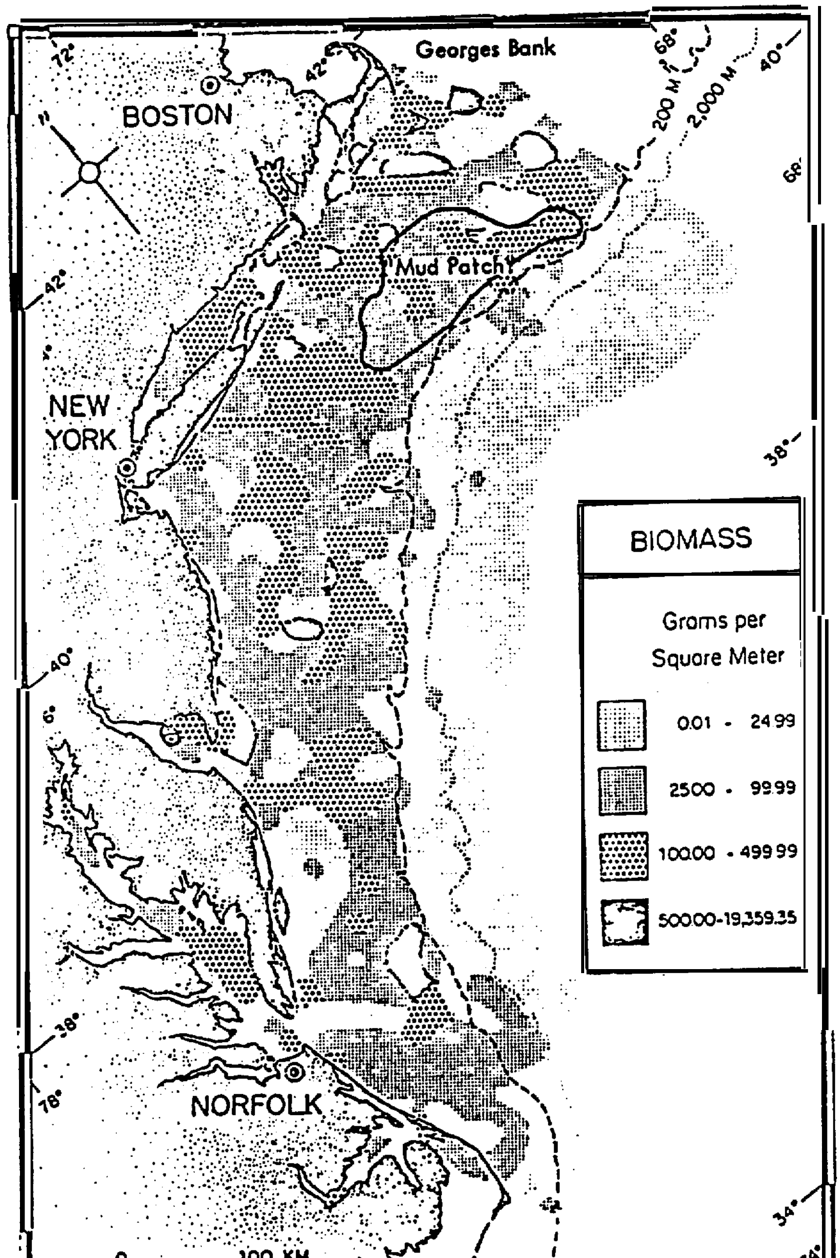


FIGURE 4-24 GEOGRAPHIC DISTRIBUTION OF THE BIOMASS OF ALL TAXONOMIC GROUPS COMBINED, EXPRESSED AS DAMP WEIGHT PER SQUARE METER OF BOTTOM (WIGLEY AND THEROUX 1976)

TABLE, 4-12

MEAN NUMBER OF INDIVIDUALS LISTED BY TAXONOMIC GROUP IN EACH BOTTOM SEDIMENT TYPE FOR THE SOUTHERN NEW ENGLAND SUBAREA

	Bottom Sediments (no. /m²)							
Taxonomic Group	Gravel	Sand-gravel	Shell	Sand-shell	Sand	Silty sand	Silt	Clay
PORIFERA	5.33	7.27		--	0.39	0.17	--	0.20
COELENTERATA	28.33	256.91	--	--	18.38	15.29	7.44	2.40
Hydrozoa	3.67	144.09	--	--	13.23	0.12	.-	--
Anthozoa	24.66	122.82	--	--	5.15	15.17	7.44	2.40
Alcyonacea		--		--	0.13	1,50	2.08	0.70
Zoantharia	10.33	1.27	--	--	4.29	12.63	4.56	0.20
Unidentified	14.33	111.55	--	--	0.73	1.04	0.00	1.50
PLATYHELMINTHES	--	21.55	--		0.40	--	0.04	--
Turbellaria	--	21.5s	--	--	0.40	--	0.04	
NEMERTEA	0.00	6.91	--	4.00	7.94	5.S6	2.52	--
ASCHELMINTHES	0.67	66.73	--	--	2.29	2.65	2.20	0.80
Nematoda	0.67	66.73	--	.-	2.29	2.65	2.20	0.80
ANNELIDA	289.00	555.18	750.00	23.00	433.31	330.82	118.52	9.10
POGONOPHORA	--	. .	. .	--	0.05	1.33	5.36	3.00
SIPUNCULIDA	--	15.73	--	. .	11.20	7.06	10.12	0.90
ECHIURA	--	--	. .	--	. .	0.04	0.24	0.80
PRIAPULIDA	--	--	--	--	. .	--	0.24	--
MOLLUSCA	1,083.33	14s.10	375.00	76.00	126.94	222.47	336.44	21.10
Polyplacophora	2.00	6.02	.-		0*37	0.98	1.32	0.20
Gastropoda	1,064.33	33.64	275.00	65.00	19.23	34.19	4.40	0.60
Bivalvia	17.00	104.64	100.00	11.00	105.51	182.73	328.00	20.30
Scaphopoda	--	--		--	0.49	1.13	2.72	--
Cephalopod	--	--	--		0.06	3.44	--	--
unidentified	--	--			1.28	--	--	--
ARTHROPODA	361.34	1,770.35	300.00	154.00	2,228.16	326.63	54.60	3.80
Pycnogonida	--	8.36	.-	. .	. .	--	--	--
Arachnida	--	--			.-	--	--	--
Crustacea	361.34	1,761.99	300.00	154.00	2,22S.16	326.63	54.60	3.s0
Ostracoda	--	1.91			0.47	--	--	--
Cirripedia	6.67	231.18	--		15.22	--	--	--
Copepoda		--		--	0.07	0.12	0.20	--
Nebaliacea	--	--		--	--	--	--	--
Cumacea	--	2.36	--		57.65	8.27	5.64	1.20
Tanaidacea	--	.-			.-	0.04	0.44	0.80
Isopoda	--	4.36	25.00	--	19.05	2.5a	0.96	0.30
Amphipoda	272.00	1,508.18	225.00	154.00	2,125.11	309.40	47.36	1.50
Mysidacea	--	--		. .	0.89	3.37	--	--
Decapoda	82.67	14.00	50.00	--	9.70	2.85	--	
BRYOZOA	3.00	267.45	1,500.00	--	5.59	0.17	--	--
BRACHIOPODA	--	--		--	--	--	--	--
ECHINODERMATA	--	0.28	--	--	58.59	187.35	81.28	a.20
Holothuroidea	--	--		. .	3.83	9.69	3.00	0.20
Echinoidea	--	.-	--		22.01	0.37	0.28	0.20
Ophiuroidea	--	0.28	. .	--	30.11	175.85	76.28	7.00
Asteroidea	--	--			2.64	1.44	1.72	--
HEMICHORDATA	--	--			0.31	0.38	0.20	--
CHORDATA	885.33	28.45		2.00	18.98	23.37	7.20	3.50
Ascidiarea	885.33	28.45	--	2.00	18.98	23.37	7.20	3.50
UNIDENTIFIED	2.33	13.73	--	--	7.33	8.10	6.88	0.30
TOTAL	2,666.67	3,15S.64	2,925.00	259.00	2,919.86	?,131.39	633.28	62.10

Source: Adapted from Wigley and Theroux 1976.

TABLE 4-13

MEAN BIOMASS OF EACH TAXONOMIC GROUP LISTED BY BOTTOM SEDIMENT TYPE FOR THE SOUTERN NEW ENGLAND SUBAREA

Taxonomic Group	Bottom Sediments (g/m^2)							
	Grave 1	Sand-gravel	Shell	Sand-shell	Sand	Silty sand	Silt	Clay
PORIFERA	0.210	1.450	--	--	0.036	0.003	--	0.127
COELENTERATA	16.600	9.225	--	--	1.470	9.294	2.576	0.920
Hydrozoa	1.133	4.019	--		0.796	0.047	--	--
Anthozoa	17.467	5.206	--	--	0.674	9.247	2.576	0.928
Alcyonacea	-	--	--	--	0.003	0.047	0.168	0.129
Zoantharia	17.047	2.793	--		0.586	9.075	2.367	0.163
Unidentif ied	0.420	2.414	--	--	0.085	0.12s	0.041	0.636
PLATYHELMINTHES	--	0.116	--	--	0.012	--	<0.001	--
Turbellaria	--	0.116	--	--	0.012	--	<0.001	--
NEMERTEA	5.813	1.111	--	0.020	0.887	0.750	0.119	--
ASCHELMINTHES	0.007	0.018	--	--	0.005	0.006	0.010	0.008
Nemotoda	0.007	0.018	--		0.005	0.006	0.010	0.008
ANNELIDA	24.283	11.169	30.500	1.670	21.470	25.835	7.427	0.445
POGONOPHORA	--	--	--	--	<0.001	0.023	0.017	0.012
SIPUNCULIDA	--	2.600	--	--	1.256	1.761	0.958	0.628
ECHIURA	--	--	--		--	0.001	0.093	0.709
PRIAPULIDA	.-		--	--	--	--	0.159	--
MOLLUSCA	16.953	223.297	4.250	0.430	252.317	22.494	10.734	0.525
Polyplacophora	0.227	7.023	--	--	0.003	0.018	0.016	0.002
Gastropoda	11.487	3.917	3.750	0.370	2 6.301	0.793	0.104	0.029
Bivalvia	5.240	212.357	0.s00	0.060	245.996	21.622	10.664	0.494
Scaphopoda		--		--	0.009	0.014	0.039	--
Cephalopod	--	--	--		0.001	0.047	--	
Unidentified		--		--	0.005	.-	--	--
ARTHROPODA	14.573	113.338	30.500	0.630	17.579	2.761	0.380	0.049
Pycnogonida	--	0.036	--	--		--	--	--
Arachnida	--	--		--	--	--	.-	--
Crustacea	14.s73	1130303	30.500	0.630	17.579	2.761	0.380	0.049
Ostracoda	--	0.019	--	--	0.003	--	--	--
Cirripedia	0.143	100.404	--	--	3.136	--		--
Copepoda		--		--	<0.001	0.001	00002	
Nebaliacea	--	--		--		--	.-	--
Cumacea	--	0.024	.-	--	0.260	0.037	0.037	0.030
Tanaidacea	--	.-		--		<0.001	0.004	0.006
Isopoda	. .	0.3s7	0.250	--	0.392	00171	0.101	0.001
Amphipoda	0.600	6.501	1.750	0.630	13.252	2.354	0.327	0.012
Mysidacea	--	--		--	0.002	0.027	. .	--
Decapoda	13.830	$.998	28.500		0.533	0.171	--	--
BRYOZOA	1.187	5.293	52.000	--	0.364	0.001	--	--
BRACHIOPODA	. .			--		. .	.-	--
ECHINODERMATA	--	1.326	--	--	23.924	35.282	49.234	0.756
Holothuroidea		--		--	7.238	21.704	35.195	0.174
Echinoidea	--	--			12.642	1.605	2.206	0.185
Ophiuroidea	--	1.326	--		3.215	9.134	3.096	0.397
Asteroidea	--	--			0.S29	2.840	7.937	--
HEMICHORDATA	--	--			0.062	0.0s0	0.002	
CHORDATA	204.080	2.646	--	0.170	1.894	6.313	2.054	0.542
Ascidiarea	204.080	2.646		0.170	1.894	6.313	2.054	0.542
UNIDENTIFIED	0.350	2.228	--	--	0.334	0.344	0.424	0.094
TOTAL	266.056	373.017	117.250	2.920	321.611	104.948	S0.906	4.823

Source: Adapted from Wigley and Theroux 1976.

Holothuroids, whose abundance was low, comprised 62 percent of the echinoderm biomass (21 percent overall), whereas ophiuroids (high abundance) comprised only 26 percent of the echinoderm biomass. Annelid worms appear to have been of equal importance with respect to biomass and numbers. Virtually all of the mollusc biomass was due to bivalves.

Benthic Invertebrates in the Canyons

Published information on the macroinvertebrate fauna of the submarine canyons on the southern flank of Georges Bank (principally Gilbert, Lydonia, and Oceanographer Canyons) is limited and may only be partially applicable to the canyons near the proposed drilling area.

Haedrich et al. (1975) described the sediments, faunal composition, and zonation of epibenthic macroinvertebrates and demersal fishes in the vicinity of Alvin Canyon on the continental slope south of New England between 140 and 1,900 m. Three physically and biologically definable zones were identified. The transition zone from shelf to slope (to about 340 m) is characterized by sand with near-bottom suspended sediment concentrations up to 250 μg/l. The upper slope, at a depth of 1,000 m, has a slope of about 1.4", silty sand to sandy silt sediments, and suspended sediment concentrations of 50 to 60 μg/l. Sediments are soft, relatively homogeneous, and exhibit evidences of current scour. The lower slope is steeper (7.6°) with greater substrate variability (i.e., smooth or hummocky sediments, talus slopes, and rock outcrops). Sediments are a stiff clayey silt and suspended sediment concentrations are low (20 μg/l).

The macroinvertebrates and fish taken by otter trawl in the Alvin Canyon region are summarized in Table 4-14. Haedrich et al. (1975) suggested that the three zones extend through the submarine canyons, but noted that (1) the presence or absence of certain species in Alvin Canyon contributed a distinctive element to faunal composition, and (2) organism abundance was somewhat higher in the canyon. Cluster analysis demonstrated that stations in Alvin Canyon and on the adjacent slope segregated into depth groups rather than on the basis of canyon or slope segment. This indicates strong faunal similarities within depth strata. However, some differences were apparent; namely, the brittle star, Amphilimna only occurred in the shallow canyon. Furthermore, catch rate data (invertebrates and fishes) for slope and canyon stations differed with 228 specimens (3.4 kg)/hr and 368 specimens (5.7 kg)/hr, respectively. Thus organism abundance and biomass may be more than 60 percent higher in the canyon.

Haedrich et al. (1975) and Rowe (1972) suggest that enhanced abundance and biomass in canyons may be due to the effects of food-rich sediments being channeled from the shelf through the canyon into deeper water. Moreover, Rowe (1971) suggested that the absence in canyons of species that are abundant on the adjacent slope at comparable depth may be related to the relative hardness of the sediments. Surface sediments (predominantly clay and silts) in the canyon are hard compared to the very soft sediments on the slope, and slope species may be unable to cope with the harder sediments. Rowe also points out that the abundance of suspension-feeding invertebrates (such as the burrowing anemone, Ceriantheomorphe braziliensis, and the sea pens Kophobelemnon

TABLE 4-14

NUMBERS AND WEIGHTS OF EACH SPECIES TAKEN IN ALVIN CANYON (BY DEPTH ZONE)

Species	Shallow 141-285 m Number	Shallow 141-285 m Weight (g)	Middle 393-1,095 m Number	Middle 393-1,095 m Weight (g)	Deep 1,270-1,928 m Number	Deep 1,270-1,928 m Weight (g)
Shallow Group						
Fish:						
Argentina striata	2	13.0	--	--	--	--
Chlorophthalmus agassizi	7	59.0	--	--	--	--
Citharichthys arctifrons	144	482.0	--	--	--	--
Coelorinchus carminatus	3	51.0	2	99.0	--	--
Helicolenus dactylopterus	44	394.0	--	--	--	--
Leopophidium cervinum	68	1,027.0	--	--	--	--
Lophius piscatorius	3	116.0	--	--	--	--
Merluccius albidus	55	430.1	1	486.0	--	--
Monolene sesillicauda	1	31.0	--	--	--	--
Myxine glutinosa	15	652.0	--	--	--	--
Paralichthys oblongus	2	196.0	--	--	--	--
Peristedion miniatum	1	42.0	--	--	--	--
Pisodonophis cruentifer	14	160.0	--	--	--	--
Urophycis regius	7	1,411.0	--	--	--	--
Echinoderms:						
Amphilimna olivacea	146	34*0	--	--	--	--
Astropecten americanus	352	559.8	--	--	--	--
Brisaster fragilis	1	10.0	--	--	--	--
Arthropods:						
Acanthocarpus alexandri	6	45.5	--	--	--	--
Cancer borealis	14	646.0	--	--	--	--
Collodes robustus	8	1.5	--	--	--	--
Munida valida	158	1,048.0	4	18.2	--	--
Coelenterates :						
Bolocera tuediae	13	170.0	15	222.0	--	--
Pennatula aculeata	1	6.0	--	--	1	6.0
Middle Group						
Fish;						
Coryphaenoides rupestris	--	--	2	3.0	--	--
Cottunculus thompsoni	--	--	3	377.0	--	--
Glyptocephalus cynoglossus	1	45.0	45	1,510.0		
Lycenchelys paxillus	--	--	5	65.0	1	15.0
Lycenchelys verrilli	--	--	50	175.0	--	--
Phycis chesteri	14	93.0	61	8,517.0	--	--
Synaphobranchus kaupi	--	--	164	4,048.0	3	161.0

Source: Adapted from Haedrich et al. 1975.

TABLE 4-14 (Continued)

NUMBERS AND WEIGHTS OF EACH SPECIES TAKEN IN ALVIN CANYON (BY DEPTH ZONE)

Species	Shallow 141-285 m Number	Shallow 141-285 m Weight (g)	Middle 393-1,095 m Number	Middle 393-1,095 m Weight (g)	Deep 1,270-1,928 m Number	Deep 1,270-1,928 m Weight (g)
Middle Group (Continued)						
Echinoderms:						
Mediaster bairdii	--	--	2	22.0	--	--
Plutonaster intermedius	--	--	7	109.8	16	139.4
Pseudarchaster parelii	--	--	1	20.0	--	--
Arthropods:						
Collosendela colossea	--	--	1	4.0	18	55.0
Geryon quinquedens	--	--	177	20,041.6	22	1,599.0
Annelids:						
Hyalinoecia artifex	--	--	236	1,192.0	--	--
Coelenterates:						
Actinauge verrilli	--	--	7	1,686.0	1	300.0
Actinostola callosa	--	--	1	348.0	--	--
Flabellum goodei	--	--	1	69.0	7	61.0
Molluscs:						
Bathypolypus typicus	--	--	7	1,871.0	--	--
Deep Group						
Fish:						
Aldrovandia affinis	--	--	--	--	1	23.0
Alepoccphalus agassizi	--	--	--	--	3	355.0
Antimora rostrata	--	--	3	572.0	27	6,245.0
Centroscyllium fabricii	--	--	--	--	1	115.0
Nezumia bairdii	--	--	84	1,975.0	30	2,882.0
Echinoderms:						
Asteronyx loveni	--	--	--	--	1	0.2
Asteroschema sp.	--	--	--	--	3	20.0
Bathyblaster vexillifer	--	--	--	--	1	9.8
Benthopecten spinosus	--	--	--	--	3	2.1
Brissopsis sp.	--	--	--	--	1	25.0
Echinus alexandri	--	--	--	--	147	8,378.0
Echinus affinis	--	--	--	--	355	8,034.3
Homalophiura inornata	--	--	--	--	232	251.3
Hygrosoma petersii	--	--	1	599.0	15	2,728.0
Molpadia musculus	--	--	--	--	14	22.2
Ophiochondrus sp.	--	--	--	--	1	0.1
Ophiumusium lymani	--	--	2	0.2	1,468	1,324.7
Ophiothrix sp.	--	--	--	--	5	1.0
Ophiura sp.	--	--	--	--	2	0.2
O. yungmani	--	--	--	--	21	1.7

TABLE 4-14 (Continued)

NUMBERS AND WEIGHTS OF EACH SPECIES TAKEN IN ALVIN CANYON (BY DEPTH ZONE)

Species	Shallow 141-285 m		Middle 393-1,095 m		Deep 1,270-1,928 m	
	Number	Weight (g)	Number	Weight (g)	Number	Weight (g)
Deep Group (Continued)						
Echinoderms: (Continued)						
O. sarsi	--	--	--	--	5	0.8
O. signata	--	--	--	--	1	0.1
Pectinaster forcipatus	--	--	--	--	7	13.4
Phormosoma placenta	--	--	--	--	182	2,606.0
Porcellanaster caeruleus	--	--	--	--	107	112.8
Psolus Sp.	--	--	--	--	2	1.0
Solaster benedicti	--	--	--	--	2	110.2
Zygothuria lactea	--	--	--	--	16	656.8
Arthropods:						
Lithodes agassizii	--	--	--	--	1	6.0
Munidopsis cuvirostrata	--	--	--	--	4	0.2
Stereomastis nana	--	--	--	--	10	23.0
Coelenterates :						
Umbelluta sp.	--	--	--	--	2	11.0

stelliferum, Pennatula aculeata, and Distichoptilum gracile) in the canyon at much greater depths than they occur on the slope indicates high concentrations of suspended, organic-rich sediments. Rowe (1972) suggests that massive, down-canyon movements of sediments associated with slumping or turbidity currents would wipe out sedentary assemblages incapable of withstanding burial, thus precluding the establishment in canyons of the types of benthic invertebrate assemblages that regularly occur on the adjacent slope. Only organisms with effective escape mechanisms (mainly fishes) could survive. Given the absence of significant deposits of these fine sediments in the canyon, there must be a high rate of sediment flushing.

Warme et al. (1978) reported that the semiconsolidated sedimentary walls of canyons off Georges Bank are extensively eroded by benthic macroinvertebrates and fishes from 150 to 1,000 m, and concluded that bioerosion of canyon walls and floors must be an important component of the sedimentation process. The three types of excavations reported were created by galatheid crabs, juvenile jonah crabs, juvenile and adult American lobster, cleaner shrimp, red crabs, and octopus, as well as benthic fish. These organisms have been observed actively enlarging the excavations and flushing loose sediments from the holes. The larger excavations are rare below 300 m where red crab and jonah crab predominate in small to medium depressions.

Hecker et al. (1980) reported on the distribution and abundance of various animals in the canyon, including soft and hard corals in about 10 canyons extending from Norfolk to Corsair Canyon. Several of the gorgonian corals observed are of potentially commercial importance (e.g., Primnoa reseda, Acanella arbuscula and Chrysogorgia agassizii). About 22 coral species were common in one or more canyons (Table 4-15); these included six sea pens, five soft corals (Alcyonacea), six gorgonians, and five stony scleractinian corals. The gorgonian Acanthogorgia armata and Paramuricea grandis are probably most common. Generally, they concluded that the distribution patterns of the various canyon species were independent of one another, and that the canyons off the southern flank of Georges Bank had richer coral faunas, probably because they are less depositional and contain more rock than southern canyons such as Baltimore Canyon. They substantiated vertical zonation patterns described by Haedrich et al. (1975) and also noted that faunal density was higher in the canyons than on the continental slope, again suggesting that this is probably a consequence of higher nutrient flux.

Of great concern with OCS oil and gas development, Haedrich et al. stated, is the possibility of changing water column characteristics in the vicinity of large canyon systems since all of the corals are filter feeders and most depend on clean hard substrate for attachment. Thus, increased suspended sediments could cause damage to populations by covering rock, fouling the colonies, or abrading their tissues. Because of morphological and ecological considerations, gorgonian and scleractinians probably constitute the group of canyon organisms most susceptible to OCS oil and gas development or other activities that would alter deep water column characteristics.

TABLE 4-15

COMMON CORALS IN BALTIMORE, LYDONIA, AND OCEANOGRAPHER CANYONS

Taxa	Canyon		
	Baltimore	Lydonia	Oceanographer
Pennatulacea - sea pens			
Distichoptilum gracile		X[a]	X
Kophobelemnon stelliferum		X	
Pennatula sp.		X	X
Stylatula elegans	X		
Sea pen	X	X	X
White sea pen	XX[a]		
Alcyonacea - soft corals			
Anthomastus arbuscula			X
A. grandifloras	X		X
Eunephthya florida	X	XX	X
E. glonicrata		X	
Trachythela rudis		X	X
Gorgonacea - sea fans			
Acanella arbuscula			X
Acanthogorgia armata	X	XX	XX
Anthothela grandiflora	X	X	X
Paragorgia arborea	X	X	
Paramuricea grandis		XX	XX
Primnoa reseda	X	X	X
Scleractinia - stony corals			
Dasmosmilia lymani	X		
Desmophyllum cristagalli	X		X
Flabellum sp.	X		
Javania cailleta			X
Lophelia prolifera			X

(a) X - common; XX - dominant
Source: Adapted from Hecker et al. 1980.

4.1.2.5 Fish

The fish fauna of the Gulf of Maine and Georges Bank is dominated by boreal species; the southern portion of this area receives summer migrant fishes from the south. Many species support important sports and commercial fisheries. Much of the known biology of the fishes of the Gulf of Maine was summarized by Bigelow and Schroeder (1953). Subsequently, Leim and Scott (1966) considered much of this fauna in their work on fishes of eastern Canada. More recently, spurred by the proposed exploration for petroleum reserves, several efforts have been made to summarize salient features of the biology of important species in the area. TRIGOM (1974) provided an overview of the biology (distribution, niche, reproduction, fecundity, larval life, growth, etc.) for 30 species. BLM (1977) incorporated much of the information in the Final Environmental Statement. CNA (1977) prepared an updated report on more recent literature and ongoing research on fishes of the area. Gusey (1977) summarized the fisheries data and some aspects of the biology of key species of commercial value.

Distribution of Groundfish Stocks

Since 1963, the NEFC has routinely surveyed the groundfish species on the Georges Bank area to monitor the condition of stocks that support commercial fisheries. The surveys are conducted to monitor stocks in several geographic regions of the bank and within three or four depth zones in each region (Figure 4-25). Pikanowski's (1977) Tables 2 and 3 serve as the basis for the values of relative abundance for principal species or species groups shown in Table 4-16.

The highest biomass (kg per tow) for all species combined was taken in Area 9 (Figure 4-25), off Nantucket, during both spring and fall surveys (Table 4-16). However, Areas 19 to 25 on the central to northern portions of Georges Bank offered a large area of relatively high fish catch. Areas 10 through 18, extending from the northeast to southern portions of the bank, produced very low-to-modest catches of all species combined during spring and fall.

Nearly all of the leased blocks are located in Areas 13 and 14 (Figure 4-25) which produced low to moderately low catches of all species combined relative to other strata (Table 4-16). Spring, with an average of 31 kg/tow, was the more productive season for Area 13. Apart from cartilaginous fishes, yellowtail flounder was the most productive species in Area 13 during spring. This level of abundance was only exceeded in Area 9 off Nantucket. During fall, the combined catch in Area 13 fell to 19.3 kg/tow. The average catch of yellowtail flounder declined slightly, but Area 13 was the most productive area for this species. Area 14 was the second and third least productive area during spring (11 kg/tow) and fall (5.2 kg/tow), respectively. Nevertheless, Area 14 was among the most productive for silver hake, other bakes, and pollock in spring and for silver hake in fall.

Area 15 lies seaward of the leased blocks and include the heads of Lydonia, Gilbert, and Oceanographer Canyons (Figure 4-25); this area ranked fifth (25.2 kg/tow) and fourth (5.9 kg/tow) lowest in total catches of groundfish in spring and fall, respectively (Table 4-16). During spring this area produced the highest average catch of silver hake and was among the more productive areas for pollock and other bakes. During fall pollock and other bakes produced the highest catch in the stratum. Haedrich et al. (1975) also sampled demersal fishes in and adjacent to Alvin Canyon (Table 4-14). Spotted hake (Urophycis regusi) contributed twice the biomass of any other species in the shallow zone (141 to 285 m). At mid-depth (393 to 1,095 m) an eel and the longfin hake comprised more than 70 percent of the biomass. In deeper water (1,270 to 1,928 m) marlin-spike and blue hake constituted nearly all of

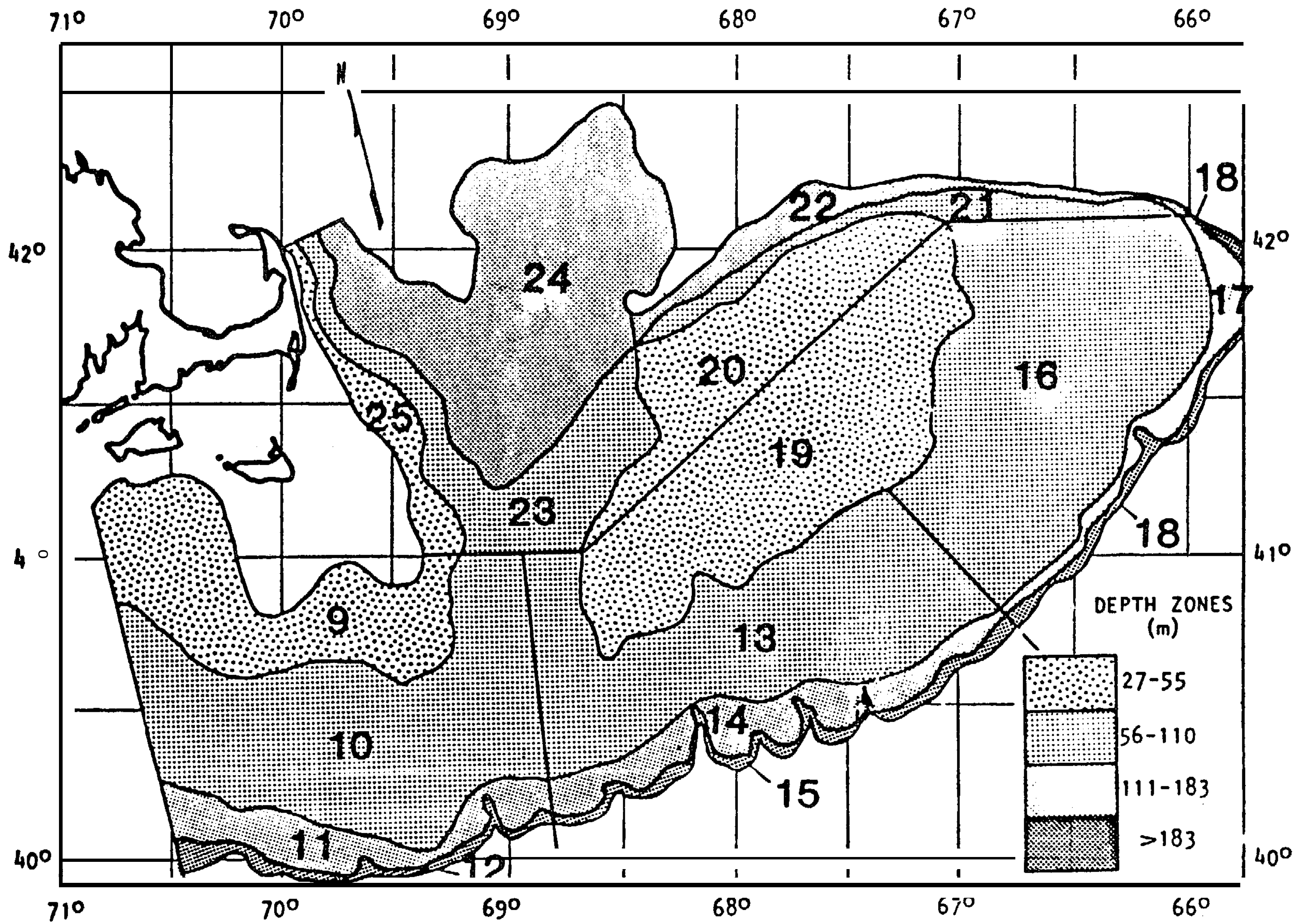


FIGURE 4-25 GEORGES BANK GROUNDFISH SURVEY STRATA (DEPTH ZONES) (PIKANOWSKI 1977)

TABLE 4-16

AVERAGE WEIGHT (kg) PER TOW OF SPECIES OR SPECIES GROUPS IN STRATA TAKEN DURING SPRING AND FALL GROUNDFISH SURVEYS ON GEORGES BANK, 1968-1972

	27 -558 Area(a)				S6 - 110 ● Area(a)					111 - 183 ■ Area(a)						184 - 346 ● Area(a)	
Taxa	9	19	20	25	10	13	16	21	23								
Spring Surveys:																	
Yellowtail flounder	12.22	2*72	0.4s	0.32	2.90	3.4s	1.79	0.26	0.84	0.02	0.05	0.15	0	0.04	0	0	0
Silver hake	0	0.01	0	0	0.42	0.09	0	0	0.01	1.94	2.68	0.09	0.66	0.22	5.45	$.75	0.56
Cod	4.31	6.26	7.26	5.53	1.0s	1.06	3.9s	3.66	7.2S	0	0	1.07	1.16	1.99	0	0	3.14
Haddock	0.1s	3.40	0.72	0.11	0.40	2. 1s	2.25	2.13	1.53	0	0.10	1.95	2.01	1.50	0	0	0.25
Pollock ● =4 other hakes	0.20	0.07	0.1s	0.83	0.54	0.37	0.04	0.8s	0.51	1.49	2.91	1.44	7.27	6.04	4.20	4.02	3.s0
Other flatfish	5.72	4.7s	2.94	1.63	3.64	0.92	1.18	0.52	2.04	0.63	1.05	0.17	2.62	3.86	0.27	0.96	0.40
sharks. ●kates ,●ndrays	24.86	11.72	13.02	4.43	13.95	6.40	7.15	13.29	12.71	1.78	1.26	3.2S	14.93	12.40	0.92	1.14	1.61
Other groundfish	23.70	2.54	1.45	2.S4	3.44	2.61	3.79	2.s1	3.9	1.13	0.65	2.3S	2.68	9.2S	1..4?	2.86	6.S1
All● p8cie9 combined	111.77	51.66	44.09	30.74	44.90	30.97	37.13	39.17	53.79	10.59	10.97	26.24	58.85	67.82	19.72	2s.22	18.70
Fall Surveys:																	
Yellowtail flounder	2.50	1.33	0.21	1.22	1*49	2.89	2.79	0.60	1.36	0	0.04	0.2s	0	0	0	0.02	0.03
Silver hake	1.08	0.4s	0.49	0.32	1.s1	0.71	0.34	O*94	2.03	0.22	1.26	0.40	2.s5	1.66	0.60	0.88	1.10
Cod	0.24	0.63	4.27	10.98	0.13	0.0s	0.67	5.40	6.21	0	0	1.22	1.35	5.43	0	0	0.92
Haddock	0	0.16	0.17	2.03	0.08	0.07	0.69	0.70	3.61	0	0	2.16	5.09	4.87	0	0	1.S6
Pollock and other hakes	0.42	0.40	0.2s	0.9s	1.56	1.33	0.78	1.61	3.52	0.78	1.19	1.25	10.85	6.88	0.41	1.79	2.41
Other flatfish	3.32	2.59	2.s2	7.69	1.57	1.13	0.97	1.17	3.07	0.16	0.43	0.28	4.06	5.40	0.16	0.27	0.s2
Sharks, skates, and rays	47.41	17.39	20.0s	10.48	4.76	4.81	6.35	13. 88	16.03	0.04	0.36	1.62	3.81	11.91	0.12	0.50	2.05
Other groundfish	4.15	1.21	0.89	4.9s	1.36	1.81	3.44	5.93	3.99	0.44	0.93	0.9s	4.02	10.41	1.56	0.93	2.57
All species combined	81.85	31.16	45.58	68.85	21.23	19.34	25.30	51.09	74.99	1.75	S.23	14.80	58.11	75.75	3.47	5.89	24.81

(a) For locations of numbered areas, see Figure 4-29.

Source# Adapted from Pikanowski 1977.

the individuals and biomass. In general, there was little overlap in fish assemblages among the three zones defined by Haedrich et al. (1975).

Survey Areas 10 and 12 (Figure 4-25) encompass much of the Mud Patch and produced very low to modest catches of all species combined during spring and fall surveys (Table 4-16). Area 10 which includes most of the Mud Patch produced average total catches of 44.9 and 21.2 kg/tow in spring and fall, respectively. During spring catches of yellowtail flounder, other flatfish, other groundfish, and cartilaginous fishes were moderate to high relative to other areas. During fall, catches declined as did their relative ranking with other areas.

Area 11 was the least productive area sampled during spring and fall surveys.

Distribution of Pelagic Stocks

The principal pelagic fishes are Atlantic herring (Clupea harengus) and Atlantic mackerel (Scomber scombrus); short-finned and long finned squid, Illex illecebrosus and Loligo pealei, respectively, are also considered here since they represent an important component of the pelagic ecosystem. The spring and autumn groundfish surveys appear to be the major source of data on the distribution and relative abundance of these species (Clark and Brown 1976). Schumaker and Anthony (1972) and Anderson (1973) determined that bottom trawl survey data accurately reflect changes in stocks of the principal pelagics. Similarly, Lange and Sissenwine (1978) used bottom trawl data to assess squid stocks.

Atlantic herring is the most abundant member of the herring family in the Gulf of Maine-Georges Bank area and is important as forage for larger fish, as well as for commercial use as bait, sardines, and fish meal. Juveniles 1 to 3 years old are primarily distributed along the coastal margins of the Gulf of Maine, but have not been located in significant numbers on Georges Bank (TRIGOM 1974). Spring and fall groundfish surveys indicate that adult schools occur in a broad band across the south-southeastern portion of the bank. According to Fritz (1965), the fall distribution of herring extends over much of Georges Bank and the Gulf of Maine. Very high densities of herring occur over spawning grounds generally characterized by gravel beds swept by swift currents. Known spawning areas occur on Nantucket Shoals, northern Georges Bank, and Browns Bank. Herring are fished heavily over the spawning grounds.

Atlantic mackerel is a swift-swimming fish that occurs in schools from coastal areas to the OCS and supports a salt mackerel industry. In winter and spring, mackerel appear to be distributed along the OCS from North Carolina to mid-Georges Bank, in depths from 92 to 183 m (Gusey 1977). According to Bigelow and Schroeder (1953), mackerel move inshore during summer and are distributed from the Nantucket-western Georges Bank area to the central coast of Maine. Based on NMFS-U.S.S.R. exploratory surveys mackerel more offshore and southward in autumn, covering much of north-central Georges Bank. Bigelow and Schroeder (1953) report that no large catches have been taken fran the eastern part of the bank.

Squid constitute an underexploited resource in the western Atlantic. The bulk of the reported U.S. catch is landed as an incidental catch to trawl fishery (Gusey 1977). The long-finned squid (*Loligo pealei*) is the principal species harvested. During winter and spring, this species is distributed along the outer margin of the continental shelf onto northeastern Georges Bank. In summer and fall, long-finned squid disperse over much of the shelf and occur across much of central to southwestern Georges Bank. The short-finned squid (*Illex illecebrosus*) is also commercially important, but is used primarily as cod bait (Gusey 1979).

Commercial Fisheries

Georges Bank is an area of intense commercial fishing activity involving both domestic and foreign fishing fleets. This section describes the use of Georges Bank fisheries resources in a context that provides one basis for assessment of potential effects of exploratory and development drilling on the commercial fisheries. The level of detail that can be attained is substantial greater for the domestic fishery, which in recent years (1972 to 1975) has accounted for only 12 percent of the catch by weight (Chenoweth 1977). Because there is no similar level of detailed information on the distribution of catch/effort for the foreign fleet, we cannot accurately predict impacts on the foreign fishery.

Chenoweth (1977) presented a broad comparison of the domestic and foreign fisheries on Georges Bank for 1972 to 1975 based on ICNAF data for subdivision 5ZE (Table 4-17). The data for this period of record indicate that the foreign catch ranged from 421,400 to 563, 175 mt/yr, compared to 61,693 to 69,885 mt/yr for the U.S. The foreign fleet took an average of 88 percent of the total catch. The annual catch for both fleets declined during the period. Aside from the overwhelming disparity in total catch between the U.S. and foreign fleets, there were remarkable differences in emphasis on species or species groups. The foreign fleet focused heavily on herring and mackerel (50 to 60 percent). These two pelagic species, along with silver hake, red hake, bivalves, cod, other fish, and squid accounted for more than 95 percent of the annual foreign catch (Table 4-17). Cod, yellowtail flounder, and other flatfish formed the core (60 to 67 percent) of the domestic catch--with silver hake, haddock, red fish, bivalves, and lobster, they accounted for 91 to 98 percent of the annual catch. Much of the difference between the foreign and domestic catch was due to the foreign fleet emphasis on pelagic species (herring, mackerel, and squid), bakes, and other bottom fish. The foreign fleet consists of modern, large vessls (up to 120 m in length) equipped with heavy bottom and midwater trawls, and seines; whereas, the domestic fleet consists of older, smaller vessels (16 to 30 m in length), 93 percent of which (in 1974) were fish trawls or dredges (Olsen and Saila 1976). The modern foreign fleet accounted for 64 percent of the total fishing effort on the bank from 1972 to 1974 (Chenoweth 1977).

The NMFS (1975) data summary provides a long-term basis for describing domestic commercial fishing activity and the geographic distribution of catch and effort. The report summarizes data for 15 statistical areas

TABLE 4-17

CATCH (METRIC TONS) FOR SELECTED SPECIES OR SPECIES GROUPS
IN ICNAF SUBDIVISION 5AE (GEORGES BANK) 1972 to 1975

Species (a)	U.S. Catch				Foreign Catch			
	1972	1973	1974	1975	1972	1973	1974	1975
Herring	11	161	172	3	149,697	169,995	128,865	135,624
Mackerel	5	0	11	1	133,859	155,006	100,574	119,109
Silver Hake	879	5,698	2,283	4,588	76,633	56,508	64,081	58,427
Bivalves	6,837	8,999	7,707	7,140	34,525	35,055	50,934	61,536
Other Fish	25	8	10	29	65,298	38,200	23,600	28,558
Cod	12,478	14,838	16,642	14,594	10,344	10,892	8,329	8,610
Red Hake	160	74	77	55	39,206	24,592	9,423	14,948
Squid	7	17	27	29	21,456	23,804	22,295	13,291
Yellowtail Flounder	18,827	21,373	19,454	16,265	4,150	260	190	91
Other Flatfish	10,251	6,579	6,930	8,815	1,935	1,358	447	1,000
Red Fish	6,007	4,950	3,220	3,114	5,811	2,844	572	1,429
Haddock	3,855	2,776	2,396	3,969	1,864	2,526	1,749	1,424
Lobster	1,046	672	1,166	1,438	204	228	988	219
Tunas/Swordfish	67	106	469	1,114	12	92	4	7
Crabs	0	71	180	128	0	0	0	0
Shrimp	15	2	0	2	8	0	0	5
Menhaden	0	0	0	0	0	0	1	83
Total of All Species in 5ZE	16,693	69,885	65,014	65,707	563,715	544,589	421,400	456,111

(a) Species listed in order of total tonnage averaged over 4 years.

Source: Chenoweth 1977: Data sources ICNAF Statistical Bulletins 22, 23,24, and Summary Documents 1976b.

shown in Figure 4-26. Statistical areas 521 through 525 include all of Georges Bank, as well as significant areas off the bank. Area 525 includes all blocks leased for drilling.

During the period from 1965 to 1974, estimated fishable stocks underwent a significant and relatively steady decline (Figure 4-27) (NMFS 1975). Peak stock abundance was during 1968, and harvestable biomass fell to a low point in 1975 (Clark and Brown 1976). Excluding principally pelagic stocks, generally ignored by the domestic fishery, peak stock abundance occurred in 1964 and gradually declined to 1975. Thus, the statistical record summarized by NMFS covers a period of estimated big" to low biomass and should represent a reasonable long-term data base for the domestic fishery.

The total domestic hailed (landed) bottom catch (trawl and dredge) for the Georges Bank-Southern New England statistical areas averaged 2,255,000 mt/yr. About 79 percent of this catch (1,780,000 mt/hr) was from Georges Bank (Statistical Areas 521 to 526). Area 525, which includes all leased drilling blocks, produced an average catch of 163,500 mt/hr or 9 percent of the Georges Bank catch.

Average monthly total hail using bottom gear ranged from 100,000 to 200,000 mt/yr (Figure 4-28) over Georges Bank (Areas 521 to 526). The higher monthly catches were from May to October, except in Area 525 where the higher monthly catches (more than 10,000 mt) occurred from October to July. Thus, the pattern of monthly catch in Area 525 was roughly the inverse of that for the bank as a whole. The catch in Area 525 at its lowest point in September accounted for only 4 percent (7,700 mt) of the Georges Bank catch for that month, and at its high point in April constituted 16 percent (24,100 mt) of the total.

Trophodynamics

The food web in offshore systems is supported largely by the production of phytoplankton. Phytoplankton is preyed upon by zooplankton that includes the meroplanktonic larvae of fish and benthic invertebrates as well as crustaceans. Smaller zooplankton (herbivorous protozoa, copepods, and cladocerans) are in turn consumed by larger zooplankton (carnivorous crustaceans and chaetognaths), fish, birds, and marine mamma ls. Zooplankton supports planktivorous nekton (e.g., herring) that in turn supports piscivorous nekton, including larger fish and some birds and mammals Phytoplankton, fecal pellets, and zooplankton are also consumed by benthic invertebrates. The benthic food web consists of herbivores and carnivores. Filter- and deposit-feeding benthos support benthic carnivores that are preyed upon by larger fish. Lastly, man consumes larger benthic invertebrates (clams, scallops, crabs, lobster, etc.) and larger components of the nekton (e.g. , herring, cod, squid, etc.).

This portion of the food web was described by Ryther (1969) for a generalized 'coastal" system, but is also applicable to offshore banks, and therefore is more properly called a "continental shelf" system (Parsons and Takahashi 1973), shown diagrammatically in Figure 4-29. This food web shows that basically three trophic levels are involved

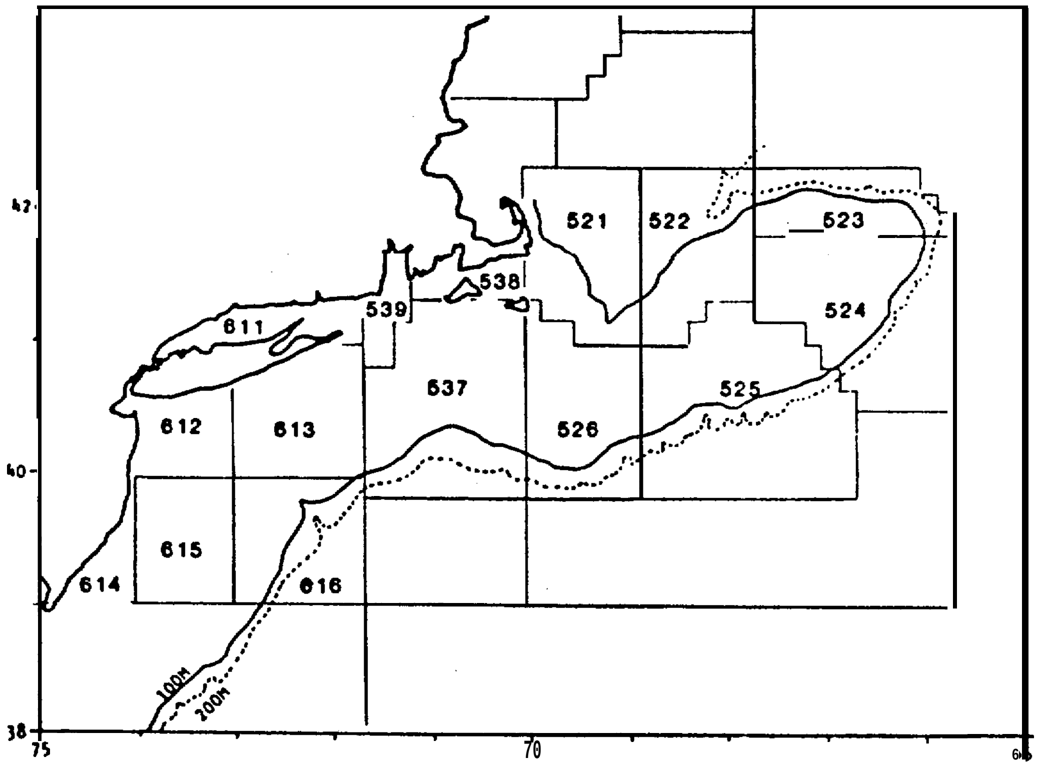


FIGURE 4-26 NMFS STATISTICAL AREAS FOR GEORGES BANK AND SOUTHERN NEW ENGLAND (NMFS 1975)

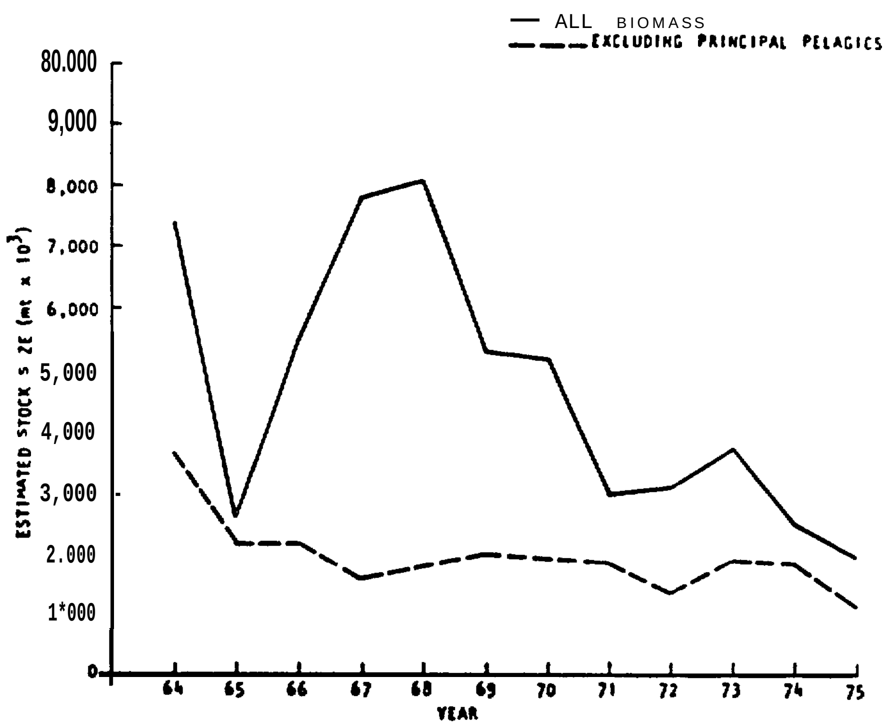


FIGURE 4-27 ESTIMATES OF FISHABLE BIOMASS BY YEAR FOR ICNAF SUB-AREA 5 AND STATISTICAL AREA 6, 1964-1975 (ADAPTED FROM CLARK AND BROWN 1976)

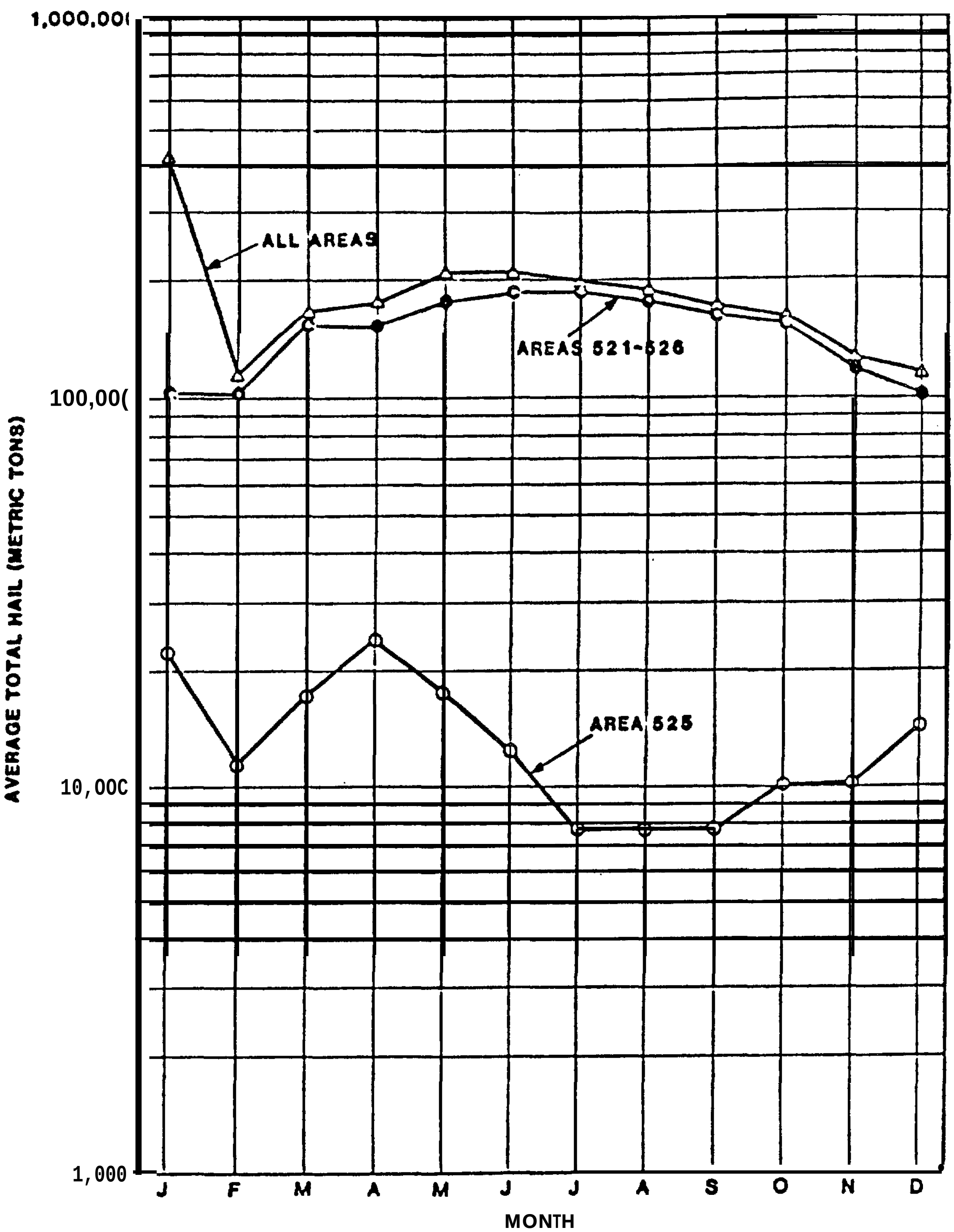
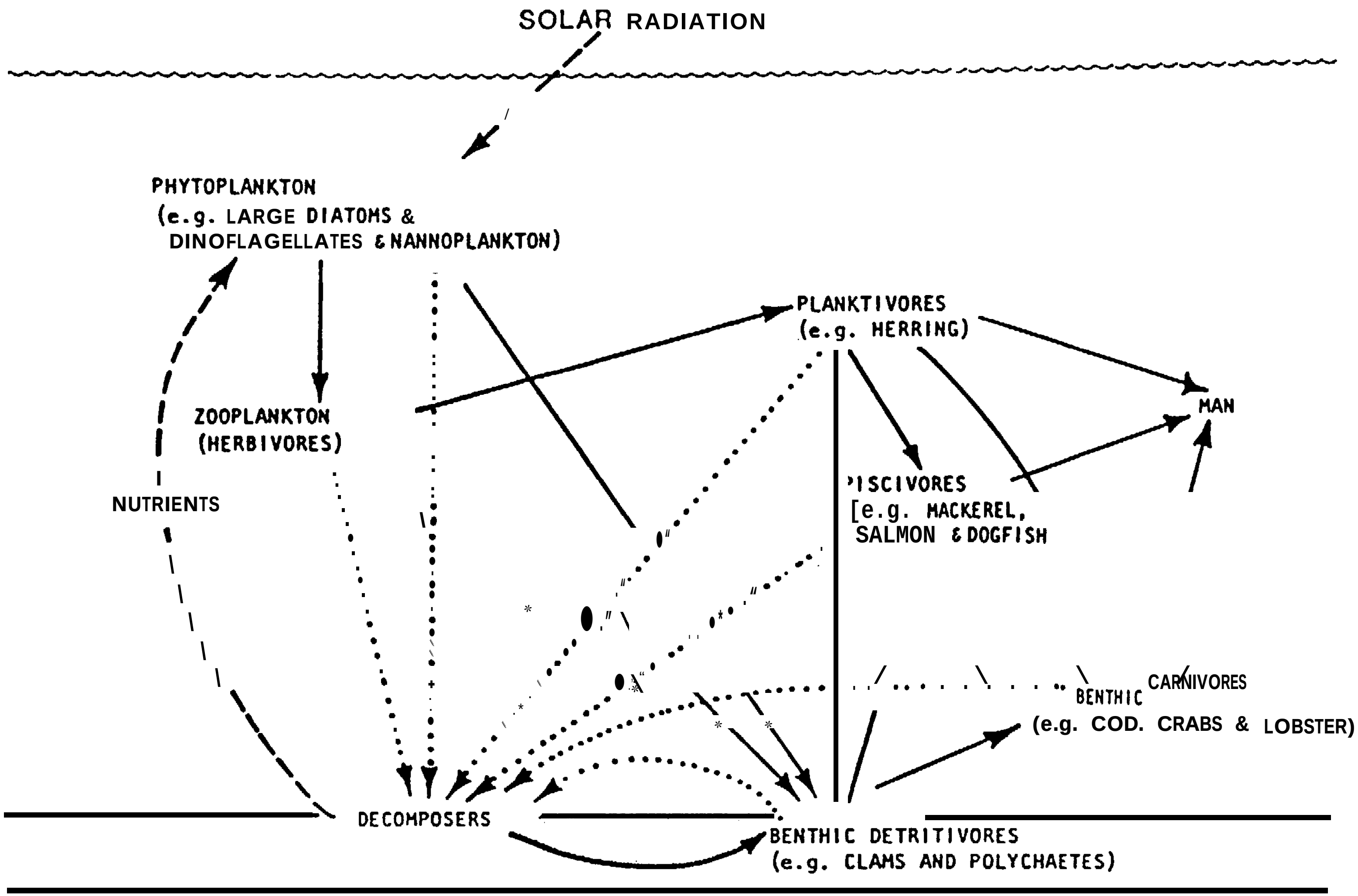


FIGURE 4-28 AVERAGE MONTHLY VARIATION OF TOTAL HAIL CATCH USING BOTTOM GEAR FOR GEORGES BANK AND SOUTHERN NEW ENGLAND FISHING GROUNDS (1 965 TO 1974) (NMFS 1975)



——— INDICATE ENERGY FLOW LOWER TO HIGH TROPHIC LEVELS.

.... INDICATE FLOW OF DETRITAL MATTER TO DECOMPOSERS

— — — — INDICATE FLOW OF SOLAR RADIATION AND NUTRIENT TO PHYTOPLANKTON

FIGURE 4-29 MAJOR COMPONENTS OFTHECONTINENTAL SHELF FOOD WEB (ADAPTED FROM RYTHER 1968; PARSONS AND TAKAHASHI 1973) in energy flow to the benthic or pelagic communities. Another important feature of this food web is the supply of organic debris and excretory products to decomposes (pelagic and benthic bacteria and other heterotrophs). These organisms process organic detritus and chemicals (mineralization) and produce essential nutrients such as nitrates and phosphates for the production of phytoplankton.

Food webs are much more complex than described and illustrated above . Virtually all organisms are dependent on a variety of other organisms for sustenance, and each of these prey is in turn dependent on a variety of organisms for food. It is evident that pelagic and benthic food webs are not independent; however, to present a simplified overview of the food webs that support Georges Bank fisheries it is necessary to treat pelagic and benthic food webs independently for invertebrates and fishes.

Pelagic and Benthic Invertebrate Food Webs

The nutritional and feeding relationships of representative components of pelagic and benthic invertebrate food webs are summarized in Table 4-18. Photosynthesis by diatoms such as Coscinodiscus, Chaetoceros and Thalassiosira is the primary source of energy captured on Georges Bank, this source of energy is therefore the base of all the food webs. In the pelagic food chain, copepods (e.g., Calanus, Centropages, Pseudocalanus) are the principal primary consumers of phytoplankton (diatoms). Larger copepods also feed on other zooplankton including invertebrate and fish larvae and arrow worms (Sagitta). Arrow worms in turn are active predators on copepods and larval fish. Euphausiids or krill (Meganyctiphanes) are filter feeders on microzooplankton and zooplankton, and actively prey on arrow worms. Jellyfish prey on a broad spectrum of animals from protozoans to small fish. This oversimplified view of the pelagic invertebrate food web underscores the great complexity of relationships among these organisms.

The benthic invertebrate food chain is equally if not more complex (Table 4-18). Nearly all of the major groups of organisms contain many species whose primary food source is suspended or deposited organic detritus. Similarly, scavengers and predators are represented in most groups of organisms listed. The relative positions in the food web of benthic invertebrates that support fisheries on the bank are described below.

American lobster are planktivores as pelagic larvae and benthic carnivores as juveniles and adults (Cobb 1976). Little is known of the feeding habits of lobster larvae, but it appears that they probably prey on smaller zooplankton such as copepods and arrow worms. Laboratory studies show that larvae will readily feed on chopped mussel or live brine shrimp as well as other larval lobsters. Cobb reported that the stomach contents of lobsters (juveniles and adults) in the woods Hole area (citing Harriman 1909) included, in descending order of quantity: fish, Crustacea (chiefly isopods and decapods), molluscs (mostly small gastropod), algae, echinoderms, and hydroids. He concluded that lobster prey on suitable organisms in proportion to their occurrence. Cooper and Uzmann (1977) reported that juveniles less than 40 mm in length are most

TABLE 4-18

FOOD ITEMS AND FEEDING MODES OF REPRESENTATIVE COMPONENTS OF PELAGIC AND BENTHIC INVERTEBRATE FOOD WEBS ON GEORGES BANK

	Representative Species on Georges Bank	Nutrition, Food Items and Feeding Mode
Pelagic Food Web		
Bacillariophyta (diatoms)	Coscinodiscus, Chaetoceros, Thalassiosira	Photosynthesis.
Copepoda	Calanus, Centropages, Pseudocalanus	Chiefly filter feeders en diatoms, some active predation on other planktonic ● nt--als such ● - invertebrate ● nd fish larvae, ● rm= worms (Sagitta ● l*gans) .
Euphausiacea (krill)	Meganyctiphanes norvegica . Thysanoessa	Primarily filter feeders on microzooplankton ● nd zooplankton, some predation on ● rrc-i worms.
Chaetognatha (arrow worms)	Sagitta elegans	Active predators on zooplankton, especially copepods and occasionally larval fish.
Cnidaria - Hydrozoa and Scyphozoa (jellyfish)		Predators on broad ● pectin= of nail animals from protozoans to small fish.
Benthic Food Web		
Cnidaria		
- Hydrozoa (hydroids)		Predators on microzooplankton, zooplankton ● nd small crustaceans.
- Anthozoa, Zoantharia (sea anemones, stony corals)	Cerianthus borealis	Predators on invertebrates ● n d fish, some ciliary feeding on plankton.
- Anthozoa, Alcyonaria (sea pens, sea fans, whip corals)		Predators on plankton and small benthic invertebrates.
Polychaeta		
- Errantia	Nephthys, Nereidae, Glyceridae	Raptorial predators on small invertebrates.
	Capitella, Ophelia, Pectinaria	Browsers on ● lqc or burrowers that feed on deposited organic matter.
- Sedentaria	Owenia, Amphitrite, Terebella	Ciliary feeders on organic detritus on or suspended over the bottom.
Amphipoda		Most are filter feeders on detrius or ● re scavengers, ● few ● r c predators.
Cumacea		Many are filter feeders on detritus, others scrape organic matter from sand particles.
Decapoda (crabs, lobster, shrimp)	Geryon, Homarus, Crangon	Most ● re predators or ● cavenqrra on ● r.AIM 1 matter, others are filter feeders on organic matter.
Mysidacea	Neomysis americana	Filter feeders on organic detritus.
Gastropoda (snails)		A full ● pact- of feeding modes including herbivores, carnivores, scavengers, ciliary feeders and parasites.
Pelecypoda		
- Protobranchia	Nucula, Yoldia, Mal letia	Ciliary feeders on bottom detritus.
- Filibranchia and Eulamellibranchia	Modiolus, Placopecten, Spisula	Ciliary feeders on small plankton, ● specially phytoplankton.
Asteroidea (starfish)	Astropecten americanus Asterias vulgaris	Predators on benthic invertebrates, ● cav-nqerc on dead animals, ● nd ● few flagellary feeders on plankton ● nd detritus.
Echinoidea (sea urchins, sand dollars)	Echinarachnius parma	Sea urchins ● re herbivores, ● and dollars feed on fine particulate organic matter in ■ edbents.
Ophiuroidea (brittle stars)	Ophiura	Filter feeding on suspended and deposited organic detritus.

susceptible to predation. Lobsters in excess of 50 mm are apparently difficult prey. Predators include sculpin, cunner, tautog, black sea bass, and sea raven. Larger lobster (up to 100 mm) are eaten by Atlantic cod, wolffish, goosefish, and sharks.

Limited information is available on the food habits of the red crab. Cursory laboratory observations of feeding reported by Gray (undated) indicate that red crab eat almost any fish or shellfish available, and are frequently taken in pots baited with dead fish and anemones; it seems likely that the species is an opportunistic benthic scavenger and predator. Red crabs are probably preyed upon by the same fish species that eat lobster.

The commercially important bivalves on Georges Bank--sea scallops, surf clams and ocean quahogs--are filter feeders on minute planktonic organisms, especially phytoplankton, and probably suspended organic debris. MacKenzie (1979) reviewed available information on the food of the sea scallop. Planktonic scallop larvae feed on plankton; based on laboratory culture studies, phytoflagellates are probably a significant food resource. Juvenile and adult sea scallops are filter feeders on plankton and possibly on detritus; scallop spat have been cultured successfully when fed phytoflagellates, and adults have been maintained when fed diatoms. MacKenzie (1979) further reported that little is known of predation on scallop larvae in the water column or on the bottom; undoubtedly, other zooplankton and planktivores such as herring consume significant quantities of larvae. Also, cerianthid anemones (such as *Ceriantheopsis americanus*) are suspected consumers of larvae. Juvenile scallops appear especially vulnerable to predation by Atlantic cod, American plaice, wolffish, and starfish such as *Asterias vulgaris* and possibly gastropod.

Specific information on the food of surf clams and quahogs was not found in the literature. Predators of surf clams and ocean quahogs include fish, crabs, and moon snails (*Lunatia heros* and *Polinices duplicata*) (Ropes 1978). Predation is heaviest on juveniles of both species due to their inability to burrow deep enough into the seafloor to escape predators. It seems likely that the more significant fish predators are skates such as *Raja laevis* and *R. erinacea* which are known predators on bivalves and are capable of excavating bivalves from bottom sediments (Bigelow and Schroeder 1953).

Significant advances have been made in recent years in describing the food habits of commercially important fishes on Georges Bank, but far more information on trophodynamics must be acquired before a predictive capability can be achieved to address concerns such as the effect on fisheries stocks of a drastic population reduction by a major prey species. Virtually all of the food web studies on Georges Bank have been conducted by the NMFS NEFC laboratories at Woods Hole, MA, and Narragansett, RI (Table 4-19) and significant data gaps are evident and biases are present. Larval and juvenile fish food habits were reported by Sherman et al. (1977) and Bowman (1979), respectively. Langton and Bowman (1977) gave an overview of predator-prey relationships for a number of fish and squid species. More detailed accounts of the diets of gadiform and pleuronectiform fishes were subsequently prepared by Langton

TABLE 4-19

PRINCIPAL PREY, EXPRESSED AS PERCENTAGE WEIGHT, OF MAJOR PELAGIC FISHES AND GROUNDFISHES ON GEORGES BANK

Fish Species	Life History Stage[a]	Principal Prey Taxa																			
		Diatoms	Anthozoa	Polychaeta	Amphipoda	Balanomorpha	Copepoda	Cumacea	Decapoda	Euphausiacea	Mysidacea	Cephalopoda	Gastropoda	Pelecypoda	Echinoidea	Ophiuroidea	Chaetognatha	Invertebrate Eggs	Pisces	Number Examined	Number Feeding
Ammodytes americanus	L						19											80		80	22
	J,A						41										40			90	58
Clupea harengus	L						100													42	1
	A						8			42							33			--	--
Scomber scombrus	A						20			12		29								--	--
Gadus morhua	L						46											42		216	176
	J				23				11	18	13								16	107	86
	A												5	9					62	667	62!
Macrozoarces americanus	A													6	72	10				110	74
Melanogrammus aeglefinus	L						93													158	95
	J				28				12	13									5	2,159	2,015
	A			24	7										6				20	352	337
Merluccius albidus	A								13										80	23	9
Merluccius bilinearis	J				7				30	44									9	440	366
	A									13									78	240	187
Pollachius virens	L						80			7										54	31
	J									56										22	21
	A									66									23	206	200

(a) L - larvae, J = juvenile, A - adult

Sources: Bowman 1977, 1979; Langton and Bowman 1977, 1980a, b; Meyer et al. 1979; Sherman et al. 1977.

PRINCIPAL PREY, EXPRESSED AS PERCENTAGE WEIGHT, OF MAJOR PELAGIC FISHES AND GROUNDFISHES ON GEORGES BANK

Fish Species	Life History Stages a)	Diatoms	Anthozoa	Polychaeta	Amphipoda	Balanomorpha	Copepoda	Cumacea	Decapoda	Euphausiacea	Mysidacea	Cephalopoda	Gastropoda	Pelecypoda	Echinoidea	Ophiuroidea	Chaetognatha	Invertebrate Eggs	Pisces	Number Examined	Number Feeding
Urophycis chuss	J				19				42	6										229	233
	A								38				17						5	208	163
Urophycis regius	J				77		7													16	10
	A											72								4	3
Urophycis tenuis	J				5				58											23	22
	A								22										63	173	133
Enchelyopus cimbruis	J				33															3	1
	A			14					58											27	--
Sebastes marinus	L						97													31	19
	A									44									21	56	37
Myoxocephalus octodecem-spinosus	L	6				8	6						29					37		134	111
	A				6				82											32	28
Citharichthys arctifrons	A			26	41				12											53	46
Glyptocephalus cynoglossus	A			88																98	92
Hippoglossoides platessoides	J			72	7															10	5
	A														72	9				287	[illegible]
Limanda ferruginea	J				39			0			33									56	53
	A		10	47	28															642	484
Paralichthys oblongus	A								39			[illegible]							24	111	65
Pseudopleuronectes americanus	A		25	5										20						321	207
Scophthalmus aquosus	A								53		20								13	228	138

and Bowman (1980a, b). The food habits of the American sand lance were reported by Meyer et al. (1973).

The major pelagic fishes (the American sand lance (Ammodytes americanus)) Atlantic herring (Clupea harengus) , and Atlantic mackerel (Scomber scombrus)) are all primarily planktivorous (Table 4-19). Larval sand lance fed extensively on invertebrate eggs (80 percent), with the remainder of the diet composed of copepods (19 percent) such as Pseudocalanus minutus (11 percent) and nauplii (6 percent). Juvenile and adult sand lance fed more heavily on copepods (41 percent); Calanus, Pseudocalanus, Temora and Tortanus each comprised 6 to 10 percent of the biomass consumed. Chaetognaths (Sagitta elegans) were the most important single prey item (40 percent). In contrast, only one of the Atlantic herring larvae examined had fed on copepods. Adult herring fed primarily on euphausiids (42 percent) and chaetognaths (33 percent), and to a limited extent on copepods (8 percent). No data were presented for larval mackerel. Adults fed mainly on copepods (29 percent), squid, (29 percent), and euphausiids (12 percent).

Shortfin (Illex) and longfin (Loligo) squid are also important predators in the pelagic food chain. However, quantification of their diets is difficult since prey are not consumed whole. Langton and Bowman (1977) state that shortfin squid prey on other squid, fish, and crustaceans such as euphausiids. Longfin squid have a similar diet.

Sand lance herring, mackerel, and squid are important links in the food chain between zooplankton and pelagic and bottom fishes of importance to commercial and sports fisheries. Sand lance are preyed upon by Atlantic cod, haddock, silver hake, and yellowtail flounder (Meyer et al. 1979) and in recent years , have increased in importance as prey for the principal fish stocks (Sherman et al. 1978). Herring is a major forage food of cod, spiny dogfish, and silver hake; among its other predators are pollock, red hake, haddock, Atlantic salmon, bluefin tuna, swordfish, and sharks (Langton and Bowman 1977). Mackerel predators include most of the aforementioned species.

The remainder of the fishes listed in Table 4-19 are generally referred to as bottom or ground fishes. However, the stomach contents of several species suggest that significant feeding occurs in the water column on pelagic prey as wll as on benthic prey. Thus, the “bottom fish” characterization refers more to where fish are taken than where they feed.

Adult Atlantic cod (Gadus morhua) fed primarily on other fish (62 percent) such as herring (37 percent), yellowtail flounder, American plaice and summer flounder, decapod crustaceans (15 percent) such as rock crabs, pandalid shrimp, and hermit crabs; and molluscs (16 percent) such as Placopecten and Pecten. Larvae preyed extensively on copepods (46 percent), especially Pseudocalanus minutus (25 percent) and copepod nauplii (20 percent), and on invertebrate eggs (42 percent). Juveniles fed mainly on a mixture of benthic and planktonic crustaceans (82 percent). Benthic crustaceans included gammarid and caprellid amphipods (23 percent) and decapods (11 percent), such as the sand shrimp Crangon septemspinosa; and planktonic crustaceans included mysids

(13 percent) and euphausiids (18 percent). Fish (Pisces) constituted 16 percent of the diet.

Data for adult ocean pout (Macrozoarces americanus) indicate that it fed heavily on echinoderms (82 percent), especially the sand dollar, Echinarachnius parma (62 percent). Pelecypods constituted 6 percent of the stomach contents.

The prey consumed by haddock (Melanogrammus aeglefinus) was similar to that of cod though fish were not of as great importance (Table 4-19). Haddock larvae fed almost exclusively on copepods (Pseudocalanus minutus, 8 percent) and copepod nauplii (85 percent). Juveniles fed mostly on benthic crustaceans (62 percent) such as amphipods (28 percent) and sand shrimp as well as annelid polychaetes (14 percent). The proportion of euphausiids (13 percent) eaten indicates that juvenile haddock are not strictly benthic carnivores. As haddock grow, there appears to be an increased emphasis on annelid worms (24 percent), accompanied by reduced consumption of crustaceans (16 percent).

The reported stomach content data for offshore hake (Merluccius albidus) suggest that adults are 80 percent piscivorous (Table 4-19). Only decapods (13 percent) were of additional consequence in the stomach contents of this species. Juvenile hake fed mainly on benthic crustaceans; the sand shrimp C. septemspinosa and amphipods were most important. Adults of each species appear to feed on different types of prey. In red hake, decapod crustaceans accounted for 48 percent of the adult diet while spotted hake (Urophycis regius) feed mainly upon squid (72 percent) and white hake (Urophycis tenuis) feed heavily on other fish (63 percent) as adults (Table 4-19).

Pollock (Pollachius virens) appear to be members of the pelagic food chain at all life stages (Table 4-19). As larvae, pollock fed extensively on copepods (87 percent). Smaller euphausiids (11 percent) were also eaten by larvae, but composed a much larger portion of the juvenile and adult diets (56 to 66 percent, respectively). The euphausiid, Meganyctiphanes norvegica, was the most important prey of adults, contributing 47 percent to the diet. Bathypelagic lanternfish (Myctophidae, 9 percent) constituted the largest fraction of fish eaten (23 percent).

America n plaice (Hippoglossoides platessoides) exhibit a striking change in diet from the juvenile to adult stage (Table 4-19). Polychaetes are the major prey (72 percent) of juveniles, but only capitellids (11 percent) and sabellids (3 percent) could be identified. Gammarid amphipods (17 percent) comprise most of the crustacean component (21 percent) of the juvenile diet. Echinoderms comprise 91 percent of the adult diet on Georges Bank and include echinoids (sand dollars, E. parma, which produce 70 percent of this biomass) and ophiuroids (19 percent).

Yellowtail flounder (Limanda ferruginea) feed heavily (94 percent) on benthic crustaceans as juveniles, but adults feed primarily on polychaetes (47 percent) in addition to crustaceans (Table 4-19). The principal crustacean taxa consumed by juveniles were amphipods

(39 percent), mysids (33 percent), and cumaceans (10 percent). Of the polychaetes eaten by adults, no particular taxon was of singular importance.

The stomach contents of juveniles and adults generally provide a clear basis for assigning a species to either the pelagic or benthic food webs. Members of the pelagic food web include American sand lance, Atlantic herring, Atlantic mackerel, pollock and redfish. The vast majority of the prey consumed by these species are characteristic of the water column. The remaining species listed in Table 4-19 can generally be assigned to the benthic food web; however, some difficulty arises where juveniles consumed significant amounts of euphausiids (e.g. juvenile cod, haddock, and silver hake), or where adults fed heavily on unidentified fish (e.g. adult cod, haddock, and most of the bakes). As expected, the flatfishes are members of the benthic food web.

It is difficult and, indeed, of possibly questionable value, to identify prey species of special importance to fishes in either the pelagic or benthic food webs. Stomach content analyses are greatly biased towards identification of larger organisms that are not readily digested because of size Or hard body parts such as exoskeletons. Furthermore, the major prey during spring and fall may not be of importance during winter or possibly summer. Nevertheless, some prey species were important components of the diet of several fishes so that it is reasonable to conclude that they are a major component of the food webs supporting the fisheries stocks on Georges Bank.

In the pelagic food web three groups of organisms appear to be important, including Sagitta legans (Chaetognatha), Meganyctiphanes norwegica (Euphausiacea), various copepods, and Ilex and Loligo (Cephalopod). Meganyctiphanes was also important to a number of fishes most of whose diet was of benthic origin.

In the benthic food web, polychaetes, amphipods, and decapods were the primary prey although other groups were of importance to certain fish. Unfortunately polychaetes and amphipods are generally very small organisms and not readily identified. These two groups were significant in the diets of several juvenile gadids and juvenile and adult flatfishes. Two species of decapod of considerable importance were the shrimp, Crangon septemspinosa and Dichelopandalus leptocerus. The sand dollar Echinarachnius parma was of exceptional importance in the diets of ocean pout and American plaice.

4.2 PROBABLE GEORGES BANK DRILLING SCENARIO

4.2.1 Drilling Activity Estimates

The drilling scenario presented here represents the current estimate of drilling activity in the Georges Bank Lease Sale No. 42 area. Estimates were originally presented by the Bureau of Land Management (BLM 1977) which indicated that exploratory drilling would begin within a year of the lease sale and be heavily concentrated within the first 5-yr period. (Leases are currently issued in renewable 5-yr periods in accordance with 43 CFR 3302.2). A revision of the exploratory drilling estimate is appropriate in light of the passage of 1.5 yr of this first lease period without the commencement of exploratory drilling. Estimates for the development phase of drilling activity (BLM 1977) are still considered as reasonable and are presented below. Drilling activities other than those associated with Lease Sale No. 42 are *not* considered in this scenario.

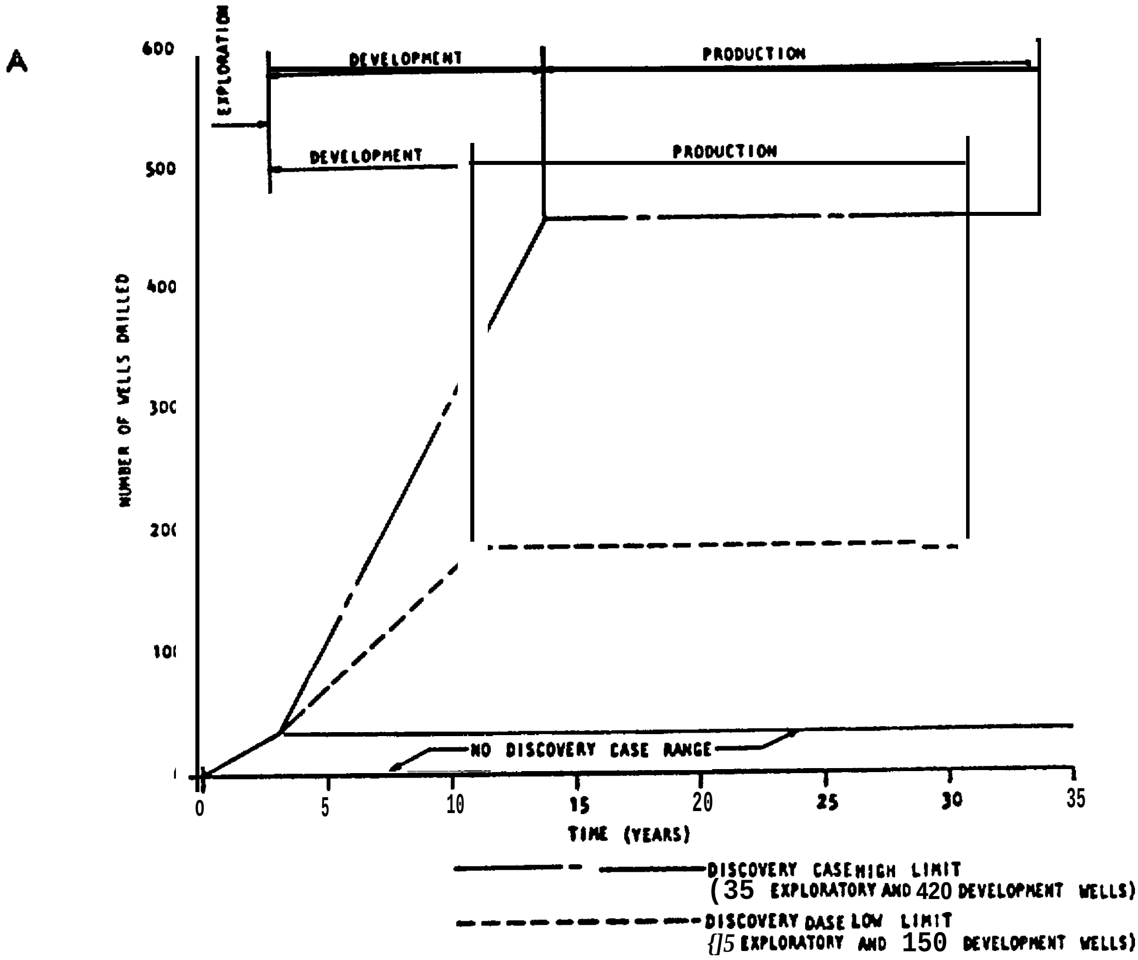
The exploratory phase estimates are based *on an* informal poll of the offshore operators included on Georges Bank. Their plans generally call for the completion of about 35 development wells during the remaining portion (about 3.5 yr) of the first 5-yr lease period. The availability of drilling rigs is largely responsible for limiting the drilling activity. Approximately three rigs will be operating at any one time. The development phase would occur if *a* significant find is made during the exploration phase. Between 150 and 420 wells are likely to be drilled during the development phase which would last about 8 to 11 yr (Figure 4-30A) Drilling would be accomplished from 11 to 28 fixed platforms. It is estimated that drilling for 7 to 14 wells may be in progress at any one time. The production phase would not involve any new well installation or development (Figure 4-30B). This phase would extend over the 20-yr estimated life of the field. No significant release of drill cuttings or drilling fluids is expected during this phase.

4.2.2 Drilling Fluids and Cuttings Estimates

The volume of drill cuttings and drilling mud discharged is a function of the purpose of the well, its diameter as a function of depth, and its drilled depth. Table 4-20 lists exploration and development well dimensions and expected yield of drill cuttings as a function of depth. Exploration wells are assumed to penetrate to about 4,600 m (15,000 ft) (BLM 1977). Development wells are expected to be drilled to similar diameters as the exploratory wells but would typically penetrate to the 3,050-m (10,000-ft) level. Drill cuttings production is estimated at 4,330 barrels (690 m^3) per exploratory well *and* 3,413 barrels (543 m^3) per development well.

The composition and discharge volumes of drilling mud for a typical exploratory well on Georges Bank is shown on Table 4-21. Since drilling muds from exploratory wells become "contaminated" with microfossils which are important in the analysis of the various stratigraphic units encountered, it is undesirable to recycle used mud to other exploratory wells. Drilling muds are therefore discharged after completion of exploratory drilling. Approximately 2.20 x 10^7 kg (24,204 t) are expected to be discharged during the exploratory phase (BLM 1977).

During the development phase, drilling muds can be recycled to other wells. In estimating the volume of mud discharged during the development phase, it is assumed that 246 t of the 328 t of mud used in each 3,050-m well is lost either to retention in the well bore, by adhesion to discharged drill cuttings, or for other required discharges to adjust the mud system. One complete jettison of approximately 328 t drilling mud per platform would also occur at the end of drilling from the platform. As stated earlier, the expected development phase activity ranges from 150 wells from 11 platforms up to 420 wells from



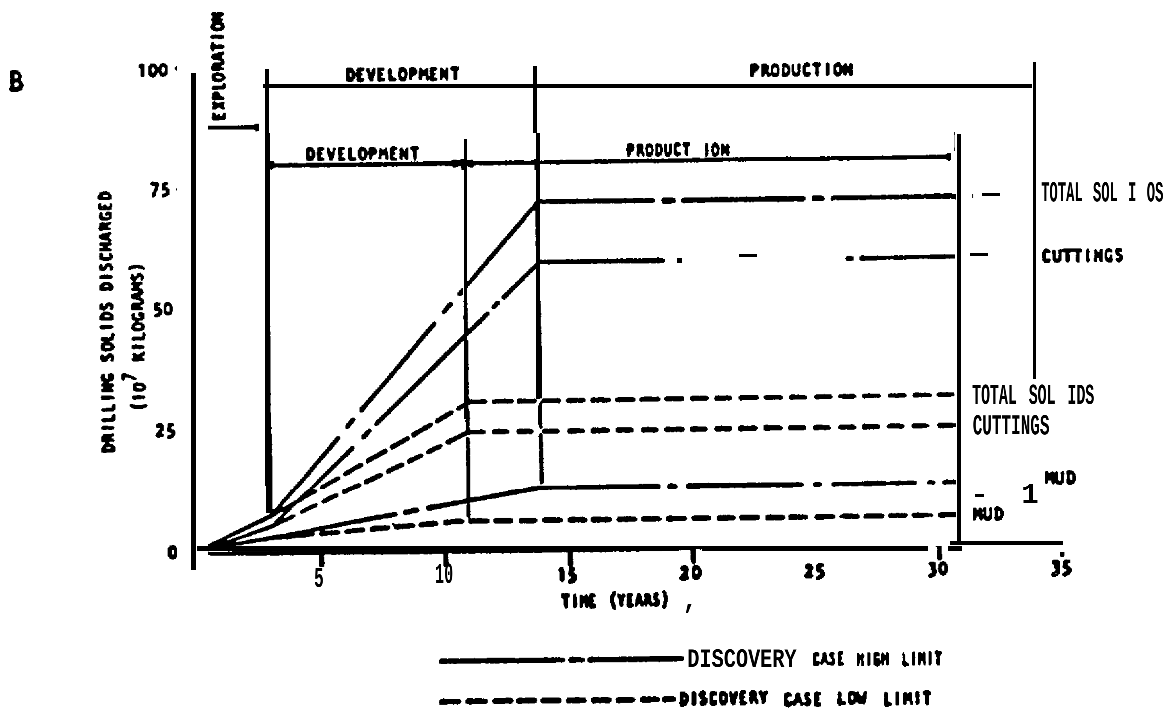


FIGURE 4-30 PROBABLE FIELD DEVELOPMENT SCENARIO AND CUMULATIVE DRILLING SOLIDS DISCHARGED FOR GEORGES BANK (AFTER BLM 1977)

TABLE 4-20

TOTAL DRILL CUTTINGS PRODUCTION

Phase	Low Limit[a,b] Volume (bbl)	Low Limit[a,b] Weight (t)	High Limit(c) Volume (bbl)	High Limit(c) Weight (t)
Exploration	151,550 (24,080 m^3)	61,565 (5.60 x 10^7 kg)	151,550 (24,080 m^3)	61,565 (5.60 X 10^7 kg)
Development	511,950 (81,400 m^3)	216,600 (1.97 x 10^8 kg)	1,433,460 (227,900 m^3)	606,480 (5.50 x 10^8 kg)
Production	--	--	--	--
Totals	663,500 (105,474 m^3)	272,105 (2.53 x 10^8 kg)	1,585,010 (251,982 m^3)	668,045 (6.06 x 10^8 kg)

(a) Discovery case low limit: 35 exploratory wells at 15,000 ft and 140 development wells at 10,000 ft.
(b) No discovery case: $\leq$35 exploratory wells at 15,000 ft and no development wells. In this case, the total cuttings production is likely to be less than 119,455 barrels.
(c) Discovery case high limit: 35 exploratory wells at 15,000 ft and 420 development wells at 10,000 ft.
Source: BLM 1977.

TABLE 4-21

GEORGES BANK EXPLORATORY PHASE MUD DISCHARGE[a]

Components	Weight Per Well (t)	Total Weight (t)
Barium sulfate (barite)	580	20,300
Clay[b]	37	1,313
Caustic	22	770
Ferrochrome lignosulfonate	48	1,663
Other(c)	5	158
Total	692 t (6.28 x 10^5 kg)	24,204 t (2.20 X 10^7 kg)

(a) assumptions: 35 exploratory wells.penetrating to 15,000 ft; approximately 692 tons of drilling mud used per well, all mud lost or discharged.
(b) Approximate clay constituents: 32.5 t bentonite, 5 t attipulgite per well.
(c) Other components include aromatic detergents, organic polymers, and sodium chromate.
Source: BLM 1977.

11 platforms up to 420 wells from 28 platforms. Table 4-22 presents the drilling mud components and total discharge volumes expected for the of development phase activity. Approximately 3.67 x 10^7 kg (40,446 t) to 1.02 X 10^8 kg (112,333 t) of drilling mud is expected to be discharged during this phase (BLM 1977).

TABLE 4-22

GEORGES BANK DEVELOPMENT PHASE MUD DISCHARGE(a)

Components	Per Well (t)	Low Limit Weight(b) (t)	High Limit Weight(c) (t)
Barium sulfate (barite)	200	33,036	91,753
Clay(d)	25	4,076	11,319
Caustic	8	1,297	3,602
Ferrochrome lignosulfonate	10	1,606	4,459
Other(e)	3	432	1,201
Total	246 t (2.05 x 10^5 kg)	40,446 t (3.67 X 10^7 kg)	112,333 t (1.02 X 10^8 kg)

(a) Assumptions: 10,000 ft well depth; approximately 328 t mud used per well, approximately 246 t mud lost per well; one complete mud jettison per platform (approximately 328 t).
(b) Low development unit: 150 wells, 11 platforms.
(c) High development unit: 420 wells, 28 platforms.
(d) Approximate clay constituents: 28 t bentonite, 5 t attapulgite per well.
(e) Other components include aromatic detergents, organic polymers, and sodium chromate.
Source: BLM 1977.

Figure 4-30B summarizes the expected drill cuttings and mud discharge estimates over the life of the Georges Bank field. Cumulative discharge components (cuttings and mud) as well as total discharges are presented for the expected range of drilling activity on Georges Bank. Between 3.1 x 10^8 kg (336,815 t) and 7.3 x 10^8 kg (804,582 t) of drilling mud and cuttings are expected to be released into the marine environment (BLM 1977).

4.3 IMPACTS ON THE PELAGIC ENVIRONMENT

4.3.1 Short-Term Fate of Fluids

Initial dilution and dispersion of the upper plume of drilling fluids (including liquids and finer particulate) discharged on Georges Bank would follow the pattern described in Section 2.5.1 for a moderate-energy environment. Rapid Initial dilution rates of 500 to 1000:1 would be expected within a few meters of the downpipe, with dilutions of

10,000:1 occurring within 100 to 200 meters. Typical high-volume and high-rate whole mud discharges (containing 250,000 mg/l solids) would be diluted within 100 m down current of the discharge to concentrations of about 100 mg/l whole mud containing some 25 mg/l of suspended particulate. At a nominal surface current of 30 cm/see, this dilution would be reached in about 6 min on Georges Bank. Beyond 100 m, the concentrations would continue to decrease but not as rapidly as' during the initial mixing nearer the discharge (Section 2.5.1). This current regime would allow continued settling of increasingly finer particulate from the upper plume.

Routine discharges from the shale shakers are near continuous during drilling and occur at considerably lower discharge rates and volumes than described above for bulk mud discharges. Typically the concentrations of suspended solids at the discharge point are on the order of 100 to 1,000 mg/l.

Liquid components of drilling fluids consist of the water fraction of the drilling muds (typically 75 percent of mud by volume) and perhaps some formation water. Large volumes of flushing water are usually flowing from the downpipe as well (Table 2-8). These liquid components would undergo the same general dispersion characteristics as would the fine particulate fractions. It is anticipated that the liquid components would become well mixed in the water column within a *few* hours of discharge.

Monitoring studies for the drilling of a stratigraphic test well, C.O.S.T. Atlantic G-1 in the Georges Bank area (ENDECO 1976) confirmed this rapid dilution. Suspended solids in seawater samples showed little indication of the subsurface discharge of mud and cuttings. The suspended solids concentrations ranged from 0.1 to 5.8 mg/l at 100 m from the discharge. Location of the upper plume down-current proved to be very difficult (ENDECO 1976).

At 2,000 m from the discharge, barium would likely be the only trace metal detectable; increases in suspended sediment concentrations would be limited to less than 5 mg/l (Section 2.5.1). At distances of 1 to 2 km, increases in any trace metal level would not be detectable using conventional sampling and analytical techniques; effects of the plume on turbidity would likewise be difficult to detect.

4.3.2 Ultimate Fate

Currents and ambient and/or induced turbulence on Georges Bank would tend to maintain micron-sized and smaller clay particles in suspension long enough for transport off the bank by one or several of the pathways described in Section 4.4.1.4 and Figure 4-8. Larger individual particles from the drilling effluents or flocculated particles may settle over a wide area, both on and off the bank, from which they would ultimately be resuspended and transported by the near-bottom processes described in Section 4.4.1.5 and Figure 4-9. Liquids in the drilling effluents would be diluted to obscurity within a few kilometers *of* the *rig* and would be ultimately lost in the water masses on the bank and through interactions with adjacent masses.

It has been hypothesized that drilling fluids could ultimately be concentrated within the Georges Bank gyre. The gyre is assumed to encompass that area of the bank above the 60-m contour or a surface area of some 5,700 km^2 (1.57×10^{10} m^2). Assuming the average depth above the 60-m contour to be 30 m, the volume of water overlying the bank becomes 4.71×10^{11} m^3. If the total volume of mud solids produced in an average yr of about 1.1×10^7 kg is assumed to be entrained and evenly mixed in the gyre, the concentration would be 0.023 mg/l (ppm) mud solids . Using the proportions given in Table 4-24 (Section 4.4.1), the total barium concentration would be about 0.01 mg/l, chromium would be about 0.00004 mg/l, or about 40 parts per trillion. These concentrations are comparable to or well below natural background concentrations of soluble barium and chromium in seawater (0.050 and 0.001 mg/l, respectively) . Zinc would be about one-third the chromium level and all other metals would be an order of magnitude lower than chromium.

4.3.3 Biological Effects

During bulk discharges from drilling rigs on Georges Bank, species actively swimming to maintain themselves within the plume a few meters from the downpipe could experience whole mud concentrations exceeding measured 96-hr LC_{50} values for many species. The likelihood of significant numbers of nektonic organisms remaining in this area long enough to suffer mortalities or other irreversible stress would be remote because of the duration of exposure (15 min to 3 hr maximum), the limited size of the near-field discharge area, and the intermittent nature of the high-volume discharges.

In the zone between a few meters and 100 m from the discharge, concentrations exceeding measured 96-hour LC_{50} values for the most sensitive species and the most toxic muds tested to date (Section 2.3.1) could be experienced infrequently, again for up to about 3 hr (once per well), by active swimmers choosing to maintain themselves in the plume. The likelihood of this occurring is less remote (but still low) given the known tendencies of fish to congregate around offshore rigs and the moderate current regime in Georges Bank waters, The limited duration and frequency of these high volume discharges would again make the likelihood of significant mortalities or stress extremely remote. Beyond 100 m from a bulk discharge, although concentrations will not drop as rapidly, they will be further reduced below 96-hour LC_{50} values for any tests reported to date. Thus, no acute effects are likely in this region.

Routine, near-continuous discharges (from the shale shakers) during drilling are of much lower rates and volumes than those described above. Because of the volume of flushing water entering the system's various components, concentration of suspended solids at exit of the downpipe are on the order of 100 to 1,000 ppm. Thus, organisms remaining within a few meters of the discharge during routine, near-continuous discharges (from the shale shakers) could receive a long-term exposure to concentrations of mud-contained toxicants that exceed those found to be lethal to the most sensitive organisms bioassayed to date (Section 2.3.1). However, relatively few, if any, nektonic organisms are likely to remain in this near-field dilution zone long enough to experience a lethal dose from continuous discharges occasionally interspersed with higher volume discharges. Since Georges Bank has relatively moderate currents, fish congregating around a drilling rig could experience some degree of sublethal stress unless they actively avoid the plume. In any case, only a negligible fraction of the population of any given species on the bank would be at risk to such sublethal stresses.

Planktonic organisms would receive a maximum exposure to drilling effluents if entrained in the plume at the downpipe during a bulk discharge. Dilution to about 100 ppm whole mud would occur over a period of about 7 to 9 min in the 25- to 35-cm/sec currents common near the surface on Georges Bank. It is possible that the high initial concentration could cause some mortalities of crustacean plankton, including shrimp and crab larvae, if they entered the plume at a highly sensitive stage of ecdysis (molting). No bioassay data are available on drilling fluid effects on ichthyoplankton, a key life history stage of many important species on Georges Bank. However, their sensitivities are likely to be no greater than those of crustacean larvae and their exposure would be similarly brief. The percentage of any plankton populations potentially affected would be negligible because of the narrow width and depth of the discharge plume and the brief duration and low frequency of mud dumps of this volume at any well.

Significant bioaccumulation of heavy metals in planktonic or nektonic organisms is not expected due to their high mobility (in the case of plankton this mobility is at the mercy of ambient currents) and the nature and duration of the discharges. The lone exception may be found in populations of fish that are attracted to and remain in the vicinity of the drilling vessel for a period of several weeks or months. Fish may browse or otherwise feed on rig-fouling organisms that may contain elevated levels of some metals. These fish therefore could experience some increase in tissue levels of heavy metals (e.g., Tillery and Thomas 1980), although uptake of heavy metals from drilling fluids by fish has not been documented in the literature (Section 2.3.4)s The significance of increases in body burden of heavy metals to the organism is poorly understood but is specific to the metal(s) in question.

In summary, based on all available information, it appears that the likelihood of significant Impacts on pelagic plankton and nekton from drilling mud and cuttings discharges on Georges Bank is remote both during the exploration and production phases. During long-term transport of materials from the bank (Section 4.4.3) some drilling muds and finely ground cuttings may be resuspended into the water column by unusual current regimes. However, concentrations within the water column at any given time would be very small and of no biological significance to pelagic organisms.

4.4 IMPACTS ON THE BENTHIC ENVIRONMENT

4.4.1 Initial Deposition

As discussed in Section 2.1, the initial portion of each hole drilled to set the casing for the well does not involve use of drilling muds, and the cuttings are deposited directly on the seafloor. These solids are likely to consist of coarser fractions since they are from near the surface and do not remain in the well bore long enough to be ground into smaller particles. About 187 bbl or about 30 m^3 of these coarse cuttings will be deposited directly on the bottom without benefit of water column dispersal. Deposition from this phase of drilling is independent of water depth and probably contributes substantially to cuttings piles observed in the immediate area of a well.

Typical average tidal current speeds range from 25 to 35 cm/sec in the general vicinity of the Georges Bank leases (see Figure 4-7, Station A) and are greater in the shallower areas of the bank. Short-term conditions can result in higher current magnitude ranges. Values of from 41 to 170 cm/sec were recorded on Georges Bank (ENDECO 1976). These currents can transport the coarse fractions of the solids plume released near the sea surface short distances from the discharge point, depending on water depth and particle size.

Lease blocks on the southern flank of Georges Bank range in depth from about 36 to 210 m, across which the dispersion of discharged solids will vary primarily with water depth and hydrodynamic conditions. The short-term or near-field physical fate of discharged solids is discussed in Section 2.2.1.5 and 2.5.2. The initial deposition of various particle sizes on the bottom in 110 m of water is shown as an idealized series of concentric elipses in Figure 2-3. From shallow water (36 to 60 m) to deep water (210 m) encompassing the range of depths in the Georges Bank lease blocks, the area of initial deposition of cuttings would increase by a factor of 7 to 10, largely as a result of the increased trajectory provided by increased water depth. Large gravel-size cuttings (>10 mm) could be deposited over an area of 0.002 to 0.022 km^2 (at 60- and 210-m depths, respectively Table 4-23). Medium gravel-size cuttings (10-2 mm) could be deposited over an area of 0.03 to 0.27 km^2, and fine gravel to medium sand particles (2 mm - 250 μ) over an area of 1.86 to 17.59 km^2. Fine sand and smaller particles (<250 μ) would be deposited over a much larger area. Obviously the accumulation per unit area would decrease by the same factor that the total area affected increases.

Review of the lease block locations shows about 85 percent lie in the 60- to 100-m depth range. The average depth of drilling on Georges Bank is expected to be about 85 m with initial exploratory wells planned for 70, 75, and 119 m of water (E.P. Danenberger, personal communicate on).

While the average volume of cuttings produced in wells on Georges Bank is expected to be closer to 300 m^3, as stated in Section 2.5., the impact discussions for Georges Bank have assumed the higher values (690 m^3 and 543 m^3 for exploratory and production wells, respectively) provided by BLM (1977).

It is anticipated that about 6.3 x 10^5 kg of drilling mud will be used in the drilling of a typical exploratory well on Georges Bank; mud components are described in Table 4-21. The relative amounts of mud components vary widely as described in Section 2.1, as do the concentrations of chemical constituents. To develop a perspective on concentration of metals that could contaminate bottom sediments following

TABLE 4-23

BOTTOM AREA[a] AND BENTHIC INVERTEBRATE BIOMASS[b] POTENTIALLY AFFECTED BY DEPOSITION OF DRILLED SOLIDS FOR A RANGE OF WATER DEPTHS AND CURRENT SPEEDS

Depth (m)	Current Speed (cm/see)	>10 mm Area (m^2)	>10 mm Biomass (kg)	10-2 mm Area (m^2)	10-2 mm Biomass (kg)	2 mm - 250 Area (m^2)	2 mm - 250 Biomass (kg)
36	50-75	3,098	7,946	38,692	99,245	2,474,004	6,345,820
60	25-40	2,328	1,392	29,066	17,381	1,858,252	1,111,235
110	25-35	5,498	583	68,722	7,285	4,398,230	466,212
210	25-35	21,991	374	274,889	4,673	17,592,919	299,080

(a) Based on extrapolation from Figure 2-3.
(b) Based on extrapolation from Figure 4-17; see Section 4.4.5.1.

discharge of muds to the ocean, it is necessary to estimate the amounts of these metals in the mud system to be used on the bank. Data of this sort are limited and are not directly available for Georges Bank. However, the total amount of barium can be determined from Table 4-21 as 58 percent of barite ($BaSO_4$) or 305,175 kg. It was assumed that the amounts of other metals would occur in proportion to barium as described for the mud system used in drilling the exploratory well in the Baltimore Canyon area (Ayers et al. 1980a). The resulting metals composition is shown in Table 4-24. While the amount of metals that could be discharged during a typical drilling operation is large, tremendous dilution occurs as muds are dispersed over a large area. The areas and concentrations presented in Tables 4-23 and 4-24 assume a radially symmetrical deposition pattern. In reality, the majority of deposition is along major current axes. Thus, areas affected would likely be one-half to one-quarter those shown and theoretical concentrations two to four times greater than shown.

Barite particles occur in the 10- to 40- range and are much smaller than the smallest particles (250 μ) whose dispersion and deposition were conceptually modeled above (Figure 2-3 and Table 4-23). These particles (≥ 250P), accounting for much of the total mud solids, all of the barium, and much of the other heavy metals, would be initially deposited well beyond 1,000 to 1,400 m from a well drilled in 110 m of water. Finer particles were not modeled as their behavior is far more complex (e.g. settling time would exceed several tidal cycles and be complicated by flocculation).

TABLE 4-24

INCREMENTAL CONCENTRATION OF MUD SOLIDS AND METALS IN TOP 1 AND 5 CM OF BOTTOM SEDIMENTS WITHIN 2-MILE (3,218-m) RADIUS OF WELL COMPARED TO AMBIENT METALS CONCENTRATIONS(a)

Mud Component	Total Amount Discharged (kg)	Concentration (mg/kg)(b) 1 cm	5 cm	Ambient Concentration (mg/kg)(b)
Mud Solids	627,500	1,205	241	--
Ba	305,175	586	117	116 (<44 - 290)
Cr	964	1•9	0.4	7.2 (2.2 - 27)
Cd	<4	0.008	00002	1.3 (1.0 - 20
Pb	23	0.044	0.009	4.2 (1.4 - 96)
Hg	<4	0.008	0.002	--
Ni	39	0.08	0.02	2.4 (1.2 - 13)
V	41	0.08	0.02	11*5 (lo - 34)
Zn	332	0.6	0*1	5.2 (1.2 - 50)

(a) Even spreading within, and zero transport beyond, 3,218 m is assumed.
(b) Data from ERCO 1980: median and range for totally digested samples from Stations 9, 12, 13, 18, 20, 21, 23, 25, 26, 28, and 29 in general vicinity of lease area.

It is conservatively assumed that in the near-term a worst case condition would be approximated by the mixing of all discharged muds and associated metals from a drilling operation in a thin upper layer (1 CM) of bottom sediments within a 3,200-an radius of the well. A longer-term situation would be approximated by the incorporation of these materials into a deeper layer (5 cm) of sediments. The resultant concentrations of drilling fluids components are given in Table 4-24 along with median background concentrations for the lease area. Except for total mud solids and barium, the incremental increases would be one to two orders of magnitude below ambient concentrations and indistinguishable from natural background levels despite the conservatism of the assumptions made.

The discharge and uniform mixing of all drilling muds into a l-cm thick layer of sediments within a 3,200-m radius of a well would result in a concentration of 1,205 mg mud/kg sediment; alternatively, mud would comprise about 0.12 percent of the top 1 cm of sediment (Table 4-24). If the mud fraction remained localized for a longer period of time and was worked into the top 5 cm, a concentration of 241 mg mud/kg sediment would result (0.02 percent mud), This increment of fine particulate mud (barite occurs primarily in particles of 10 to 40μ) can be placed in perspective by comparison with the percent weight of similar or smaller size fractions (Phi 4 or smaller assumed) in natural sediments within the lease area. Sediment data for stations listed in Table 4-11 were extracted from Hathaway (1971). These data are summarized as frequency histograms of the number of stations at which sediments contained various percentages of fine particles (Figure 4-31). An average of 3.7 percent fines (arc sine transformation was used) occurs in the lease area at 30- to 60-m depths. This fraction increased very slightly (X = 5.3 percent) at 61- to 100-m depths. Beyond 100 m the fine fractions comprised a significant proportion of natural sediments (101 to 200 m: $\bar{X}$ = 11.8 percent; 201+ m: $\bar{X}$ = 25.5 percent). Thus, in shallow water (30 to 60 m) natural fine particulate occur in an average concentration of 37,000 mg/kg. Assuming worst case conditions, an increment of 1,205 mg/kg of drilling mud would raise the concentration to 38,205 mg/kg or increase fine particulate to 38 percent. At increasingly greater depths the relative increase in fines would be progressively less.

In summary, the percent weight of fine particles in natural sediments can be taken as a measure of the likelihood of drilling muds remaining in the area of a well after deposition (Figure 4-31). The very small percentages of fines from 30- to 100-m depths suggest that deposited drilling muds would remain in the vicinity of initial deposition a very short period of time. In contrast, drilling muds deposited on the bottom in depths over 100 m would probably have a significantly greater residence time near a well. These conclusion are substantiated by the results of sediment mobility studies on Georges Bank (Section 4.1.1.5).

Background sediment concentrations of barium in the lease area ranged from <44 to 290 mg/kg (ERCO 1978), with a median concentration of 116 mg/kg. No obvious relationship between barium and depth was apparent. In the hypothetical depositon model (l-cm mixing) an increment of 586 mg/kg of barium would be added to background levels, resulting in a median concentration of 702 mg/kg (range 630 to 876 mg/kg). Increments for all other metals listed in Table 4-24 when added to background median values for the lease area would be well within the range of values observed. In the hypothetical case of mixing in the top 5 cm as might occur in the long term, incremental contributions to background concentrations would be reduced by 80 percent. Of the metals discharged in drilling mud, only barium would be detectable at these levels. The same processes that rapidly disperse finer mud particles from sediments above 100 m will also disperse the metals associated with those metals.

Results of monitoring drilling fluid discharges at the C.O.S.T. well Atlantic G-1 in 48 m of water on Georges Bank (ENDECo 1976) confirm that drilling mud and associated metals rapidly disperse in shallow water (Section 2.2.2). However, the results of the Baltimore Canyon (mid-Atlantic) study (Mariani et al. 1980) suggest a much wider influence on the benthic environment in the direction of prevailing currents (Section 2.2.2)* Much of the increased area of influence can be attributed to the increased dispersion afforded by greater water depth (120 m). However, lower currents and increased water depth would also have resulted in a lower rate of transport of muds and associated metals following initial deposition.

Since the mid-Atlantic study leaves open the possibility that effects could have extended 3,200 m or more from the well, the conservative approach requires the assumption that drilling effluents could have

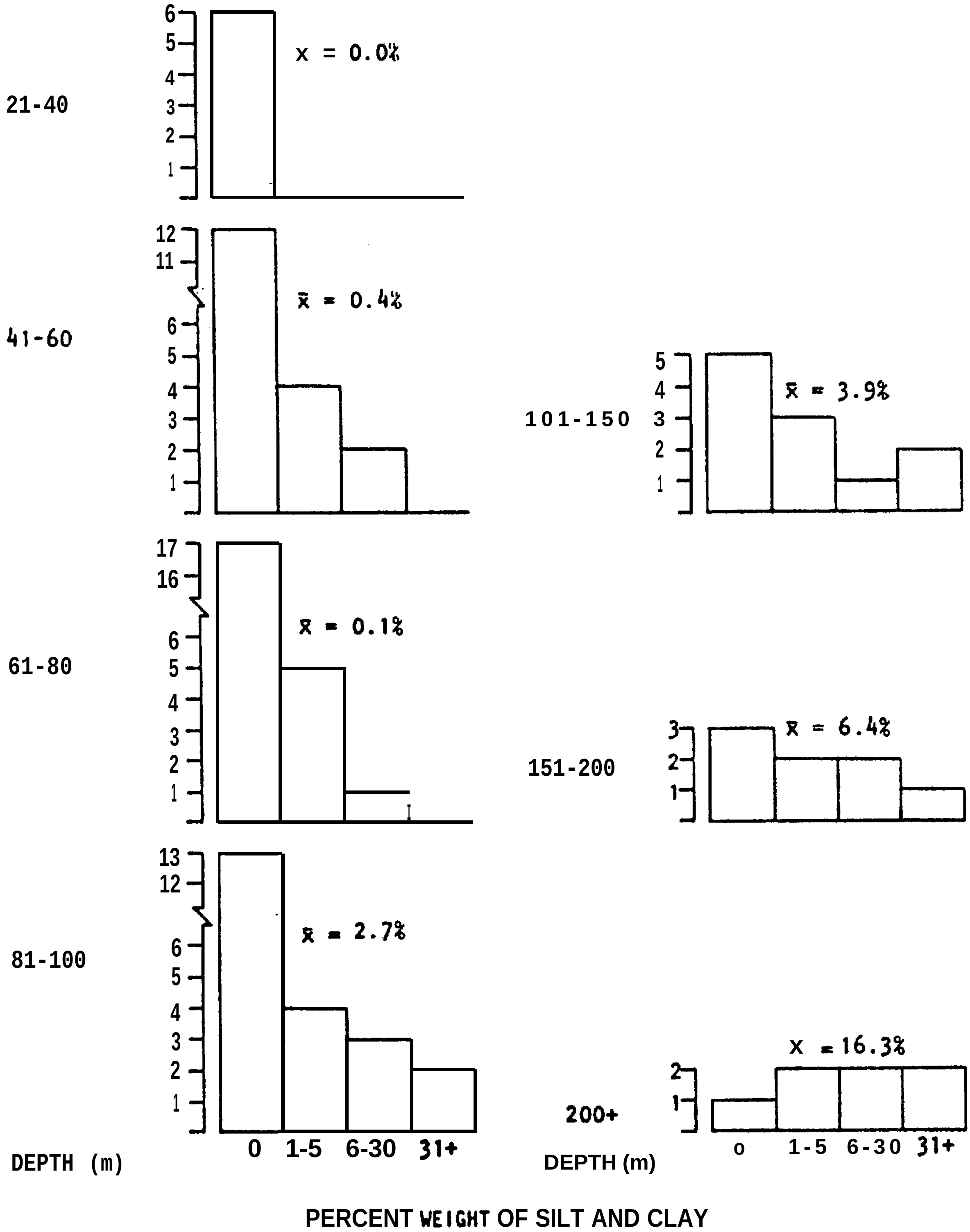


FIGURE 4-31 FREQUENCY OF OCCURRENCE OF NATURAL FINE SEDIMENTS ON THE SOUTHERN FLANK OF GEORGES BANK

affected the benthic environment to at least that distance. Results of a l-yr postdrilling survey are not yet available as a basis for assessing whether elevated concentrations of metals and clay persist. The worst case hypothetical model of muds deposition out to 3,200 m (Table 4-24) only coincidently agrees with one possible conclusion of the possible influence of drilling muds in the Baltimore Canyon example. Wells drilled in deeper water (say 200 m) could affect the benthic environment over a still larger area. However, the potential for adverse effects is reduced as drilling fluids are diluted through dispersion over the larger area.

4.4.2 Resuspension and Transport

It is unlikely that cuttings or mud solids initially deposited on the seafloor of Georges Bank will remain there in readily detectable quantities. Tidal currents can easily resuspend almost all of the solids fractions discharged during drilling. Circulatory patterns on Georges Bank are capable of transporting resuspended material and fluids to points where they can be carried off the bank into the Gulf of Maine or onto the continental shelf. Moreover, physical and biogenic processes will act to reduce the sizes of larger particles, especially mud cake. Flocculation of finer materials will have the reverse effect, increasing particle size and reducing transportability. Working of cuttings into the sediments by near-bottom currents and through biogenic activity, while not expected to occur to the extent seen in lower Cook Inlet (Section 3.3), will also greatly reduce the transportability of particles.

Critical water velocities necessary to initiate sediment motion of the unconsolidated, initially-deposited materials without the "surface armoring" effect of bottom benthic community are shown in Table 4-25. Three separate zones of initial sediment deposition are classified depending on ranges of water depth and typical tidal current strength. These zones coincide with those classified by Butman (1980) in his discussion of reworking of existing bottom sediments in the lease areas on the southern flank of Georges Bank. The critical velocities show a general decreasing trend with decreasing particle grain size. However, an increase in critical velocity is noted for particle sizes ranging from 250 μ to 74μ. Within this particular range of grain sizes, decreasing grain size results in increasing degree of cohesiveness, raising the critical water velocity required to initiate sediment motion.

Most classes of solids fractions, except coarse materials, can potentially be reworked periodically by bottom tidal currents in depths shallower than 60 m. It is likely that initially-deposited medium- to intermediate-sized sediments are susceptible to motion by bottom tidal currents in the depth range from 60 to 100 m. Under storm conditions, a fraction of intermediate to coarse materials, can be resuspended in these depth ranges. In water depths greater than 100 m, bottom tidal currents are weak and unable to resuspend post classes of sediments. However, under storm conditions, fractions of medium- to intermediate-sized material including all but the coarsest cuttings can potentially be mobilized.

TABLE 4-25

CRITICAL VELOCITIES FOR THE INITIATION OF SEDIMENT MOTION AND SUSCEPTIBILITY TO MOTION IN THE GEORGES BANK AREA

			Susceptibility to Motion Under the Influence of:[(a,b)]					
		Critical[(c)] Velocity	Normal Bottom Tidal Currents/Depth Range (m)			Storm Wave Currents Superimposing on Bottom Tidal Currents/Depth Range (m)		
Sediment Classification	Grain Size	(cm/sec)	50-60 m	60-100 m	>100 m	50-60 m	60-100 m	>100 m
Coarse (fine-medium gravel)	10 mm	90 - 135	B	A	A	B-c	B	B
	2mm	20 - 55	C-D	A-B	A	D-E	B-C$^-$	B
Intermediate (medium sand-fine gravel)	250 μ	15 - 25	E	c	B-C$^-$	E$^+$	C-D	c
medium (coarse silt-medium sand)	74 μ	17- 31	D-E	B-C$^-$	A-B	E	c	B-c

(a) The susceptibility to motion is considered for unconsolidated, initially-deposited sediments with the least effect of bottom benthic community on reduction of sediment erodibility. The relative ratings are: A = Extremely Low, B = Low, C = Medium, D = High, and E = Very High.

(b) The susceptibility to motion under the influence of storm events is developed with data provided by the discussion on low-frequency currents in the "Mean Circulation on Georges Bank," Butman et al. (1980).

(c) Source: Vanconi 1975.

4.4.3 Potential Pathways of Drilling Discharges

This section discusses the potential pathways and points to exit of drilling fluids from Georges Bank. Near-surface and subsurface flow systems in the area of the bank were described in Section 4.1.1.4. The present discussion considers the potential behavior of drilling fluids introduced into the Georges Bank circulation and transport system at various depths and locations to establish a basis for assessing the ultimate physical and biological fates and effects of these fluids.

Discharges of drilling fluids in locations with water depths less than 60 m may result in particles being trapped in the Georges Bank gyre system for a time period as long as the circuit time around the bank, estimated to be about 2 months around the 60-In isobath. In depths shallower than 60 m, the residence time may be longer than 2 months. The results of a simple diffusion model (Butman et al. 1980), based on small low-frequency current variability observed over the shallower region of the bank, has suggested a residence time of 2 to 3 months during the summer and perhaps less than 1 month during the winter. While a more sophisticated model may be required for a better estimate of the residence time in different regions of the bank, these results may reflect the relative time periods that the discharged materials can be retained in the shallower region of the bank in different seasons of the year. On the southern flank, subsurface flows in intermediate water depths of about 80 to 100 m are mainly isobath-parallel in all seasons, and the northward to northeastward flow is believed to be a permanent subsurface feature on the eastern side of Great South Channel (Butman et al. 1980). This leaves the northern flank and northeastern corner as the probable exits of water circulating around the 60-m isobath and the crest of the bank (Figures 4-8 and 4-9). The fluctuations of the northeastward flowing jet axis on the steep northern flank can deviate the flow path out of the shallow waters into the deeper water off the slope, resulting in flow directed toward the Gulf of Maine area.

Drilling fluids produced by wells drilled in water depths from 60 to 100 m may cross the Great South Channel. Butman et al. (1980) estimate that about 70 percent of the flow along the southern flank of Georges Bank crosses the channel, whereas 30 percent or less turns northward following the Georges Bank system. Flows remaining in the Georges Bank circulation system may, at a certain point, exit out of the system at the locations described above, the Gulf of Maine being one possible area of ultimate deposition. However, as a substantial amount of flow is estimated to cross the Great South Channel, westerly transport of drilling fluids along the shelf toward the mid-Atlantic seems to be the more likely pathway.

In water depths greater than 100 m, mean current magnitudes are typically smaller than those occurring in shallower water. These areas are in the close proximity of the shelf/slope break and the Georges Bank canyons where slope water circulation can have a strong influence on the flow dynamics. It is likely that in this depth range, drilling fluids will follow the slope transport system in the direction of the canyons and deeper ocean waters.

4.4.4 Hypathetical Deposition Scenarios

In the following section, several hypothetical scenarios are developed to explore the upper limits of disturbance that could occur from drilling fluid and cuttings discharges reaching several potentially sensitive areas. The areas considered include major depositional areas where available data (Section 4.1.1) suggest drilling discharges may come to rest, as well as potential transport routes that may be particularly sensitive. Several assumptions in the following scenarios, while they are grossly conservative, have been made to compensate for our inability to confidently defend logical refinements. For example, since we do not know how many wells will be drilled on Georges Bank, we have assumed the high estimate from the BLM (1977). Since we cannot determine what fraction of drilling fluids and cuttings produced will not be transported to the Gulf of Maine, we have assumed that all are. In turn, we have assumed that all are transported to the Mud Patch on the continental shelf to the south, or transported to the nearby canyons.

4.4.4.1 The Gulf of Maine

In the Gulf of Maine, Meade (1972) suggests that relict sediment is the principal source of suspended matter. When the last ice sheet withdrew from the Gulf of Maine it left a topographically irregular area of the shelf covered with a poorly sorted mixture of particle sizes that ranged from boulders to clay. As the sea refilled the area, the fine-grained fraction of this material was winnowed from the elevated areas of the bottom and redeposited in the basins. The resulting pattern of distribution of bottom sediments now shows gravels on top of the ridges and ledges, muds in the bottom of the basins, and poorly sorted mud-sand-gravel mixtures (the basically unchanged glacial deposit) at intermediate depths.

Suspended matter is distributed as normally low concentrations of mostly organic material in waters near the surface, and several times greater concentrations of predominantly (about 90 percent) inorganic material in the water near the basin floors (Spencer and Sachs 1970). Meade (1972) postulates that the near-bottom material Is resuspended bottom sediment. Its essential lack of relation to modern river inputs is shown by the large quantity in suspension. Spencer and Sachs (1970) calculated that the total amount of inorganic suspended matter in the Gulf of Maine is about 37 million mt, more than half of which is suspended in the near-bottom waters of the deep basins. This total is about an order of magnitude greater than the annual contribution of sediment by the rivers tributary to the Gulf (Meade 1972).

The Gulf of Maine has two deep basin's (>200 m depth): the Wilkinson Basin in the southwestern gulf and the Jordan Basin in the northeastern gulf (Figure 4-l). These basins have approximate areas of 8,800 and 9,300 km^2, respectively.

Conceptual Deposition Model

Potential transport pathways from Georges Bank into the Gulf of Maine have been described above. In general, drilling effluents are likely to enter the Gulf in the vicinity of the Greater South Channel and along the northern flank of Georges Bank (Figures 4-8 and 4-9). Drilling effluents would then come under the influence of the Gulf of Maine mean circulation pattern which would carry them toward the northeast along a counter-clockwise flow path (Figure 4-3).

A worst case conceptual depositional model assumes that the entire volume of drilling produced solids (mud and cuttings) for all exploratory and developmental wells eventually finds its way into the Gulf of Maine and is deposited in a single deep basin. The Wilkinson Basin is a likely choice for ultimate deposition of some of these materials due to its proximity to Georges Bank and the potential flow exit points near the Great South Channel "and along the northern flank of Georges Bank. Using the high range of drilling activity for exploratory and development well drilling, an estimated 7.3 x 10^8 kg of cuttings and drilling mud would be discharged over an 11- to 14-yr period. If all this material were to be transported into, and spread evenly over, the Wilkinson Basin, the estimated thickness of the deposited drilling solids would be on the order of 83 μ. For reference, colloidal bentonite particles are typically 2μ or less. The deposited sediment thickness would therefore be roughly equivalent to 40 to 50 colloidal particles in thickness. This would amount to about 0.08 kg/m^2 of mud (17 percent of total by weight) and cuttings (83 percent).

Physical Effects of Deposition

Under the worst case deposition model for Wilkinson Basin, the total sediment layer thickness related to drilling discharges would be about 831-I . Assuming that the deposition would occur over a time period comparable to the period of discharge (11 to 14 yr), the expected annual rate of deposition would be 6.0 to 7.6μ/yr. This rate of deposition (equivalent to 0.6-0.8 cm/1,000 yr) is extremely Small even in geologic scales and would be undetectable for all practical purposes.

Although the Wilkinson Basin is deep (>200 m), resuspension of bottom sediments is apparently common. The total solids contribution from drilling (7.3 x 10^8 kg of cuttings and mud) if entirely in suspension would represent about 2 percent of the total suspended solids in the Gulf of Maine (3.7 x 10^{10} kg, Spencer and Sachs [19701). In contrast, the worst case annual drilling solids contributions would be an order of magnitude less than the river-borne contributions (Meade 1972).

A conservative resuspension model is useful in illustrating near-bottom water column effects should the drilling effluents reach the Wilkinson Basin. If the entire mass of drilling solids (7.3 x 10^8 kg) were to be resuspended Into a 5-cm thick layer on the floor of Wilkinson Basin, the average suspended solids contribution to that layer would be about 16 mg/l. This is comparable to the diluted plume concentrations (on the order of 25 mg/l) which are typically found about 100 m down current of bulk mud discharges.

Chemical Effects of Deposition

The most noticeable change in sediment chemistry is likely to be the elevation of the barium concentration at points of deposition. Barium is present as barium sulfate (barite)in drilling muds. Elemental barium comprises about 58 percent of barium sulfate by weight. Considering the typical drilling mud compositions estimated to be used on Georges Bank (Section 4.2), about 48 percent of the weight of the whole mud mixture will be barium.

A conservative model approach is again adopted to estimate the magnitude of barium concentration elevation in the affected sediments. The total high estimate amount (1.2×10^8 kg) of drilling mud is assumed to be uniformly deposited in Wilkinson Basin. The drilling muds are assumed to be reworked by ambient currents and biological activity so as to distribute the muds uniformly within the upper 5 cm of the natural bottom sediments. This would result in an incremental increase of about 82 mg Ba/kg sediments:

$$\left(\frac{1.2 \times 10^8 \text{ kg mud} \times 0.48 \text{ Ba} \times 10^6 \text{ mg/kg}}{8.8 \times 10^9 \text{ m}^2 \times 80 \text{ kg sediments/m}^2 \text{ (Q 5 cm deep)}} = 81.8 \text{ mg/kg}\right).$$

Typical barium concentrations in near-shore sediments average 750 mg/kg while ocean bottom sediments average 2,200 mg/kg of barium (Hatcher and Segar 1976). However, sediment barium concentrations for the southern Gulf of Maine (Table 4-26) measured during the BLM Georges Bank benchmark studies ranged from <37 to 500 mg/kg (ERCO 1978). This range is based on only two data pointsfrom stations located in water depths of <100 m and are probably not representative of Wilkinson Basin where higher concentrations of 750 mg/kg seems to be a more reasonable estimate. An 82 mg/kg increment would increase surficial barium levels to 832 mg/kg or about an 11 percent increase over ambient. A more realistic deeper mixing of surficial sediments (e.g., 20 to 25 cm [Bothner et al. in press] vs. 5 cm) would proportionately reduce these worst cast values. If the level of geographic and seasonal variation measured on Georges Bank (ERCO 1978) also applies to Wilkinson Basin, then an 82 mg/kg increment of barium would be difficult to detect.

Similar calculations for chromium and zinc, two of the more abundant metals in drilling mud, indicate tht increases of 0.3 and 0.09 mg/kg, respectively, would occur. Comparison of these values to ambient median values of 15 and 16 mg/kg for chromium and zinc, respectively, show that the incremental input from drilling would not be detectable against background variation. This also holds for other metals present in far smaller quantities in muds.

4.4.4.2 The Southern New England Continental Shelf (The Mud Patch)

Effluents originating at drilling sites on Georges Bank having water depths in the 60- to 100-m depth range are likely to be transported along the continental shelf. As discussed earlier, an estimated 70 percent of the flow along the southern flank of Georges Bank crosses the Great South Channel and continues along the continental shelf. The net current drift on the middle and outer continental shelf in the vicinity of Georges Bank is to the southwest (Bumpus 1976). Suspended material from this area of Georges Bank would therefore be transported along the continental shelf in that direction.

TABLE 4-26

COMPARISON OF AMBIENT AND WORST CASE INCREMENTAL METALS CONCENTRATIONS FOR THREE HYPOTHESIZED DEPOSITIONAL AREAS

Metal	Total Metal Discharged (kg)	Metal Concentration (mg/kg)					
		Wilkinson Basin		Mud Patch		Gilbert Canyon	
		Ambient[a]	Increase	Ambient[b]	Increase	Ambient[c]	Increase
Barium	5.8×10^7	268 (<37-500)	82	288 (175-400)	55	116 (<44-290)	2,253
chromium	1.8×10^5	15 (11-20)	0.3	30 (24-36)	0.2	7.2 (2.2-27)	7.1
Zinc	6.3×10^4	16 (11-52)	0.09	30 (27-32)	0.06	5.2 (1.2-50)	2.5

(a) Data from ERCO 1978, Stations 40-42; data given are for median and range of totally digested samples.
(b) Data from ERCO 1978, Stations 6 and 7.
(b) Data from ERCO 1978, Stations 9, 12, 13, 18, 20, 21, 23, 25, 26, 28, and 29.

An anomalous deposit of fine-grained sediment known as the Mud Patch is located in the flow path from Georges Bank south of Martha's Vineyard in water depths between 60 and 150 m (Figure 4-21). Sandy in the literature. Some investigators (Garrison and McMaster 1966; Meade 1972, Milliman et al. 1972; Schlee 1973) have suggested that the feature is relict and was deposited shortly after the sea level transgressed onto the shelf about 10,000 years ago. Others cite evidence for a modern deposit (Emery and Uchupi 1972; Twichell et al. in press; Bothner et al. in press).

Bothner et al. (in press) indicate that ^{14}C ages of the sediment increase systematically with depth Up to a maximum age of 8,000 to 10,000 yr, suggesting a continuous depositional pattern. Estimated sedimentation rates have decreased from about 130 cm/1,000 yr when deposition began to about 25 cm/1,000 yr recently. Inventories of ^{210}Pb also show flux rates more than twice those expected from atmospheric and overlying water sources. Bothner et al. conclude that the deposit may be a modern sink for fine-grained sediments and is therefore a Potential sink for sediment-related contaminants such as the drilling effluents from Georges Bank. They note, however, that the Mud Patch may not be a permanent trap for all incoming sediments. A persistent nepheloid layer is present (Parmenter et al. 1979) and changes in the suspended matter concentrations in this layer (primarily associated with storms and the persistence of southwesterly bottom currents, Twichell et al. in press) imply that some material may be removed from this deposit at times. Based on studies of clay mineralogy in Long Island Sound sediments, Wakeland (1979) suggests that the Long Island Sound materials may have been eroded from the Mud Patch and transported into the sound. Also, some material may bypass the Mud Patch or be periodically resuspended and transported southwestward.

Conceptual Deposition Model

A simple but conservative conceptual model was devised to estimate the worst case effects of drilling effluent deposition at the Mud Patch. The deposition model assumes that the total amount of drilling-related solids is transported and deposited uniformly over the approximately 13,000-km^2 area of the Mud patch. Using the high estimate of drilling activity, an estimated 7.3 x 108 kg of cuttings and drilling mud would be discharged over an 11- to 14-yr period. If all this material were to be transported into and deposited evenly over the Mud Patch, the thickness of the accumulated drilling-related solids would be 56p. This would amount to 0.06 kg/m^2 of mud (17 percent) and cuttings (83 percent).

Physical Effects of Deposition

The worst case conceptual deposition model for the Mud Patch suggests that the total sediment layer related to drilling discharges would be about 56 μ. Assuming that the deposition would occur over a time period comparable to the period of discharge (11-14 yr), the expected annual rate of deposition would be 4.0 to 5.1 μ/yr. This rate of deposition (equivalent to 0.4 to 0.5 cm/1,000 yr) is very small compared to the recent sedimentation rates of 25 cm/1,000 yr for this area (Bothner et al. in press).

Drilling solids resuspended from the Mud patch would contribute to the persistent nepheloid layer of suspended sediment described by Parmenter et al. (1979). A conservative resuspension model is useful in estimating the contribution of drilling solids to the suspended sediment concentrations in the nepheloid layer. If the entire mass of drilling solids were to be resuspended into a 5-m thick layer above the Mud patch, the average suspended solids contribution to that layer would be about 11 mg/l.

Using the procedures outlined above (Section 4.4.4.1), the concentrations of barium, chromium, and zinc were calculated assuming that the total amount of these metals discharged are deposited in the Mud patch (Table 4-26). Barium would increase by 55 mg/kg. Ambient concentrations of barium at two benchmark stations on the shallow perimeter of the Mud Patch ranged from 175 to 400 mg/kg (ERCO 1978). It is likely that ambient concentrations in the Mud Patch would be *higher.* The highest value was for the station nearer to the Mud Patch and is taken as the more representative value. A resultant concentration of 455 mg/kg would amount to a 14-percent increase in barium that would likely be detectable. The incremental increases of chromium (0.2 mg/kg) and zinc (0.06 mg/kg) would be undetectable.

Sediments, including drilling-related solids, undergo diagenetic chemical changes after deposition that tend to bring them toward equilibrium with their aqueous environment. A sedimentary environment such as occurs within the Mud Patch with its high volume of resuspended sediments is likely to be an environment which favors the release of metals to the water column. Resuspension would Inhibit the formation of metal sulfides which bind metals in insoluble forms. This reworking provides for longer sediment exposure so that oxidation of organic and equilibration of inorganic phases could occur.

4.4.4.3 The Outer Continental Margin

This section discusses the fate of drilling effluents which may be transported to the shelf break and beyond onto the continental slope and rise environments. Drilling effluents which reach these areas are likely to originate from the deeper drill sites on the southern flank of Georges Bank. Near-surface flow components in the offshore direction have been observed in those locations and tend to be more developed in water deeper than 100 m (see Section 4.1.1.4).

The prevailing view of the shelf edge is that it is a locus of strong turbulence and currents which keep fine sediment in suspension or resuspend it frequently; thus, fine material is transported to the continental slope or beyond without permanent deposition near the shelf break (Southard and Stanley 1976). Physical phenomena which contribute to the energetic environment in the vicinity of the shelf break include surface waves, tidal motions, pressure-induced currents, and internal wave 8. Komar et al. (1972) noted that surface waves may have oscillatory ripple effects on the bottom at depths of up to 200 m. Such sediment movement would be important in resuspending any small amounts of fine sediment deposited on the sand bed of the shelf break between major storm occurrences.

In many areas there appears to be a maximum in tidal currents near the shelf break (Fleming and Revelle 1939, in Southard and Stanley 1976). Where tidal transport of water is parallel to the coast, the maximum tidal velocities are proportional to the distance from shore divided by the local water depth. As this ratio is often the greatest at the shelf break, the strongest tidal currents should also be found there.

Gait (1971) has found that under certain conditions a moving storm can produce a wave which will generate bottom currents which are concentrated at the shelf break. The current could extend throughout the water column and parallel the bottom contours. The estimated speeds are on the order of 10 cm/sec which could augment tidal and wave-produced currents to the point where they could resuspend fine particles near the shelf break (Southard and Stanley 1976). Furthermore, internal waves can exist in density-stratified waters over the shelf break. It is thought that both standing and progressive waves might move sediment on the shelf and slope, but this seems unlikely unless there is direct interaction with the bottom in the form of internal wave breaking.

The canyons which incise the continental shelf off Georges Bank can also provide an energetic environment suitable to the transport of drilling solids. Among these canyons, Hydrographer is the largest and penetrates farthest (14 km) into the continental shelf (Figure 4-l). It is a narrow canyon with steep (locally vertical) walls. Core samples show that sand is common. In addition, ripple marks and rock bottom have been seen in many bottom photographs and observed from deep-diving vehicles, suggesting relatively strong currents (Shepard et al. 1979). Transport of relatively coarse sediment in Hydrographer Canyon '(710 m) showed ripple marks in the sand bottom, apparently migrating down-canyon whenever currents (1 m above bottom) exceeded 26 cm/sec. Internal wave-generated velocities are clearly capable of transporting fine-grained sediments such as the drilling mud components throughout the canyon (Section 4.1.1.7).

In other Georges Bank canyons the internal wave amplitudes may not be as great as in Hydrographer Canyon. The conditions in these *canyons* may be similar to those in Hudson Canyon. The internal wave field in most of Hudson Canyon does not produce large enough velocities to move sediment significantly (Hotchkiss 1980). The storm currents occasionally sweep out all of the loose sediment and keep it from filling the outer parts of the canyon. The concentration of internal wave energy in the canyon head keeps sediment suspended there and possibly erodes the rock walls of the canyon. Other mechanisms influencing sediment movement in submarine canyons include gravity-controlled and biologic processes (Kelling and Stanley 1976) described in Section 4.1.1.7.

Two different conceptual models of sedimentation/sediment transport in canyons *were* used to develop worst case estimates of drilling effects on canyons. The first is a suspended transport model for use in Hydrographer Canyon where the occurrence of high amplitude, internal, wave-generated currents is likely to keep deposition to a minimum. The second model is a simple deposition scheme *for a* smaller canyon where sediment accumulation is assumed to build up between storm periods when flushing would occur. The models and their estimated worst case effects are discussed below.

Hydrographer Canyon Conceptual Model

In this conceptual model, all the drilling muds are assumed to be transported to the head of Hydrographer Canyon as they are produced. The high estimate for mud discharge is 1.25 x 10^8 kg over 14 yr. The average rate is therefore 0.28 kg/sec (about 280 cm^3/sec). The canyon cross-section is steep-sided so side slopes of 30° are assumed for a typical cross-section. Shepard et al. (1979) indicate that there is vertical coherence in the flows at least up to 30 m above the canyon floor. The depth of flow which can carry the sediment is conservatively assumed to be 30 m. The typical flow cross-section is a triangle with an altitude of 30 m, a base (upper surface of flow) of 104 m, and an area of 1,560 m^2.

The current meter at the shallow canyon head station (Shepard et al. 1979) shows a net down-canyon flow of about 8 cm/sec. The net down-canyon flow through the typical cross-section is therefore 125 m^3/sec. If the drilling muds are assumed to be uniformly mixed throughout this net down-canyon flow, an average suspended particulate concentration of about 224 mg/l is obtained. If the drilling muds are more realistically assumed to be uniformly transported to the six canyons on the flank of Georges Bank, the resulting concentration would be about 37 mg/l. This concentration is comparable to the concentrations typically found about 100 m down-current of a mud discharge, thus indicating the conservatism of this approach.

Gilbert Canyon Conceptual Model

In this conceptual model, all the drilling-related solids are assumed to be deposited in the head of a small canyon. Gilbert Canyon was chosen for this purpose because it has the smallest indentation into the continental shelf. Gilbert Canyon has a 9.6-km (6-mi) indentation and a width/length ratio of 1/2 at the 200 m level (Pratt 1967). The area for deposition is very conservatively assumed to be the horizontally projected area of the shelf indentation or 23.3 km^2 (9 mi^2), a small fraction of the actual canyon floor area which actually extends a length of 105 km (65 mi) (Pratt 1967).

The drilling solids are assumed to be deposited during calm periods between storms. This period is very conservatively estimated to be 1 yr. The total drilling solids production has a high estimate of 7.3 x 10^8 kg so that the average annual production rate for 14 yr is about 5.2 x 10^7 kg of mud and cuttings. This is equivalent to about 5.2 X 10^{10} cm^3 of solids. The uniform deposition of this volume of solids over a 23.3 km^2 area would result in an accumulation of drilling solids 0.2-cm thick in the head of the canyon. Seventeen percent of this layer would be drilling muds and 83 percent would be cuttings.

Following the procedures outlined previously for calculating sediment concentrations of metals that would result from this depositional model (using 1/14 of the total metals for the amount released in 1 yr), the values shown in Table 4-26 result. Not too surprisingly the concentrations are much higher than for the other depositional sinks considered because of the small area of Gilbert Canyon head. No background data are available for canyon heads (ERCO 1978), but comparison with metals concentrations for the adjacent lease area provides some scale for these hypothetical values. Barium (2,253 mg/kg) deposited annually by this scenario in Gilbert Canyon head would be nearly 20 times the background for the lease area. Chromium (7.2 mg/kg) and zinc (2.5 mg/kg) would be of the same order of magnitude as in the lease area or would constitute on the order of 100 percent increase. However, it is noteworthy that the incremental addition of 7.1 mg/kg of chromium to the median concentration (7.2 mg/kg) for the lease area would result in a concentration of 14.3 mg/kg which is within background range. Zinc concentration would also be within background range.

Continental Slope

Coarse- and fine-grained drilling-related sediments could be transported to the continental slope through mechanisms described above and in Section 4.1.1. Continental slope areas could serve as potential sinks for such sediments. Limited current data show the slope and rise to be a quiescent environment suitable for the permanent deposition of sediments. This section characterizes that environment and also describes local features which would result in further transport of some of the sediment farther seaward.

Wunsch and Hendry (1972) present limited current data from meter deployments on the continental slope and rise south of Cape Cod. Typical slope currents recorded showed a net westward flow in the near-bottom levels with speed of about 4 to 5 cm/sec. Current directions were more irregular on the continental rise. The data show a long-term net southwestward flow near bottom. The current speed in that direction was about 7 to 8 cm/sec.

The weak currents occurring on the continental slope and rise generally contain insufficient energy to resuspend bottom sediments. Very fine materials in the water column may, however, be transported in colloidal suspension by these currents. The transport would be in west to southwest directions as indicated by the existing data (Wunsch and Hendry 1972). This transport may carry particles into deeper portions of the canyons which incise the continental slope. Further transport within the canyons is possible as discussed above.

Gravity-controlled and biological processes which have been discussed in Section 4.1.1.7 with respect to mass transport in submarine canyons can also be responsible for downslope sediment movement on the continental slope. The gravity processes include sliding and slumping, creep, mass flow, grain flows, fluidized flows, debris flows, and turbidity flows, as well as biogenic activities.

In summary, the continental slope area may represent at least a temporary sink for drilling-related sediments. Estimating the physical and chemical effects of such deposition is extremely difficult. The current knowledge of the physical environment does not allow one to draw reasonable limits on the area likely to receive drilling-related sediments. The existence of local mechanisms to transport these sediments out of the continental slope environment further complicates matters. Rough scaling, however, suggests that accumulations on the slope are likely to be far less than those developed in the Gulf of Maine or Mud Patch depositional models discussed earlier. This is primarily because of the large area over which deposition can potentially occur on the continental slope.

Deep-Ocean Nepheloid Layer

Materials transported down the continental slope as suspended particulate or as deposited particles remobilized by gravity or biologic processes or as materials transported down submarine canyons eventually must approach the ocean floor where they either are deposited or become incorporated into the nepheloid layer. Figure 4-32 is a schematic of the source of some suspensates that may contribute to the nepheloid layer on the continental rise.

In the northwestern Atlantic Basin the nepheloid layer attains an average thickness of about 1 km and is best developed over the continental rise and the adjacent abyssal plain. Figure 4-33 shows the extent of the nepheloid layer in this region. Here the layer appears to include modest concentrations (0.2 mg/l) of particulate matter averaging 12 µ in diameter, most of which is terrigenous clay (Eittreim and Ewing 1972).

It is considered that the nepheloid layer represents a semi-permanent feature of deep ocean basins being composed of a concentration of clay particles maintained in suspension by turbulence (Kelling and Stanley 1976). In the northwestern Atlantic this turbulent mixing is ascribed to the effects of the geostrophic Western Boundary Undercurrent (see Section 4.1.1.2). This flow parallels the continental margin moving generally southward until it moves seaward off of the Blake Plateau (Figure 4-34).

A hypothetical model of sediment input/output for the nepheloid layer is shown in Figure 4-35. Materials from several sources including particulate matter transported down the continental slope provide input to the layer where typical residence times are on the order of a year. The suspended materials are then deposited on the seafloor or are carried south by the Western Boundary Undercurrent (Eittreim and Ewing 1972). Bottom currents such as the Western Boundary Undercurrent may be far from steady-state conditions. Deposition in any one area could alternate with transportation or erosion, depending on the magnitude of the fluctuations. Once deposition has taken place, velocities necessary to resuspend cohesive sediments may seldom be exceeded except in the core of the current (Pierce 1976).

Should any of the drilling effluents actually be transported to the continental slope, their incorporation into the nepheloid layer and subsequent transport along the continental rise/abyssal plain would result in its dispersion and eventual deposition over a tremendous expanse of ocean floor as is suggested by Figure 4-33. Concentrations of drilling-related solids would be undetectable and the physical and chemical effects of the drilling solids deposition would likewise be undistinguishable.

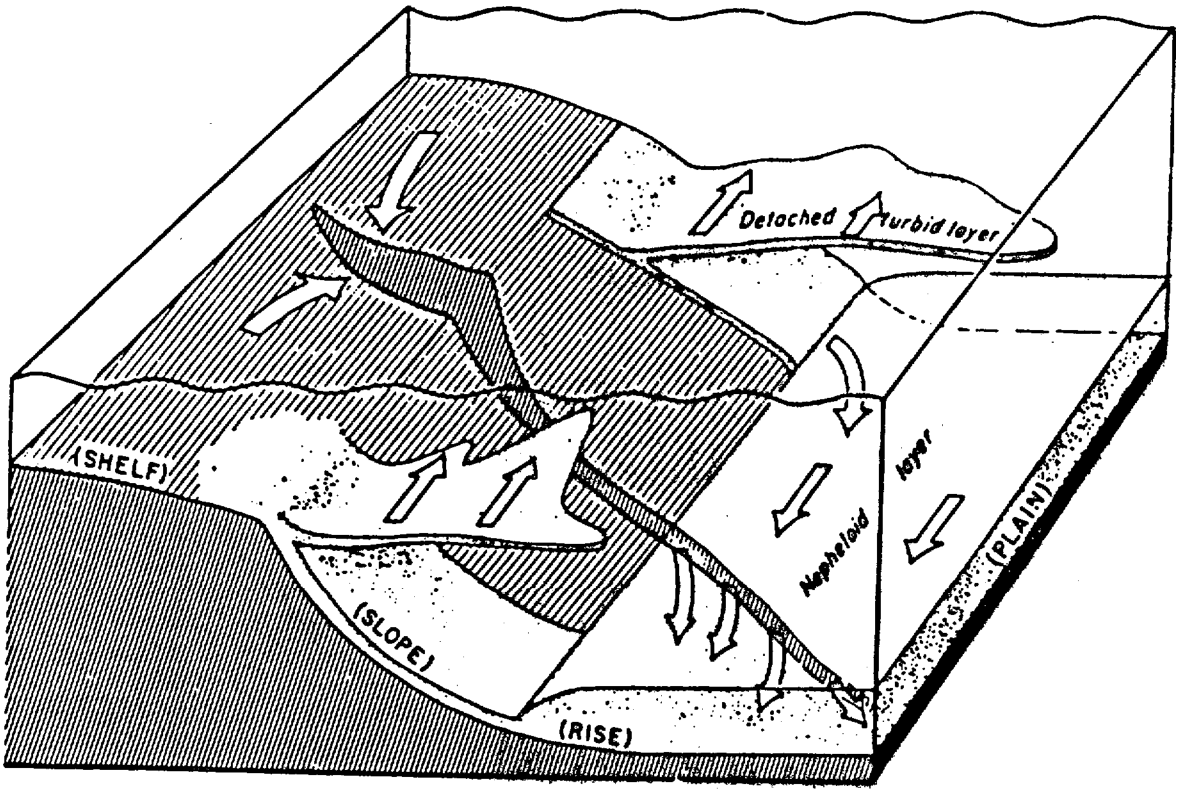
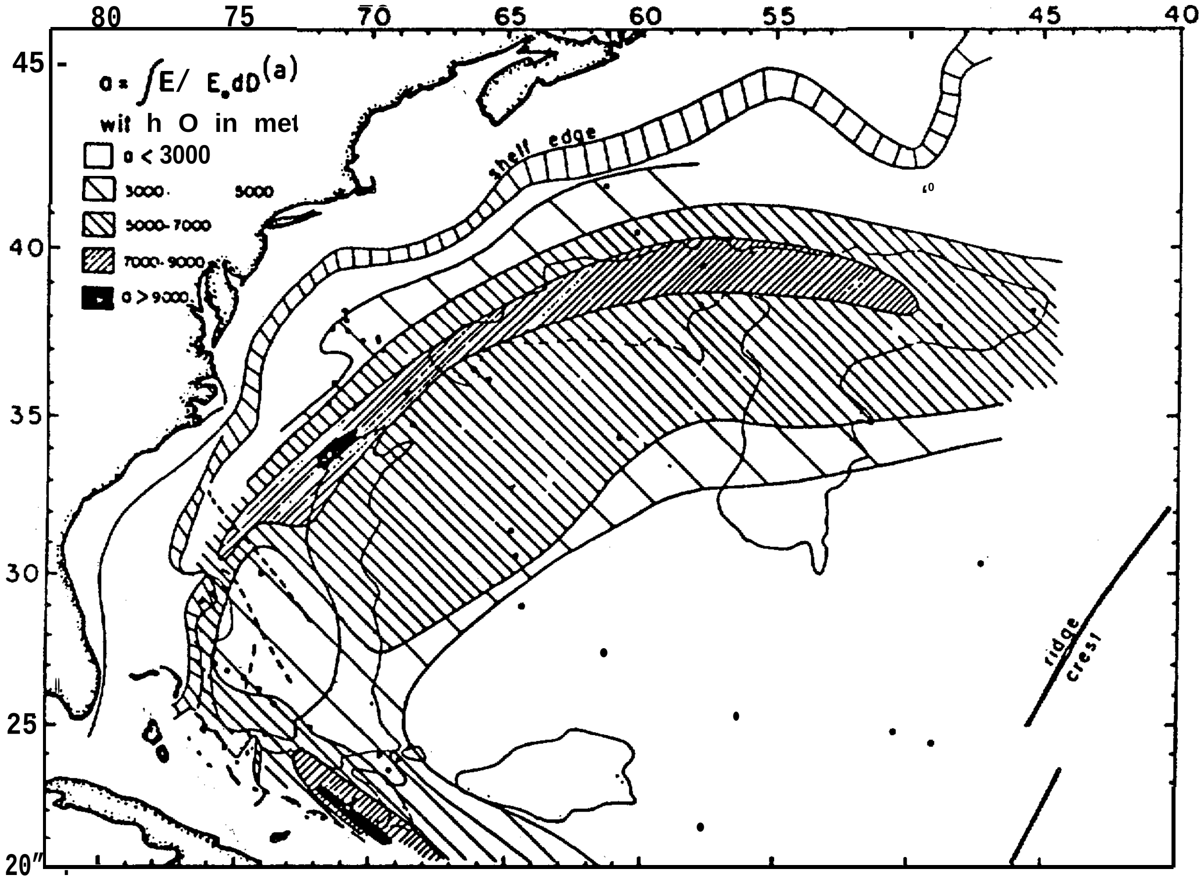


FIGURE 4-32 SUSPENSATE SOURCES TO CONTINENTAL RISE NEPHELOID LAYER (PIERCE 1976)



Notes:
(a) Values of "a" proportional to volume of suspended matter in nepheloid layer at each station.

FIGURE 4-33 CONCENTRATIONS OF SUSPENDED MATTER IN NORTHWESTERN ATLANTIC BOTTOM WATERS (EITTREIM AND EWING 1972)

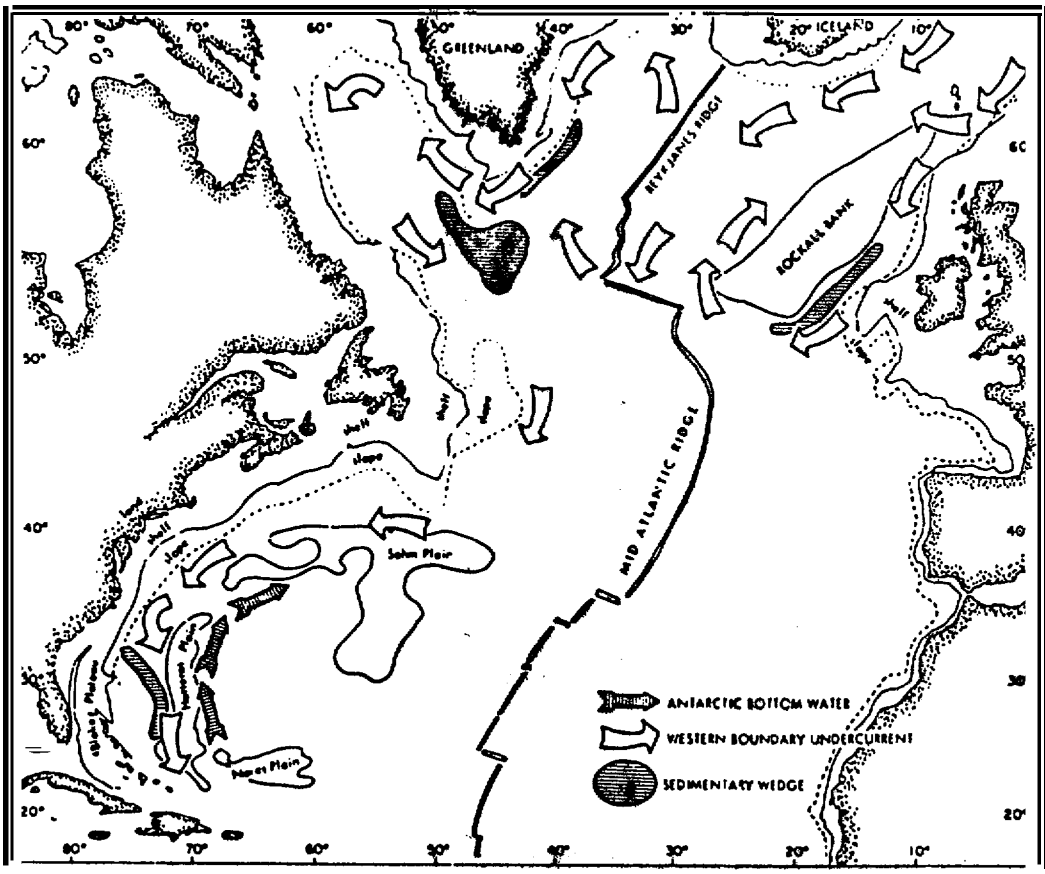
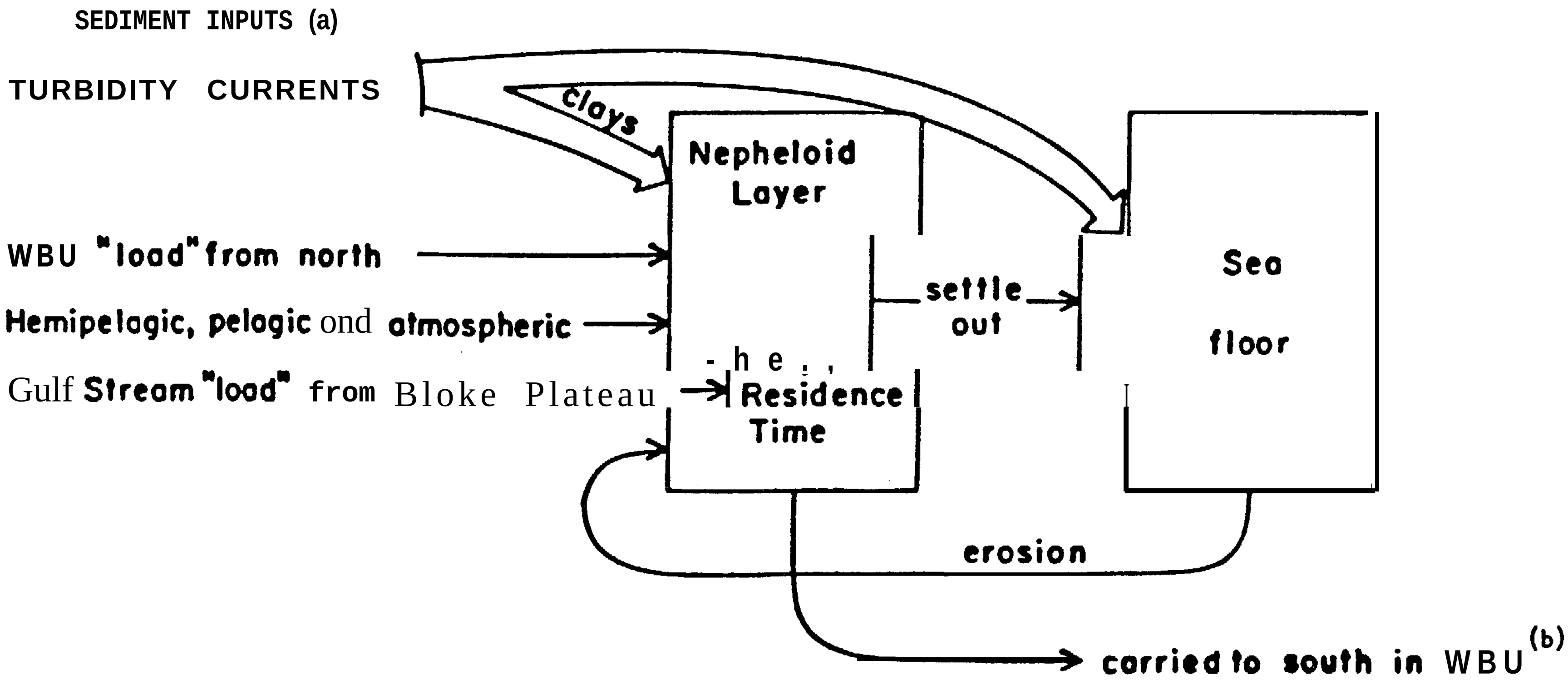


FIGURE 4-34 **DEEP WATER CIRCULATION IN THE NORTHWEST ATLANTIC BASIN (PIERCE 1976)**



Notes:
(a) Inputs in probable decreasing order of importance from top to bottom.
(b) Western boundary undercurrent (WBU).

FIGURE 4-35 HYPOTHETICAL SEDIMENT INPUT/OUTPUT MODEL FOR THE NEPHELOID LAYER (FROM EITTREIM AND EWING 1972)

4.4.4.4 Discussion

This discussion of the ultimate fate and effects of drilling effluents from the Georges Bank lease areas was based on worst case conceptual models of effluent transport and deposition. Highly conservative models were required to compensate for the lack of detailed knowledge of the physical environment, the physical and chemical processes affecting the transport and deposition of drilling effluents, and the magnitude and nature of the drilling program which will take place. The models were developed to estimate the worst case conditions which could occur given effluent transport to any one of several possible ultimate deposition sites. The specific areas studied with respect to drilling effluent effects included the Gulf of Maine, the Mud Patch on the continental shelf south of Martha's Vineyard, the submarine canyons incised into the continental shelf along the southern flank of Georges Bank, the continental slope, and the deep ocean. Each area was evaluated in turn, assuming that it alone would receive the entire volume of drilling effluents which would be conservatively transported there without loss (i.e., as if in a pipeline).

Actual conditions in the field, involving the complex interaction of several factors, would make the volume of drilling effluents which could actually reach an individual area several times smaller than estimated by the worst case models. The first of these factors is the likelihood that some deposition would occur in all of the areas studied. Earlier discussion of effluent pathways showed that the location of effluent release, especially the water depth, is important in determining the probable pathway. Table 4-27 summarizes the probable location of wells by water depth based on areas which have been leased. It is assumed that all lease blocks are equally likely to be developed. The bulk of the lease blocks (85.1 percent) are located in 60 to 100 m of water. The most likely flow path is along the south flank of Georges Bank and across the Great South Channel toward the Mud Patch and other areas along the continental shelf. Even assuming no losses in transport, only 60 percent of the total effluent volume (85.1 percent of source x 70 percent of flow) is likely to reach the Mud patch as compared to 100 percent assumed in the worst case model. Other areas would receive even smaller portions of the effluent volume.

Losses of volume in route to depositional sites is also a factor not considered in the conceptual models, Coarse fractions of drilling cuttings (>10 mm) will probably remain near the drill sites on Georges Bank where they are likely to be worked into and be buried by the mobile sandy sediments. Significant quantities of colloidal particles may also remain in suspension indefinitely and be transported well beyond the listed depositional areas. Perturbations of the mean circulation pattern can also transport material into other small-scale semi-permanent or permanent sinks. In general, significant quantities of drilling effluents will probably be untraceable lost within the overall system.

In spite of the very conservative features of the conceptual models, the worst case estimates of long-term deposition indicate minimal to virtually undetectable thickness of drilling effluents would be found in the receiving area sediments. The model-estimated drilling mud thickness

TABLE 4-27

POSSIBLE PATHWAYS AND DEPOSITION AREAS FOR DRILLING EFFLUENTS

Depth Zone of Release (m)	Estimated Number of Wells Completed: Exploration	Estimated Number of Wells Completed: Development	Percent of Drilling Activity	Possible Pathways and Deposition Areas	Possible Distribution of Effluents (percent)
<60	1	6/18	4.3	Gulf of Maine via Great South Channel	4
60-100	30	120/357	85*I	Continental shelf/ Mud Patch via flow across Great South Channel (∿70 percent)	60
				Gulf of Maine via Great South Channel (∿30 percent)	25
<1oo	4	16/45	10.6	Canyons/continental slope and rise via offbank flow	11
Total	35	150/420	100		100

in the southern portions of the Gulf of Maine (Wilkinson Basin) is about 82 μ. Other long-term depositional areas listed above do not have confinement characteristics as well defined as those of the Gulf of Maine. As a result, the estimated worst case accumulations at the other areas are less than those in the Gulf of Maine.

Conditions in some canyon head areas may allow a gradual temporary accumulation of sediment when the normal oscillatory current velocities are low. Periodically, storms result in higher current magnitudes which would be capable of flushing out the sediments. The conceptual model of this behavior developed for the Gilbert Canyon area provides a worst case accumulation estimate of 0.2 cm over a l-yr period. Storm-related flushing would prevent further buildup.

The estimated chemical increments contributed by drilling effluents to sediments in the potential depositional areas show similar low levels of influence. Incremental concentrations of metals constituents within a 3.2-mi radius of a single well are typically in the range of ambient metals concentrations. Similar approaches to background concentration levels are expected at the long-term deposition sites.

4.4.5 Biological Effects

The benthic environment is most susceptible to significant impacts from discharged drilling fluids and cuttings, and the range of potential impacts is broad (Section 2.5.2). In this section potential impacts on benthic assemblages on and near Georges Bank are assessed from the perspective of a single exploratory well extrapolated to multiple wells and ultimately to multiple development wells drilled from one or more platforms. A complicating factor stems from the range of water depths and hydrodynamic conditions on Georges Bank that may translate to variation in dispersion and dilution of drilling fluids. The benthic biota also varies across the lease area in species composition, abundance, and biomass; hence, biological susceptibility to drilling fluids will vary throughout the area. Effects on the biota may occur due to drilled solids, muds, or chemicals or due to synergistic effects of these components. In the longer-term, as drilling materials are transported out of the lease area and are possibly deposited in "sinks" relatively far from their source, cumulative effect on the benthos may occur.

The discussion of drilling fluid impacts on the benthic environment focuses on very sedentary benthic invertebrate epifauna and infauna. It is generally conceded that this group has the greatest probability of sustaining significant adverse impacts from drilling fluids due to their inability to avoid contact with these materials or to leave contaminated areas. More mobile organisms such as starfish, lobster, crabs, larger gastropod, and demersal fish will presumably be less adversely affected because they can avoid adverse conditions. Nevertheless, mobile organisms may be affected because of over-riding attractive characteristics of a drilling operation that result in concentrations of some species near a rig. Furthermore, most of these more mobile organisms are predators that, if attracted to a drilling location, could accumlate drilling fluid pollutants in their body tissues making them available to higher trophic levels.

4.4.5.1 Effects of Drilling in the Vicinity of a Typical Well

Effects of Solids Deposition

Drilled solids may adversely affect sedentary benthic invertebrates by burial and suffocation near a well where the rate of deposition and accumulation is highest. With increased distance the rate of deposition and accumulation decreases as does solids particle size. Effects on sedentary organisms in these areas would occur more likely as a result of changes in near-surface sediment composition. The relationship of benthic infauna species composition and abundance with sediment type has been broadly described (see for example Sanders 1958, 1960; Thorson 1966; Young and Rhoads 1971). Realistically, it would be difficult to ascribe adverse effects to solids deposition alone except in the immediate vicinity of the well where significant deposition and accumulation of solids would clearly bury and suffocate organisms. Beyond this area the effects of drilling muds deposition and associated chemical additives and solids would probably have the dominant effect. The extent of potential effects of drilled solids on sedentary benthic invertebrates will vary with the depth of water and hydrodynamic conditions at each well location. Two approaches are available to estimate this area of effect: the theoretical and the empirical.

The idealized, initial deposition pattern of drilled solids shown in Figure 2-3 depicts a *series* of concentric elipses for various sizes of discharged solids. Table 4-23 summarizes the theoretical areas of bottom potentially affected by various particle sizes for typical wells drilled at four water depths (36, 60, 110, and 210 m) in a range of current speeds. Such great variation exists in the distribution of cuttings particle sizes among wells that it is impossible to estimate the proportion of total solids produced by a well that would be deposited over a given area. Thus, the areas given in Table 4-23 are conservative estimates of the amount of bottom possibly influenced by solids.

Another theoretical approach to indicate the maximum area over which mortality of infauna may occur (as opposed to the area where deposition may occur) is to assume a depth of burial (e.g., 5 cm) that will kill infaunal organisms. To estimate the worst case impact that could occur due to burial by solids, it is assumed that all of the 688 m^3 of solids would be deposited uniformly in a layer 5 mm thick which would cover an area of 137,600 m^2 that, if circular, would have a radius of 209 m. This assumption conservatively ignores the fact that finer solids would be dispersed over a much larger area and that during drilling (90 days or longer period) much of the deposited solids would be worked into the sediments or transported and dispersed along the bottom. Furthermore, the differential effects of wider dispersion due to increased water depth are not considered.

Empirical evidence from the mid- and north Atlantic indicates that cuttings piles would be substantially smaller than those described above and would be strongly skewed in the direction(s) of the prevailing currents. About 450 m^3 of cuttings and 217 m^3 of muds were discharged into currents that ranged from 0.8 to 3.3 knots (41 to 170 cm/see) at the Georges Bank G-1 C.O.S.T. well (ENDECO 1976). Drill cuttings were not detected beyond 91.4 m from the rig. Thus, drill cuttings may have covered a bottom area of 26,245 m^2. If cuttings pile deposition is directly proportional to the volume of cuttings produced, then the 688 m^3 of cuttings anticipated for a typical exploratory well on Georges Bank would possibly cover an area of 40,126 m2 with a radius of 113 m at this location (48 m of water). The mid-Altantic exploratory well was drilled to a depth of 4,970 m in 120 *m of water* with about 503 m^3 of formation solids discharged (Ayers et al. 1980a). Average current speeds for the 10-m depth were 21.5 and 26.9 cm/sec predominantly to the southwest. Cuttings accumulations were observed over a 150-m diameter area in the vicinity of the well with a deposition pattern skewed to the southwest (Menzie et al. 1980). Approximately 17,671 m2 of bottom may have been covered by cuttings piles. Scaled to the volume of cuttings expected on Georges Bank (688 m^3), an area *of* 24,170 m^2 with a radius of 88 m would be covered *in* 120 m of water on Georges Bank. The empirical data from studies *of* these two drilling operations, taken as observed *or* scaled to expected cuttings volumes for Georges Bank, indicate that visible cuttings piles would probably be restricted to a 1OO-RI radius around a well. A slightly larger area might be affected in deeper than in shallower water. This difference probably reflects the greater dispersion of particles achieved in deeper water. Note that presence of a visible cuttings pile is dependent primarily on presence of larger particles (e.g., 2 mm or larger), thus bringing the theoretical prediction (Table 4-23) very close to the empirical results.

Very few data are available on the persistence of cuttings piles, but fortunately such information will be published in the near future for wells on Georges Bank and Baltimore Canyon. NMFS biologists conducted a survey (August 1980) of the bottom in the immediately vicinity of C.O.S.T. well G-2 (lat. 40°45'N, long. 67°25'W) drilled in 79 m of water in 1977. Fathometer records, underwater photographs, and observations made from a submersible revealed no evidence of a residual cuttings pile. Based on the presence of appreciable numbers of sea scallops, jonah crabs, and bakes, the area was not adversely affected (R.A. Cooper 1981, NMFS NEFC, personal communication, Jan. 8). The water depth of this well is close to the water depth (85 m) at which most exploratory wells will be drilled on the bank. Results of a field survey (August 1980) conducted 1 year after drilling the Baltimore Canyon well are not yet available (T. Sauer, Exxon, personal communication).

The benthic *invertebrate* biomass that could be affected by discharged drilling fluids can be estimated for a well drilled in a specific water depth on Georges Bank from data illustrated in Figure 4-17 where biomass is plotted as a function of water depth. A least squares regression of biomass (y) on depth (x) gives the equation:

$$\log y = -2.849 \log x + 7.843 \quad (r = 0.65,\ P<0.01).$$

This analysis averages the geographic variation of biomass that occurs ● long depth contours over the bank (Figure 4-18). The average biomass (wet weights) in the vicinity of wells drilled in 36, 60, 110, and 210 m of water are 2,565, 598, 106, and 17 g/m^2, respectively. Table 4-23 gives estimates of total invertebrate biomass potentially affected by drilled solids of various sizes under the theoretical deposition scenario.

For the purpose of estimating potential worst-case losses of benthic invertebrates due to burial, it is assumed that the area arrived at in Section 2.5.2, 60,000 m^2 (138-m radius) would be covered by cuttings. Using the biomass-depth relationship estimates of total invertebrate biomass lost per well as a function of depth and this cuttings pile area can be developed. If all of the organisms were lost then 1,020 to 154,000 kg of biomass could be affected (in 210 and 36 m of water, respectively) . At the average depth (85 m) of an exploratory well 13,310 kg would be lost. This number would include numbers lost due to deposition of the first 30 m^3 of cuttings at the seafloor. ,

Effects of Fine Solids and chemicals

The Atlantic G-1 C.O.S.T. well in 48 m of water" indicated that physical and chemical *effects* on the benthic environment were restricted *to* an ● rea of about 0.05 km^2 (ENDECO 1976). Biological effects were not measured. The study at the mid-Atlantic well in 120 m of water

(Ayers et al. 1980a, Mariani et al. 1980, and Menzie et al. 1980) could be interpreted as showing that adverse biological impacts may have extended 1,600 to 3,200 m from the well (Section 2.4.3.2). These results are confusing because possible drilling-related depression of benthic invertebrate abundance (all major taxa) appeared to be fairly uniform along a gradient downcurrent (Figure 2-5). Pollution studies generally show a depression of organism abundance near the pollutant source with a decrease in effect (increased abundance) with distance from the source. The absence of this pattern leaves open the possibility that the effects of the drilling operation were much greater than reported elsewhere.. In Section 4.4.1 a worst case conceptual model was presented in which all of the mud solids and metals expected to be discharged in the drilling of an exploratory well was assumed to be uniformly mixed in the top l-cm layer of sediment over an area within a 3,200-m radius of the well. With the exception of barium, the increment of metals added to median background concentrations appears negligible. Hence, it is difficult to imagine that a drilling operation could adversely affect an area the size of that seemingly affected at the mid-Atlantic well.

Aside from these issues, there is reason to doubt whether the results of the mid-Atlantic study can be extrapolated directly to Georges Bank due to differences in hydrodynamic regimes. Georges Bank is thought to be a more rigorous hydrodynamic environment than the mid-Atlantic. Thus, drilling fluids would be diluted more rapidly and drilled solids, once deposited, would be dispersed more rapidly on the bank. A long-term measure of this difference would be the relative amount of fine sediments at comparable depths in the two areas. Sediment fractions in the range of Phi 4 or smaller comprised about 16 percent of the sediments in the vicinity of the mid-Atlantic well. A summary of the occurrence of these fine fractions on the southern flank of Georges Bank (Figure 4-31) shows that on the average 16 percent fines occurs only below 200-m depth; at 120-m depth these fractions comprise an average of 3.9 percent on the bank. Recognizing that sediment composition is Influenced by many factors in addition to currents and storms, the four-fold difference in fines composition at about 120 m suggests that fine drilled solids deposited in 120 m or less of water on Georges Bank would be rapidly dispersed In contrast to the mid-Atlantic, where long-term residence is possible.

These concerns cast serious doubt on the accuracy of any set of predicted Impacts on the benthic environment based on these sources, especially since 85 percent of the lease blocks are in water depths between the depths of the Georges Bank (48 m) and mid-Atlantic (120 m) wells. This would be true even if more confidence could be placed in the 'mid-Atlantic results because no data are available to scale effects over the intervening 72 m of depth (between 48 and 120 m). As shown in Figure 4-17 benthic invertebrate biomass decreases dramatically with increased depth with the result that an error in estimating the extent of effects could result in a gross overestimate of impact. Nevertheless, an effort is made to set upper and lower limits on potential effects so that cumulative impacts can be placed in perspective.

To scale upper and lower limits of effects across the depth range in which drilling may occur on Georges Bank, the following assumptions are made:

1. Biological effects in the vicinity of C.O.S.T. well Atlantic G-1 were constrained to the limits of detectable physical and chemical effects.

2. The extent of biological effects apparently observed at the mid-Atlantic well (to 3,200 m) could only occur in much deeper water on Georges Bank (200 m or more) where comparable amounts of fine sediments are present.

3. On a plot of radial extent of effects versus water depth, a straight line between the Georges Bank and mid-Atlantic data points would approximate the upper limit on radial extent of effects for intermediate depths.

4. The lower limit on radial extent of effects would be one-half that of the upper limit.

These assumptions are embodied in Figure 4-36. In reality there is no reason to believe that lower and upper limits on extent of effects would be approximated by straight lines. For example, if the percent of fines in sediments on the southern part of the bank reflect hydrodynamic conditions at various depths and thus potential for transport of these fine particles, then the extent of effects would be curvilinear as shown on Figure 4-36. It is of interest to note that when the range of percent fines is scaled to depths at which they occur on the bank, the resultant curve is very similar to the assumed lower approximation of extent of effects down to about 160 m.

To estimate upper and lower limits on potential effects on the benthic environment, the following procedure was used. The depth distribution of exploratory drilling efforts was assumed to follow that of the lease blocks (Table 4-28). For a particular water depth, upper and lower radial extent of effects from the well was taken from Figure 4-36. The area(s) of bottom affected was calculated (assuming a circular area of deposition) and the invertebrate biomass potentially affected was estimated based on the equation:

$$\log y = -2.849 \log X + 7.843$$

which relates invertebrates biomass (y) to water depth (x). These calculations and estimates are summarized in Table 4-29. For a well drilled in shallow water (55 m), lower and upper estimates of biomass potentially affected are 8,675 and 133,070 kg, respectively; for a deep location (135 m), these estimates are 118,627 and 474,506 kg, respectively. At a well drilled in the average water depth (85 m), the range of potential adverse effects is from 62,769 to 392,306 kg. Estimated potential effects on the benthos during the development phase of drilling are discussed in the following section on cumulative effects in the lease areas.

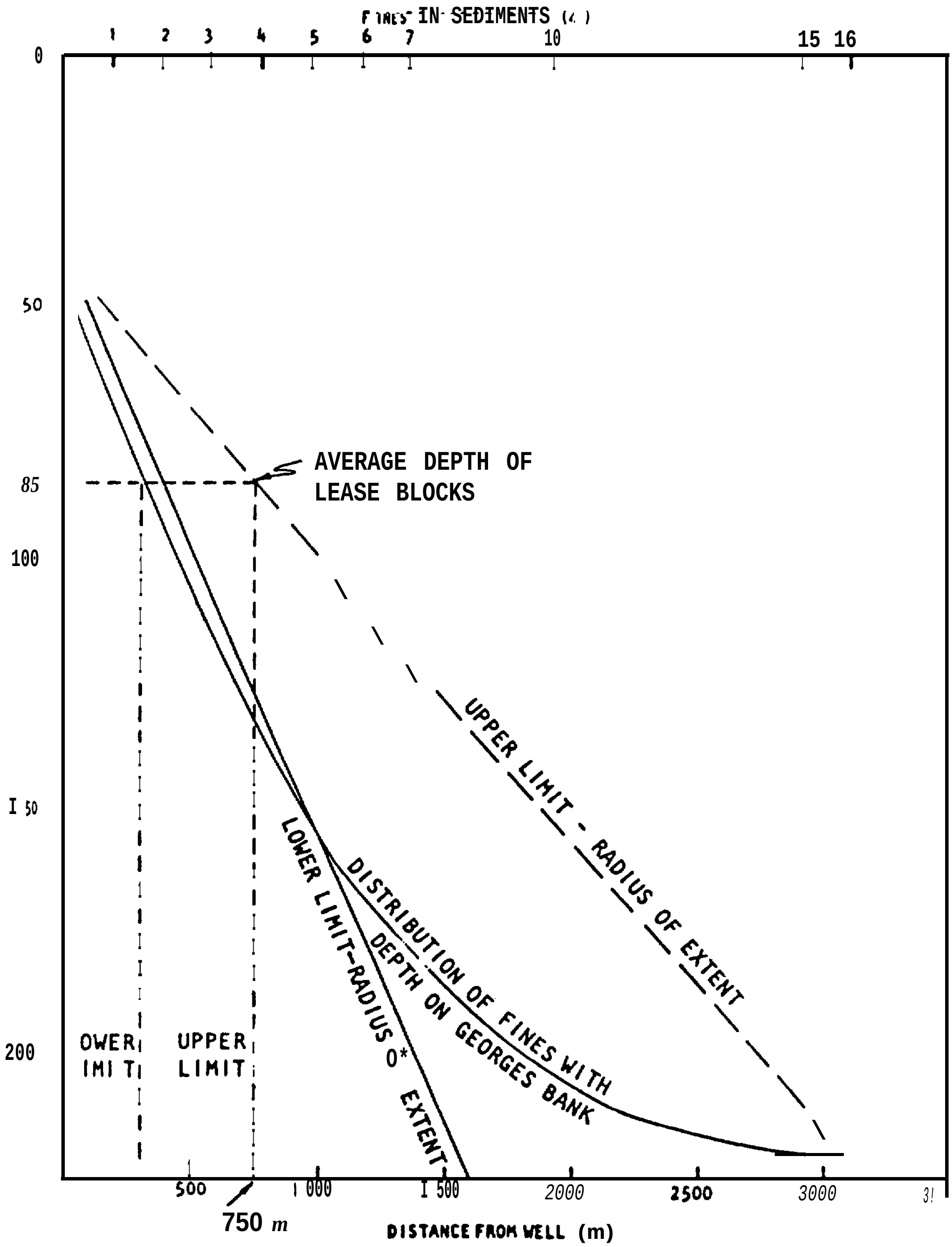


FIGURE 4-36 HYPOTHETICAL EXTENT OF DRILLING MUD EFFECTS

TABLE 4-28

ASSUMED DEPTH DISTRIBUTION OF EXPLORATION AND DEVELOPMENT DRILLING OPERATIONS ON GEORGES BANK

Depth Range (m)	Lease Blocks	Exploration Wells	Low Estimate Development Number Wells	Low Estimate Development Number Platforms	High Estimate Development Number Wells	High Estimate Development Number Platforms
51-60	2	1	6	1	18	1
61-70	6	5	19	1	54	3
71-80	10	8	32	2	89	6
81-90	13	10	42	3	116	8
91-100	11	8	35	3	98	7
101-110	0					
111-120	1	1	3	1	9	1
121-130	1		3		9	
131-140	2	2	7		18	2
141-150	1		3		9	
Total	47	35	150	11	420	28

4.4.5.2 Cumulative Effects in Lease Area

This section considers the potential cumulative effects of drilling in the lease area resulting from the drilling and discharge of drilling fluids at 35 exploratory wells and at 150 to 420 development wells drilled from 11 to 28 platforms (Section 4.2). To explore the range of potential effects in a simplified manner, only the area affected by drilling muds and chemical is considered because the area affected by solids deposition would be included within this larger area.

To assess the effects of multiple (generally 10 to 20) wells drilled from a production platform, several factors must be considered. The volume of drilled solids and muds produced in the drilling of a single development well is substantially less than for an exploration well (Tables 4-20 through 4-22). Consequently, the potential effects on the benthos should be less than for an exploratory well. However, the cumulative effect of drilling multiple development wells from one platform would not be a simple multiple of the number of wells drilled. An area of initial impact would be established with the drilling of the first well. Subsequent wells would probably extend the area of impact somewhat with each incremental extension smaller than the former. At some point an equilibrium would be reached at which the discharge of drilling fluids would be offset by dispersal and dilution of deposited materials. Benthic organisms would recover or re-establish within the affected area, possibly between periods of drilling, and certainly following completion of all drilling from the platform. The duration of the recovery period is unknown, but some indication may be forthcoming from the results of the 1-yr postdrilling study conducted at the mid-Atlantic well.

To estimate the extent of potential effects due to multiple wells drilled from one platform, it was assumed that each of the first four additional wells would extend the radius of the affected area by 10 percent of the initially estimated distance; thereafter, additional wells would not extend the area affected. The area and biomass affected throughout the lease area can be calculated (as done previously, Section 4.4.4.I) as a function of the depth distribution and number *of platforms* in a given depth range.

Lower and upper cumulative estimates of benthic invertebrate biomass potentially affected or lost due to exploratory drilling operations are given in Table 4-29. About 13.4 to 70.6 km^2 of bottom would be affected over a 3-yr period. Within this area roughly 2.176 to 12.779 mt of benthic invertebrates would be affected or possibly lost. Use of the term "lost" does not imply loss to the ecosystem, since virtually all debilitated or dead organisms are consumed by scavengers or predators. Possible consequences of these losses are explored in Section 4.4.5.4. Most (77 percent) of the potential biological impact would *occur at* moderate depths (70 to 100 m) where most (26) of the wells would be drilled. Only three wells would be drilled in deeper water but would account for 16 percent of the potential impact. The six wells drilled in shallow water (50 to 70 m) would account for only 7 percent of the potential impact.

Lower and upper estimates of benthic *invertebrate* biomass potentially *affected* during development phase *of* drilling are given in Tables 4-30 and 4-31. Based on the low development scenario (150 wells drilled from 11 platforms), about 8.4 to 44.6 km^2 of bottom would be affected over an 8-yr period. Within this area about 1.343 to 7.847 mt of invertebrate biomass would be affected. Based on the high development scenario (420 wells, 28 platforms), the area of bottom affected over an 11-yr period would range from 25.1 to 126.9 km^2 and would contain about 3.580 to 20.521 mt of benthic invertebrate biomass. The depth distribution of this potential impact follows that discussed for exploratory drilling.

The total amount of benthic invertebrate biomass potentially affected by drilling fluids and cutting during exploration and development phases would range from 3,519 to 33,300 mt (Table 4-32) over an 11- to 14-yr period. During exploration about 725 to 4,260 mt/yr would be affected annually (168 to 1,866 mt/yr) as compared to exploratory drilling. Amortized over an 11- to 14-yr period, total biomass affected would range *between 320 and* 2,379 mt/yr.

It is difficult to place such losses in perspective, but the simplest means of doing so is to convert invertebrate biomass to equivalent fish biomass or by comparison with fish catch statistics. Following the "rule-of-thumb" that 10 *percent* of the biomass from a lower trophic level is converted into predator biomass, the benthic invertebrate biomass data of Table 4-32 *were* converted to bottom fish and invertebrate predator biomass (Table 4-33). Thus, *during* exploration the food resource supporting about 73 to *426* mt/yr of fish (or invertebrate predators) would be affected, and during development 17 to 187 ret/x would be affected. If 'affected* were *to* mean total mortality that was

TABLE 4-29

LOWER AND UPPER ESTIMATES OF BENTHIC INVERTEBRATES
POTENTIALLY AFFECTED DUE TO DISCHARGE OF DRILLING FLUIDS DURING
EXPLORATORY DRILLING OPERATIONS

Depth (m)	Invertebrate Biomass (%2)	Number of Wells	Lower Estimate (per well) Extent of Effects (m)	Lower Estimate (per well) Area of Effects (km^2)	Lower Estimate (per well) Biomass Per Well (kg)	Total Biomass Affected All Wells (kg)	Upper Estimate (per well) Extent of Effects (ITI)	Upper Estimate (per well) Area of Effects (km^2)	Upper Estimate (per well) Biomass Per Well (kg)	Total Biomass Aff ected All Wells (kg)
55	767	1	60	0.01	8,675	8,675	235	0.17	133,070	133,070
65	476	5	140	0.06	29,309	146,545	400	0.50	239,264	1,196,320
75	317	8	225	0.16	50,417	403,336	575	1.04	329,264	2,634,112
85	222	10	300	0.28	62,769	627,690	750	1*77	392,306	3,923,060
95	162	8	400	0.50	81,430	651,440	925	2.69	435,460	3,483,680
110	106	1	550	0.95	100,735	100,735	1,175	4.34	459,760	459,760
135	59	2	800	2.01	118,627	237,254	1,600	8.04	474,506	949,012
Total		35				2,175,675				12,779,014

TABLE 4-30

LOWER AND UPPER ESTIMATES OF BENTHIC INVERTEBRATES POTENTIALLY AFFECTED DUE TO DISCHARGE OF DRILLING FLUIDS DURING DRILLING OPERATIONS UNDER THE LOW DEVELOPMENT SCENARIO

				Lower Estimate				Upper Estimate			
				One Platform			All Platforms	One Platform			All Platforms
Depth (m)	Invertebrate Biomass (g/m^2)	Number of Wells	Number of Platforms	Extent of Effects (m)	Area Affected (km^2)	Biomass Affected (kg)	Total Biomass Affected (kg)	Extent of Effects (m)	Area Affected (km^2)	Biomass Affected (kg)	Total Biomass Affected (kg)
55	767	6	1	84	0.02	17,002	17,002	330	0.34	262,406	262,406
65	476	19	1	196	0.12	57,447	57,447	560	0.99	468,957	468,957
75	317	32	2	315	0.31	96,817	197,633	80s	2.04	64 S,3S6	9,290,717
●S	222	42	3	420	0*SS	123,027	369,082	1,0S0	3.46	768,921	2,306,762
9s	162	3s	3	560	0●99	1S9,603	478,809	1,295	S.27	8s3, s02	2,s60, s0s
125	74	13	1	980	3.02	223,272	223,272	2,030	12.9S	958,0$8	9s8,-010
Total		1s0	11				1,343,245				7,847,365

TABLE 4-31

LOWER AND UPPER ESTIMATES OF BENTHIC INVERTEBRATES POTENTIALLY AFFECTED DUE TO DISCHARGE OF DRILLING FLUIDS DURING DRILLING OPERATIONS UNDER THE HIGH DEVELOPMENT SCENARIO

				Lower Estimate				upper Estimate			
				One Platform			All Platforms	One Platform			All Platforms
Depth (m)	Inverte- brate Biomass (g/m2)	Number of Wells ●	Number of htforu	Extent of Effects (9)	Area Affected (km2)	Bit-Am Affected (kg)	Total Biomass Affected (kg)	Extent of Effects (9)	Area Affected (km2)	Biomass Affected (kg)	Total Biomass Affected (kg)
55	767	18	1	64	0.02	17,002	17,002	330	0.34	262,406	262,406
65	476	54	3	196	0.12	57,447	172,341	S60	0*99	468,957	1,406,871
75	317	69	6	31s	0*31	98,817	592,902	80 5	2.04	645,3S6	3,872, 148
85	222	116	8	420	0.s5	123,027	984,216	1.050	3,46	766.921	6,1 S1,366
95	162	96	7	S40	0 ●99	1S9,603	1,117,221	1,29S	5.27	f) S3, 502	5.974,S94
120	03	18	1	910	2.60	21 S,929	21 S,929	1,890	11.22	931,433	931,433
140	54	27	2	1, 190	4.4s	240,236	480,472	2,380	17.00	960,943	1,921,886
Total		420	20				3,s80,083				20,520,626

TABLE 4-32

BENTHIC INVERTEBRATE BIOMASS POTENTIALLY AFFECTED DUE TO DISCHARGE OF DRILLING FLUIDS UNDER THE DRILLING SCENARIO FOR GEORGES BANK

Phase of Activity	Duration (years)	Biomass (ret) Lower Estimate Total	Annual	Upper Estimate Total	Annual
Exploration	3	2,176	725	12,779	4,260
Low Development	8	1,343	168	7,847	981
High Development	11	3,580	325	20,521	1,866
Total	11-14	3,519-5,756	320-411	20,626-33,300	1,875-2,379

TABLE 4-33

BOTTOM FISH AND BENTHIC INVERTEBRATE PREDATOR BIOMASS POTENTIALLY AFFECTED BY DISCHARGE OF DRILLING FLUIDS UNDER THE DRILLING SCENARIO FOR GEORGES BANK

Phase of Activity	Duration (years)	Biomass (ret) Lower Estimate Total	Annual	Upper Estimate Total	Annual
Exploration	3	218	73	1,278	426
Low Development	8	134	17	785	98
High Development	11	358	33	2,052	187
Total	11-14	352-576	32-41	2,063-3,330	188-238

not ultimately converted to higher trophic levels (through the action of detritivores, bacteria, etc.), this would amount to 0.01 to 0.2 percent of the reported total annual catch by U.S. and foreign fleets averaged over the period 1972 to 1975 (Table 4-34). Since the annual catch is a fraction of the total stocks on the bank, this ratio becomes increasingly small.

Epibenthic shellfish probably constitute the commercial resources most vulnerable to drilling discharges. The potential cumulative impact on sea scallops in the lease area can be roughly estimated from the raw data on sea scallop density summarized in Figure 4-19 and the amount of area potentially affected (Tables 4-29 through 4-31). The vast majority of sea scallops in the lease area occur between 40 and 100 m. The average density within this area is $0.085/m^2$. During exploration roughly

TABLE 4-34

TOTAL U.S. AND FOREIGN CATCH (mt)
FOR SELECTED BENTHIC PREDATORS AND SCAVENGERS
IN ICNAF SUBDIVISION 5AE (GEORGES BANK) 1972 TO 1975[a]

Species	1972	1973	1974	1975
Cod	22,822	25,730	24,971	23,204
Haddock	5,719	5,302	4,145	5,393
Red Hake	39,366	24,666	9,500	15,003
Silver Hake	77,512	62,206	66,364	63,015
Yellowtail Flounder	22,977	21,633	19,644	16,356
Other Flatfish	12,186	7,937	7,377	9,815
Other Fish	65,323	38,208	23,610	28,587
Lobster	1,250	900	2,154	1,657
Crabs	0	71	180	128
Shrimp	23	2	0	7
Total	247,178	186,655	157,945	163,165
Annual Average				188,736

(a) Compiled from Table 4-17.

713,150 to 4,267,850 scallops would be present in areas potentially affected by drilling fluids. Under the low-development scenario, about 457,300 to 2,686,000 scallops could be affected. Or, under the high-development scenario, about 1,153,450 to 6,810,200 scallops could be affected. During exploration and development phases of drilling, about 106,400 to 791,300 scallops would be potentially affected annually. It is important to note that not all of the scallops potentially affected would be killed or unfit for consumption. Within an affected area, scallops in the immediate vicinity of a well might be buried by drill cuttings or mud solids. Beyond this area some level of metals accumulation would be possible. Laboratory bioassays of the effects of drilling fluids on sea scallops (Section 2.3.1.1) suggest a high level of sensitivity, but at this time insufficient field data on sediment metals concentrations in the vicinity of a drilling operation are available to relate laboratory studies to field conditions. There is evidence that scallops do not accumulate metals in the adductor muscle (Liss et al. 1980) so there is little chance of effect on human consumers. At present there are insufficient distributional and abundance data on American lobster in the lease area or adjacent canyons to serve as a basis for estimating the range of potential effects.

The conservatism inserted in every step of these impact scenarios is considerable, especially the final assumption that "affected" means loss to the ecosystem. Actual effects on fisheries would likely be totally insignificant based on considerations described in this report.

4.4.5.3 Effects in Hypothesized Depositional Sinks

Three general locations off Georges Bank have been hypothesized as the ultimate sinks or principal pathways of drilling fluids introduced into the bank's hydrodynamic regime. The depositional areas or sinks are the Gulf of Maine and the Mud Patch. The submarine canyons on the southern flank of the bank may channel drilling fluids off the shelf into deeper water.

For each of these areas the following questions were asked: what concentrations of drilling fluids and metals would result if all materials produced were deposited in one of the sinks (Sections 4.4.4.1, 4.4.4.2) or were transported down only one canyon (Section 4.4.4.3); and, what would be the biological consequences? For the Gulf of Maine (Wilkinson Basin) and the Mud Patch, increases in concentrations of barium, chromium, and zinc would probably be undetectable and, therefore, the biological effects, if any, would not be detectable. A more realistic scenario based on 85 percent of the drilling occurring in 60 to 100 m of water and 70 percent of the water flowing through this region of the bank continuing along the continental shelf, suggests that at most 60 percent of the total drilling fluids produced could be deposited in the Mud Patch. Hence, without refining the argument further, there appears to be very little chance of exploratory and development drilling having a significant effect on the benthic environment in these areas.

Similar conceptual modeling of the effects of drilling fluids deposition in low-energy environments of submarine canyons is more difficult because hydrodynamic conditions are thought to be more dynamic. A deposition model was developed for Gilbert Canyon head, the smallest canyon on the southern flank of Georges Bank. This model assumed that all drilling fluids produced in 1 yr would be deposited in the canyon head, resulting in increments of 2,253 kg/mg of barium, 7.2 mg/kg of chromium, and 2.5 mg/kg of zinc. Resultant concentrations of chromium and zinc, when added to ambient median values for the lease area, would be within the range of concentrations for the lease area. A more realistic scenario of deposition in this canyon head reduces these concentrations by 89 percent, since only about 11 percent of the drilling fluids is expected to potentially be deposited in any of the canyon heads (Table 4-27). Consequently, the concentrations of chromium and zinc would be undetectable when compared to ambient values. Barium concentrations would still be high, but probably of little biological significance given the low volubility of barium. The deposition model can be refined further to justifiably and realistically reduce the estimated concentrations that would occur (e.g. the 11 percent of the total drilling fluids would be distributed over several canyons) to the extent that incremental increases in barium, the most abundant metal, would be undetectable. For these reasons, it is doubtful that significant biological effects would occur due to deposition of drilling fluids in canyon heads.

Within submarine canyons along the southern flank of the bank, a major cause of biological impact would be a significant increase in sedimentation rate and associated suspended solids concentrations. Concern has been expressed that sessile filter-feeding organisms such as corals and sponges would be adversely affected, because the hard substrates on which they occur could be coated with a fine layer of sediment, reducing settling success of larvae (Hecker et al. 1980). High sedimentation rates could foul established colonies causing polyp retraction (e.g., Thompson and Bright 1980), reduced feeding efficiency, and growth (e.g., Hudson and Robbin 1980). Recovery from one-time applications would be likely (Hudson and Robbin 1980), but repeated or long-term exposure could cause the death of the colony. A conservative model was developed for Hydrographer Canyon in which. it was assumed that all of the drilling fluids produced *in* 1 yr would be channeled through this canyon. The rate of incremental sediment transport would be 0.28 kg/see with a suspended solids concentration of 224 mg/l. In reality only 11 percent of the drilling fluids would be potentially available for transport down the canyons and in all likelihood more than one canyon would be involved. Thus, an upper estimate of 25 mg/l suspended solids transported at a rate of 0.03 kg/see would result if all these drilling fluids are channeled through Hydrographer Canyon. These estimates diminish further if the materials are channeled through additional canyons. These hypothetical estimates cannot at present be compared to background conditions because field measurements have not been made. Field studies are currently underway to develop this information (Lamont-Ooherty Geological Observatory under contract to BLM) . It is premature at this time to reach a conclusion on the effects of Increased sedimentation on the biota of the canyons, especially on sessile filter-feeders like coral sand sponges.

4.4.5.4 Trophodynamic Effects

A major *concern* has been raised that drilling on Georges Bank with attendant discharge of drilling fluids containing large amounts of heavy metals will affect commercial fisheries due to biomagnification of these metals through the food web (ELM 1977). Effects on various stocks would presumably be reflected in greatly magnified tissue concentrations of one or more metals so that consumption would be deemed a hazard to the health of consumers. Or, high tissue burdens of metals might reduce the overall fitness of a stock leading to a decline in abundance. There is precedent behind such concerns in the documented cases of biomagnification of chlorinated hydrocarbons and mercury.

BLM (1977) discussed this issue at length and summed up its discussion as follows (pp. 12-73):

> ‘The input of heavy metals to the marine environment and accumulation in the food web due to offshore petroleum operations should be far less significant than sources of heavy metals from land in *most* coastal waters such as river runoff, sewage effluent and industrial wastes. Since the effects of heavy metal input from offshore petroleum operations into the marine food web are largely unknown, it is advisable to continue to observe and monitor the marine environment for possible accumulation in the food web.”

The benthic invertebrates of Georges Bank comprise a substantial portion of the food web that support the major fisheries stocks. Under the high development scenario only 127 km^2 of bottom area would be potentially affected which amounts to less than 0.2 percent of the area of Georges Bank (25,920 km^2). Juvenile fish in particular appear to be dependent upon the benthos for food with adults of *many* species feeding heavily on other fish (Table 4-19). Most adult flatfish appear to feed heavily on benthic invertebrates. Polychaete worms and amphipod and decapod crustaceans are the principal prey of most bottom-feeding fishes, although echinoids and ophiuroids are of importance in the diets of a few species. It is difficult to imagine how fish stocks on the bank would be adversely affected by drilling fluids discharge that in the conservative worst case would affect only 0.2 percent of the substrate over which they feed.

A detailed review of more recent literature and current research on bioaccumulation and food web biomagnification is presented in Section 2.3.4. There is little question that the metals typically found in drilling fluids could be accumulated by sessile or sedentary benthic organisms in the vicinity of a well If bottom sediment concentrations were elevated for a sufficient period of time. For example, Liss et al. (1980) showed in the laboratory that the sea scallop Placopecten magellanicus would accumulate chromium and barium in kidney tissue in significant concentrations when exposed continuously for 4 weeks to relatively high concentrations of synthetic and used muds or mud components. In the mid-Atlantic study, unexpectedly high concentrations of several metals were measured in tissues of molluscs, polychaetes, and brittle stars in the vicinity of the well (Mariani et al. 1980). Hake, starfish, and jonah crab were present in substantially increased densities in the vicinity of this well following cessation of drilling, possibly attracted by the presence of debilitated benthic prey. These organisms were not sampled and analyzed for tissue metals and there has been no documentation of biomagnification of heavy metals from drilling muds. A comparison was made with an area of heavily contaminated bottom sediments near a major sewage outfall where benthic invertebrate tissues are burdened with high metals concentrations (Section 2.3.4.3). However, tissue concentrations of a flatfish and five other bottom-feeding fish from this area did not provide evidence of biomagnification. The difficulty in interpreting results of this type of study is that there is always some doubt regarding the source of metals in predator tissues because of their generally high level of mobility.

At this time there is circumstantial evidence that biomagnification of metals from drilling fluids would not be likely to occur. On the other hand, there is insufficient evidence to conclude that it will not occur in all cases for all metals.

4.5 ADDITIONAL AREAS FOR RESEARCH

Substantially more or better quality of Information would be required to generate more confidence in, or to refine the predictions of, potential effects made in this study. In general, wherever an assumption was made that affected an important estimate, there is a need for additional information. The most important areas in which assumptions were made and the information required to supplant these assumptions are described below:

1. Additional empirical information is required on the fate and effects of drilling fluids that would be directly applicable to Georges Bank. At present, there are insufficient data on the areal extent and relative severity of benthic environmental effects to accurately predict impact of drilling across the depth range (5o to 150 m) of proposed drilling on the bank. USGS plans to monitor one exploratory drilling operation. However, there is reason to believe that the behavior of discharged drilling fluids will vary significantly with depth of water and location. Thus, it may be necessary to monitor at least two drilling operations in moderate and deep water to provide a basis for assessing the probable impact of exploratory drilling (in addition to the G-1 C.O.S.T. well data in shallow water) .

2. Similar information would be required to assess the impact of development phase drilling with investigations aimed at assessing incremental and cumulative effects of drilling multiple wells from one platform.

3* The results of the BLM-sponsored benchmark study for Georges Bank should be fully analyzed and reported to facilitate assessment of potential drilling-related impacts. Additional, replicate, background data may be needed on levels of key trace metals (e.g., barium, chromium, lead, mercury) in sediments and biota on the bank and in surrounding depositional sinks.

4. Physical, chemical, and biological characteristics of the submarine canyons on the southern flank of the bank should be described to facilitate assessment of drilling-related impacts. Lament-Doherty Geological Observatory is presently conducting such a study under contract to BLM.

5. There is a need to develop an information base that would provide for ready comparison of field data on sediment and tissue concentration of metals to laboratory bioassay results. At least two sets of measurements are needed from field samples of sediments and organism tissues: totally digested and weak-acid leached metals concentrations. The same is true of the sediments and organisms used to assay the toxicity of drilling muds and chemical additives. At present it is extremely difficult to assess whether measured or calculated metals concentrations in bottom sediments and organism tissues are sufficient to be toxic.

6. There are insufficient data available on American lobster distribution and abundance to serve as a basis for estimating possible impacts of drilling on this species.

5. REFERENCES

Aaron, J.M., B. Butman, M.H. Bothner, and N.G. Sylvester, 1980. Environmental conditions relating to potential geologic hazards on the United States Northeastern Atlantic Continental Margin, Map. MF-1 193.

Anderson, E.D., 1973. Assessment of Atlantic mackerel in ICNAF Subarea 5 and Statistical Area 6. Int. Comm. Northwest Atlantic Fish. Annual Meet. 1973, Res. Dec. No. 14, Serial No. 2916, 37 pp.

Anderson, J.B. and R.R. Schwarzer, 1979. Sedimentology and trace metal concentrations in sediments and organisms. In: W.B. Jackson, ed. Environmental assessment of an active oilfield in the northwestern Gulf of Mexico, 1977-1979. Volume III, physical and chemical investigations. NOAA/NMFS/Environmental Protection Agency.

Armstrong Associates, 1968. Causeway studies, Turnagain Arm crossing, Alaska. Report of Alaska Dept. of Highways, November.

Ayers, R.C., Jr., 1980. Comments on the fate and effects of drilling discharges in the marine environment. Response for U.S. Senate Joint Hearing of the Committee on Commerce, Science, and Transportation and the Subcommittee on Energy Resources and Materials regarding Senate Bill S-2119, Georges Bank Protection Act.

Ayers, R.C., Jr., T.C. Sauer, Jr., R.P. Meek, and G. Bowers, 1980a. An environmental study to assess the Impact of drilling discharges in the mid-Atlantic. 1. Quantity and fate of discharges. Proc. Symposium Research on Environmental Fate and Effects of Drilling Fluids and Cuttings, Lake Buena Vista, Florida, January 21-24, 1980.

Ayers, R.C., Jr., T.C. Sauer, Jr., D.O. Stuebner, and R.P. Meek, 1980b. An environmental study to assess the effect of drilling fluids on water quality parameters during high rate, high volume discharges to the ocean. Proc. Symposium Research on Environmental Fate and Effects of Drilling Fluids and Cuttings, Lake Buena Vista, Florida; January 21-24, 1980.

Barrett, J.R., Jr., 1965. Subsurface currents off Cape Hatteras. Deep-Sea Research, 12:173-184.

Bascom, W., 1964. Waves and beaches, the dynamics of the ocean surface. Doubleday, Anchor Books, Science Study Series, New York, NY.

Bayne, B.L., J. Widdows, and C. Worrall, 1977. Some temperature relationships on the physiology of two ecologically distinct bivalve populations, 379-400. In: F.J. Vernberg, A.C. Calabrese, F.P. Thurberg, and W.B. Vernberg, eds. Physiological Responses of Marine Biota to Pollutants. Academic Press, New York, NY.

BCF (Bureau of commercial Fisheries), 1958. Deck logs from the 1958 R.V. John N. Cobb exploratory shrimp trawl survey in lower Cook Inlet.

_____, 1963. Deck logs from the 1963 R.V. Yaquina exploratory shrimp trawl survey in lower Cook Inlet.

_____, 1968. Deck logs from the 1968 R.V. Viking Queen exploratory scallop fishing survey in lower Cook Inlet.

B.C. Research, Division of Applied Biology, 1976. Marine toxicity studies on drilling fluid wastes. B.C. Research, 28 pp.

Beak Consultants, Ltd., 1978. Heavy metals project, MacKenzie Delta and Estuary. A Report for Imperial Oil Limited, Calgary, Alberta, Canada, January.

Beardsley, R.C., W.D. Boicourt, and D.V. Hansen, 1976. Physical oceanography of the Middle Atlantic Bight. Limnology and Oceanography Special Symposium, 2:20-24.

Beckett, A., B. Moore, and R. Weir, 1976. Acute toxicity of select drilling components to rainbow trout. Can. Environ. Protection Service. Edmonton, Alberta, Canada.

Benayoun, G., S.W. Fowler, and B. Oregioni,1974. Flux of cadmium through euphausiids. Mar. Biol., 27:205-212.

Benech, S.V., R. Bower, and R.A. Pimentel, 1980. Chronic effects of drilling fluids exposure to fouling community composition on a semi-submersible exploratory drilling vessel. Proc. symposium Research on Environmental Fate and Effects of Drilling Fluids and Cuttings, Lake Buena Vista, Florida, January 21-24, 1980.

Betzer, P.R. and M.E.Q. Pilson, 1971. Particulate iron and the nepheloid layer in the western north Atlantic, Caribbean, and Gulf of Mexico. Deep Sea Research, 18:753-761.

Biesinger, K.W. and G.N. Christensen, 1972. Effects of various metals on survival growth, reproduction and metabolism of _Daphnia magna_. J. Fish, Res. Bd. Canada, 29:1691-1700.

Bigelow, H.B., 1927. Physical oceanography of the Gulf of Maine. U*S. Fisheries Bulletin, 40(2):511-1027.

_____, 1933. Studies of the waters on the continental shelf. Cape Cod to Chesapeake Bay. Part 1. The cycle of temperature. Pap. Phys. Oceanogr., 2(4):135 pp.

Bigelow, H.B., L. Lillick, and M. Sears, 1940. Phytoplankton and planktonic protozoa of the offshore waters of the Gulf of Maine. Part I. Numerical distribution. Trans. Am. Phil. Soc., 31:149-191.

Bigelow, H.B. and W.C. Schroeder, 1953. Fishes of the Gulf of Maine. Fishery Bulletin 74. U.S Fish and Wildlife Service, Washington, DC, 577 pp.

Bigelow, H.B. and M. Sears, 1935* Studies of the waters on the continental shelf. Cape Cod to Chesapeake Bay. Part II, Salinity. Pap. Phys. Oceanogr., 4(l).

Blackburn, J., 1977. Pelagic and demersal fish assessment *in the* lower Cook Inlet estuary system. Annual report from Alaska Department *of* Fish and Game to NOAA/OCSEAP.

Blackburn, J.E., K. Anderson, C.I. Hamilton, and S.J. Staff, 1979. Pelagic and demersal fish assessment in the lower Cook Inlet estuary sys tern. Final report from Alaska Department of Fish and Game to NOAA/OCSEAP, 330 pp.

BLM (Bureau of Land Management), 1976. Lower Cook Inlet final environmental impact statement. 3 volumes.

_____, 1976. Proposed 1976 outer continental shelf oil and gas lease sale-- lower Cook Inlet. Final EIS. Vol. 4, 562 pp.

_____, 1977. Final environmental statement. OCS Sale No. 42, Offshore the North Atlantic States. U.S. Department of the Interior, Washington, DC., Volumes 1-5.

_____, 1979. Final environmental impact statement. Proposed 1979 Outer Continental Shelf oil and Gas Lease Sale Offshore the Mid-Atlantic States. OCS Sale No. 49, Vol. 1 of 3. (Section 4.1).

_____, 1979[?]. Final supplement to environmental statement. OCS Sale No. 42, Offshore the North Atlantic States. U.S. Department of the Interior, Washington, DC.

_____, 1980. Draft EIS for proposed OCS oil and gas lease sale, lower Cook Inlet and Shelikof Strait, Sale No. 60, Vol. 3, part 2.

Blom, B.E., T.F. Jenkins, D.C. Leggett, and R.P. Murrmann, 1976. Effect of sediment organic matter on various chemical constituents during disposal of dredged material. Contract Report D-76-7. U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Bothner, M.H., E.C. Spiker, W.M. Ferrebee, and D.L. Peeler, 1980. Texture, clay mineralogy, trace metals, and age of cored sediments in environmental geologic studies in the Georges Bank area, United States northeastern Atlantic outer continental shelf, 1975-1977. John M. Aaron, ed. United States Geological Survey Open File Report No. S0-240.

Bothner, M.H., E.C. Spiker, and PoP. Johnson (in press). ^{14}C and ^{210}Pb profiles in the 'Mud Patch" *on* the continental shelf off southern New England. Evidence for Modern Accumulation.

Bouma, A.H., M.A. Hampton, T.P. Frost, M.E. Torresan, R.C. Orlando, and J.W. Whitney, 1978. Bottom characteristics *of* lower Cook Inlet, Alaska. U.S. Geological Survey Open File Report No. 78-236.

Bouma, A.H., M.A. Hampton, and R.C. Orlando, 1977. Sand waves and other bedforms in lower Cook Inlet, Alaska. Marine Geotechnique, 2:291-308.

Bouma, A.H. M.A. Hampton, M.L. Rappeport, P.G. Teleki, J.W. Whitney, R.C. Orlando, and M.E. Torresan, 1977 (manuscript). Movement of sandwaves in lower Cook Inlet, Alaska. Offshore Tech. Conf., OTC 3111, 18 pp.

_____, 1978. Movement of sandwaves in lower Cook Inlet, Alaska. Offshore Tech. Conf., OTC 3311, p. 2271-2284.

Bouma, A.H., M.A. Hampton, M.P.Wennekens, and J.A. Dygas, 1977. Large dunes and other bedforms in lower Cook Inlet, Alaska. Offshore Tech. Conf., OTC 2737.

Bouma, A.H., R. Rezak, and R.F. Chmelik, 1969. Sediment transport along ocean density interfaces. Geol. Sot. Am. Abstr., 7:259-260.

Bourne, N., 1964. Scallops and the offshore fishes of the maritime. Fisheries Research Board Canada, Bulletin No. 145, 60 pp.

Bowers, G.W. and M.K. Goldenblatt, 1978. Calibration of a predictive model for instantaneously discharged dredged material. EPA 600/3-70-089, September, 1978, 155 pp.

Bowers, S.P., 1976. Modeling of coastal dredged material disposal: In: Proc. of the Specialty Conference on Dredging and Its Environmental Effects, p. 202-225.

Bowman, R.E., 1977. Seasonal food habits of demersal fish In the northwest Atlantic--1972. NMFS, Northeast Fisheries Center, Woods Hole, MA. Lab. Ref. No. 77-01. 3 pp.

Bowman, R.E., 1979. Feeding habits of ten northwest Atlantic juvenile groundfish. NMFS, Northeast Fisheries Center, Woods Hole, MA. Lab. Ref. No. 79-43, 22 pp.

Brandsma, M.G., L.R. Davis, R.C. Ayers, and T.C. Sauer, Jr., 1980. A computer model to predict the short-term fate of drilling discharges in the marine environment. Proc. Symposium Research on Environmental Fate and Effects of Drilling Fluids and Cuttings, Lake Buena Vista, Florida, January 21-24, 1980.

Brandsma, M.G. and D.J. Divorky, 1976. Development of models for prediction of short-term fate of dredged material discharged in the estuarine environment. Contract Rpt. D-76-5. U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Britch, R.P., 1976. Tidal currents in Knik Ann, Cook Inlet, Alaska. Masters thesis prepared at University of Alaska, Institute of Marine Resources, Fairbanks, AK.

Brewer, U.A., Jr., H.W. Searby, J.L. Wise, H.F. Diaz, and A.S. Prechtel, 1977* Climatic atlas of the outer continental shelf waters and coastal regions of Alaska. Arctic Environmental Information and Data Center and National Climatic Center, 439 pp.

Brown, B.E., 1980. The status of the fishery resources on Georges Bank. NMFS, Northeast Fisheries Center, Woods Hole, MA. Lab. Ref. No. 80-10.

Brown, D.A., C.A. Bowden, K.W. Chatel, and T.R. Parsons, 1977. The wildlife community of Ions Island jetty, Vancouver, BC, and heavy-metal pollution effects. Environ. Conserv., 4:213-216.

Bumpus, D.F. , 1973. A description of the circulation on the continental shelf of the east coast of the United States. Progress in Oceanography, 6:111-157.

_____, 1976. Review of the physical oceanography of Georges Bank. International Commission for the Northwest Atlantic Fisheries Research Bulletin, 12:119-134.

Bumpus, D.F. and L.M. Lauzier, 1965. Surface circulation on the continental shelf of eastern North America between Newfoundland and Florida. American Geographic Society Serial Atlas of the Maine Environment. Folio 7, HPL, 8 pp.

Burbank, D.C., 1974. Suspended sediment transport and deposition in Alaskan coastal waters. University of Alaska, Institute of Marine Science, 222 pp.

_____, 1977. Circulation studies in Kachemak Bay and lower Cook Inlet, Alaska. In: L.L. Trasky, L.B. Flagg, and D.C. Burbank, eds. Environmental Studies of Kachemak Bay and Lower Cook Inlet, Alaska Department of Fish and Game, Anchorage, AK. Vol. III.

Burrell, D.C. and D.W. Wood, 1967. Clay-inorganic and organic-inorganic association in aquatic environments, Part II, Institute of Marine Science, University of Alaska, Fairbanks, AK.

Butman, B., 1980. Aspects of currents and sediment movement on Georges Bank. Lowell Lecture Series, presented at the New England Aquarium.

Butman, B., R.C. Beardsley, B. Magnell, J.A. Vermersch, R.J. Schlitz, R. Limeburner, and M.A. Noble, 1980 (in press). The mean circulation of Georges Bank. WHOI Contribution No. 4722.

Cabrera, J., 1968. Survival of the oyster Crassotrea virginica (Gmelin) in the laboratory under the effects of oil drilling fluids spilled in the Laguna de Tamiahua, Mexico. Gulf Research Reports (3): 197-213.

Calabrese, A., F.P. Thurberg, M.A. Dawson, and D.R. Wenzloff, 1975. Sublethal physiological stress induced by cadmium and mercury in the winter flounder Pseudopleuronectes americanus. In: J.H. Koeman and J.J.T.W.A. Strik, eds. Sublethal Effects of Toxic Chemicals on Aquatic Animals, Elsevier Publishing Co., Amsterdam, p. 15-21.

Cantelmo, F.R., MoE. Tagatz, and K.R. Rae, 1979. Effects of barite on meiofauna in a flow through experimental ecosystem. Marine Environmental Research, 2:301-310.

Capuzzo, J.M., and J.J. Sassner, 1977. The effect of chromium on filtration rates and metabolic activity of Mytilus edulis L. and Mya arenaria L. In: F.J. Vernberg, A. Calabrese, F.P. Thurberg, and W.B. Vernberg, eds. Physiological Responses of Marine Biota to Pollutants. Academic Press, Inc., New York, NY, v. 225-237.

Cardwell, RoD., C.E. Woelke, M.I. Carr, and E. Sanborn, 1976. Sediment and elutriate toxicity to oyster larvae. In: Proc. of the Specialty Conf. on Dredging and its Environmental Effects. Mobile, Alabama, January 26-28, p. 684-718.

Carlisle, J.B., C.H. Turner, and E.E. Ebert, 1964. Artificial habitat in the marine environment. California Dept. of Fish and Game, Fish. Bull., 124:73-74.

Carls, M.G. and S.D. Rice, 1981. Toxicity of oil well drilling muds to Alaskan larval shrimp and crabs. Final report for Outer Continental Shelf Energy Assessment Program. U.S. Department of the Interior, Bureau of Land Management. 33 pp.

CarlSon, R.F. and C.E. Behlke, 1972. A computer model of the tidal phenomena in Cook Inlet, Alaska. Institute of Water Resources Report IWR-17, University of Alaska, Fairbanks, AK.

Carney, L.L. and L. Harris, 1975. Thermal degradation of drilling mud additives. In: Conf. Proc. on Environmental Aspects of Chemical Use in Well-Drilling Operations, Houston, Texas, May 21-23, EPA-560/1-75-004, p. 203-221.

Carr, R.S., L.A. Reitsema, and J.M. Neff, 1980. Influence of a used chrome lignosulfonate drilling mud on the survival, respiration, feeding activity, and net growth efficiency of the opposum shrimp Mysidopsis almyra. Proc. Symposium Research on Environmental Fate and Effects of Drilling Fluids and Cuttings, Lake Buena Vista, Florida, January 21-24, 1980.

Carsola, A.J., 1975. Oceanographic and meteorological study of the lower Cook Inlet, Alaska. Prepared by Lockheed Ocean Laboratory for Shell Oil Company, 156 pp.

Chen, K.Y., S.K. Gupta, A.Z. Sycip, J.C.S. Lu, M. Knezevic, and W-W. Choi, 1976. Research study on the effect of dispersion, settling, and resuspension on migration of chemical constituents during open-water disposal of dredged material. Contract Report D-76-1. Us. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Chenoweth, 1977. In: TRIGOM, undated.

Chesser, B.G. and W.H. McKenzie, 1975. Use of a bioassay test evaluation on the toxicity of drilling fluid additives on Galveston Bay shrimp. In: Conf. Proc. on Environmental Aspects of Chemical Use in Well-Drilling Operations. Houston, Texas, May 21-23. EPA-560/l-75-004.

Chow, T.S. and C.B. Snyder, 1980. Barium in marine environment: a potential indicator of drilling contamination. Proc. symposium Research on Environmental Fate and Effects of Drilling Fluids and Cuttings, Lake Buena Vista, Florida, January 21-24, 1980.

Clark, R.C., 1976. Levels and sources of critical trace metals in the marine environment. OCSEAP Final Rpt., RU 75, November 1976. In: Biol. Studies, March 1979 (5).

Clark, R.C. and J.S. Finley, 1974 (*In* preparation). Uptake and loss of petroleum hydrocarbons by mussels (Mytilus edulis) in laboratory experiments.

Clark, S.H. and B.E. Brown, 1976. Changes in biomass of finfishes and squids from the Gulf of Maine to Cape Hatteras, 1963-74, as determined from research vessel survey. Fish. Bull. 75(1):1-21.

Clemens, H.P. and W. Jones, 1954. Toxicity of brine water from oil wells. Trans. Am. Fish. Sot., 84:97-109.

CNA (Center for Natural Areas), 1977. A summary and analysis of environmental information on the continental shelf from the Bay of Fundy to Cape Hatteras, Vol. 1, Bk. 1.

_____, 1977. A summary *and* analysis of environmental information on the continental shelf from the Bay of Fundy to Cape Hatteras, Vol. 1, Bk. 2, Chapters VI-XIV. Prepared for Bureau of Land *Management.*

Cobb, S.J., 1976. The American lobster: the biology of Homarus americanus. Univ. Rhode Island, Kingston, RI, 32 pp.

Cohen, E.B. and W.R. Wright, 1979. Primary productivity on Georges Bank with an explanation of why it is so high. NMFS, Northeast Fisheries Center, Woods Hole, MA. Lab. Ref. No. 79-53, 7 pp.

ColtOn, J.B., Jr. and R.R. Byron, 1977. Gulf of Maine-Georges Bank ichthyoplankton collected on ICNAF larvae herring surveys, September 1971-February 1975. NOAA Tech. Report SSRF-717, 34 pp.

Colton, J.B., R.R. Marak, S. Nickerson, and R.F. Stoddard, 1968. Physical, chemical, and biological observations on the continental shelf, Nova Scotia to Long Island, 1964-66. U.S. Fish and Wildlife Service. Data Report 23. Microfiche, 1 p.

Colton, J.B., Jr., W.G. Smith, A.W. Kendall, Jr., P.L. Berrien, and M.P. Fahay, *1979.* Principal spawning areas and times *of* marine fishes, Cape Sable to Cape Hatteras. Fish. Bull., 76(4):911-915.

Colton, J.B. and R.F. Stoddard, 1972. Average monthly seawater temperatures. Nova Scotia to Long Island, 1940-1959. Amer. Geogr. Sot. Serial Atlas of the Marine Environment. Folio 21.

Conklin, P.J., D.G. Doughtie, and K.R. Rae, 1980. Effects of barite and used drilling muds on crustaceans with particular reference to the grass shrimp, Palaemonetes pugio. Proc. Symposium Research on Environmental Fate and Effects of Drilling Fluids and Cuttings, Lake Buena Vista, Florida, January 21-24, 1980.

Cooper, R.A. and J.R. Uzmann, 1977. Ecology of juvenile and adult clawed lobsters, Homarus americanus, Homarus gammarus, and Nephrops nowegicus. In: B.F. Phillips and J.S. Cobb, eds. Workshop on Lobster and Rock Lobster Ecology and Physiology. Div. Fisheries and Oceanography, C.S.I.R.O. , Melbourne, Australia, Circ. No. 7, p. 187-208.

Crippen, R.W., G. Green, and S.L. Hodd, 1980. Metal levels in sediment and benthos resulting from a drilling fluid discharge into the Beaufort Sea. Proc. Symposium Research on Environmental Fate and Effects of Drilling Fluids and Cuttings, Lake Buena Vista, Florida, January 21-24, 1980.

Cunningham, P.A. and M.R. Tripp, 1975a. Accumulation, tissue distribution, and elimination of $^{203}HgCl_2$ and $CH_3{}^{203}HgCl$ in tissues of the American oyster, Crassostrea virginica. Mar. Biol., 31:321-334.

_____, 1975b. Factors affecting the accumulation and removal of mercury from tissues of the American oyster, Crassostrea virginica. Mar. Biol., 31:311-319.

Dale, N.G., 1974. Bacteria in intertidal sediments: factors related to their distribution: Limnol. Oceanogr., 19:509-518.

Dames & Moore, 1976. Marine plant community studies, Kachemak Bay, Alaska. Final report for Alaska Department of Fish and Game, 288 pp.

_____, 1977a. Reconnaissance of the intertidal and shallow subtidal biotic assemblages in lower Cook Inlet. Final report for Department of Commerce, NOAA/OCSEAP, 315 pp.

_____, 1977b. An ecological assessment of the littoral zone along the outer coast of the Kenai Peninsula. Final report for Alaska Department of Fish and Game, 101 pp.

_____, 1978a. Drilling fluid dispersion and biological effects study for the lower Cook Inlet C.O.S.T. well. Final report to the Atlantic Richfield Company, Anchorage, Alaska. 309 pp.

_____, 1978b. Lower Cook Inlet biological studies, lease block clearing, Area 2. Prepared for Exxon Company, U.S.A., 38 pp.

_____, 1978c. Lower Cook Inlet biological studies, lease block clearing, Area 5. Prepared for ARCO Oil and Gas Co., 39 pp.

_____, 1978d. Lower Cook Inlet biological studies, lease block clearing, Area 4. Prepared for Marathon Oil Company, 35 pp.

_____, 1978e. Lower Cook Inlet biological studies, lease block clearing, Area 3. Prepared for Exxon Company, U.S.A., 46 pp.

_____, 1978f. Lower Cook Inlet biological studies, lease block clearing, Area 1. Prepared for Marathon Oil Company, 31 pp.

_____, 1979. Ecological studies of intertidal and shallow subtidal habitats in lower Cook Inlet. Annual report for Department of Commerce, NOAA/OCSEAP, 261 pp.

_____, 1980a. Investigations on shallow subtidal habitats and assemblages in lower Cook Inlet. Final Report prepared for Inst. of Mar. Sci., Univ. of Alaska, 184 pp.

_____, 1980b. Ecological studies of intertidal and shallow subtidal habitats in lower Cook Inlet, Alaska. Final Report prepared for NOAA/OCSEAP, 406 pp.

Daugherty, F.W., 1951. Effects of some chemicals used in oil well drilling on marine animals. Sewage and Industrial Wastes. 23(10): 1282-1286.

Dawson, M.A., E. Gould, F.P. Thurberg, and A. Calabrese, 1977. Physiological response of juvenile striped bass, Morone saxatilis, to low levels of cadmium and mercury. Chesapeake Sci., 18:353-359.

de Goeij, J.J.M., V.P. Gwinn, D.R. Young, and A.J. Mearns, 1974. Neutron activation analysis trace-element studies of Dover sole liver and marine sediments. In: Comparative Studies of Food and Environmental Contamination. International Atomic Energy Agency, Vienna, p. 189-200.

Derby, C.D. and J. Atema, 1980 (to be published). Influence of drilling muds on the primary chemosensory neurons in walking leg of the lobster, Homarus americanus. Boston University Marine Program.

Dey, D.B. and D.M. Damkaer, 1977. Initial zooplankton investigations in Prince William Sound, Gulf of Alaska and lower Cook Inlet. Annual Report for NOAA/OCSEAP by NOAA/PMEL, 138 pp.

Dickey, T.D. and M.D. Fortin, 1980. A numerical model of dispersion of drilling discharges in the marine environment. Proc. symposium Research on Environmental Fate and Effects of Drilling Fluids and Cuttings, Lake Buena Vista, Florida, January 21-24, 1980.

Dillon, W.P. and H.B. Zimmerman, 1970. Erosion by biological activity in two New England submarine canyons. Journal of Sedimentary Petrology, 40:542-547.

Drake, D.E., 1971. Suspended sediment and thermal stratification in Santa Barbara Channel, California. Deep Sea Research, 18:763-769.

_____, 1976. Suspended sediment transport and mud deposition on continental shelves. In: D.J. Stanley and D. J.P. Swift, eds. Marine Sediment Transport and Environmental Management, John Wiley & Sons, New York, NY, p. 127-158.

Drake, D.E., R.L. Kolpak, and P.J. Fischer, 1972a. Comments on the dispersal of suspended sediment across the continental shelves. In: D.J.P. Swift, D.B. Duane and O.H. Pilkey, eds. Shelf Sediment Transport: Process and Pattern. Dowden, Hutchinson & Ross, Stroudsburg, PA.

_____, 1972b. Sediment transport on the Santa Barbara-Oxnard Shelf, Santa Barbara Channel, California. In: D.J.P. Swift, D.B. Duane and O.H. Pilkey, eds. Shelf Sediment Transport: Process and Pattern. Dowden, Hutchinson & Ross, Stroudsburg, PA.

Drapeau, D., 1973. Sedimentology of herring spawning grounds on Georges Bank. ICNAF Res. Bulletin, (10):151-162.

Driskell, W., 1977. Benthic reconnaissance of Kachemak Bay, Alaska. In: L.L. Trasky, L.B. Flagg, and D.C. Burbank, eds. Environmental Studies of Kachemak Bay and Lower Cook Inlet. Alaska Department of Fish and Game, Anchorage, AK. Vol. VII.

Dube, G.P., R.G. Lough, and R.E. Cohen, 1977. Comparison of Georges Bank zooplankton community in relation to growth and mortality of herring larvae during two winter periods. NMFS, Northeast Fisheries Center, Woods Hole, MA. Lab. Ref. No. 77-15 (also ICES Doc. C.M. 197/L:27).

Ecomar, Inc., 1978. Tanner Bank mud and cuttings study. Prepared for Shell Oil Company.

Edge, B.L. and B.C. Dysart, 1972. Transport mechanisms governing sludges and other materials barged to sea. Civil Engineering and Environmental Systems Engineering, Clemson University, Clemson, SC.

Eganhouse, R.P. and D.R. Young, 1978. Total and organic mercury in benthic organisms near a major submarine wastewater outfall system. Bull. Environ. Contain. Toxicol. 19:758-766.

Eganhouse, R.P., D.R. Young, and J.N. Johnson, 1978. Geochemistry of mercury in Pales Verdes sediments. Environ. Sci. & Tech. 12:1151-1157.

Einstein, H.A. and R.B. Krone, 1962. Experiments to determine modes of cohesive sediment transport in saltwater. Journal Geophys. Res., 67:1451-1561.

Eittreim, S. and M. Ewing, 1972. Suspended particulate matter in the deep waters of the North American basin. In: A.L. Gordon, ed. Studies in Physical Oceanography, New York, NY, p. 123-167.

Emery, X.0, 1956. Deep standing waves in California basins. Limnology and Oceanography, 1:35-41.

_____, 1969. The continental shelves. Scientific American, 221:106-122.

Emery, K.O. and E. Uchupi, 1972. Western North Atlantic ocean. Topography, rocks, structure, water, life and sediments. Amer. Assoc. Petr. Geol., Memoir, 17:532 pp.

ENDEco (Environmental Devices Corp.), 1976. Summary--special water monitoring study, C.O.S.T. Atlantic G-1 well conducted during the period April 14 to July 14, 1976.

English, T.S., 1977. Lower Cook Inlet meroplankton. Annual Report from the University of Washington to NOAA/OCSEAP.

ERCO, 1978. Marine environmental studies of the New England Outer Continental Shelf. Draft Final Report, prepared for the Bureau of Land Management. 5 volumes.

Erikson, D., 1977. Distribution, abundance, migration, and breeding locations of marine birds, lower Cook Inlet. In: L.L. Trasky, L.B. Flagg, and D.C. Burbank, eds. Environmental Studies of Kachemak Bank and Lower Cook Inlet, Alaska Department of Fish and Game, Anchorage, AK, 182 pp.

Evans, C.D., E. Buck, R. Buffler, G. Fisk, R. Forbes, and W. Parker, 1972. The Cook Inlet environment--a background study of available knowledge. Resource and Science Services Center, University of Alaska, Anchorage, AK.

Evans, D.J., 1971. Nova Scotia environmental report. Prepared for Shell Canada Resources, Ltd. by Ocean Science and Engineering, Inc., Rockville, MD.

Ewing, J.A. 1973. Wave-induced bottom currents on the outer shelf. Marine Geology, 15:M31-M35.

Ewing, M. and E.M. Thorndike, 1965. Suspended matter in deep ocean water. Science, 147:1291-1294.

Falk, M.R. and M.J. Lawrence, 1973. Acute toxicity of petrochemical drilling fluids components and wastes to fish. Environment Canada, Fisheries and Marine Service Technical Rpt., Ser. No. CEN T-73-1.

Feder, H.M., A.J. Paul, M. Hoberg, S. Jewett, et al., 1980. Distribution, abundance, community structure, and trophic relationships of the nearshore benthos of Cook Inlet. Final Report to NOAA/OCSEAP, 609 pp.

Feeley, R.A. and J.D. Cline, 1979. Composition, transport, and deposition of suspended matter in lower Cook Inlet and Shelikof Strait, Alaska. NOAA-OCSEAP/BLM, RU 159, 64 pp.

Feeley, R. A., J.D. Cline, and G.J. Massoth, 1978. Transport mechanisms and hydrocarbon absorption properties of suspended matter in lower Cook Inlet. NOAA/BLM Annual Reports of Principal Investigations for the year ending March 1978, Vol. VIII, pp. 11-69.

Feeley,R.A. , G.J. Massoth, A.J. Paulson, and M.F. Lamb, 1980. Distribution and composition of suspended matter in Norton Soutn and lower Cook Inlet, Alaska. Annual Report from NOAA/PMEL to NOAA/OCSEAP, 101 pp.

Feulner, A.J., J.M. Childers, and V.W. Norman, 1971. Water resource of Alaska. U.S. Geological Survey, Water Resources Division, Alaska District, Open File Report.

Flagg, C.N., 1979. Interaction of a warm-core eddy with the New England continental Shelf. Abstract presented at the 2nd Informal Workshop on the Oceanography of the Gulf of Maine and Adjacent Seas, May 1979. Dalhousie University, Halifax, Nova Scotia.

Folger, D.W., S.A. Wood, M.H. Bothner, and B. Butman, 1980. Submersible operations on Georges Bank. Environmental Geologic Studies in the Georges Bank area, United States northeastern Atlantic outer continental shelf. Journal of Physical Oceanography, 1:82-91.

Fritz, R.L., 1965. Autumn distribution of groundfish species in the Gulf of Maine and adjacent waters, 1955-1961. Serial Atlas of the Marine Environment, Am. Geol. Sot. Folio 1O-A.G.I.

Gait, J.A., 1971. A numerical investigation of pressure-induced storm surges over the continental shelf. Journal of Physical Oceanography, 1:82-91.

Gambrell, R.P., R.A. Khaud, and W.H. Patrick, Jr., 1978. Disposal alternatives for contaminated dredged material as a management tool to minimize environmental effects. Technical Report DS-78-8. U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Gambrell, R.P., R.A. Khaud, M.G. Verloo, and W.H. Patrick, Jr., 1977. Transform tions of heavy metals and plant nutrients in dredged sediments as affected by oxidation reduction potential and pH, Volume 11: Materials and Methods/Results and Discussion. Contract Report D-77-4. U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Garrison, L.E. and R.L. McMaster, 1966. Sediments and geomorphology of the continental shelf off southern New England: Marine Geology, 4:273-289.

Gatto, L.W., 1976. Baseline data on the oceanography of Cook Inlet, Alaska. Cold Regions Research and Engineering Laboratory, Hanover, NH, CRREL Report 76-25, 84 pp.

George, R. Y., 1975. Potential effects of oil drilling and dumping activities on marine biota. In: Conf. Proc. on Environmental Aspects of Chemical Use in Well-Drilling Operations, Houston, Texas, May 21-23, 1975. EPA-550/1-75-004, p. 333-356.

Gerber, R.P., E.S. Gilfillan, B.T. Page, D.S. Page, and J.B. Hotham, 1980. Short and long term toxic effects of used drilling fluids on marine organisms. Proc. Symposium Research on Environmental Fate and Effects of Drilling Fluids and Cuttings, Lake Buena Vista, Florida, January 21-24, 1980.

Gettleson, D.A. and C.E. Laird, 1980. Benthic barium levels in the vicinity of six drill sites in the Gulf of Mexico. Proc. Symposium Research on Environmental Fate and Effects of Drilling Fluids and Cuttings, January 1980, Lake Buena Vista, Florida.

Giam, C.S., cd., 1977. Pollutant effects on marine organisms. Proceedings of a workshop held in May 1976. Lexington Books, D.C. Heath and Company, 211 pp.

Gilfillan, E.S., R.P. Gerber, S.A. Hanson, and D.S. Page, 1980. Effects of various admixtures of used drilling mud on the development of a boreal soft bottom community. Proc. Symposium Research on Environmental Fate and Effects of Drilling Fluids and Cuttings, Lake Buena Vista, Florida, January 21-24, 1980.

Gilfillan, E.S. and J.H. Vandermeulin, 1978. Alterations in growth and physiology of soft-shell clams, Mya arenaria, chronically oiled with Bunker C from Chedabucto Bay, Nova Scotia, 1970-76. J. Fish. Res. Bd. Can., 35:630-636.

Gould, F., R.S. Collier, J.J. Karolus, and S. Givens, 1976. Heart transaminase in the rock crab, Cancer irroratus, exposed to cadmium salts. Bull. Envir. Contain. To%., 15:635-643.

Graham, J.J. and S.B. Chenoweth, 1973. Distribution and abundance of larvae herring, Clupea haengus harengus L. over egg beds on Georges Bank. ICNAF Res. Bull., No. 10:141-150.

Grahl-Nielsen, O., S. Sundby, K. Westerheim, and S. Wilhelmsen, 1980. Petroleum hydrocarbons in sediment resulting from drilling discharges from a production platform in the North Sea. Proc. Symposium Research on Environmental Fate and Effects of Drilling Fluids and Cuttings, Lake Buena Vista, Florida, January 21-24, 1980.

Grantham, C.K. and J.P. Sloan, 1975. Toxicity study drilling fluid chemicals on aquatic life. In: Conf. Proc. on Environmental Aspects of Chemical Use in Well-Drilling Operations? Houston, Texas, May 21-23, 1975. EPA-550/l-75-004, p. 103-112o

Gray, G.W., Jr., undated. Investigation of the basic life history of the red crab (Geryon quinqudens). Completion Rpt. P.L. 88-309, Project 3-46-R. Rhode Island Div. Conservation, 6 pp.

Griffiths, R.P. and R.Y. Morita, 1979. Study of microbial activity and crude oil-microbial interactions in the waters and sediments of Cook Inlet and the Beaufort Sea. Annual Report to NOAA/OCSEAP, 80 pp.

Gripenberg, S., 1934. A study of the sediments in the north Baltic and adjoining seas. Fennia, 60(3):1-231.

Grosslein, M.D. and E. Bowman, 1973. Mixture of species in SA 566. International Commission for the Northwest Atlantic Fisheries, Redbook 1973, Part XII, 169.

Gusey, W.F., 1977. The fish and wildlife resources of the Georges Bank region. Shell Oil Company, Houston, TX.

Haedrich, R.L., G.T. Rowe, and P.T. Polloni, 197S. Zonation and faunal composition of epibenthic populations on the continental slope south of New England. Journal of Marine Research, 33(2):191-212.

Harlett, J.C. and L.K. Kulm, 1973. Suspended sediment transport on the northern Oregon continental shelf. Geological Society of America Bulletin, 84:3815-3826.

Hatcher, P.G. and D.A. Segar, 1976. Chemistry and continental shelf sedimentation. In: D.J. Stanley and D.J.P. Swift, eds. Marine Sediment Transport and Environmental Management. Wiley-Interscience, New York, NY.

Hathaway, John C. compiled and cd., 1971. Data file, Continental Margin Program, Atlantic Coast of the United States. vol. 2. Samples Collection and Analytical Data. Woods Hole Oceanographic Inst., Ref. No. 71-15, U.S. Geol. Survey, Woods Hole, MA.

Hausknecht, K.A., 1979. Concentration and distribution of trace metals in suspended particulate matter on the New England outer continental shelf. Abstract presented at the 2nd Informal Workshop on the Oceanography of the Gulf of Maine and Adjacent Seas, May 1979. Dalhousie University, Halifax, Nova Scotia.

Haven, D.S. and R. Morales-Alamo, 1972. Biodeposition as a factor in sedimentation of fine suspended solids in estuaries. In: C.W. Nelson, cd.. Environmental Framework of Coastal Plain Estuaries, Geol. Sot. Am. Mere., 133:121-130.

Hayes, MoO., P.J. Brown, and J. Michel, 1977. Coastal morphology and sedimentation, lower Cook Inlet, Alaska. In: L.L. Trasky, L.B. Flagg, and D.C. Burbank, eds. Environmental Studies of Kachemak Bay and Lower Cook Inlet, Alaska Department of Fish and Game, Anchorage, AK* Vol. II, 107 pp.

Haynes, E.B., 1977. Summary status on the distribution of king crab and pandalid shrimp larvae, Kachemak Bay--lower Cook Inlet, Alaska, 1976. In: L.L. Trasky, L.B. Flagg, and D.C. Burbank, eds. Environmental Studies of Kachemak Bay and Lower Cook Inlet, Alaska Department of Fish and Game, Anchorage* AK. vol. IV, 52 pp.

Hecker, B., G. Blechschmidt, and P. Gibson, 1980. Final report for the canyon assessment study in the mid- and north Atlantic areas of the Us. Outer Continental Shelf. U.S. Department of the Interior, Bureau of Land Management, BLM1-AA551-CT8-49.

Hedgpeth, J.W., 1957. Sandy beaches. In: J.W. Hedgpeth, ed. Treatise on Marine Ecology and Paleoecology, Geol. Sot. Amer. Memoir 67, Washington, DC, p. 587-608.

Hein, J.R., A.H. Bouma, M.A. Fisher, M.A. Hampton, E.W. Scott, and C.L. Wilson, 1979. Resource report for proposed OCs Sale No. 60, Lower Cook Inlet-Shelikof Strait, Alaska. U.S.G.S. Open File Report No. 79-600, 38 pp.

Hennemuth, R.C., 1976. Fisheries and renewable resoruces of the Northwest Atlantic Shelf. In: B. Manowitz, ed. Effects of Energy Related Activities on the Atlantic Continental Shelf. Brookhaven National Laboratory, Associated Univ., Inc., p. 146-166.

Herbert, D.W.M., J. S. Alabaster, M.C. Dart, R. Lloyd, 1961. The effect of China-clay wastes on trout streams. *Air Water* Pollution, 5:56-74.

Hodgins, H.O. and J.W. Hawkes, 1976. Pathology of arctic and subarctic marine species and exposure to trace metals associated with petroleum. OCSEAP Final Rpt., RU 75, November 1976. In: Biol. Studies, March 1979 (8).

Hollingsworth, J.W. and R.A. Lockhart, 1975. Fish toxicity of dispersed clay drilling mud deflocculants. In: Conf. Proc. on Environmental Aspects of Chemical Use in Well-Drilling Operations, Houston, Texas, May 21-23, 1975. EPA-550/1-75-004, p. 113-124.

Holmes, C.W. and S.S. Barnes, 1977. Trace metal and mineralogical analysis of suspended and bottom sediment. In: Environmental Studies South Texas Outer Continental Shelf Rig Monitoring Program. Final Report. U.S. Bureau of Land Management Contr. No. AA-CT6-37. Chapter 6, 18 pp.

Horrer, P.L., 1967. Methods and devices for measuring currents. In: Estuaries, American Association for the Advancement of Science, Washington, DC, Publication No. 83, p. 80-89.

Hotchkiss, F.L.S., 1980. Internal gravity waves and sediment transport in Hudson submarine canyon. M.S. Dissert., Mass. Inst. of Tech.

Houghton, J.P., 1973. The intertidal ecology of Kiket Island, Washington, with emphasis on age and growth of Protothaca staminea and Sxidomus giganteus (Lamellibranchia: Veneridae). Ph.D. thesis, University of Washington, 154 pp.

Houghton, J. P., R.P. Britch, R.C. Miller, A.K. Runchal, and C.P. Falls, 1980a. Drilling fluid dispersion studies at the lower Cook Inlet C.O.S.T. well. Proc. Symposium Research on Environmental Fate and Effects of Drilling Fluids and Cuttings. Lake Buena Vista, Florida, January 21-24, 1980.

Houghton, J.P., D.L. Beyer, and E.D. Theilk, 1980b. Effects of oil well drilling fluids on several important Alaskan marine organisms. Proc. Symposium Research on Environmental Fate and Effects of Drilling Fluids and Cuttings. Lake Buena Vista, Florida, January 21-24, 1980.

Hudson, J.H. and D.M. Robbin, 1980. Effects of drilling mud on the growth rate of the reef-building coral, Montastrea annularis. Proc. Symposium Research on Environmental Fate and Effects of Drilling Fluids and Cuttings, Lake Buena Vista, Florida, January 21-24, 1980.

Hutcheon, J., 1972. Forecasting ice in Cook Inlet, Alaska. NOAA Technical Memorandum AR-5. Anchorage, AK.

IMCO Services, undated. Pocket guide for mud technology.

Ingham, M.C., 1976. Variation in the shelf-water front off the Atlantic coast between Caps Hatteras and Georges Bank. In: Goulet, J.R., ed. The environment of the United States living marine resources-1974. MARMAP Contrib. No. 104, NMFS, Washington, DC.

Jan, T.K., M.D. Moore, and D.R. Young, 1977. Metals in seafoods near outfalls. In: Annual Report for the Year Ending June 3, 1977. Southern California Coastal Water Research Project, El Segundo, CA. Access No. PB 274463/AS, National Technical Information Service, Springfield, VA, p. 153-157.

Jan, T.K. and D.R. Young, *1978*. Chromium speciation in municipal waste-water and seawater. J. Water Pollut. Control Fed., 50:2327-2336.

Johnson, B.H., 1974. Investigation of mathematical models for the physical fate prediction of dredged materials. U.S. Army Engineer Waterways Experiment Station, Hydraulics Laboratory, Vicksburg, MS.

Johnson, R.G., 1970. Variations in diversity within benthic marine communities. Amer. Natur., 104:285-300.

Johnson, R.G. and S. LeGore, 1976. Physical and toxicity bioassay studies in Cook Inlet, Alaska during drilling operations June-August 1976. Nalco Environmental Sciences. 98 pp.

Johnston, C.S., R.G. Jones, and R.D. Hunt, 1977. A seasonal carbon budget for a laminarian population in a Scottish sea-lock. Helgal. Wiss. Meeresant, 30:525-545.

Joint IMCO/FAQ, UNESCO, WMO Group of Experts on the Scientific Aspects of Marine Pollution, 1969. Abstract of first session report. Water Research, (3):995-1005.

Kalil, E.K., 1980. Chemical analysis of drill muds for tracing discharge plumes. Proc. Symposium Research on Environmental Fate and Effects of Drilling Fluids and' Cuttings, Lake Buena Vista, Florida, January 21-24, 1980.

Keller, G.H. and F.P. Shepard, 1978. Currents and sedimentary processes in submarine canyons off the northeast United States. In: D.J. Stanley and G.H. Kelling, eds. Sedimentation in submarine canyons, fans, and trenches. Dowden, Hutchinson and Ross, Inc., Stroudsburg, PA, Chapter 2.

Kelling, G. and D.J. Stanley, 1976. Sedimentation in canyon, slope, and base slope environments. In: J.D. Stanley and D.J.P. Swift, eds. Marine sediment transport and environmental management. Wiley-Interscience, New York, NY.

Ketchum, B.H. and W.L. Ford, 1952. Rate of dispersion in the wake of a barge at sea. Transactions, American Geophysical Union, 33(5):680-684.

Kinney, P.J., J. Groves, and D.K. Button, 1970. Cook Inlet environmental data, R.V. Acona Cruise 065, May 21-28, 1968. Institute of Marine Science Report R-70-2, University of Alaska, Fairbanks, AK.

Klinkhart, E., 1966. The beluga whale in Alaska. Alaska Department of Fish and Game, Juneau, AK.

Koh , R.C.Y., 1971. Ocean sludge disposal by barges. Water Research, 7(6).

Koh , R.C.Y. and Y.C. Chang, 1973* Mathematical model for barged ocean disposal wastes. EPA Grant No. 16070 FBY, EPA Pacific Northwest Environmental Research Laboratory, EPA-660/2-73-029.

Komar, P.D., R.H. Neueck, and L.D. Kulm, 1972. Observations and significance of deep water oscillatory ripple marks on the Oregon continental shelf. p. 601-619. In: D.J.P. Swift, DoB. Duane, and P.H. Pickey, eds. Shelf sediment transport: process and pattern. Dowden, Hutchinson and Ross, Stroudsburg, PA.

Kramer, J.R., H.D. Grundy, and L.G. Hammer, 1980. Occurrence and rate of trace metals in barite for ocean drilling operations. Proc . Symposium Research on Environmental Fate and Effects of Drilling Fluids and Cuttings, Lake Buena Vista, Florida, January 21-24, 1980.

Krank, K., 1975. Sediment deposition from flocculated suspensions Sedimentology, 22:111-123.

Krishnappan, BoG., unpublished. Dispersion of granular material dumped in deep water. Hydraulics Division Project 3-1W-HY-019, Canada Centre for Inland Waters.

Krone, R.B., 1962. Plume studies of the transport of sediment in estuarial shoaling process, final report. Hydraulic Engineering Lab and Sanitary Engineering Research Lab., University of California, Berkeley, p. 110.

_____, 1972. A field study of flocculation as a factor In estuarial shoaling processes. Tech. Bulletin 19, U.S. Army Corps of Engineers, Committee on Tidal Hydraulics, 62 pp.

Krone, M.A. and D.C. Biggs, 1980. Sublethal metabolic responses of the hermatypic coral Madracis decactis exposed to drilling mud enriched with ferrochrome lignosulfonate. Proc. Symposium Research on Environmental Fate and Effects of Drilling Fluids and Cuttings, Lake Buena Vista, Florida, January 21-24, 1980.

LaFond, E.C., 1961. Internal wave motion and its geological significance. in: Mahadeuvan Vol. Osnania. University Press. Andrha Prades, India, p. 61-77.

_____, 1962. Internal waves. In: M.N. Hill, ed. The Sea. Wiley-Interscience, New York, NY, Vol. 1, p. 731-751.

Land, B., 1974. The toxicity of drilling fluid components to aquatic biological systems. Environment Canada, Fisheries and Marine Services Technical Rpt. No. 487.

Lange, A.M.T. and M.P. Sissenwine, 1978. Loligo peali stock status: November 1977. NMFS, Northeast Fisheries Center, Woods Hole, MA. Laboratory Ref. No. 77-78, 8 pp.

Langton, R.W. and R.E. Bowman, 1977. An abridged account of predator-prey interactions for some northwest Atlantic fish and squid. NMFS, Northeast Fisheries Center, Woods Hole, MA. Lab. Ref. No. 77-17, 34 pp.

_____, 1980a. Food of eight northwest Atlantic pleuronectiform fishes.

_____, 1980b. Food of fifteen northwest Atlantic gadiform fishes. NOAA Tech. Rept. NMFS SSRF-740, 23 pp.

Larrance, J.D., and A.J. Chester, 1979. Source, composition, and flux of organic detritus in lower Cook Inlet. Final Report for NOAA/OCSEAP, NOAA/PMEL, 50 pp.

Larrance, J.D., D.A. Tennant, A.J. Chester, and P.A. Ruffio, 1977. Phytoplankton and primary productivity in the northeast Gulf of Alaska and lower Cook Inlet. Final Report for NOAA/OCSEAP, NOAA/PMEL, 63 pp.

Lawrence, M. and E. Scherer, 1974. Behavioral responses of whitefish and rainbow trout to drilling fluids. Canada Fisheries and Marine Service, Research and Development Directorate Technical Report No. 502.

Lees, D.C. and J.P. Houghton, 1980. Effects of drilling fluids on benthic communities at the lower Cook Inlet C.O.S.T. well. Proc. Symposium Research on Environmental Fate and Effects of Drilling Fluids and Cuttings, Lake Buena Vista, Florida, January 21-24, 1980.

Lees, D.C., J.P. Houghton, D.E. Erikson, W.B. Driskell, and D.E. Boettcher, 1980. Ecological studies of intertidal and shallow subtidal habitats in lower Cook Inlet, Alaska. Final Report OCSEAP RW 417, May 1980.

Leim, A.H. and W.B. Scott, 1966. Fishes of the Atlantic coast of Canada. Fish. Res. Bd. Can. Bulletin No. 1S5.

Lewis, *R.S.*, R.E. Sylvester, J.M. Aaron, D.C. Twichell, and K.M. Scanlon, 1980. Shallow sedimentary framework and related potential geologic hazards of the Georges Bank area. In: John M. Aaron, ed. Environmental geologic studies in the Georges Bank area, United States northeastern *Atlantic outer* continental shelf, 1975-1977. United States Geological Survey Open-File Report No. 80-240.

Lillick, *L.G.*, 1940. Phytoplankton and planktonic protozoa of the offshore waters of the Gulf of Maine. Part IX, Qualitative Composition of the Planktonic Flora. Trans. Am. Phil. Sot., 31(3):193-237.

Limeburner, R., 1977. Hydrography and circulation about Nantucket shoals. M.S. Thesis. Department of Meteorology, Massachusetts Institute of Technology.

Limeburner, R., W. Esaias, and R.C. Beardsley, 1980. Biological and hydrographic *station data* obtained in the vicinity of Nantucket shoals. May 1978-May 1979. Woods Hole Oceanographic Institute Tech. Rep. WHOI 80-7.

Liss, R.G., F. Knox, D. Wayne, and T.R. Gilbert, 1980. Availability of trace elements in drilling fluids to the marine environment. Proc. Symposium Research on Environmental Fate and Effects of Drilling Fluids and Cuttings, Lake Buena Vista, Florida, January 21-24, 1980.

Lloyd, D., 1980. Effective chrome-free muds developed for sensitive areas. Oil and Gas Journal, 78(35):124-126.

Logan, W.J., J.B. Sprague, B.D. Hicks, 1973. Acute lethal toxicity to trout *of* drilling fluids and their constituent chemicals as used in the NoW. Territories. Canada Dept. of the Environment, Fisheries Service (Central Region), 21 pp.

Lu, J.C.S., B. Eichenberger, M. Knezevic, and K.Y. Chen, 1978. Characterization of confined disposal area influent and effluent particulate and petroleum fractions. Technical Report D-78-16. U.S. Army Engineer Waterways Experiment Station.

Lyall, A.K., D.J. Stanley, HoN. Giles, *and* A. Fischer, 1971. Suspended sediment and transport at the shelf break and on the slope. Marine Technology Society Journal, 5s15-20.

MacGinitie, G. E., 1955. Distribution and ecology of the marine invertebrates of Point Barrow, Alaska. Smithsonian Misc. Collections, 12S(9).

MacInnes, J.R., FoP. Thurberg, R.A. Greig, and E. Gould, 1977. Long-term cadmium stress in the cunner, Tautogolabrus adspersus. Fish. Bull., 75:199-203.

MacKenzie, C.L., Jr., 1979. Biological and fisheries data on sea scallop, Placopecten magellanicus (Omelin) NOAA, NMFS, Northeast Fisheries Center Tech. Sea. Rept. No. 19, February 1979. 41 pp.

Magnell, B.A., S.L. Spiegel, R.J. Scarlet, and J.B. Andrews, 1980. The relationship of tidal and low-frequency currents on the north slope of Georges Bank. Journal of Physical Oceanography, 10(8):1200-1212.

Manheim, F.T., R.H. Meade, and G.C. Bond, 1970. suspended matter in surface waters of the Atlantic continental margin from Cape Cod to the Florida *Keys.* Science, 167:371-376.

Marak, R.R. and J.B. Colton, Jr., 1961. Distribution of fish eggs and larvae temperature, salinity, in the Georges Bank-Gulf of Maine area, 1953. U.S. Fish and Wildl. Serv. Spec. Sci. Rept. Fish No. 398:61 pp.

Marak, R.R., JoB. ColtOn, Jr., and D.B. Foster, 1962a. Distribution of fish eggs and larvae temperature and salinity in the Georges Bank-Gulf of Maine area, 1955. U.S. Fish. Wildl. Serv. Spec. Sci. Rept. Fish. No. 411:66 pp.

Marak, R.R., JoB. Colton, Jr., D.B. Foster, and D. Miller, 1962b. Distribution of fish eggs and larvae temperature and salinity in the Georges Bank-Gulf of Maine area, 1956. U.S. Fish.Wildl. Serv. Spec. Sci. Rept. Fish No. 412:95 pp.

Mariani, G.M., L.V. Sick, and C.C. Johnson, 1980. An environmental monitoring study to assess the impact of drilling discharges in the mid-Atlantic. III. Chemical and physical alterations in the benthic environment. Proc. Symposium Research on Environmental Fate and Effects of Drilling Fluids and Cuttings, Lake Buena Vista, Florida, January 21-24, 1980.

Marine Advisers, Inc., 1965. A study of the oceanographic conditions in the Anchorage area relevant to sewage outfall planning. Report prepared for Tryck, Nyman, and Hayes, and Stevens and Thompson, La Jolla, CA.

_____ (undated). Oceanographic survey of Beluga-Moose Point pipeline route across Cook Inlet, Alaska. Prepared for Standard Oil Company of California, La Jolla, California.

Marshall, W.H. *and* L.K. Brandt, 1978. Solids control in a drilling fluid. Society *of* Petroleum Engineers of AIME, SPE 7011. Third Symposium on Formation Damage Control, Lafayette, LA.

Massachusetts CZM, 1980. Prime fishing grounds visuals 2a and 2b. Spawning areas, visual 3.

Matthews, J.B. and D.H. Rosenberg, 1969. Numeric modeling of a fjord estuary. Institute of Marine Science Technical Report R69-4. University of Alaska, Fairbanks, AK.

McAtee, J.L., Jr. and N.R. Smith, 1969. Ferrochrome lignosulfonates. I. X-ray absorption edge fine structure spectroscopy. II. Interaction with ion exchange resins and clays. J. Colloid. Interface Sci., 29:389-398.

McAuliffe, C.D. and L.L. Palmer, 1976. Environmental aspects of offshore disposal of drilling fluids and cuttings. Proc. 46th Ann. California Regional Meeting of the Society of Petroleum Engineers of AXME. Paper No. SPE 5864.

McCulloch, W.L., J.M. Neff, and R.S. Carr, 1980. Bioavailability of heavy metals from used offshore drilling muds to the clam Rangia cuneata and the oyster Crassostrea gigas. Proc. Symposium Research on Environmental Fate and Effects of Drilling Fluids and Cuttings, Lake Buena Vista, Florida, January 21-24, 1980.

McDermott-Ehrlich, D., D.R. Young, G.A. Alexander, T.K. Jan, and G.P. Hershelman, 1978. Chemical studies of offshore platforms in the Santa Barbara Channel. In: J. Lindstedt-Sive, ed. Proceedings, Energy Environment 78: A Symposium on Energy Development Impacts. Internat. Society of Petroleum Industry Biologists, Los Angeles, CA, p. 133-144.

McGarity, G.E., 1977. Bathymetric map, marine high-resolution survey, lower Cook Inlet, Alaska. U.S. Geological Survey Open File Report 77-358. Scale 1:96,000.

McGlothlin, R.E. and H. Krause, 1980. Water base drilling fluids. In: Proc. Symposium Research on Environmental Fate and Effects of Drilling Fluids and cuttings, Lake Buena Vista, Florida, January 21-24, 1980.

McLeay, J., 1975. Marine toxicity studies on drilling fluid wastes. Prepared for Working Group "A." APOA/Government Research Program on Drilling Fluid Wastes. Environment Canada. Environmental Protection Services, Edmonton, Alberta, Canada.

McLeod, G.C., T.R. Gilbert, R. Stone, and N. Riser, 1980. Indices of sublethal stress in biovalve molluscs exposed to drilling muds: an overview. Abs. of paper given at Symposium on Research on Environmental Fate and Effects of Drilling Fluids and Cuttings, January 21-24, 1980, Lake Buena Vista, Floria.

McMordie, W.C., Jr., 1980. 011 base drilling fluids. In: Proc. symposium Research on Environmental Fate and Effects of Drilling Fluids and Cuttings, Lake Buena Vista, Florida, January 21-24, 1980.

Meade, R.H., 1972. Transport and disposition of sediments in estuaries. In: B. Nelson, cd., Environmental Framework of Coastal Plain Estuaries. Geol. Sot. Am. Mere. 133, p. 91-120.

_____, undated. Sources and sinks of suspended matter on continental shelves. In: D.J.P. Swift, D.B. Duane, and O.H. Pilkey, eds. Shelf sediment transport: process and pattern. Dowden Hutchinson & Ross, Inc., Stroudsburg, PA.

Meek, R.P. and J.P. Ray, 1980. Induced sedimentation, accumulation and transport resulting from exploratory drilling discharges of drilling fluids and cuttings on the southern California outer continental shelf. In: Proc. Symposium Research on Environmental Fate and Effects of Drilling Fluids and Cuttings, Lake Buena vista, Florida, January 21-24, 1980.

Menzie, C.A., D. Usurer, and W.A. Leathem, 1980. An environmental monitoring study to assess the impact of drilling discharge in the mid-Atlantic. IV. The effects of drilling discharges on the benthic community. Proc. Symposium Research on Environmental Fate and Effects of Drilling Fluids and Cuttings, Lake Buena Vista, Florida, January 21-24, 1980.

Merrill, A.S. and J.A. Posgay, 1964. Estimating the natural mortality rate of the eea scallop (Placopecten magellanicus). ICNAF Res. Bull., 1:88-106.

Merrill, A.S. and J.W. Ropes, 1969. The general distribution of the surf clam and ocean quahog. Proc. N.J. Shellfish Assoc., 59:40-45.

Meyer, T.L., R.A. Cooper, and R.W. Langton, 1979. Relative abundance, behavior, and food habits of the American sand lance, Ammodytes americanus from the Gulf of Maine. Fish. Bull., 77(1):243-253.

Milchem, undated. Drilling fluids reference manual, Chapter 4.

Miller, R.C., R.B. Britch, and R.V. Shafer, 1980. Physical aspects of disposal of drilling fluids and cuttings in shallow ice covered arctic seas. Proc. Symposium Research on Environmental Fate and Effects of Drilling Fluids and Cuttings, Lake Buena Vista, Florida, January 21-24, 1980.

Milliman, J.D., M.H. Bothner, and C.M. Parmenter, 1980. Seston in New England shelf and slope waters, 1976-1977. In: John M. Aaron, cd., Environmental Geologic Studies in the Georges Bank area, United States northeastern Atlantic outer continental shelf, 1975-1977. United States Geological Survey Open File Report No. 80-240.

Milliman, J.D., O.H. Pilkey, and D.A. Ross, 1972. Sediments of the continental margin off the eastern United States. Geological Society of America Bulletin 83, p. 1315-1333.

Monaghan, P.H., C.D. McAuliffe, and F.T. Weiss, 1977. Environmental aspects of drilling muds and cuttings from oil and gas extraction operations in offshore and coastal waters. Proc. Ninth Offshore Technology Conference, Houston, Texas, p. 251-256.

Muench, RoD, H.O. Mofjeld, and R.L. Charnell, 1978. Oceanographic conditions in lower Cook Inlet - spring and summer, 1973. Journal of Geophysical Research, 83(C10)O

Mungall, J.D.Ii. and J.B. Matthews, 1970. Available-boundary numerical tidal model. Institute of Marine Science Report R70-4, University of Alaska, Fairbanks, AK.

Murphy, R.W., R.F. Carlson, D. Nyquist, and R. Britch, 1972. Effect of waste discharges into a silt-laden estuary, a case study of Cook Inlet, Alaska. Institute of Water Resources Report IWR-26, University of Alaska, Fairbanks, AK.

National Ocean Survey, 1976. Tide tables 1977, west-coast of North and South America. U.S. Department of Commerce, National Oceanic and Atmospheric Administration.

Neff, J.M., 1980. Review of the toxicity and biological effects of used offshore drilling fluids to marine animals. Response for U*S. Senate Joint Hearing of the Committee on Commerce, Science, and Transportation and the Subcommittee on Energy Resources and Materials regarding Senate Bill S-2119, Georges Bank protection Act.

Neff, J.M. and J.W. Anderson. 1975. An ultraviolet spectrophotometric method for the determination of naphthalene and alkyl napthalenes in the tissues of oil-contaminated marine animals. Bull. Environ. Contain. Toxicol., 14:122-128.

Neff, J.M., R.S. Carr, and W.L. McCulloch, 1981 (in press). Acute toxicity of a used chrome lignosulfonate drilling mud to several species of marine invertebrate. Marine Environmental Research, vol. 4.

Neff, J.M., W.L. McCulloch, R.S. Carr, and K.A. Retzer, 1980. Comparative toxicity of four used offshore drilling muds to several species of marine animals from the Gulf of Mexico. Proc. Symposium Research on Environmental Fate and Effects of Drilling Fluids and Cuttings, Lake Buena Vista, Florida, January 21-24, 1980.

Neu, H.J.A, 1972. Extreme wave height distribution along the Canadian Atlantic coast. Ocean Industry, July:45-49.

Newell, R.C., 1970. Biology of intertidal animals. Paul Elek Limited, London, 555 p.

Nimmo, D.W.R., D.V. Lightner, and L.H. Bahner, 1977. Effects of cadmium on the shrimps, Penaeus duorarum, Palaemonetes pugio, and Palaemonetes vulgaris, p. 131-183. In: F.J. Vernberg, H. Calabrese, F.P. Thurberg, and W.B. Vernberg, eds. Physiological Responses of Marine Biota to Pollutants. Academic Press, Inc., New York, NY, p. 131-183.

NMFS (National Marine Fisheries Service), Northeast Fisheries Center, 1975. Statistics and market news. Plots of USA *Fishing* Vessel Activity. New England Fishery Interviews 1965-1974. Vol. II. U.S. Dept. of Commerce, NOAA.

NORTEC (Northern Technical Services), 1980 (proprietary). Forecast service report. Hawk One, lower Cook Inlet. Prepared for Atlantic Richfield Co., 88 pp.

_____, 1981. Beaufort sea drilling effluent study. Prepared for Reindeer Island stratigraphic test well participants. Northern Technical Services, Anchorage, AK, 329 pp.

Oetking, P., R. Back, R. Watson, and C. Meeks, undated. Surface and shallow subsurface sediments *of* the nearshore continental shelf of south central Louisiana. Gulf Universities Research Consortium Contract GU853-8.

Okubo, A., 1962. A review of theoretical models of turbulent diffusion in the sea. Technical Report 30, Chesapeake nay Institute, Johns Hopkins University, Baltimore, MD.

_____, 1970. Oceanic mixing. Technical Report 62. Chesapeake Bay Institute, Johns Hopkins University, Baltimore, MD.

Olsen, S.B. and S.B. Salia, 1976. Fishing and petroleum interactions on Georges Bank: Vol. 1, Areas of particular interest to the industries: Energy Program Technical Report 76-3, New England Regional Commission.

Orlando, R.C. (in press). Overall sediment distribution and grain size relationships in lower Cook Inlet. In: A.H. Bouma, ed. Geology of Lower Cook Inlet, Alaska. USGS Professional Paper.

Page, D.S., B.T. Page, and J.R. Hotham, 1980. Bioavailability of toxic constituents of used drillng muds. Proc. Symposium Research on Environmental Fate and Effects of Drilling Fluids and Cuttings, Lake Buena Vista, Florida, *January 21-24, 1980.*

Parmenter, C.M., M.H. Bothner, B. Butman, and J.D. Milliman, 1979. Characteristics and causes of the bottom nepheloid layer on the continental shelf, southeastern New England (Abstract). Geological Society *of America,* Abstracts with Programs, Vol. IX, No. 7, p. 492.

Parnkratov, A.M. and K. Sigajev, 1973. Studies on Georges Bank herring spawning in 1970. ICNAF Res. Bull., (10):125-130.

Parsons, T.R. and M. Takahashi, 1973. Biological Oceanographic Processes. Pergamon Press, New York, NY, 186 pp.

Pawlowski, R.J. and W.R. Wright, 1978. National Marine Fisheries Service, Northeast Fisheries Center, April 1978. Spring and fall sea-surface temperature and salinity on the northeastern continental shelf; Cape Hatteras to Cape Sable, 1972-1977.

Pequegnat, W.E., 1978. An assessment of the potential impact of dredged material disposal in the open ocean. Technical Report No. D-78.2, Us. Army Engineer Waterways Experiment Station, Vicksburg, MS.

PESA (Petroleum Equipment Suppliers Association), Environmental Affairs Committee, 1980. Appendix A: Chemical components and uses of drilling fluids. In: L.W. Calahan, 1980. Statement for American Petroleum Institute before U.S. Senate Joint Hearing of the Committee on Commerce, Science, and Transportation and the Subcommittee on Energy Resources and Materials Production regarding Senate Bill S-2119, Georges Bank Protection Act.

Pierce, J.W., 1970. Clay mineralology of cores fom the continental margin of North Carolina. Southeast Geology, 12:33-51.

_____, 1976. Suspended sediment transport at the shelf break and over the outer margin. In: Stanley and Swift, eds., Marine Sediment Transport and Environmental Management. John Wiley & Sons, New York, NY, p. 437-459.

Pikanowski, R.A., 1977. An analysis of data from the National Marine Fisheries Service groundfish survey for use in assessing oil-related environmental impacts. In: Fishing and Petroleum Interactions on Georges Bank. Vol. II, 10 pp.

Pratt, R.M., 1967. The seaward extension of submarine canyons off the northeast coast of the United States. Deep Sea Research, 14:409-420.

Rabinowitz, P.D. and S.L. Eittreim, 1974. Bottom current measurements in the Labrador Sea. Journal of Geophysical Research, 79:4085-4090.

Ramp, SR., R.J.Schlitz, and W.P. Wright, 1980. Northeast channel flow and the Georges Bank nutrient budget. NMFS , Northeast Fisheries Center, WHOI, Woods Hole, MA.

Ray, J.P. and R.P. Meek, 1980. Water column characterization of drilling fluids dispersion from an offshore exploratory well on Tanner Bank. In: Proc. Symposium Research on Environmental Fate and Effects of Drilling Fluids and *Cuttings,* Lake Buena Vista, Florida, January 21-24, 1980.

Ray, J.P. and E.A. Shinn, 1975. Environmental effects of drilling muds and cuttings. In: Conf. Proc. on Environmental Aspects of Chemical Use in Well-Drilling Operations, Houston, Texas, May 21-23, 1975. EPA-550/1-75-004.

Reichart, W.R. Behavioral and physiological effects induced by sublethal levels of heavy metals. OCSEAP Final Rpt., RU 75, November 1976. In: Biol. Studies, March 1979 (5).

Reish, D.J., S.G. Appan, MoE. Bender, C.H. Ward, T.L. LintOn, and J.M. Sharp, 1980. Long-term cumulative effects of petroleum drilling on benthic polychaete community structure. Proc. Symposium Research on Environmental Fate and Effects of Drilling Fluids and Cuttings, Lake Buena Vista, Florida, January 21-24, 1980.

Rhoads, D.C. and D.K. Young, 1970. The influence of deposit feeding organisms on sediment stability and community trophic structure. J. Mar. Research, 28:150-178.

Rice, S.D., S. Kern, C.C. Broderson, S.A. Lindsay, and S.A. Andrews, 1981. Toxicity of ballast water treatment effluent to marine organisms at Port Valdez, Alaska. Presented at 1981 Oil Spill Conference, March 2-5, 1981. Atlanta, GA.

Richardson, P.L., 1973. Current measurements under the Gulf Stream near Cape Hatteras, North Carolina. Ph.D. Dissert. , Univ. of R.I., Kingston.

Riley, G.A., 1941. Plankton studies. IV. Georges Bank. Bull. Bingh. Oceanogr. Call., 7(4):1-73.

Riley, G.A. and D.F. Bumpus, 1946. Phytoplankton-zooplankton relationship on Georges Bank. Journal of Mar. Res. 6(1):33-47.

Robichaux, T.J., 1975. Bactericide used in drilling and completion operations. In: Conf. Proc. on Environmental Aspects of Chemical Use in Well-Drilling Operations, Houston, Texas, May 21-23, 1975. EPA-550/1-75-004, p. 183-191.

Robson, D.S., C.A. Menzie, and H.F. Mulligan, 1980. An environmental monitoring study to assess the impact of drilling discharges in the mid-Atlantic. II. An experimental design and statistical methods to evaluate impacts on the benthic environment.

Rogers, R., 1963. Composition and properties of oil well drilling fluids . Third Edition, Gulf Publishing Company, Houston, TX.

Ropes, J.W., 1978. Biology and distribution of surf clams (Spisula solidissima) and ocean quahogs (Arctics islandica) off the northeast coast of the United States. In Proc. Northeast Clam Industries: Management for the Future, April 27-28, 1978. Hyannis, MA, p. 47-66.

Rosenberg, D.H., D.C. Burrell, KV. Natarajan, and D.W. Hood, 1967. Oceanography of Cook Inlet with special reference to the effluent from the Collier Carbon and Chemical Plant. Institute of Marine Science Report No. R67-5, University of Alaska, Fairbanks, AK.

Rosenthal, R.J. and D.C. Lees, 1979. A preliminary assessment of composition and food webs for demersal fish assemblages in several shallow subtidal habitats in lower Cook Inlet, Alaska. Prepared by Dames & Moore for Alaska Department of Fish and Game, 58 pp.

Rowe, G.T., 1971. Observations on bottom currents and epibenthic populations in Hatteras Submarine Canyon. Deep Sea Research, 18:569-581.

_____, 1972. The exploration of submarine canyons and their benthic faunal assemblages. Proc. R.S.E.(B), 73(17):159-169.

Rowe, G.T., G. Keller, H. Edgerton, N. Staresink, and J. MacKlvaine, 1974. Time-lapse photography of the biological reworking of sediments in the Hudson Canyon. Journal of Sedimentary Petrology, 44(2):403-416.

Royer, T.C., 1975. Seasonal variations of waters in the northern Gulf of Alaska. Deep Sea Research, 22:403-416.

Rubinstein, N.I., R. Rigby, and C.N. D'Asaro, 1980. The effect of drilling muds on representative estuarine organisms and developing benthic communities. Proc. Symposium Research on Environmental Fate and Effects of Drilling Fluids and Cuttings, Lake Buena Vista, Florida, January 21-24, 1980.

Ryther, J.H., 1969. Photosynthesis and fish production in the sea. The production of organic matter and its conversion to higher forms of life vary throughout the world ocean. Science, 166:72-76.

SAI (Scientific Applications, Inc.), 1977. Lower Cook Inlet, Alaska--a preliminary environmental synthesis. Prepared for NOAA/OCSEAP/ERL, 169 pp.

Sandberg, K.A. and O. Clausen, 1977. Post-larval king crab (Paralithodes Camtschatica) distribution and abundance in Kachemak Bay, lower Cook Inlet, Alaska, 1976. Prepared by Alaska Department of Fish and Game, Marine/Coastal Habitat Management Div., 36 pp.

Sanders, H.L., 1958. Benthic studies in Buzzards Bay. I. Animal-sediment relations. Limnology and Oceanography, 3:245-258.

_____, 1960. Benthic studies in Buzzards Bay. II. The structure of the soft bottom community. Limnology and Oceanography, 5:138-153.

Schlee, J. and R.M. Pratt, 1970. Atlantic continental shelf and slope of the United States--gravels of the northeastern part. USGS Professional Paper 529-H.

Schlee, J., 1973. Atlantic continental shelf and slope of the eastern United States--sediment texture of the northeast part. USGS Professional Paper 529-L. App.

Schlichting, H., 1968. Boundary-layer theory. Sixth Edition, McGraw-Hill Book Company, New York, NY.

Schlitz, R.J. and R.W. Trites, 1979. The Atlantic larval herring patch study of 1978. Part VIII. Current observations on northern Georges Bank. Abstract presented at the 2nd Informal Workshop on the Oceanography of the Gulf of Maine and Adjacent Seas May 1979. Dalhousie University, Halifax, Nova Scotia.

Schmitz, W.J., A.R. Robinson, and F.C. Fuglister, 1970. Bottom velocity observations directly under the Gulf Stream. Science, 170:1192-1 194*

Schneider, E.D., P.J. Fox, D.C. Hollister, H.D. Needham, and B.C. Heezen, 1967. Further evidence of contour currents in the western North Atlantic. Earth Planetary Scientific Letters, 2:351-359.

Schumaker, A, and V.S. Anthony, 1972. Georges Bank (ICNAF Division 52 and Subarea 6) Herring Assessment, Int. Comm. Northwest Atl. Fish. Annu. Meet. 1972, Res. Dec. No. 24, Serial No. 2715, 36 pp.

Sears, M., 1941. Notes on the phytoplankton on Georges Bank in 1940. J. Mar. Res., 4(3):247-257.

Second Informal Workshop of the Physical Oceanography of the Gulf of Maine and Adjacent Seas, July 1979. A summary. Flagg, C., Interaction of a warm core eddy with the New England Continental Shelf; Hauskencht, K., Concentration and distribution of trace metals in suspended particulate matter on the New England OCS; Home, E., Interleaving at the subsurface front in the slope off Nova Scotia; Schlitz, R. and R. Trites, Current observations on northern Georges Bank.

Sharma, G.D., and D.C. Burrell, 1970. Sedimentary environment and sediments of Cook Inlet, Alaska. American Assoc. of Petroleum Geologists Bulletin, 4(4):647-654.

Sharma, G.D., F.F. Wright, and J.J. Burns, 1973. Sea ice and surface water circulation, Alaskan continental shelf. 2nd Semi-annual Report for ERTS Project 110-H, University of Alaska, Fairbanks, AK.

Sharma, G.D., F.F. Wright, J.J. Burns, and D.C. Burbank, 1974. Sea surface circulation, sediment transport, and marine mammal distribution, Alaska continental shelf. Final Report of ERTS Project 110-H, University of Alaska, Fairbanks, AX.

Shepard, F.P., 1963. Submarine geology. Harper and Rowe, New York, NY, 557 pp.

Shepard, F.P. and R.F. Dill, 1966. Submarine canyons and other sea valleys. Rand McNalley.

Shepard, F.P. and N.F. Marshal, 1973. Currents along floors of submarine canyons. American Association of Petroleum Geologists Bulletin, 57:244-264.

Shepard, F.P., N.F. Marshall, and P.A. McLaughlin, 1974a. Internal waves advancing along submarine canyons. Science, 183:195-198.

______ 1974b. Currents in submarine canyons. Deep Sea Research, 21:691-706.

Shepard, F.P., N.F. Marshall, P.A. McLaughlin, and G.G. Sullivan, 1979. Currents in submarine canyons and other sea valleys. American Association of Petroleum Geologist, Tulsa, OK.

Sherman, K., R. Maurer, R. Byron, and D. Bearse, 1977. Relationship between larvae fish communities and zooplankton prey species in an offshore spawning ground. International Council Explor. Sea, C.M. 197/L:28 Plankton Comm.

Sherman, K., L. Sullivan, and R. Byron, 1978. Pulses in the abundance of zooplankton prey of fish on the continental shelf off New England. International Council Explor. Sea Committee. C.M. 1978/L:25 Biol. Oceanog., 11 pp.

Shinn, E.A., 1974. Effects of oil field brine, drilling mud, cuttings and oil platforms on the offshore environment. In: Proceedings of the Entrance Research Federation Outer Continental Shelf Conference and Workshop. University of Maryland, December 2-4, 1974.

Shinn, E.A., J.H. Hudson, D.M. Robbin, and C.K. Lee, 1980. Drilling mud plumes from offshore drilling operations: implications for coral survival. Proc. Symposium Research on Environmental Fate and Effects of Drilling Fluids and cuttings, Lake Buena Vista, Florida, January 21-24, 1980.

Shirazi, M.A. and L. R. Davis, 1974. Workbook of thermal plume prediction. Volume 2: Surface Discharge. EPA-R2-72-005b .

Skelly, W.C. and J.A. Kjellstrand, 1966. The thermal degradation of modified lignosulfonates in drilling mud. API, Division of Production, Dallas, Texas, March 2-4, 1966.

Skelly, W.G. and D.E. Dieball, 1969. Behavior of chromate in drilling fluids containing chromate. Proc. 44th Ann. Meeting of the Society of Petroleum Environeers of AIME. Paper No. SPE 2539, 6 pp.

Smayda, T.J., 1969. Some measurements of the sinking rates of fecal pellets. Limnol. Oceanogr., 14:621-626.

Southard, J.B. and D.J. Stanley, 1976. Shelf break processes and sedimentation. In: D.J. Stanley and D.J.P. Swift, eds. Marine Sediment Transport and Environmental Management. John Wiley & Sons, New York, NY, p. 351-377.

Spencer, D.W., and P.L. Sachs, 1970. Some aspects of the distribution, chemistry, and mineralology of suspended matter in the Gulf of Maine. Mar. Geol., 9:117-136.

Sprague, J. B., 1973. The ABCs of pollutant bioassays using fish, biological methods for the assessment of water quality. ASTM STP 528. American Society for Testing and Materials, p. 6-30.

Sprague, J.B. and W.J. Logan, 1979. Separate and joint toxicity to rainbow trout of substances used in drilling fluids for oil exploration. Environ. Pollut., 19:269-281.

Stanley, D.J., 1970. Flyschoid sedimentation on the outer Atlantic margin of northeastern North America. Geological Assoc. Can., Special Paper No. 7, p. 179-210.

Stanley, D.J., P. Fenner, and G. Kelling, 1972. Currents and sedimentation transport at the Wilmington Canyon shelfbreak as observed by underwater television. In: D.J.P. Swift, D.B. Duane, and O.H. Pilkey, eds. Shelf Sediment Transport: Process and Pattern. Dowden, Hutchinson and Ross, Stroudsburg, PA, p. 621-644.

Stanley, D.J. and N.P. James, 1971. Distribution of Echinarachnius parma (Lamarck) and associated fauna on Sable Island Bank, Southeast Canada. Smithsonian Contrib. Earth Sci., Vol. 6, 24 pp.

Stetson, H.C., 1937. Current measurement in the Georges Bank canyons. Transactions Geophysical Union. 18th Annual Meeting p. 216-219.

Sundberg, K.A., and D. Clausen, 1977. Post-larval king crab (Paralithodes camtschatica) distribution and abundance in Kachemak Bay, lower Cook Inlet, Alaska. In: L.L. Trasky, L.B. Flagg, and D.C. Burbank, eds. Environmental Studies of Kachemak Bay and Lower Cook Inlet. Alaska Department of Fish and Game, Anchorage, AK., Vol. V, 36 pp.

Tagatz, M.E., J.M. Ivey, H.K. Lehman, and J.L. Oglesby, 1978. Effects of a lignosulfonate-type drilling mud on development of experimental estuarine macrobentic communities. Northeast Gulf Science, 2(l): 35-42.

Tagatz, M.E. and M. Tobia, 1978. Effect of barite ($BaSO_4$) on development of estuarine communities. Estuarine and Coastal Marine Science, 7:401-407.

Tagatz, M.E., J.M. Ivey, H.K. Lehman, M. Tobia, and J.L. Oglesby, 1980. Effects of drilling mud on development of experimental estuarine macrobenthic communities. Proc. Symposium Research on Environmental Fate and Effects of Drilling Fluids and Cuttings, Lake Buena Vista, Florida, January 21-24, 1980.

Tagatz, M.E., J.M. Ivey, and M. Tobia, 1978. Effects of dowicide™ G-ST on development of experimental estuarine macrobenthic communities. In: K. Ranga Rae, ed. Pentachlorophenol. Plenum Publishing Corporation, New York, NY, p. 157-163.

Thomas, D.C., 1979. Thermal stability of starch and carboxymethyl cellulose polymers used in drilling fluids. Society of Petroleum Engineers of AIME, SPE 8463, 11 pp.

Thompson, E.P. and D.L. Harris, 1972. A wave climatology for U.S. coastal waters. Coastal Eng. Res. Center Reprints.

Thompson, J.H, Jr., and T.J. Bright, 1980. Effects of an offshore drilling fluid on selected corals. Proc. Symposium Research on Environmental Fate and Effects of Drilling Fluids and Cuttings, Lake Buena Vista, Florida, January 21-24, 1980.

Thorson, G., 1957. Bottom communities (sublittoral or shallow shelf). In: J.W. Hedgpeth, ed. Treatise on Marine Ecology and Paleoecology. Geol. Sot. Amer. Memoir 67, Washington, DC, p. 461-534.

Thorson, G., 1966. Some factors influencing the recruitment and establishment of marine benthic communities. Neth. J. Sea Res., 3:267-293.

Tillery, J.B., 1980. Long-term fate and effect of heavy metal contamination from petroleum production in the Gulf of Mexico. Proc. Symposium Research on Environmental Fate and Effects *of* Drilling Fluids and Cuttings, Lake Buena Vista, Florida, January 21-24, 1980.

Tillery, J.B. and R.E. Thomas, 1980. Heavy metal contamination from petroleum production platforms in the central Gulf of Mexico. Proc. Symposium Research on Environmental Fate and Effects of Drilling Fluids and Cuttings, Lake Buena Vista, Florida, January 21-24, 1980.

Tornberg, L.D., E.D. Thielk, *RoE.* Nakatani, R.C. Miller, and S.0. Hillman, 1980. Toxicity of drilling fluids to marine organisms in the Beaufort Sea, Alaska. Proc. Symposium Research on Environmental Fate and Effects of Drilling Fluids and Cuttings, Lake Buena Vista, Florida, January 21-24, 1980.

TRIGOM (The Research Institute of the Gulf of Maine), 1976. Summary of environmental information on the continental slope Canadian/United States border to Cape Hatteras, NC. Prepared for the Bureau of Land Management, New York.

_____, 1974. Socioeconomic and environmental inventory of the North Atlantic region, Sandy Hook to the Bay of Fundy. Vol. 1, Book 1-3, submitted to BLM.

Tucholke, B.E., W.R. Wright, and D. Hollister, 1973. Abyssal circulation over the Greater Antilles outer *ridge.* Deep-Sea Research, 20(11): 973-995.

Turk, T.R., M.J. Risk, R.W.El. Hirtle, and R.Ii, Yeo, 1980. Sedimentological and biological *changes* in the Windsor mudflat, an area *of* induced siltation. Can. J. Fish. Aquatic Sci., 37:1387-1397.

Twichell, D. C., C.E. McClennen, and B. Butman, 1980 (in press). Morphology and processes associate with the accumulation of the fine-grained sediment deposit on the southern New England shelf. Journal of Sedimentary Petrology.

Tyson, J.W., 1975. Offshore ecology investigation. In: Conf. Proc. on Environmental Aspects of Chemical Use in Well-Drilling Operations, Houston, Texas, May 21-23, 1975. EPA-550/l-75-004, p. 387-432.

U.S. Department of Commerce, 1973. Environmental conditions within specified geographical regions.

U.S. Department of Commerce. NOAA. Environmental Data and Information Service, 1980. A climatological and oceanographic analysis of the Georges Bank region of the outer continental shelf.

USEPA (U.S. Environmental Protection Agency), 1976. Quality criteria for water. Washington, DC.

USEPA/COE (U.S. Environmental Protection Agency/Corps of Engineers), 1977. Ecological evaluation of proposed discharge of dredged materials into ocean waters. Environmental Effects Laboratory, Vicksburg, MS.

USGS (U.S. Geological Survey), 1977. Preliminary bathymetric charts for lower Cook Inlet, Alaska. Open file map.

Van Olphen, H., 1966. An introduction to clay colloid chemistry. Interscience Publishers, New York, NY.

Vanoni, V.A., cd., 1975. Sedimentation engineering. Manuals and Reports on Engineering Practice No. 54. ASCE, New York, NY.

Varanasi, U. and D.C. Malins, 1976. Metabolism of trace metals: bioaccumulation and biotransformation in marine organisms. OCSEAP Final Rpt., RU 75, November 1976. In: Biol. Studies, March 1979 (5).

Vernberg, F.J., A. Calabrese, F.P. Thurberg, and W.B. Vernberg, eds, 19770 Physiological resposes of marine biota to pollutants. Proceedings of a Symposium held in November 1975. Academic Press, New York, NY, 462 pp.

Voorhis, A.D., D.C. Webb, and D.C. Millard, 1976. Current structures and mixing in the shelf/slope water front south of New England. Journal of Geop. Res., 8-1(2).

Wagner, D.G., R.S. Murphy, and C.E. Behlke, 1969. A program for Cook Inlet, Alaska, for the collection, storage, and analysis of baseline environmental data: Institute of Water Resources Report No. IWR-7, University of Alaska, Fairbanks, AK.

Wakeland, M.E., 1979. Occurrence and dispersal patterns of fine-grained sediment in Long Island Sound. Ph.D. thesis, University of Connecticut.

Ward, E. G., D.T. Evants, and J.A. Pomps, 1977. Extreme wave heights along the Atlantic coast of the United States. Proceedings of 1977 Offshore Technology Conf.

Warme, J.E., R.A. Slater, and R.A. Cooper, 1978. Bioerosion in submarine canyons. In: Fan and Trench Sedimentation in Submarine Canyons, p. 65-70.

Weatham, P.E., 1958. The high temperature stability of sodium carboxy-methyl cellulose in drilling fluids. API Drilling Fluid Study Committee, Houston, Texas, May 23, 1958.

Weir, R.H. and B. Moore, 1975. Acute toxicity of well-drilling muds to rainbow trout (Salmo gairdneri). In: Conf. Proc. on Environmental Aspects of Chemical Use in Well-Drilling Operations, Houston, Texas, May 21-23, 1975. EPA-550/1-75-004.

Wennekens, MoP., I.B. Flagg, L. Trasky, D.C. Burbank, R. Rosenthal, and F.F. Wright, 1975 (unpublished). Kachemak Bay--a status report. Alaska Department of Fish and Game, Habitat Protection Report, 221 pp.

Wheeler, R.B., J.B. Anderson, R.R. Schwarzer, and C.L. Hokanson, 1980. Sedimentary processes and trace metal contaminants in the Buccaneer Oil/Gas Field, Northwestern Gulf of' Mexico. Environmental Geology, 3:163-175.

Whitehouse, V.G., L.J. Jeffrey, and J.D. Debrecht, 1960. Differential settling tendencies of clay minerals in saline waters. In: Clay and Clay Minerals. Proc. 7th Nat. Conf. Clays and Clay Minerals, National Academy Sciences/National Research Council, p. 1-76.

Widdows, J. and B.L. Bayne, 1971. Temperature acclimation of Mytilus edulis with reference to its energy budget. J. Mar. Biol. Assoc. U.K., 51:827-843.

Wigley, R., 1961a. Bottom sediments of Georges Bank. J. Sedimentary Petrology, 31(2):165-188.

_____, 1961b. Benthic fauna of Georges Bank. Trans. 26th North Amer. Wildl. Nat. Res. Conf., p. 310-317.

_____, 1965. Density dependent food relationships with references to New England groundfish. ICNAF Spec. Publ., 6:51-514.

_____, 1968. Benthic invertebrates of the New England fishing banks underwater naturalist, Bull. of Amer. Littoral Soc., 5(1):8-13.

Wigley, R.L., and R.B. Theroux, 1976. Macrobenthic invertebrate fauna of the middle Atlantic bight region: Part 11. Faunal Composition and Quantitative Distribution. Dept. Commerce, NOAA, NMFS, NEFC, Woods Hole, MA, 395 pp.

Wigley, R. L., R.B. Theroux, and H. E. Murray, 1975. Deep-sea red crab, Geryon quinquedens, survey off northeastern United States. Marine Fisheries Review, Paper 154, 37(8):21 pp.

Wright, F.F., 1970. An oceanographic reconnaissance of the waters around Kodiak Island, Alaska. Institute of Marine Science Report R70-19, University of Alaska, Fairbanks, AK.

_____, 1975. Surface circulation for lower Cook Inlet--a drift card study. Prepared for the Alaska Department of Fish and Game.

Wright, W.R., 1976. The limits of shelf water south of Cape Cod, 1941 to 1972. Jour. of Mar. Res., 34 (1):1-14.

Wunch, C. and R. Hendry, 1972. Array measurements of the bottom boundary layer and the internal wave field on the continental slope. Journal of Geophysical Fluid Mechanics, 4:101-145.

Young, D.K. and D.C. Rhoads, 1971. Animal-sediment relations in Cape Cod Bay, Massachusetts. I. A transect study. Mar. Biol., 11:242-254.

Young, D.R. and G.V. Alexander, 1977. Metals in mussels from harbors and outfall areas. In: Annual Report for the Year Ended 30 June 1977. Southern California Coastal Water Research Project, El Segundo, CA. 92245. Access No. PB 274463/AS, National Technical Interaction Service, Springfield, VA, p. 159-165.

Young, D.R., C. Bertine, D. Brown, E. Crecelius, J. Martin, F. Morel, and G. Roseijadi, 1979. Trace metals. In: E.G. Goldberg, ed. Proceedings of a Workshop on Scientific problems Relating to Ocean Pollution. U.S. Department of Commerce, Washington, DC, p. 130-152.

Young, D.R. and T.K. Jan, 1979. Trace metal contamination of the rock scallop, Hinnites giganteus, near a large southern California municipal outfall. Fish. Bull., 76:936-939.

Young, D.R., T.K. Jan, and T.C. Heesen, 1978. Cycling of trace metal and chlorinated hydrocarbon wastes in the southern California Bight. In: M.W. Wiley, ed. Estuarine Interactions. Academic Press, New York, NY, p. 481-496.

Young, D.R., D.J. McDermott, T.C. Heesen, and T.K. Jan, 1975. Pollutant inputs and distributions off southern California. In: T.M. Church, ed. Marine Chemistry in the Coastal Environment. American Chemical Society, Washington, DC, p. 424-439.

Young, R.A., 1978. Suspended-matter distribution in the New York Bight apex related to hurricane Belle. Geology, 6:301-304.

Zemel, B., 1980. The use of radioactive traces to measure the dispersion and movement of a drilling mud plume off Tanner Bank, California, 1980. Proc. Symposium Research on Environmental Fate and Effects of Drilling Fluids and Cuttings, Lake Buena Vista, Florida, January 21-24, 1980.

Zimmerman, H. B., 1971. Bottom currents on the New England continental rise. J. Geophy. Res. 76.

Zingula, R. P., 1975. Effects of drilling operations on the marine environment. In: Conf. Proc. on Environmental Aspects of Chemical Use in Well-Drilling Operations, Houston, Texas, May 21-23, 1975. EPA-550/1-75-004, p. 443-450.

Zitko, V., 1975. Toxicity and environmental properties of chemicals used in well-drilling operations. In: Conf. Proc. on Environmental Aspects of Chemical Use in Well-Drilling Operations, Houston, Texas, May 21-23, 1975. EPA-550/1-75-004, p. 311-332.

APPENDIX A

LIST OF EXPERTS ON PHYSICAL/CHEMICAL/BIOLOGICAL ASPECTS OF DRILLING NUD USE AND DISPOSAL

Daniel T. Acosta
Manager, Technical Training
IMCO Services
P.O. BOX 22605
Houston, TX 77027
Phone: (713) 671-4885
Expertise: Properties of Drilling Fluids

R. Allred
Sun Company
P.O. BOX 639
Richardson, TX 75080
Phone: (214) 739-7386
Expertise: Drill Mud Engineering and Mud Chemistry

W. J. Artigue
District Superintendent
Amoco Production Company
P.O. Box 51921
Lafayette, LA 70505
Phone: (318) 261-5100
Expertise: Drilling Operations

Robert C. Ayers, Jr., Ph.D.
Research Associate
Exxon Production Research Co.
P.O. Box 2189
Houston, TX 77001
Phone: (713) 965-4344
Expertise: All Aspects

Gary W. Bowers
Oceanographer
EG&G, Environmental Consultants
151 Bear Hill Road
Waltham, MA 02154
Phone: (617) 890-3710
Expertise: Drilling Mud Disposal

Maynard G. Brandsma, P.E.
445 East 5th Avenue
Durango, CO 81301
Phone: (303) 259-3487
Expertise: Effluent Modeling

Robert P. Britch, P.E.
Senior Engineer
Northern Technical Services
750 West 2nd Avenue, Suite 100
Anchorage, AK 99501
Phone: (907) 276-4302
Expertise: Physical Aspects

Leroy L. Carney
Chemical Research and Development Department
Halliburton Services
Duncan, OK 73533
Phone: (405) 251-3760
Expertise; Drilling Fluid Composition

D. W. Chamberlain
Science Advisor
Atlantic Richfield Co.
515 South Flower
Los Angeles, CA 91765
Phone: (213) 486-3511
Expertise: Drilling Fluid Disposal

Robert W. Crippen
Director of Marine Studies
Beak Consultants Limited
6870 Goreway Drive
Mississauga, Ontario L4V 1L9
Canada
Phone: (416) 671-2600
Expertise: Chemical Aspects of Marine Disposal

Kenneth R. Critchlow, Ph.D.
Senior Marine Biologist
Dames & Moore
1100 Glendon Avenue, Suite 1000
Los Angeles, CA 90024
Phone: (213) 879-9700
Expertise: Biological Aspects of Marine Disposal

Loren R. Davis
Department of Mechanical
Engineering
Oregon State University
Corvallis, OR 97331
Phone: (503) 754-0123
Expertise: Physical *Aspects*

Hugh M. French, Ph.D.
Professor
Department of Geology
University of Ottawa
Ottawa KIN 6N5
Canada
Phone: (613) 231-6829
Expertise: Arctic Disposal
Practices

G. Friesen
ESSO

Expertise: Drilling Fluid
Disposal

David A. Gettleson
Biological Oceanographer
Continental Shelf Associates, Inc.
P.O. Box 3609
Tequesta, FL 33458
Phone: (305) 746-7946
Expertise: Chemical Aspects *of*
Marine Disposal

Otto Grahl-Nielsen
Research Chemist
Institute of Marine Research
P.O. Box *1870*
Bergen, Norway N-5000
Expertise: North Sea Disposal
practices

G. Green

Expertise: Chemical Aspects of
Marine Disposal

Lawrence Harris, Ph.D.
Development Chemist
Chemical Research & Development
Department
Halliburton Services
Duncan, OK 73533
Phone: (405) 251-3760
Expertise: Drilling Fluid
Composition

Jonathan P. Houghton, Ph.D.
Senior Marine Ecologist
Dames & Moore
155 NE 100th Street
Seattle, WA 98125
Phone: (206) 523-0560
Expertise. Environmental Effects

Steve E. Hrudey
Associate Professor
Dept. of Civil Engineering
University of Alberta
Edmonton, Alberta T6G 2G7
Canada
Phone: (403) 432-4235
Expertise: Onshore Disposal

Connie C. Johnson
College of Marine Studies
University of Delaware
Lewes, DE 199S8
Phone: {302) 645-4000
Expertise: Physical and Chemical
Benthic Effects

Duane L. Johnson
Reclamation Specialist
Hardy Associates, Ltd.
3939 12 Street, N.E.
Calgary, Alberta T2E GRB
Canada
Phone: (403) 272-8761
Expertise: Onshore Disposal Effects

Emil K. Kalil, Ph.D.
Geochemist
Uranium West Laboratories, Inc.
15515 Sunset Boulevard, B07
Pacific Palisades, CA 90272
Phone: (213)
Expertise: Radioactive Tracer Techniques

James R. Kramer
Department of Geology
McMaster University
Hamilton, Ontario L8S 4M1
Canada
Phone: (416) 525-9140
Expertise: Chemical Aspects

Harold Krause
Manager, Technical Services
Dresser Magcobar
Box 6504
Houston, TX 77005
Phone: (713) 972-6684
Expertise: Drilling Mud Additives

C. R. Knowles
Arco Oil & Gas Company
P.O. Box 360
Anchorage, AK 99510
Phone: (907) 277-5637
Expertise: Physical Aspects

Dennis C. Lees
Senior Marine Ecologist
Dames & Moore
155 NE 100th Street
Seattle, WA 98125
Phone: (206) 523-0560
Expertise: Biological Aspects of Marine Disposal

George U. Mariani
EG&G, Environmental Consultants
151 Bear Hill Road
Waltham, MA 021054
Phone: (617) 890-3710
Expertise: Physical and Chemical Benthic Effects

Clayton D. McAuliffe
Senior Research Associate
Chevron Oil Field Research Company
Box 446
La Habra, CA 90631
Phone: (213) 694-7557
Expertise: Drilling Operations

Raymond E. McGlothlin
Manager, Research
Dresser Magcobar
P.O. Box 1407
Houston, TX 77001
Phone: (713) 972-6684
Expertise: Drilling Mud Additives

W. C. McMordie, Jr., Ph.D.
Oil Base, Inc.
3625 Southwest Freeway
Houston, TX 77027
Phone: (713) 666-0106
Expertise: Oil Base Drilling Muds

Robert P. Meek
President
Ecomar, Inc.
158 Santa Felicia Drive
Goleta, CA 93017
Phone: (805) 968-2577
Expertise: Physical Aspects of Marine Disposal

Richard C. Miller, Ph.D.
Senior Partner
Northern Technical Services
750 West 2nd Avenue, Suite 100
Anchorage, AK 99S01
Phone: (907) 276-4302
Expertise Physical and Chemical Aspects of Marine Disposal

H. R. Moseley, Jr.
Manager, Environmental
Engineering
Dresser Industries, Inc.
Oilfield Products Group
P.O.Box 6504
Houston, TX 77005
Phone: (713) 972-3873
Expertise: Physical Aspects

Charles Perricone
Milchem, Inc.
P.O. Box 22111
Houston, TX 77027
Phone: (713) 965-8312
Expertise: Drilling Mud
Additives

Mark M. Psutka
Frontier Planning
Esso Resources Canada Limited
500 6th Avenue, S.W.
Calgary, Alberta T2M 3C9
Canada
Phone: (403) 267-1110
Expertise: Arctic Disposal
Practices

James P. Ray, Ph.D.
Environmental Affairs
Shell Oil Company
P.O. Box 4320
Houston, TX 77210
Phone: (713) 241-3060
Expertise: All Aspects

Ted C. Sauer, Jr., Ph.D.
Exxon Production Research
Company
P.O.Box 2189
Houston, TX 77001
Phone: (713) 965-4344
Expertise: Physical Aspects

Roger Schlueter, Ph.D.
Dames & Moore
1100 Glendon Avenue, Suite 1000
Los Angeles, CA 90024
Phone: (213) 870-9700
Expertise: Effluent Modeling

Richard V. Shafer
Sohio Alaska Petroleum Company
Pouch 6-612
Anchorage, AK 99502
Phone: (907) 265-0000
Expertise: Arctic Disposal
Techniques

Eugene A. Shinn
Geologist
U.S. Geological Survey
Fisher Island Station
Miami Beach, FL 33139
Phone: (305) 350-5382
Expertise: Physical Aspects of
Marine Disposal

Lowell V. Sick
College of Marine Studies
University of Delaware
Lewes, DE 19958
Phone: (302) 645-4000
Expertise: Physical and Chemical
Benthic Effects

J. P. Simpson
O'Brien Goins Engineering
Incorporated
Executive Plaza, Suite 475
4615 Southwest Freeway
Houston, TX 77027
Phone: (713) 961-4013
Expertise: Drilling Fluid
Properties

Gerald A. Specken
Sump Operations Manager
Wilson Mud Service Ltd.
8004-82 Avenue
Edmonton, Alberta T6A 3T9
Canada
Phone: (403) 465-5206
Expertise: Onshore Disposal
Practices

Mel T. Strosher
Professional Associate
Kananaskis *Center for*
Environmental Research
University of Calgary
Calgary, Alberta T2N 1N4
Canada
Phone: (403) 284-5271
Expertise: Drilling Fluid Composition

David O. Stuebner
Exxon Production Research Company
P.O. Box 2189
Houston, TX 77001
Phone: (713) 965-4344
Expertise: Physical Aspects

John B. Tillery
Senior Reserach Chemist
Southwest Research Institute
6220 Culebra Road
San Antonio, TX 78002
Phone: (512) 684-5111
Expertise: Chemical Aspects

Walter E. Younkin
Research Director
Hardy Associates, Ltd.
3939 12th Street, N.E.
Calgary, Alberta T2E GR8
Canada
Phone: (403) 272-8761
Expertise: Onshore Disposal Effects

Bernard Zemel
Senior Research Chemist
Shell Development Company
P.O. Box 481
Houston, TX 77001
Phone: (713) 241-6161
Expertise: Radioactive Tracer Techniques

Richard R. Zingula
Senior Exploration Geologist
Exxon Company, U.S.A.
P.O. Box 2180
Houston, TX 77001
Phone: (713) 656-4849
Expertise: Physical Aspects

Additional Experts

R.K. Clark
Shell Development
P.O. Box 481
Houston, *Texas* 77001
Phone: (713) 663-2421
Expertise. Drilling Fluid Engineering and Chemist)

Robert W. Crippen, Ph.D.
Director of Marine Studies
Beak Consultants Limited
6870 Goreway Drive
Mississauga, Ontario
Canada L4V 1L9
Expertise. Environmental Effects

J.C. Davis
Assistant Director - Research
Fisheries & Oceans
1090 West Pender Street
Vancouver, British Columbia
Canada V7V 1N6
Expertise. Environmental Effects

David A Gettleson, Ph.D.
Biological Oceanographer
Continental Shelf Associates, Inc.
P.O. Box 3609
Tequesta, Florida 33458
Expertise: Biological Effects

Thomas R. Gilbert
Associate Director, Research
New England Aquarium
Central Wharf
Boston, Massachusetts 02110
Expertise: Biological Effects

Edward S. Gilfillan
Director
Marine Research Laboratory
Bowdoin College
Brunswick, Maine 04011
Expertise: Biological Effects

Sharon O. Hillman
Environmental Scientist
Sohio Alaska Petroleum Company
Pouch 6-612
Anchorage, Alaska 99502
Expertise: Biological Effects--Arctic

Maurice Jones
Coordinator of Environmental Regulations
IMCO Services
P.O.Box 22605
Houston, Texas 77027
Phone. (713) 671-3684
Expertise: All Aspects

Charles A. Menzie, Ph.D.
Senior Scientist
EG&G, Environmental Consultants
151 Bear Hill Road
Waltham, Massachusetts 02154
Expertise: Marine Effects

Jerry M. Neff, Ph.D.
Battelle Columbus Laboratories
W.F. Clapp Labs, Inc.
Duxbury, Massachusetts 02332
Expertise: Bioassays and Bioavailability

K. Rango Rae, Ph.D.
Professor
University of West Florida
Department of Biology
Pensacola, Florida 32504
Expertise: Biological Effects

Norman" L. Richards, Ph.D.
Associate Director for External Activities
U.S. Environmental Protection Agency
Sabine Island
Gulf Breeze, Florida 32561
Expertise: Environmental Effects

Normal I. Rubinstein
Research Aquatic Biologist
U.S. Environmental Protection Agency
Sabine Island
Gulf Breeze, Florida 32561
Expertise; Bioassays

R.V. Stauble
Drilling Engineer
Mobil 011 Corporation
P.O. Box 900
Dallas, Texas 75221
Expertise: Drilling Operations

Marlin E. Tagatz
Aquatic Biologist
Environmental Protection Agency
Environmental Research Laboratory
Gulf Breeze, Florida 32561
Expertise: Bioassays

John B. Tillery
Senior Research Chemist
Southwest Research Institute
6220 Culebra Road
San Antonio, Texas 78002
Expertise: Heavy Metals

Larry Tornberg
Fisheries Biologist
University of Washington
1100 N.W. 58th
Seattle, Washington 98107
Expertise; Bioassays

Robert H. Weir, Ph.D.
Senior Biologist
Environment Canada
Environmental Protection Service
4th Floor, Place Vincent Massey
Ottawa, Ontario
Canada K1A 1C8
Expertise: Biological Effects

APPENDIX B

DRILLING MUD PRODUCTS, COMPONENTS, USES, AND REPORTS

TABLE B-1

LIST OF SELECTED DRILLING MUD PRODUCTS BY TRADE NAME

MILCHEM	SARO1O	MAGCOBAR	IMCO	DESCRIPTION
Weight Materials and Viscosifiers				
Flosal	Flosal	Visquick	IMCO Shurlift	Asbestos Fibers
Galena	Galena	Super-Wate	Galena	Pulverized Lead Ore
Green Band	Baroco	High Yield	IMCO Klay	Sub Bentonite
Mil-Bar	Baroid	Magcobar	IMCO Bar	Barite
Milgel	Aquagel	Magcogel	IMCO ccl	Bentonite Clay
Mil-Polymer 102				Polysaccharide Polymer
Salt Water Gel	Zeogel	Salt Gel	IMCO Brinegel	Attapulgite Clay
Super-COl	Quik-Gel	Kwik-Thik	Inca HYB	Extended Benton ite
woo.]0		Lo Wate	IMCO Wate	Calcium Carbonate
XC Polymer	XC Polymer	Duovis	XC Polymer	Xanthum Gum Polymer
Deflocculants-Thinner				
Chemtrol3 CLS				Chrome Lignosulfonate
Desco	Desco	Desco	Desco	Organic Mud Thinner
Mil Flo				Polyflavinoid Compound
Mil Quebracho	Tannex	MC Quebracho	IMCO QBT	Quebracho-Lignite Blend
Qhfos	Barafos	Magco-Phos	IMCO Phos	Sodium Tetraphosphate
Rayflo	Rayflo	Rayflo	Rayf10	Hemlock Extract
SAPP	SAPP	SAPP	SAPP	Sodium Acid Pyrophosphate
Uni-Cal	Q-Broxin	Spersene	IMCO VC-10	Chrome Lignosulfonate
Filtration Control Materials				
Chemtrol-X		Resinex	IMCO Poly Ax	Polymer Blend
Cypan	Cypan	Cypan	Cypan	Sodium Polyacrylate
Drispac	Drispac	Drispac	Drispac	Polyanionic Cellulose Polymer
Drispac Lo-Vis	Drispac LV		Drispac Super-Lo	Polyanionic Cellulose Polymer Low Viscosity
Ligco	Carbonox	Tann-A-Thin	IMCO Lig	Mined Li nite
Ligcon	CC-16	Caustalig	IMCO Thin	Causticí ed Lignite
Lo Loss	Lo LOSS	Lo Loss	Lo Lose	Chem Tre ted Guar Cum
Milchem CMC-Med	Cellex-Reg	Magco CMC-Reg	IMCO CMC-Reg	Carboxym thylcellulose
Mi lchem CMC-HV	Cellex-HV	Mag co CMC-HV	IMCO CMC-HV	Carboxym thylcellulose
Mil Con		XP- 20		Heavy Me al Modified Lignite
Milstarch	Impermex	My-Lo-Jel	IMCO Loid	Pregelat nized Starch
Preservative	Aldacide	My-Lo-Jel Preservative	Preservaloid	Paraform ldehyde
Perma-Lose				Non-Ferm nting Organic Polyme
Starlose	Dextrid	Pemstarch	IMCO Permaloid	Non-Ferm nting Organic Polyme
SPA	SPA	SPA	SPA	Sodium P lyacrylate
WL-100	WL-100	WL-1OO	ML-1OO	Sodium P lyacrylate
Loss of Circulation Additives				
Diaseal M	Diaseal M	Diaseal M	Diaseal M	Mixture of Filter Aid materiels
Xwik-Seal	Kwik-Seal	Kwik-Seal	Kwik-Seal	Combination of Granules, Flakes and Fibers
Nil-Cedar Plug	Plug-Git	Chip-Seal		Shredded Cedar Fibers
Mil-Fiber	Fibertex	Mud Fiber	IMCO Fyber	Processed Cane Fibers
Milflake	Jelflake	Cell-O-Seal	IMCO Flakes	Shredded Cellophane Flakes
Milmica	Micatex	Magco Mica	I MCO Myca	Flake Mica
Mil-Plug	Wail-Nut	Nut Plug	IMCO Plug	Ground Nut KU lls
Specialty Additives				
Alum Stearate	Alum Stearate	Alum Stearate	Alum Stearate	Aluminum Stearate Defoamer
Ami-TEC	Coat 415	Magco Inhibitor 202	IMCO PT102	Oil Soluble. Water Dispersible Amine Corrosion Inhibitor
Ampli-Foam	Quik-Foam	Magco Foamer 66		Gen Purpose Foaming Agent for Brackish or Salt Water
Aquanul S01	Surflo B11			Anionic Microbiocide
Aquatec	Coet 122	Magco Inhibitor 101		Amine Corrosion Inhibitor for Water, Air-Mist Drilling
Atlosol	Trimulso	Magconate		Anionic Non-tonic Emulsifier

Source: Milchem 1977

TABLE B-1 (Continued)

LIST OF SELECTED DRILLING MUD PRODUCTS BY TRADE NAME

MILCHEM	BAROID	MAGCOBAR	IMCO	DESCRIPTION
Specialty Additives (continued)				
Atlosol-S	Seemxl	Salinex	IMCO SWS	Salt Water Emulsifier
Ben-Ex	Ben-Ex	Ben-Ex	Ben-Ex	Copolymer. Flocculent and Clay Extender
C-88				Oxalic Acid
Caltrol	Shale-San	T-0	IMCO SCR	Shale Control Reagent
DME		Surfak E	DME	Non-tonic emulsifier
DMS	Aktoflo S	Surfak M	DMS	Non- Ionic Surfactant
Drillaid 405	Drill aid 405	Drillaid 405	Drillaid 405	NonFluorescent Lubricant
Gel-Air				Gen Purpose Foaming Agent for Fresh Water-Stiff Foam
IPI (M. D.)	Baroid Asphalt	Stabil-Hole	IMCO Holecoat	Powdered, Water Dispersible Asphalt
LD-8		Magconol	IMCO Foamban	Non-Hydrocarbon Defoamer
Lo-sol	X-Tend	Rapidrill	IMCO Gelex	Liquid Bentonite Extender
Lubri-Film	E P Mudlube	sit Lube	IMCO C P Lube	Extreme Pressure Lubricant
Lubri-Sal				Biodegradable Bore Hold Lubricant for Brackish Water
Mil-Clean				Biodegradable Detergent
Milchem MD	Condet	00	IMCO no	Mud Detergent
Mi l-Emulsifier				Oil Soluble Emulsifier
Mil-Free	Shot Free	Pipe Lax	IMCO Freepipe	Surfactant to be Mixed with Diesel to Free Stuck Pipe
Mil-Card	coat 45		IMCO Sulf-X	Sulfide Scavenger
Mil-Graphite	Graphite	Flake Graphite	Graphite	Graphite
Mil -Plate	Torq-Trim	DOS-3	Lubrikleen	Biodegradable Sore Hole Lubricant for Fresh Water
Mil-Temp				High Temp Stabilizer for Water Base Mud
Noxygen	Coat 888	0s-1		Oxygen Scavenger
Noxygen L	coat 777	OS-1L	IMCOX-02	Oxygen Scavenger-Liquid
Scale-Ban	SURFLO H35	SI 1000		Scale inhibitor
Select Floc	Drill aid 421	Floxit		Drilled Solids Flocculant
Separan	Separan	Separan	Separan	Clay Flocculant
Super Shale-Trol 202				Additive for Gumbo Shale Drilling
Soltex	Sol tex	Sol tex	Sol tex	Sulfonated Residuum
XKB-Lig	K-Lig		IMCO Inpac	Potassium Lignite
XKB-Thin	K-Flo		IMCO Inpac	Iron-Complexed Lignosulfate
Oil Base Mud Additives				
CARBO-FREE	Ez spot		IMCO Spot	Variable Density Oil Phase Spotting Fluid Cone for Oil Mud
CARBO-GEL	Gel tone	VG-69	IMCO Ken Gel	Organophilic Colloid
CARBO-MIX	Invermul	Vertoil	IMCO Ken X	Basic Oil Mud Emulsifier
CARBO-MUL	E z Mul	SC-II		Quick Emulsification & Rapid Oil Wetting of Solids
CARBO-SEAL		011 Seal		Granular Hydrocarbon
CARBO-TEC			IMCO Xen X-3	Emulsifier for High Temp Systems
CARBO-TROL	Duratone	w-22	IMCO Ken X-2	Filtration Control at High Temp
SURF-COTE	OMC	w-33	IMCO Ken-Thin	011 Wetting Agent
Workover Additives				
W. O. TM20	Workover One	Polybrine	IMCO Safe-Vis	Polymeric Viscosifier & Fluid Loss Control Agent
W. O. TM21			IMCO safe-visa	High Yielding Polymeric Viscosifier
W. O. TM30		Mixical	Safe-Seal	Graded Calcium Carbonate
W. O. TM50		Ceastop	Safe-Perfseal	One Package Additive for Preparing Viscous Pill
W. O. TM60				Acid-SOlublc Polymeric Viscosifier
W. O. TMDEFOAM		Magconol	Foamban	Alcohol Saae Defoamer

Chemicals (Commercial Chemicals Widely Used In Drilling Muds)

Bicarbonate of Soda	Dowcide C	Pots#slum Chloride
Calcium Chloride	Gypsum	Soda Ash
Caustic Soda	Lime	Sodium Bichromate
Chrome Alum	Salt	Sodium Chromate
Chromic Chloride		

Source: Milchem 1977

TABLE B-2

PHYSICAL-CHEMICAL CHARACTERISTICS AND CONDITIONS OF USE OF SELECTED MUD COMPONENTS (a)

Component	Primary Purpose	Physical/ Chemical Characteristics	Alteration of Product with Use and Discharge to Seawater	Quantities Typically Used ppb	Comments
Aluminum Stearate	Defoamer	$AlOH(C_{18}H_{35}O_2)_2$	Insoluble	0.01-01	
Ben-Ex	Flocculant/ Clay ● lttir	Anhydride copolymer compound	Solubility 2.5 9/1	0.05	
Bit Lube	Lubricant	Phenolics	Insoluble	3-6	
C-88 (Milchem)	pH Control/ Viscosifier	HOOCCOH $2H_2O$ Oxalic acid	Soluble	0.1-0.5	
Calcium bromide	Completion fluid	$CaBr_2$	Solubility 170 g/100 ml @25°C	0-210	
Calcium chloride	Completion fluid	$CaCl_2$	Soluble to saturation: ● volva heat with water contact	0-210	
Caustalig	Filtration control	Causticized lignite	soluble	0.5-8	
Caustic potash	pH control	KOH	Soluble	0.25-2	Corrosive
Caustic soda	pH control	NaOH	Soluble; avoid rapid dilution	0.25-2.3	Corrosive
Ceascal	Deflocculant	$CaCO_3$ + lignosulfonate	Appreciably soluble	5-10	
Ceastop	Deflocculant	$CaCO_3$ + lignosulfonate + polymer	Slightly soluble	5-25	
Celloseal	Lost circulation material	$(C_6H_{10}O_5)N$ Cellophane	Insoluble	0.6-15	
Chip Seal	Lost circulation material	$(C_6HOO_5)X$	Insoluble	2-15	
Chrome Alum	Viscosifier for polymer muds	$KCr(SO_4)_2$ $12H_2O$	Soluble	0.3 lb/1 lb XC Polymer	Corrosive
Chromic chloride	Viscosifier for polymer muds	$CrCl_3$ $6H_2O$	Soluble	0.3 lb/1 lb XC Polymer	Corrosive
Cypan	Filtration Control	Sodium polyacrylate	Appreciably soluble	0.5-1	
D.D.	Mud detergent	Surfactants	Appreciably soluble	0.1	
Desco	Deflocculant	Tannin-dichromate mixture	Soluble	2-5	
E-55	Weighting	Blend: bentonite, silica, stearic acid, polymer	Insoluble	2-4	
Diaseal M	Lost circulation material	Diatomacious earth + asbestos	Insoluble	Variable	Contains asbestos
DOS-3	Freshwater lubricant	Cosmetic diesel Oil	Insoluble	2-4% by volume	
Douvis	Viscosifier/ Fluid Loss Control	Xanthum gum polymer	Hygroscopic; biodegradable	0.3-1	
Drispac	Saltwater viscosifier/ Fluid loss control	Cellulose	Complete solubility @25°C	0.25-2	
W-22	Filtration control for oil base mud	Metallic oxides + asphalt	Insoluble	0.25	Not discharged (oil mud product

(a) Unless noted, components are listed by their Magcobar product name. Notation NA indicates information is not available.

TABLE B-2 (Continued)

PHYSICAL-CHEMICAL CHARACTERISTICS AND CONDITIONS OF USE OF SELECTED MUD COMPONENTS (O)

Component	Primary Purpose	Physical/ Chemical Characteristics	Alteration of Product with Use and Discharge to Seawater	Quantities Typically Used (ppb)	Comments
DV-33	Oil mud detergent	Detergent alkylates in hydrocarbon carrier	Slightly soluble	0.5-6	Not discharged (oil mud product)
Emulsite	Dispersant	Causticized lignite	Moderately soluble	1-8	
Floxit	Flocculant	Copolymer of acrylamide and acrylic acid	Appreciably soluble	0.01-0.04	
Geo-Gel	Weighting/ Viscosifier	$Si_{12}Mg_8O_{30}(OH)_4(H_2O)_4$	Negligible solubility	0-15	
Gypsum	Gypsum base muds	$CaSO_4$	Negligible solubility	Saturate with Ca^{++} 500-800 ppm	
High Yield	Weighting/ Viscosifier	Subbentonite	Insoluble	10-40	
Kleenup	Detergent	Surfactant blend	Soluble ; biodegradable	Variable	
Kwik Seal	Lost circulation material	Cane fiber, nut shells, mica	Negligible solubility	10-40	
Kwik Thik	Viscosifier	Bentonite + Polyacrylic acid	Insoluble	12-20	
Lime	Lime base muds	CaO	Appreciably soluble	0.5-2	"incompatible with water" (Magcobar Products Listing, 1976).
Lo Loss	Filtration control	Hydroxypropyl guar (legume seeds)	Appreciably soluble	1-2	
Lo Wate	Weighting/ Viscosifier for oil muds	$CaCO_3$	Negligible solubility	8-12 lbs/gal	Not discharged (oil mud product)
Lube Kote	Lubricant	Graphite	Insoluble	Variable	
Magcobar	Weighting/ Viscosifier	$BaSO_4$	Insoluble	40	
Magco CFL	loccu	Chrome free lignosulfonate	Soluble	1-10	Substitute for chrome lignosul -
Magco CMC	Filtration control	$(C_{30}H_{43}O_{26}Na_3)n$	Appreciably soluble	0.1-2	
Magco Foamer	Foaming agent for brine, salt or high calcium make-up water	Surfactant blend	Soluble	1-2 gal/ 10bbl water	
Magco Gel	Weighting/ Viscosifier	$Na_nAl_2O_3 4SiO_2 H_2O$ (Bentonite clay)	Insoluble	20-100	Contains 4% asbestos
Magco Inhibitor	Corrosion inhibitor	Morpholine compound	Dispersible only	1-4	
Magco Lube	Lubricant	Blend of sulfurized triglyceride	Soluble only in freshwater	0.5-2	
Magco Mica	Lost circulation material	$H_2KAl_3(SiOH)_3$ Mica	Insoluble	2-30	
Magconate	Emulsifier	Lignite + Petroleum sulfonate	Insoluble, nondispersible in saltwater	0.5-2	
Magconol	Defoamer	$C_4H_9CH(C_2H_5)C_2H_2OH$	Negligible	0.1-2	

(0) Unless noted, components are listed by their Magcobar product name. Notation NA indicates information is not available.

TABLE B-2 (Continued)

PHYSICAL-CHEMICAL CHARACTERISTICS AND CONDITIONS OF USE OF SELECTED MUD COMPONENTS (O)

Component	Primary Purpose	Physical/ Chemical Characteristics	Alteration of Product with Use and Discharge to Seawater	Quantities Typically Used (ppb)	Comments
Magco Phos	Deflocculant	$Na(PO_3)_4$	Soluble	0.1-0.5	
Magco Poly Sal	Filtration control	Modified starch	Appreciably soluble	0-12	
Magoxide	Bactericide	MgO	Slightly soluble	0.5	
McQuebrancho	loccu	$C_{76}H_{52}O_{46}$ TwinIn-l ignite blend	Moderately soluble, biodegradable	2-s	
Mixical	Workover additive	$CaCO_3$	Insoluble	5-25	
Mud Fiber	Lost circulation material	Cane fibers	Insoluble	0.6	
My-Lo-Jel	Filtration control	$(C_6H_{10}O_5)X$ Pregelatinized starch	70% solubility	1-s	Generally used with bactericide
My-Lo-Jel Preservat ive	Bactericide	Paraformaldehyde	Solubility is pH and temperature dependent	0.3-0.3	
Nut Plug	Lost circulation material	Nut Hulls	Negligible solubility	1s-30	
Oilfaze	Emulsifier for oil muds	Fatty acid, resin, clay, emulsifier blend	Insoluble	22-40	Not discharged (oil mud product 1
OS-1	Oxygen scavenger	Na_2SO_3	Soluble	Maintain excess sulfite at 20-300 ppm	
OS-7-L	Liquid oxygen caveng	NH_4HSO_3	Soluble	Maintain excess sulfite at 100-300 ppm	Toxic sulphur dioxide gas emitted when heated
Permstarch	Filtration control	Organic polymer	Insoluble	2-6	
Pipelax	Free stuck pipe	Surfactant blend	Insoluble	1-1.5	
Polybrine	Viscosifier/Fluid loss control	Polymers and carbonates	Insoluble	3-6	
Potassium chloride	Potassium base muds	KCL	Soluble to saturation	10-17	
Rapidrill	Bentonite ● xtemkr	Sodium polyacrylate and polyacrylamide blend	Solubility 2.5 9/1	Variable	
Resinex	Filtration control	Lignosulfonate and resin copolymer	Soluble	2-5	
Salines	Saltwater emulsifier	Alcohol ether sulfate	Appreciably soluble	1-3	
salt Gel	Weighting/ Viscosifier	$(CH_2)_4(OH)_2Mg_5SiO_2O4H_2O$ Attapulgite clay	Negligible solubi 1 ity	15	
SAP?	Deflocculant	$Na_2H_2P_2O_7$	Soluble	0.1-0.2	
SE - 11	011 base mud additive	Dodecyl benzene sulfonates	Insoluble	0.5-4	Not discharged, (oil mud product)
Selec Floc	Flocculant	Selective flocculants	Slightly soluble	0.01-0.04	
SI 1000	Scale inhibitor	Acrylic polymer	Soluble	Maintain excess phosphate at 5-10 ppm	
SHP - 300	Viscosifier	Modified asbestos fibers	Insoluble	5-10	Asbestos fibers
Soda Ash	Calcium remover	Na_2CO_3	Moderately soluble	0.25-2	

(a) Unless noted, components are listed by their Magcobar product name. Notation NA indicates information is not available.

TABLE B-2 (Continued)

PHYSICAL-CHEMICAL CHARACTERISTICS AND CONDITIONS OF USE OF SELECTED MUD COMPONENTS (a)

Component	Primary Purpose	Physical/ Chemical Characteristics	Alteration of Product with Use and Discharge to Seawater	Quantities Typically Used (ppb)	Comments
Sodium bicarbonate	Calcium remover	$NaHCO_3$	Soluble	0.25-2	
Sodium chromate	Prevent high temperature gelation	Na_2CrO_4	Soluble	0.25-2	Chrome treated mud.
Sodium dichromate	Prevent high temperature gelation	$Na_2Cr_2O_7$ $2H_2O$	Soluble	0.25-2	Chrome treated mud.
Soltex	Emulsifier	Sodium asphalt sulfonate complex	Insoluble, non-biodegradable	2-8	
Spersene	Deflocculant	Chrome lignosulfonate; contains 2-4 % trivalent chromium	Soluble	t-lo	Chrome treated mud.
Stabil Hole	Wall cake	Powdered asphalt	Insoluble	5-10	
Superwate	We ighting/ Viscosities	Pulverized lead ore	Insoluble	2300 for 32 ppb mud	
Surf ak-E	Non-ionic emulsifier	Ethylene oxide nonylphenol	Appreciably soluble	0.1	
Surfak M	Emulsifier	$C_{75}H_{144}O_{31}$ (Phenol ● UVIWW oxide)	Partially soluble	0.5-1	
Tannathin	Filtration control	Lignite, brown coal	Soluble in higher pH ranges (10.5) ·	1-4	
Verithin	Deflocculant	Hydrocarbon blend	Insoluble	NA	
Vertoil	Oil base mud emulsifier	Blend of surface active agents and resins	Insoluble	22-40	Not discharged (oil mud product)
VG-69	oil base mud viscosifier	Organo bentonite clay	Dispersible	0.5-2	Not discharged (oil mud product)
Vi sbestos	Viscosifier	$(Ca, Mg)_2$ SiO_4 Asbestos	Insoluble	5-10	Asbestos fibers
XP-20	Filtration control	Chrome lignite	Appreciably soluble	l-4	Chrome treated mud.
xl%- 2000	Corrosion inhibitor	Organic corrosion preventative	Insoluble	NA	
X inc bromide		$ZnBr_2$	Solubility 447 9/100 ml	NA	"Prevent contamination of fresh or Atwater systems" (Magcobar Products Li sting, 1976).
Zinc chromate	Corrosion control	$ZnCrO_4$	Insoluble	NA	Corrosive

(a) Unless noted, components are listed by their Magcobar product name.
Notation NA indicates information is not available.

TABLE B-3

MID-ATLANTIC BIOASSAY PROGRAM

*Mud Number #2 - Seawater Lignosulfonate Mud

Composition

Components	Concentration #/bbl	Concentration wt%
Barite	176.0	35.0
Bentonite/Drill Solids	32.1	6.3
Chrome Lignosul fonate	1.8**	0.4
Lignite	0.9**	0.[illegible]
Drispac (Polyanionic cellulose)	0.2	0.0
Salt	10.0	2.0
Caustic	0.9	0.2

Properties

Mud Density	12.1 lbs/gal
Percent Solids (wt%)	43.5%
Calcium	650 mg/l

Metals Analysis

Metal	Concentration (ppm-whole mud basis)
Arsenic	2.0
Barium	141,000
Cadmium	<1
Chromium	227
Copper	11.3
Lead	< 1
Mercury	< 1
Nickel	1.5
Vanadium	18
Zinc	181

* Flowline mud samples obtained from Ocean Victory. OCS-A-0028 #3 uC; operator-Texaco. Collected March 16. 1980. Stored In refrigerator ● t EG&G until analysis by bioassay contractor.

**Estimated concentrations outside range for chrome lignosulfonate (2-15 #/bbl). lignite (1-10 #/bbl).

*Mud Number 3 - Lime Mud

Composition

Components	Concentration #/bbl	Concentration wt%
Barite	64.0	14.[illegible]
Bentonite	20.0	5.[illegible]
Drill Solids	35.0	6.[illegible]
Chrome Lignosulfonate	3.5	[illegible]
Lignite	1.8	0.4
Lime	1.5**	0.5
Caustic	1.5	0.3

Properties

Mud Density	10.4 lbs/gal
Percent Solids (wt%)	27.8
pH	10.0

Metals Analysis

Metal	Concentration (ppm - whole mud basis)
Arsenic	3
Barium	76,200
Cadmium	< 1
Chromium	192
Copper	8
Lead	4
Mercury	< 1
Nickel	3
Vanadium	27
Zinc	58

● Flowlinc mud sample obtained from ri9 In Section 5 Township 10. South Range 7W, Louisiana, 3/4 miles ● ast of Lake Charles. Collected November 1. 1980 by PESA.

● *[sttmttcd concentration outside range for 1 ime (2-20 #/bbl)

TABLE B-3

MID-ATLANTIC BIOASSAY PROGRAM (Continued)

*Mud Number 24 - Non-Dispersed Mud

Composition

Components	Concentration #/bbl	Concentration Wt%
Barite	10.8**	2.8
Bentonite	20.0**	5.2
Drill Solids	49.0	12.7
Drispac (Polyanionic cellulose)	1.0	0.3
Lignite	0.1	

Properties

Mud Density	9.2 lbs/gal
% solids (by wt.)	21.0
Chlorides	1,200 mg/l

Metals Analysis

Metal	Concentration (ppm - whole mud basis)
Arsenic	2.0
Barium	13,300
Cadmium	< 1
Chromium	10
Copper	7
Lead	2
Mercury	< 1
Nickel	4
Vanadium	22
Zinc	16

* Flowline mud samples taken from Well No. 1, GM&O Railroad, WC/EUCUTTA Field, Wayne County. Mississippi. Collected November 27. 1920 by PESA.

**Estimated concentration outside range for Barite (25-180) and Bentonite (5-15)

*Mud Number 5 - Seawater Spud Mud

Composition

Components	Concentration #/bbl	Concentration Wt%
Barite	[illegible]	[illegible]
Drill Solids	52	[illegible]
Bentonite	22	[illegible]
Lime	[illegible]	[illegible]
Soda Ash/Sodium Bicarbonate	[illegible]	[illegible]
Caustic	[illegible]	[illegible]

Properties

Mud Density	[illegible]
Percent Solids (by wt)	[illegible]

Metals Analysis

Metal	Concentration (ppm - whole mud basis)
Arsenic	3
Barium	2,630
Cadmium	<1
Chromium	16
Copper	5
Lead	4
Mercury	<1
Nickel	6
Vanadium	35
Zinc	21

*Flowline mud samples obtained Ship Shoal, Block 224, OCS-G-10-Z3, Well [illegible], Nobel-27. Collected October 23. 1980 by PESA.

TABLE B-3

MID-ATLANTIC BIOASSAY PROGRAM (Continued)

*Mud Number 6 - Seawater/Freshwater Gel Mud

Composition

Components	Concentration #/bbl	Concentration Wt%
Barite	21.2	5.4
Bentonite	9.7**	2.5
Drill Solids	14.1**	3.6
Drispac (Polyanionic cellulose)	0.5	0.1
Cellex (CMC)	0.1	0.1
Caustic	0.4**	0.1

Properties

Mud Density	9.3 lbs/gal
% Solids (by wt)	11. t
Chlorides	250 mg/l
Calcium	40 mg/l

Metals Analysis

Metal	Concentration (ppm - whole mud basis)
Arsenic	2
Barium	?S .605
Cadmium	< 1
Chromium	2
Copper	2
Lead	< 1
Mercury	< 1
Nickel	1
Vanadium	6
Zinc	12

*Flowline mud samples taken from rig in Standard Draw 2-10, Carbon County, Wyoming Collected November 1, 1980 by PESA.

** Limited concentration outside range for Bentonite (10-50), Drill Solids (20-100), Caustic (0.5-3).

*Mud Number 7 - Lightly Treated Lignosulfonate Freshwater/Seawater Mud

Composition

Components	Concentration #/bbl	Concentration wt %
Drill Solids	46	12
Bentonite	25	6.2
Barite	9	2.2
Chrome Lignosulfonate	4	1.0
Lignite	5	1.2
Cellulose Polymer (Drispac)	0.5	0.1

Properties

Percent Solids (wt%)	24.1%
Mud Density	9.6 lbs/gal
pH	10.2
Chlorides	7500 mg/l

Metals Analysis

Metal	Concentration (ppm-whole mud basis)
Arsenic	<1
Barium	11,500
Cadmium	<1
Chromium	265
Copper	26
Lead	24
Mercury	<1
Nickel	6
Vanadium	30
Zinc	82

* Flowline mud sample obtained from Alaskan Star Drilling for Exxon USA in Block 599 Exxon OCS A-0029 Well #1.

TABLE B-3

MID-ATLANTIC BIOASSAY PROGRAM (Continued)

*Mud Number 8 - Lignosulfonate Freshwater Mud

Composition

Components	Concentration #/bbl	wt%
Barite	1s.1	3.9
Bentonite	15.1	3.9
Drill Solids	28.1	7.2
Chrome Lignosulfonate	1.7**	0.4
Lignite	2.8	t. 7
Caustic	1.2**	0.3
Lime	Trace	.

Properties

Mud Density	9.3 lbs/gal
% Solids (by wt)	16.4
Chlorides	1800 mg/l
pH	9.0
Calcium	40 mg/l

Metals Analysis

Metal	Concentration (PPm - whole mud basis)
Arsenic	3
Barium	14,000
Cadmium	< 1
Chromium	48
Copper	4
Lead	9
Mercury	< 1
Nickel	8
Vanadium	18
Zinc	1S

● floulfnc mud sample obtained from South Allenhorst Prospect. Caney Field, C. R. Bostwick and Brotherton Survey A-6. Matagora County, Texas. Collected November 16, 1980 by PESA.

**Estimated concentrations outside range for Chrome Lignosulfonate (4.15), caustic (2-S).

IMCO SERVICES
A Division of HALLIBURTON Company
9400 West Loop South, P.O. Box 22605
Houston, Texas 77027 A/C 713 671-4000

DRILLING MUD REPORT REPORT NO.

DATE ____ 19 ____ DEPTH ____

API WELL NO | STATE | COUNTY | WELL | ST

OPERATOR	CONTRACTOR	RIG NO
ADDRESS	ADDRESS	SPUD DATE
REPORT FOR MR	REPORT FOR MR	SECTION TOWNSHIP RANGE

WELL NAME AND NO	FIELD OR BLOCK NO	COUNTY PARISH OR OFFSHORE AREA	STATE/PROVINCE

OPERATION		CASING	MUD VOLUME (BBL)		CIRCULATION DATA	
PRESENT ACTIVITY		SURFACE IN AT FT	HOLE	PITS	PUMP SIZE X IN	ANNULAR VEL FT/MIN
BIT SIZE (IN)	NO	INTERMEDIATE IN AT FT	TOTAL CIRCULATING VOLUME		PUMP MAKE MODEL	OPPOSITE DP / OPPOSITE COLLAR
DRILL PIPE SIZE	TYPE	PRODUCTION OR LINER IN AT FT	IN STORAGE	WEIGHT	BBL/STROKE STROKE/MIN	CIRCULATING PRESSURE PSI / BOTTOMS UP (MIN)
DRILL COLLAR SIZE	LENGTH	MUD TYPE			BBL/MIN	SYSTEM TOTAL (MIN)

Sample from ☐ Flowline ☐ Pit; Flowline Temperature °F	MUD PROPERTIES		
Time Sample Taken			
Depth (ft)			
Weight ☐ (ppg) ☐ (lb/cu ft)			
Mud Gradient (psi/ft)			
Funnel Viscosity (sec/qt) API at ____ °F			
Plastic Viscosity cp at ____ °F			
Yield Point (lb/100 sq ft)			
Gel Strength (lb/100 sq ft) 10 sec/10 min	/	/	/
pH ☐ Strip ☐ Meter			
Filtrate API (ml/30 min)			
API HP HT Filtrate (ml/30 min) at ____ °F			
Cake Thickness 32nd in API ☐ HTHP ☐			
Alkalinity Mud (Pm)			
Alkalinity Filtrate (Pf/Mf)	/	/	/
Salt ☐ ppm ☐ gpg; Chloride ☐ ppm ☐ gpg			
Calcium ☐ ppm ☐ Gyp ppb			
Sand Content (% by Vol)			
Solids Content (% by Vol)			
Oil Content (% by Vol)			
Water Content (% by Vol)			
Methylene Blue Capacity (ml/ml Mud)			
Methylene Blue (lb/bbl Bentonite Eq)			

EQUIPMENT

	SIZE	HRS TOUR			SIZE	HRS TOUR	
Centrifuge				Desilter			
Degasser				Shaker			
Desander				Other			

DAILY COST	CUMULATIVE COST

MUD PROPERTIES SPECIFICATIONS

WEIGHT	VISCOSITY	FILTRATE

BY AUTHORITY ☐ OPERATOR'S WRITTEN ☐ OPERATOR'S REPRESENTATIVE ☐ DRILLING CONTRACTOR ☐ OTHER

RECOMMENDED TOUR TREATMENT

- ☐ IMCO BAR
- ☐ IMCO GEL
- ☐ IMCO BRINEGEL
- ☐ IMCO RD-111
- ☐ IMCO VC-10
- ☐ IMCO THIN
- ☐ IMCO CAUSTIC SODA
- ☐ IMCO M D
- ☐ IMCO POLY RX
- ☐
- ☐

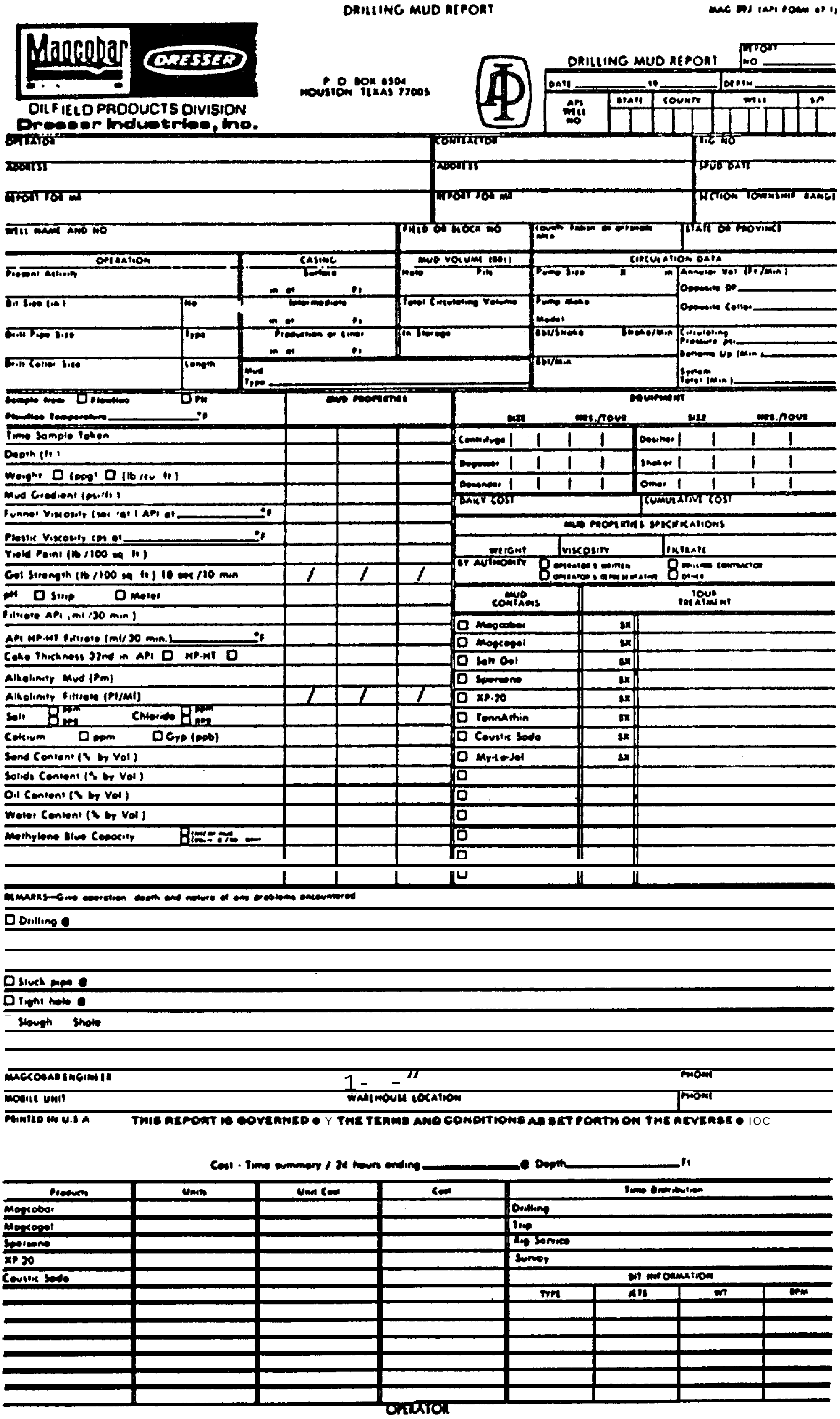
REMARKS

IMCO REPRESENTATIVE	HOME ADDRESS	TELEPHONE
OPERATOR	WAREHOUSE LOCATION	TELEPHONE

Form 515 Rev. / 11-79 / Printed in USA

NOTICE: ANY OPINION AND/OR RECOMMENDATION EXPRESSED ORALLY OR WRITTEN HEREIN HAS BEEN PREPARED CAREFULLY AND MAY BE USED IF THE USER SO ELECTS. HOWEVER, NO REPRESENTATION OR WARRANTY IS MADE BY OURSELVES OR OUR AGENTS AS TO ITS CORRECTNESS OR COMPLETENESS AND NO LIABILITY IS ASSUMED FOR ANY DAMAGES RESULTING FROM THE USE OF SAME.

FIGURE B-1 IMCO DRILLING MUD REPORT



DRILLING MUD REPORT

MAG 89J (API FORM 47 1)

Magcobar DRESSER

OILFIELD PRODUCTS DIVISION
Dresser Industries, Inc.

P. O. BOX 6504
HOUSTON, TEXAS 77005

DRILLING MUD REPORT

REPORT NO. ____

DATE ____ 19 ____ DEPTH ____

API WELL NO. | STATE | COUNTY | WELL | S/T

OPERATOR	CONTRACTOR	RIG NO.
ADDRESS	ADDRESS	SPUD DATE
REPORT FOR MR.	REPORT FOR MR.	SECTION TOWNSHIP RANGE
WELL NAME AND NO.	FIELD OR BLOCK NO. / COUNTY, PARISH OR OFFSHORE AREA	STATE OR PROVINCE

OPERATION	CASING	MUD VOLUME (BBL)	CIRCULATION DATA
Present Activity	Surface ____ in. at ____ ft.	Hole / Pits	Pump Size ____ X ____ in. / Annular Vel. (Ft./Min.) Opposite DP ____ Opposite Collar ____
Bit Size (in.) / No.	Intermediate ____ in. at ____ ft.	Total Circulating Volume	Pump Make / Model
Drill Pipe Size / Type	Production or Liner ____ in. at ____ ft.	In Storage	Bbl/Stroke / Stroke/Min. / Circulating Pressure psi ____ Bottoms Up (Min.) ____
Drill Collar Size / Length	Mud Type ____		Bbl/Min. / System Total (Min.) ____

	MUD PROPERTIES		
Sample from ☐ Flowline ☐ Pit			
Flowline Temperature ____ °F			
Time Sample Taken			
Depth (ft.)			
Weight ☐ (ppg) ☐ (lb/cu. ft.)			
Mud Gradient (psi/ft.)			
Funnel Viscosity (sec/qt.) API at ____ °F			
Plastic Viscosity cps at ____ °F			
Yield Point (lb/100 sq. ft.)			
Gel Strength (lb/100 sq. ft.) 10 sec/10 min	/	/	/
pH ☐ Strip ☐ Meter			
Filtrate API (ml/30 min.)			
API HP-HT Filtrate (ml/30 min.) ____ °F			
Cake Thickness 32nd in. API ☐ HP-HT ☐			
Alkalinity Mud (Pm)			
Alkalinity Filtrate (Pf/Mf)	/	/	/
Salt ☐ ppm ☐ gpg / Chloride ☐ ppm ☐ gpg			
Calcium ☐ ppm ☐ Gyp (ppb)			
Sand Content (% by Vol.)			
Solids Content (% by Vol.)			
Oil Content (% by Vol.)			
Water Content (% by Vol.)			
Methylene Blue Capacity ☐ cm³/cm³ mud ☐ lb/bbl equiv.			

EQUIPMENT

	SIZE	HRS./TOUR		SIZE	HRS./TOUR
Centrifuge			Desilter		
Degasser			Shaker		
Desander			Other		

DAILY COST | CUMULATIVE COST

MUD PROPERTIES SPECIFICATIONS

WEIGHT | VISCOSITY | FILTRATE

BY AUTHORITY ☐ OPERATOR'S WRITTEN ☐ OPERATOR'S REPRESENTATIVE ☐ DRILLING CONTRACTOR ☐ OTHER

MUD CONTAINS		TOUR TREATMENT
☐ Magcobar	SX	
☐ Magcogel	SX	
☐ Salt Gel	SX	
☐ Spersene	SX	
☐ XP-20	SX	
☐ TannAthin	SX	
☐ Caustic Soda	SX	
☐ My-Lo-Jel	SX	
☐		
☐		
☐		
☐		
☐		
☐		

REMARKS—Give operation, depth and nature of any problems encountered

☐ Drilling @

☐ Stuck pipe @

☐ Tight hole @

Slough Shale

MAGCOBAR ENGINEER ____ PHONE ____

MOBILE UNIT ____ WAREHOUSE LOCATION ____ PHONE ____

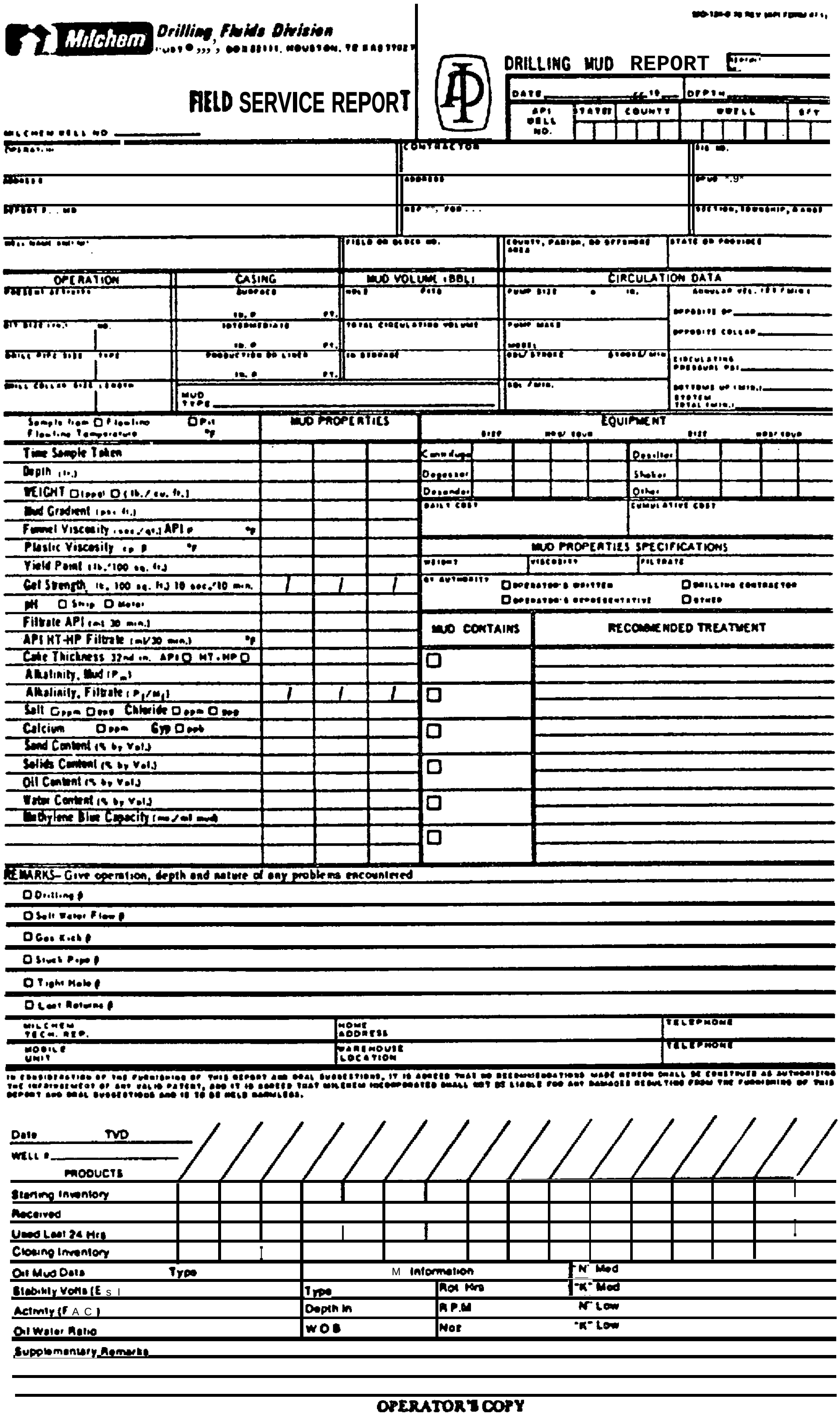
PRINTED IN U.S.A. THIS REPORT IS GOVERNED BY THE TERMS AND CONDITIONS AS SET FORTH ON THE REVERSE SIDE

Cost - Time summary / 24 hours ending ____ @ Depth ____ Ft

Products	Units	Unit Cost	Cost	Time Distribution			
Magcobar				Drilling			
Magcogel				Trip			
Spersene				Rig Service			
XP 20				Survey			
Caustic Soda				BIT INFORMATION			
				TYPE	JETS	WT	RPM

OPERATOR

FIGURE B-2 MAGCOBAR DRILLING MUD REPORT



Milchem Drilling Fluids Division

FIELD SERVICE REPORT

DRILLING MUD REPORT

DATE	DEPTH	API WELL NO.	STATE / COUNTY / WELL
MILCHEM WELL NO.			
OPERATOR	CONTRACTOR	RIG NO.	
ADDRESS	ADDRESS	SPUD	
REPORT FOR	REPORT FOR	SECTION, TOWNSHIP, RANGE	
WELL NAME AND NO.	FIELD OR BLOCK NO.	COUNTY, PARISH, OR OFFSHORE AREA	STATE OR PROVINCE

OPERATION	CASING	MUD VOLUME (BBL)	CIRCULATION DATA
PRESENT ACTIVITY	SURFACE	HOLE / PITS	PUMP SIZE / ANNULAR VEL.
BIT SIZE / NO.	INTERMEDIATE	TOTAL CIRCULATING VOLUME	PUMP MAKE / OPPOSITE DP / OPPOSITE COLLAR
DRILL PIPE SIZE / TYPE	PRODUCTION OR LINER	IN STORAGE	BBL/STROKE / STROKE/MIN / CIRCULATING PRESSURE PSI
DRILL COLLAR SIZE / LENGTH	MUD TYPE		BBL/MIN / BOTTOMS UP / SYSTEM TOTAL

MUD PROPERTIES			
Sample from ☐ Flowline ☐ Pit; Flowline Temperature °F			
Time Sample Taken			
Depth (ft.)			
WEIGHT ☐ (ppg) ☐ (lb./cu. ft.)			
Mud Gradient (psi/ft.)			
Funnel Viscosity (sec./qt.) API @ °F			
Plastic Viscosity cp @ °F			
Yield Point (lb./100 sq. ft.)			
Gel Strength (lb./100 sq. ft.) 10 sec./10 min.	/	/	/
pH ☐ Strip ☐ Meter			
Filtrate API (ml/30 min.)			
API HT-HP Filtrate (ml/30 min.) °F			
Cake Thickness 32nd in. API ☐ HT-HP ☐			
Alkalinity, Mud (P_m)			
Alkalinity, Filtrate (P_f/M_f)	/	/	/
Salt ☐ ppm ☐ epm; Chloride ☐ ppm ☐ epm			
Calcium ☐ ppm; Gyp ☐ ppb			
Sand Content (% by Vol.)			
Solids Content (% by Vol.)			
Oil Content (% by Vol.)			
Water Content (% by Vol.)			
Methylene Blue Capacity (me/ml mud)			

EQUIPMENT (Size / Hrs/Tour): Centrifuge, Degasser, Desander, Desilter, Shaker, Other

DAILY COST / CUMULATIVE COST

MUD PROPERTIES SPECIFICATIONS: WEIGHT / VISCOSITY / FILTRATE

BY AUTHORITY: ☐ OPERATOR'S WRITTEN ☐ DRILLING CONTRACTOR ☐ OPERATOR'S REPRESENTATIVE ☐ OTHER

MUD CONTAINS | RECOMMENDED TREATMENT

REMARKS– Give operation, depth and nature of any problems encountered

☐ Drilling #

☐ Salt Water Flow #

☐ Gas Kick #

☐ Stuck Pipe #

☐ Tight Hole #

☐ Lost Returns #

MILCHEM TECH. REP.	HOME ADDRESS	TELEPHONE
MOBILE UNIT	WAREHOUSE LOCATION	TELEPHONE

Date TVD

WELL #

PRODUCTS

Starting Inventory															
Received															
Used Last 24 Hrs															
Closing Inventory															

Oil Mud Data Type	M Information		"N" Med
Stability Volts (E S)	Type	Rot Hrs	"K" Med
Activity (F A C)	Depth In	R P M	"N" Low
Oil Water Ratio	W O B	Noz	"K" Low

Supplementary Remarks

OPERATOR'S COPY

FIGURE B-3 MILCHEM DRILLING MUD REPORT

Swaco

SWACO FLUID PROCESSING SYSTEMS
Solids Control Report

CHECK NO. ________ DATE ________

OPERATOR ________	WELL NAME ________
REPORT FOR ________	LOCATION ________
________	CO ________
CONTRACTOR ________	MUD SERVICE ________
REPORT FOR ________	

BIT		CASING		MUD VOLUME		RIG PUMPS	
SIZE	NO	SURFACE	●	HOLE	PITS	PUMP SIZE	x
MAKE	TYPE	INTERMEDIATE	●	TOTAL CIRCULATING VOLUME		PUMP MAKE	MODEL
DEPTH IN		LINER	●	STORAGE		BBL/STK	STK/MIN
DEPTH OUT		m o o	●	WATER USE GALS/DAY		BBL/MIN	

REPORT FOR 24 HR. PERIOD ENDING A.M. P.M.

SWACO SOLIDS CONTROL EQUIPMENT	OPER HRS. (E_t)	DISCARD GAL/HR TOTAL (Q_3)	DISCARD GAL/HR DRILL SOLIDS (Q_{s3})	DISCARD GAL/HR BARITE (Q_{b3})	DISCARD GAL/HR WATER (Q_{w3})	DISCARD GAL/DAY DRILL SOLIDS	DISCARD GAL/DAY BARITE	DISCARD GAL/DAY WATER	MUD SOLIDS COMPOSITION SUCTION PIT
SUPER SCREEN NO 1 SCREEN MESH, TOP ___ BOTTOM ___									VISCOSITY, SEC/QT.
SUPER SCREEN NO. 2 SCREEN MESH, TOP ___ BOTTOM ___									WEIGHT, LB/GAL
SUPER SCREEN No. 3 SCREEN MESH, TOP ___ BOTTOM ___									BENTONITE LB/BBL
D-SANDER o 11? o 212 o 313									DRILL SOLIDS LB/BBL
D-SILTER 0474 o 6T4 o 8T4									BARITE LB/BBL
									S.G. SOLIDS
									SOLIDS VOL %
SOLIDS SEPARATOR CYCLONE NO. ___ SIZE ___ SCREEN, 4x8 ☐ 2x6 ☐ MESH									WATER VOL %
SOLIDS SEPARATOR CYCLONE NO ___ SIZE ___ SCREEN, 4x8 ☐ 2x6 ☐ MESH ___									OIL VOL %
SUPERCLONE, NO. CLONE'S ___									
CENTRIFUGE TYPE ___									MUD PROPERTIES FROM REPORT
CENTRIFUGE TYPE ___									PV ___ YP ___ GELS ___
CENTRIFUGE TYPE ___									MW ___ VIS ___ MBT ___
									CL ___ CA ___ FL ___
	COLUMN TOTALS								

REMARKS	OPERATING HOURS
	DRILLING ___
	TRIPS ___
	RIG SERVICE ___
	FT. DRLG. LAST 24 HRS. ___
	TOTAL DEPTH ___

SWACO Personnel

1. ________
2. ________

Total Gallons Solids Removed ________
Total Gallons Solids Generated (Gauge Hole) ________

FIGURE B-4 SWACO SOLIDS CONTROL REPORT

APPENDIX C

SUMMARY OF LABORATORY STUDIES ON BIOLOGICAL EFFECTS OF DRILLING FLUIDS ON MARINE ORGANISMS

This appendix provides three tables summarizing results of bioassays reported in the literature that are most relevant to assessment of drilling fluid impacts in north temperate and subarctic regions. Results of acute tests (Table C-1) are generally grouped by study in approximate decreasing order of relevance. Tables C-2 and C-3 contain results of sublethal and bioaccumulation tests, respectively.

The bioassays reported in the literature were performed with five different fractions of used drilling fluid (or some component of drilling fluid) and seawater mixtures. These are designated in these tables as:

Layered Solid Phase (LSP). A known volume of drilling fluid is layered over the bottom or added to seawater. Although little or no mixing of the slurry is done, the water column contains very fine particulate fractions which do not settle out of solution.

Suspended Solids Phase (SSP). Known volumes of drilling fluids are added to seawater, and the mixture is kept in suspension by aeration or other mechanical means.

Suspended Particulate Phase (SPP). One part by volume of drilling fluid is added to nine parts of artificial seawater. The drilling fluid-seawater slurry is well mixed, and the suspension is allowed to settle for 4 h before the supernatant (100% SPP) is siphoned off for immediate use in bioassays.

Mud Aqueous Fraction (MAF). One part by volume of drilling fluid is added to nine parts of seawater. The mixture is stirred thoroughly and then allowed to settle for 20 h. The resulting supernatant (100% MAF) is siphoned and is used immediately in the bioassays. The MAF is similar to the SPP except that longer settling times of MAF allow for a lower concentration of particulate.

Filtered Mud Aqueous Fraction (FMAF). The mud aqueous fraction (MAF) or whole drilling fluid is centrifuged and/or passed through a 0.45-μ filter, eliminating all particulate greater than this size.

SW is used in these tables as an abbreviation for seawater, and chrome lignosulfonate is abbreviated CLS.

Table C-1. Summary of Results of Acute Drilling Fluid Bioassays on Marine Organisms

Test Material	Test Organism	Test Conditions	Results (LC50)[b]	Reference
Used Cook Inlet lignosulfonate drilling fluid	Stage I larvae of: *Paralithodes camtschatica* (king crab) *Cancer magister* (Dungeness crab) *Chionoecetes bairdi* (Tanner crab)	SW, 28.4-30.9 ppt, 4.5-7.5°C Static LSP, FMAF[a]	(144-h) 0.20-0.94% LSP (144-h EC50)[c] 0.28%LSP (king crab larvae only) (144-h LC50) 1.41-3.34% FMAF (144-h EC50) 0.56-2.58% FMAF	Carls and Rice 1981
Used Cook Inlet lignosulfonate drilling fluid	Stage I larvae of: *Eualus suckleyi* (kelp shrimp) *Pandalus hypsinotus* (coonstripe shrimp) *Pandalus danae* (dock shrimp)	SW, 28.4-30.9 ppt, 4.5-7.5°C Static LSP, FMAF	(144-h) 0.05-0.44% LSP (144-h EC50) 0.05-<0.50% LSP (144-h) 0.30-0.90% FMAF (144-h) 0.32-0.56% W	Carls and Rice 1981
Used Prudhoe Bay lignosulfonate drilling fluid	Stage I larvae of: *Pandalus hypsinotus* (coonstripe shrimp)	SW, 28.4-30.9 ppt, 4.5-7.5°C Static LSP, FMAF	(144-h) 15.31% FMAF (144-h) 9.07% FMAF	Carls and Rice 1981
New Prudhoe Bay drilling fluid without lignosulfonate	Stage I larvae of: *Paralithodes camtschatica* (king crab) *Pandalus hypsinotus* (coonstripe shrimp)	SW, 28.4-30.9 ppt, 4.5-7.5°C Static LSP, FMAF	(144-h) 2.33-3.23% FMAF (144-h EC50) 2.42% FMAF (*Pandalus* only) (144-h EC50) <1% LSP	Carla and Rice 1981
Used Homer spud mud	Stage I larvae of: *Paralithodes camtschatica* (king crab)	SW, 28.4-30.9 ppt, 4.5-7.5°C Static LSP, FMAF	(144-h) 9.45% FMAF (144-h EC50) 6.60% FMAF	Carla and Rice 1981
New Homer drilling fluid	Stage I larvae of: *Paralithodes camtschatica* (king crab) *Pandalus hypsinotus* (coonstripe shrimp)	SW, 28.4-30.9 ppt, 4.5-7.5°C Static LSP, FMAF	(144-h) <5-7.17% FMAF (144-h EC50) <5-6.18% FMAF (144-h EC50) <1% LSP (king crab)	Carls and Rice 1981
Used Homer drilling fluid	Stage I larvae of: *Paralithodes camtschatica* (king crab) *Pandalus hypsinotus* (coonstripe shrimp)	SW, 28.4-30.9 ppt, 4.5-7.5°C Static LSP, FMAF	(144-h) 30.08-37.62% FMAF (144-h EC50) 18.05-26.79% F14AF (144-h EC50) 1.53-2.98% LSP	Carls and Rice 1981

[a] FMAF used by Carls and Rice began with 50% whole mud in seawater rather than 10% used by most other authors.
[b] 96-h LC50 given unless otherwise stated.
[c] EC50 = concentration at which 50% of organisms ceased swimming.

Table C-1. Summary of Results of Acute Drilling Fluid Bioassays on Marine Organisms (Continued)

Test Material	Test Organism	Test Conditions	Results (LC50)[b]	Reference
Used Cook Inlet lignosulfonate drilling fluid	Stage I larvae of: *Paralithodes camtschatica* (king crab) *Pandalus hypsinotus* (coonstripe shrimp)	SW, 28.4-30.9 ppt, 4.5-7.5°C Static LSP, FMAF[a] Test for toxicity of aged drilling fluid	(144-h) 1.47-3.9% FMAF at 7 d (144-h EC50)[c] 0.92-2.4% FMAF at 7 d (144-h) 4.08-6.03% FMAF at 14 d (144-h EC50) 2.49-3.63% FMAF at 14 d (144-h) 5.63-5.83% FMAF at 21 d (144-h EC50) 2.87% FMAF at 21 d (144-h) 4.19% FMAF at 28 d (144-h EC50) 3.82% FMAF at 28 d	Carls and Rice 1981
Used high density lignosulfonate drilling fluid	*Pandalus hypsinotus* (coonstripe shrimp)	SW, 29 ppt, 12°C Static LSP	3.2% to >15.0% (5 experiments)	Houghton et al. 1980b
Used high density lignosulfonate drilling fluid	*Pandalus hypsinotus* (coonstripe shrimp)	SW, 27 ppt, 13°C Static SSP	4.4% 5.0% <48-h LC50 <10.0%	Houghton et al. 1980b
Used high density lignosulfonate drilling fluid	*Oncorhynchus gorbuscha* (pink salmon) fry	SW, 29 ppt, 13.5°C Static LSP	2.9%	Houghton et al. 1980b
Used high density lignosulfonate drilling fluid	*Oncorhynchus gorbuscha* (pink salmon) fry	SW, 29 ppt, 12°C Static SSP	0.3-1.9% (2 experiments)	Houghton et al. 1980b
Used high density lignosulfonate drilling fluid	*Eogammarus confervicolous* (amphipod)	SW, 29 ppt, 11.4°C Static LSP	>20% 1% (<48-h LC50 <5%	Houghton et al. 1980b
Used high density lignosulfonate drilling fluid	*Eogammarus confervicolous* (amphipod)	SW, 29 ppt, 10°C Static SSP	>7%	Houghton et al. 1980b
Used high density lignosulfonate drilling fluid	*Neomysis integer* (mysid)	SW, 26 ppt, 13°C Static LSP	(48-h LC50) 7.4% 10% <48-h LC50 <15%	Houghton et al. 1980b
Used high density lignosulfonate drilling fluid	*Neomysis integer* (mysid)	SW, 26 ppt, 13°C Static SSP	1% <96-h LC50 <5%	Houghton et al. 1980b
Used high density lignosulfonate drilling fluid	*Neomysis integer* (mysid)	SW, 26 ppt, 13°C Static SSP	38-h LC50 >10%	Houghton et al. 1980b
Used high density lignosulfonate drilling fluid	*Gnorimosphaeroma oregonensis* (isopods)	SW, 29 ppt, 10°C Static SSP	>7%	Houghton et al. 1980b

Table C-1. Summary of Results of Acute Drilling Fluid Bioassays on Marine Organisms (Continued)

Teat Material	Test Organism	Test Conditions	Results (LC50)[b]	Reference
Used high density lignosulfonate drilling fluid	*Leptocottus armatus* (staghorn sculpin) juveniles	SW, 12.4°C Static SSP	10% <48h LC50 <20%	Houghton et al. 1980b
Used high density lignosulfonate drilling fluid	*Modiolus modiolus* (mussel)	SW, Static LSP	(13.6 d LC50) >3%	Houghton et al. 1980b
Used CMC/Resinex/ Tannathin/Gel drilling fluid	*Melaenis loveni* (polychaete) *Natica clausa*, *Neptunea* sp., *Buccineum* sp. (snails)	Sw, -20 ppt, -0"c Static LSP	>60%	
Used CMC/Resinex/ Tannathin/Gel drilling fluid	*Saduria entomon* (isopod)	Sw, '25 ppt, '3°C Static LSP	-53% to >60% (2 experiments)	Tornberg et al. 1980
Used CMC/Resinex/ Tannathin/Gel drilling fluid	*Melaenis loveni* (polychaete) *Natica clausa*, *Neptunea* SP., *Buccineum* sp. (snails)	Sw, -22 ppt, ~1.2°C Static LSP	>70%	Tornberg et al. 1980
Used CMC/Gel/Resinex drilling fluid	*Mysis* sp. (mysid)	SW, 3.3 ppt, 11.8°C Static LSP	>6% to 7.3% (2 experiments)	Tornberg et al. 1980
Used CMC/Gel/Resinex drilling fluid	*Myoxocephalus quadricornis* (fourhorn sculpin) juveniles	Sw, 5 ppt, 10"C Static LSP	5% to 7% (2 experiments)	Tornberg et al. 1980
Used CMC/Gel drilling fluid	*Mysis* sp. (mysid)	SW, 11 ppt, 7.8°C Static LSP	21.5%	Tornberg et al. 1980
Used CMC/Gel drilling fluid	*Myoxocephalus quadricornis* (fourhorn sculpin) juveniles	SW, 11 ppt, 7.8°C Static LSP	12%	Tornberg et al. 1980
Used CMC/Gel drilling fluid	*Eliginus navaga* (saffron cod)	SW, 15 ppt, 7.8°C Static LSP	17% to 30%	Tornberg et al. 1980
Used CMC/Gel drilling fluid	*Coregonus nasus* (broad whitefish) juveniles	SW, 9.8 ppt, 10.3"C Static LSP	> 20%	Tornberg et al. 1980

Table C-1. Summary of Results of Acute Drilling Fluid Bioassays on Marine Organisms (Continued)

Test Material	Test Organism	Test Conditions	Results (LC50)[b]	Reference
Used XC-polymer/ Unical drilling fluid	Saduria entomon (isopod)	SW> 20 ppt, 0"C Static LSP	31.4% <96-h LC50 <50%	Tornberg et al. 1980
Used XC-polymer/ Unical drilling fluid	Onisimus sp. and Boeckosimus sp. (amphipods)	SW, 22 ppt, 1°C Static LSP	22.1% to 38.1% (6 experiments)	Tornberg et al. 1980
Used XC-polymer drilling fluid	Mysis sp. (mysid)	SW> 15 ppt, 10"C Static LSP	5% <96-h LC50 <17% (3 experiments)	Tornberg et al. 1980
Used XC-polymer drilling fluid	Myoxocephalus quadricornis (fourhorn sculpin) juveniles	SW, 16 ppt, 10°C Static LSP	5% to 21.5% (5 experiments)	Tornberg et al. 1980
Used XC-polymer drilling fluid	Myoxocephalus quadricornis (fourhorn sculpin) juveniles	SW, 6.5 ppt, 11°C Static SPP. Maximum test concentration 25% drilling fluid to seawater (V/V)	25%	Tornberg et al. 1980
Used XC-polymer drilling fluid	Coregonus nasus (broad whitefish) juveniles	SW* loppt, 7.5°C Static LSP	6.4% to 37% (4 experiments)	Tomberg et al. 1980
Used XC-polymer drilling fluid	Coregonus nasus (broad whitefish) juveniles	SW, 8 ppt, 9°C Static SPP. Maximum test concentration 25% drilling fluid to seawater (V/V)	10% 96-h LC50 17%	Tornberg et al. 1980
Used XC-polymer drilling fluid	Boreogadus saida (Arctic cod)	SW, 17 ppt, 10.8"c Static LSP	25%	Tornberg et al. 1980
Used lignosulfonate drilling fluid	Myoxocephalus quadricornis (fourhorn sculpin)	Sw, 15 ppt, 9°c Static LSP	35%	Tornberg et al. 1980
Used lignosulfonate drilling fluid	Coregonus nasus (broad whitefish)	SW, 20 ppt, 9.9*C Static LSP	<10%	Tornberg et al. 1980
Used lignosulfonate drilling fluid	Boreogadus saida (Arctic cod)	SW, 18 ppt, 7.6°C Static LSP	20% <96-h LC50 <25%	Thornberg et al. 1980
Used lignosulfonate drilling fluid	Coregonus autumnalis (Arctic cisco)	SW, 20.8 ppt, 7.1°C Static LSP	40%	Tornberg et al. 1980

Table C-1. Summary of Results of Acute Drilling Fluid Bioassays on Marine Organisms (Continued)

Test Material	Test Organism	Test Conditions	Results (LC50)[b]	Reference
Used KCl-polymer drilling fluid	Salmo gairdneri (rainbow trout) juveniles, saltwater-acclimated	SW, 26 ppt, 12°C Static SSP	2.4%	Division of Applied Biology B.C. Research 1976
Used KCl-polymer drilling fluid	Oncorhynchus kisutch (coho salmon) juveniles	SW, 26 ppt, 12°C Static SSP	2.9%	Division of Applied Biology B.C. Research 1976
Used KCl-polymer drilling fluid	Oncorhynchus keta (chum salmon) juveniles	SW, 26 ppt, 12°C Static SSP	2.4%	Division of Applied Biology B.C. Research 1976
Used KCl-polymer drilling fluid	Oncorhynchus gorbuscha (pink salmon) juveniles	SW, 26 ppt, 12°C Static SSP	4.1%	Division of Applied Biology B.C. Research 1976
Used KCl-polymer drilling fluid	Nereis vexillosa (mussel worm)	SW, 26 ppt, 12°C Static SSP	3.7%	Division of Applied Biology B.C. Research 1976
Used KCl-polymer drilling fluid	Mya arenaria (soft-shelled clam)	SW, 26 ppt, 12°C Static SSP	4.2%	Division of Applied Biology B.C. Research 1976
Used KCl-polymer drilling fluid	Hemigrapsus nudus (purple beach crab)	SW, 26 ppt, 12°C Static SSP	5.3%	Division of Applied Biology B.C. Research 1976
Used SW/polymer drilling fluid	Oncorhynchus kisutch (coho salmon) juveniles	SW, 26.5 ppt, 12°C Static SSP	13.0%	Division of Applied Biology B.C. Research 1976
Used SW/polymer drilling fluid	Nereis vexillosa (mussel worm)	SW, 26.5 ppt, 12°C Static SSP	22.0%	Division of Applied Biology B.C. Research 1976
Used SW/polymer drilling fluid	Mya arenaria (soft-shelled clam)	SW, 26.5 ppt, 12°C Static SSP	32.0%	Division of Applied Biology B.C. Research 1976
Used SW/polymer drilling fluid	Hemigrapsus nudus (purple beach crab)	SW, 26.5 ppt, 12°C Static SSP	53.0%	Division of Applied Biology B.C. Research 1976
Used SW/polymer drilling fluid	Orchestia traskiana (sand flea)	SW, 26.5 ppt, 12°C Static SSP	23.0%	Division of Applied Biology B.C. Research 1976

Table C-1. Summary of Results of Acute Drilling Fluid Bioassays on Marine Organisms (Continued)

Test Material	Test Organism	Test Conditions	Results (LC50)[b]	Reference
Used KCl-XC polymer drilling fluid	Oncorhynchus kisutch (coho salmon) juveniles	SW, 27 ppt, 12°C Static SSP	2.3%	Division of Applied Biology B.C. Research 1976
Used KCl-XC polymer drilling fluid	Nereis vexillosa (mussel worm)	SW, 27 ppt, 12°C Static SSP	4.1%	Division of Applied Biology B.C. Research 1976
Used KCl-XC polymer drilling fluid	Mya arenaria (soft-shelled clam)	SW, 27 ppt, 12°C Static SSP	5.6%	Division of Applied Biology B.C. Research 1976
Used KCl-XC polymer drilling fluid	Hemigrapsus nudus (purple beach crab)	SW, 27 ppt, 12°C Static SSP	7.8%	Division of Applied Biology B.C. Research 1976
Used KCl-XC polymer drilling fluid	Orchestia traskiana (sand flea)	SW, 27 ppt, 12°C Static SSP	1.4%	Division of Applied Biology B.C. Research 1976
Used weighted polymer drilling fluid	Oncorhynchus kisutch (coho salmon) juveniles	SW, 26.8 ppt, 12°C Static SSP	1.5%	Division of Applied Biology B.C. Research 1976
Used weighted polymer drilling fluid	Nereis vexillosa (mussel worm)	SW, 26.8 ppt, 12°C Static SSP	2.3%	Division of Applied Biology B.C. Research 1976
Used weighted polymer drilling fluid	Mya arenaria (soft-shelled clam)	SW, 26.8 ppt, 12°C Static SSP	1.0%	Division of Applied Biology B.C. Research 1976
Used weighted polymer drilling fluid	Hemigrapsus nudus (purple beach crab)	SW, 26.8 ppt, 12°C Static SSP	6.2%	Division of Applied Biology B.C. Research 1976
Used weighted polymer drilling fluid	Orchestia traskiana (sand flea)	SW, 26.8 ppt, 12°C Static SSP	3.4%	Division of Applied Biology B.C. Research 1976
Used weighted Gel/XC polymer drilling fluid	Oncorhynchus kisutch (coho salmon) juveniles	SW, 24.5 ppt, 12°C Static SSP	19. 0%	Division of Applied Biology B.C. Research 1976
Used weighted Gel/XC polymer drilling fluid	Nereis vexillosa (mussel worm)	SW, 24.6 ppt, 12°C Static SSP	32.0%	Division of Applied Biology B.C. Research 1976

Table C-1. Summary of Results of Acute Drilling Fluid Bioassays on Marine Organisms (Continued)

Test Material	Test Organism	Test Conditions	Results (LC50)[b]	Reference
Used weighted Gel/XC polymer drilling fluid	*Mya arenaria* (soft-shelled clam)	SW, 24.6 ppt, 12°C Static SSP	56.0%	Division of Applied Biology B.C. Research 1976
Used weighted Gel/XC polymer drilling fluid	*Orchestia traskiana* (sand flea)	SW, 24.6 ppt, 12°C Static SSP	42.0%	Division of Applied Biology B.C. Research 1976
Used Gel Chemical XC drilling fluid	*Oncorhynchus kisutch* (coho salmon) juveniles	Sw, 28 ppt, 12°C Static SSP	3.9%	Division of Applied Biology B.C. Research 1976
Used Gel Chemical XC drilling fluid	*Nereis vexillosa* (mussel worm) *Mya arenaria* (soft-shelled clam) *Hemigrapsus nudus* (purple beach crab)	SW, 28 ppt, 12°C Static SSP	>56 .0%	Division of Applied Biology B.C. Research 1976
Used Gel Chemical XC drilling fluid	*Orchestia traskiana* (sand flea)	SW, 28 ppt, 12°C Static SSP	8.0%	Division of Applied Biology B.C. Research 1976
Used Gel XC-polymer drilling fluid	*Oncorhynchus kisutch* (coho salmon) juveniles	SW, 28 ppt, 12°C Static SSP	396	Division of Applied Biology B.C. Research 1976
Used Gel-XC polymer drilling fluid	*Nereis vexillosa* (mussel worm)	SW, 28 ppt, 12°C Static SSP	20%	Division of Applied Biology B.C. Research 1976
Used Gel XC-polymer drilling fluid	*Mya arenaria* (soft-shelled clam) *Hemigrapsus nudus* (purple beach crab) *Orchestia traskiana* (sand flea)	SW, 28 ppt, 12°C Static SSP	>56%	Division of Applied Biology B.C. Research 1976

Table C-1. Summary of Results of Acute Drilling Fluid Bioassays on Marine Organisms (Continued)

Test Material	Test Organism	Test Conditions	Results (LC50)[b]	Reference
Used drilling fluid containing fresh-water sodium montmorillinite, $BaSO_4$, NaOH, XC-polymer, potassium chrome alum, polyanionic cellulose polymer, vinyl acetate-maleic acid copolymer; CLS may or may not be present	*Oncorhynchus gorbuscha* (pink salmon) fry, 48 mm T.L.	SW, 12.5°C, static, media stirred once each hour to resuspend mixture; media was not changed after beginning of experiment; 96-h exposure	Observed mortality less than 10% for concentrations of drilling fluid to SW of 1.0 to 10.% (V/V) except at 5.6% concentration where 2 organisms died (17% mortality)	Johnson and LeGore 1976
Same drilling fluid as above, plus paraformaldehyde at a concentration of 0.25 lb/barrel mud	*Oncorhynchus gorbuscha* (pink salmon) fry, 48 mm T.L.	SW, 12.5°C, static, media stirred once each hour to resuspend mixture; media was not changed after beginning of experiment; 96-h exposure	Observed mortality less than 10% for all text concentrations (1.0-10.0% by volume)	Johnson and LeGore 1976
Drilling fluid as above, with and without paraformaldehyde	*Pandalus borealis* (pink shrimp) *Pandalus danae* (dock shrimp) *Spirontocaris* sp. (shrimp)	SW, 12.5°C, static, SPP; media waa not changed after beginning of experiment, 96-h exposure	3 deaths in all teat concentrations including the control tank; 10% drilling fluid had no apparent toxic effect	Johnson and LeGore 1976
Drilling fluid as above, without paraformaldehyde	Copepods and mysids	SW, 6.0-8.1°C, static, SSP; media was not changed after beginning of experiment; test concentrations 1.0-10.0% drilling fluid to sea-water by volume; 48-h exposure	40-60% copepod mortality in test concentrations >1.8%, control mortality of 30%. No significant mysid mortality at concentrations <4.5%, Concentrations >5.6% had 40% mortality	Johnson and LeGore 1976
Drilling fluid as above, with paraformaldehyde (1.0 lb/barrel)	Copepods and mysids	SW, 6.0-8.1°C, static, SSP; media *was* not changed after beginning of experiment; teat concentrations 1.0-10.0% drilling fluid to sea-water by volume; 48-h exposure	Mortality of 80-100% after 48-h exposure of SSP media concentrations of 1.0-10.0% for both copepods and mysids	Johnson and LeGore 1976
Drilling fluid as above, with Lubrikleen (1.0 lb/barrel)	Mysids	SW, 10.8-12.0*C, static, SPP; media waa *not* changed after beginning of experiment; test concentrations 1.0-10.0%; 48-h exposure	No significant mortalities, excluding an apparent experimental artifact at 1.0% concentration (80% mortality)	Johnson and LeGore 1976
Drilling fluid as above, with paraformaldehyde (0.25 lb/barrel) and Lubrikleen (1.0 lb/barrel)	Mysids	SW, 10.8-12.0"C, static, SPP; media waa not changed after beginning of experiment; test concentrations 1.0-10.0%; 48-h exposure	No significant mortalities	Johnson and LeGore 1976

Table C-1. Summary of Results of Acute Drilling Fluid Bioassays on Marine Organisms (Continued)

Test Material	Test Organism	Test Conditions	Results (LC50)[b]	Reference
Used SW CLS drilling fluid composed primarily of SW, bentonite, CLS, lignite, caustic soda, lime, and barite	Clibanarius vittatus (hermit crab>–' adults	Static MAF; changed daily	28. 7%	Neff et al. 1980
	Penaeus aztecus (brown shrimp) juveniles	Static MAF; changed daily	41. 5%	Neff et al. 1980
	Penaeua duorarum (shrimp) postlarvae	SW, 28 ppt, 22°C Static MAF	86%	Neff et al. 1981
	Palaemonetes pugio (grass shrimp)	SW, 16 ppt, 22°C		
	1st zoeae	Static MAF; changed daily	27.5%	Neff et al. 1980
	4-day zoeae	Static MAF	34%	Neff et al. 1981
	postlarvae	Static MAF	67%	Neff et al. 1981
	adul ta	Static MAF	90%	Neff et al. 1981
	adults	Static MAF; changed daily	92.4%	Neff et al. 1980
	Donax variabilis (coquina clam)	SW, 35 ppt, 22°C, n = 20-25		
	adults	Static SPP; changed daily	(72-h) 92.4%	Neff et al. 1980
	adults	Static SPP; changed daily	53.7%	Neff et al. 1980
	juveniles	Static MAF	>100%	Neff et al. 1981
	adults	Static MAF	86%	Neff et al. 1981
	Neanthes arenaceodentata (marine annelid worm)	SW, 32 ppt, 25°C		Neff et al. 1981
	juvenilea	Static MAF	96%	
		Static FMAF	>100%	
	adults	Static MAF	51%	
	adults	Static MAF; changed daily	10%	
	Ophryotrocha labronica (marine annelid worm) adults	SW, 34 ppt, 25°C		Neff et al. 1981
		Static NAP	>100%	
		Static FMAF	>100%	
	Dinophilus sp. (marine annelid worm) adults	SW, 33 ppt, 25°C Static MAF	76%	Neff et al, 1981
	Ctenodrilus serintus (marine annelid worm) adults	SW, 35 ppt, 25°C, n = 40		Neff et al. 1981
		Static MAF	32%	
		Static FMAF	45%	
		Static MAF	(480-h) 13%	
		Static FMAF	(480-h) 15%	

Table C-1. Summary of Results of Acute Drilling Fluid Bioassays on Marine Organisms (Continued)

Test Material	Test Organism	Test Conditions	Results (LC50)[b]	Reference
Same CLS mud as above	Mysidopsis almyra (opossum shrimp)	SW, 20 ppt, 25°C		
	1-day-old postlarvae	Static MAF; changed daily	(48-h) 32.0%	Neff et al. 1980
		Static MAF; changed daily	(72-h) 29.0%	Neff et al. 1980
		Static MAF; changed daily	27%	Neff et al. 1981
		Static MAF	40%	Neff et al. 1981
	3-day-old postlarvae	Static MAF	79%	Neff et al. 1981
	7-day-old postlarvae	Static MAF	73%	Neff et al. 1981
		Static MAF; changed daily	81%	Neff et al. 1980
	14-day-old postlarvae	Static MAF	96%	Neff et al. 1981
	Mercenaria compechiensis (hard shell clam) adults	SW, 20 ppt, 22°C Static MAF	>100%	Neff et al. 1981
	Rangia cuneata (marsh clam) adults	SW, 20 ppt, 22°C Static MAF	>100%	Neff et al. 1981
	Penaeus duorarum (shrimp) adults	SW, 28 ppt, static, SPP; changed daily; 10 ml drilling fluid/1 SW (10,000 ppm, or 1.0% by volume); 168-h exposure	71% survival	Neff et al. 1981
	Penaeus aztecus (brown shrimp) juveniles	SW, 28 ppt, static, SPP; changed daily; 10 ml drilling fluid/1 SW (10,000 ppm, or 1.0% by volume); 168-h exposure	40% survival	Neff et al. 1981
	Portunus spinicarpus (crab) adults	SW, 35 ppt, static, SSP; changed daily; 20 ml drilling fluid/1 SW (20,000 ppm, or 2.0% by volume); 168-. exposure	100% survival	Neff et al. 1981
	Mercenaria compechiensis (hard shell clam) adults	SW, 20 ppt, static, SSP; changed daily; 20 ml drilling fluid/1 SW (20,000 ppm, or 2.0% by volume); 168-h exposure	100% survival	Neff et al. 1981
	Rangia cuneata (marsh clam) adults	SW, 20 ppt, static, SSP; changed daily; 20 ml drilling fluid/1 SW (20,000 ppm, or 2.0% by volume); 168-. exposure	100% survival	Neff et al. 1981
	Donax variabilis texasiana (coquina clam) juveniles and adults	SW, 35 ppt, 22°C, static, LSP; changed daily; 100 ml drilling fluid/1 SW (100,000 ppm, or 10% by volume); 96-h exposure	32% survival of juveniles (<1 cm) and 0% survival of adults	Neff et al. 1981

Table C-1. Summary of Results of Acute Drilling Fluid Bioassays on Marine Organisms (Continued)

Teat Material	Test Organism	Test Conditions	Results (LC50)[b]	Reference
Same CLS as above	Aequipecten amplicostatus (estuarine scallop) adults	Sw, 20 ppt, 22°C Static LSP changed daily; 96-h exposure to 20 ml drilling fluid/ 1 SW (20,000 ppm or 2% by volume)	40% survival	Neff et al. 1981
	Neanthes arenaceodentata (marine worm) juveniles and adults	SW, 32 ppt, 22°C Static LSP changed daily; 96-h exposure to 40 ml drilling fluid/ 1 SW (40,000 ppm or 4% by volume)	77.5% survival of juveniles and 25% survival of adults	Neff et al. 1981
	Ophryotrocha labronica (marine worm) adults	Sw, 34 ppt, 22*C Static LSP changed daily; 96-h exposure to 50 ml drilling fluid/ 1 SW (50,000 ppm or 5% by volume)	95% survival	
	Mysidopsis almyra (opposum shrimp) l-day olds	SW, 20 ppt, 22°C Static LSP changed daily; 168-h exposure to 25 ml drilling fluid/ 1 SW (25,000 ppm or 2.5% by volume)	55% survival	Neff et al. 1981
	Crangon septemspinosa (sand shrimp)	SW, 31-33 ppt, 7-12*C, static MAF	>100%	Gerber et al. 1980
	Mytilus edulis (blue mussel)			
	Nereis virens (sand worm)			
	Fundulus heteroclitus (killifish)			
Used low density lignosulfonate drilling fluid	Crangon septemspinosa (sand shrimp)	SW, 31-33 ppt, 8-22°C Static MAF, SSP; flow-through LSP	>100% MAF at 8°C 98% MAF at 18°C 71% LSP at 18°C >15,000 ppm SSP at 18°C	Gerber et al. 1980
	Carcinus maenas (green crab)	SW, 31-33 ppt, 8-22°C Static MAF, SSP; flow-through LSP	>100% MAF at 8°C 89% LSP at 8°C >15,000 ppm SSP at 8*C	Gerber et al. 1980
	Homarus americanus (American Lobster)	SW, 31-33 ppt, 8-22°C Static MAF, SSP; flow-through LSP		
	stage V larvae adults		5% MAF at 18°C 19-25% MAF	

Table C-1. Summary of Results of Acute Drilling Fluid Bioassays on Marine Organisms (Continued)

Test Material	Test Organism	Test Conditions	Results (LC50)[b]	Reference
Used low density lignosulfonate	Macoma balthica (clam) Placopecten magellanicus (ocean scallop) Littorina littorea (periwinkle) Thais lapillis (dog whelk) Nereis virens (sand worm) Strongylocentrotus droebachiens is (green sea urchin)	SW, 31-33 ppt, 8-22°C Static MAF, SSP; flow-through LSP	>100% MAF at 8°C 49% to 100% LSP >15,000 ppm SSP for Macoma and Thais	Gerber et al. 1980
Used medium density lignosulfonate mud composed primarily of SW, bentonite, clay, CLS, lignite, NaOH, barite	Mysidopsis almyra (opposum shrimp)	SW, 20 ppt, 25°C Static exposure		Carr et al. 1980
		1st-day juveniles, LSP	100% mortality in 2 d of 25,000 ppm drilling fluid 96% mortality in 4 d of 50% SSP 12% mortality in 7 d of 50% FMAF	
		1st-day juveniles, static SPP 1-14 days old, static MAF 1st-day juveniles, MAF changed daily	32% SPP 41-112.8% MAF 26 .8% MAF	
Note: Drilling and exposure reduced biomass production and net growth efficiency of mysids at sublethal concentrations in the range of .15 to 30% MAF.				
	Clibanarius vittatus adults	SW Static MAF changed daily	34.5%	Neff et al. 1980
	Penaeus aztecus juveniles	SW Static MAF changed daily	16%	Neff et al. 1980
	Palaemonetes pugio (grass shrimp)			
	1st zoeae	Static MAF changed daily	35 .0%	Neff et al. 1980
	adults	Static MAF changed daily	91.0%	
	Ophryotrocha labronica (marine worm) adult	Static MAF changed daily	60.0%	Neff et al. 1980
	Mysidopsis almyra (opposum shrimp)	Static MAF changed daily		Neff et al. 1980
	1-day-old postlarvae		(24-h) 47.9% (48-h) 28.5% (72-h) 14.5% (96-h) 12.8%	
	7-day-old postlarvae		(24-h) 22.0% (48-h) 18.0% (72-h) 14.5% (96-h) 13.0%	

Table C-1. Summary of Results of Acute Drilling Fluid Bioassays on Marine Organisms (Continued)

Test Material	Test Organism	Test Conditions	Results (LC50)[b]	Reference
Used medium density lignosulfonate mud composed primarily of fresh water, bentonite, CLS, lignite, NaOH, lime, and barite	Donax variabilis (coquina clam) adult	Static SPP changed daily	(48-h) 49% (72-h) 38% (96-h) 29% (192-h) 20%	Neff et al. 1980
	Crassostrea gigas (oyster) spat 3-10 mm	Static SPP	(48-h) 83% (72-h) 65% (96-h) 53%	Neff et al. 1980
	10-25 mm		(72-h) 72% (96-h) 50%	
	Crangon septemspinosa (sand shrimp) Gammarus locusts (amphipod) Carcinus maenas (green crab) Homarus americanus (American lobster)	SW, 31-33 ppt, 6-12°C Static MAF, SSP Flow-through LSP	>100% MAP >15,000 ppm SSP (Crangon and Carcinus only) 96-h LC50 = 29-90% LSP	Gerber et al. 1980
	Mytilus edulis (blue mussel) Littorina littorea (periwinkle) Nereis virens (sand worm)	Sw, 31-33 ppt, 10-12″C Static MAF, SSP Flow-through LSP	>100% MAF >3.5,000 ppm SSP (Mytilus only) >100% LSP	Gerber et al. 1980
	Pandalus borealis (northern shrimp) Stage I larvae	Sw, 31-33 ppt, 5°C Static MAE, FMAF	17% MAP 19% FMAF	Gerber et al. 1980
	Placopecten magellanicus (ocean scallop)	SW, 31-33 ppt, 13°C Flow-through LSP	3,200 ppm (0.32%) LSP	Gerber et al. 1980
	Fundulus heteroclitus (killifish)	Sw, 31-33 ppt, 14°C Static MAF, SSP	>100% MAF >15,000 ppm SSP	Gerber et al. 1980

Table C-1. Summary of Results of Acute Drilling Fluid Bioassays on Marine Organisms (Continued)

Test Material	Test Organism	Test Conditions	Results (LC50)[b]	Reference
Used high-weight lignosulfonate drilling fluid. Composed primarily of fresh water, bentonite, CLS, lignite, NaOH, soda ash, $NaHCO_3$, polyanionic cellulose derivative, barite	Clibanarius vittatus adults	Static MAF changed daily	65.6%	Neff et al. 1980
	Palaemonetes pugio (grass shrimp) 1st zoeae adults	Static MAF changed daily	<18.0% 93.3% survival in 96 h	Neff et al. 1980
	Ophryotrocha labronica (marine worm) adult	Static MAF changed daily	87.5% survival in 96 h	
	Mysidopsis almyra (opposum shrimp) 1-day-old postlarvae	Static MAF changed daily	(24-h) 93.0% (48-h) 20.0% (72-h) 16.0% (96-h) 16%	Neff et al. 1980
	7-day-old postlarvae		(48-h) 90.0% (72-h) 38.0% (96-h) 32.5%	Neff et al. 1980
	Donax variabilis (coquina clam)	Static SPP changed daily	(48-h) 95% (72-h) 77% (96-h) 56% (192-h) 41%	Neff et al. 1980
	Crassostrea gigas (oyster) 3-10 mm spat	Static SPP changed daily	(48-h) 97% (72-h) 84% (96-h) 74%	Neff et al. 1980
	10-25 mm spat	Static SPP changed daily	(72-h) 84% (96-h) 73%	Neff et al. 1980
	Palaemonetes pugio (grass shrimp) 1-day (21)	Static SPP changed daily	(48-h) 18.0% (72-h) 13.2% (96-h) 11.8%	Neff et al. 1980
	5-day (23)	Static SPP changed daily	(24-h) 23.2% (48-h) 20.6% (72-h) 15.8% (96-h) 13.2%	Neff et al. 1980
	10-day (24-25)	Static SPP changed daily	(24-h) 60.0% (48-h) 17.6% (72-h) 15.5% (96-h) 11.7%	Neff et al. 1980

Table C-1. Summary of Results of Acute Drilling Fluid Bioassays on Marine Organisms (Continued)

Test Material	Test Organism	Test Conditions	Results (LC50)[b]	Reference
Used high density lignosulfonate drilling fluid	Crangon septemspinosa (sand shrimp) Gammarus locusta (amphipod) Carcinus maenas (green crab)	SW, 31-33 ppt, 6-14°C Static MAF, SSP Flow-through LSP	>100% MAF >15,000 ppm SSP 28 to >100% LSP	Gerber et al. 1980
	Mytilus edulis (blue mussel) Macoma balthica (clam) Littorina littorea (periwinkle) Nereis virens (sand worm)	SW, 31-33 ppt, 7-12°C Static MAF, SSP Flow-through LSP	>100% MAF >15,000 ppm SSP for Mytilus only >100% LSP	Gerber et al. 1980
	Pandalus borealis (northern shrimp) Stage I larvae	Sw, 31-33 ppt, 2°C Static MAF, FMAF	65% MAP 55% FMAF	Gerber et al. 1980
	Fundulus heteroclitus (killifish)	Sw, 31-33 ppt, 14°C Static MAF, SSP	>100% MAF >15,000 ppm SSP	Gerber et al. 1980
Used spud mud	Palaemonetes pugio 1st zoeae and adults Ophryotrocha labronica adults Mysidopsis almyra 1- and 7-day postlarvae Donax variabilis adults Crassostrea gigas spat	Static MAF or SPP changed daily	All bioassays >100%MAF or SPP	Neff et al. 1980
	Mysidopsis almyra 1- and 7-day postlarvae	Static MAF changed daily	100% survival after 96-h exposure	Neff et al. 1980
	Donax variabilis texasiana adults	Static SPP changed daily	100% survival after 192-h exposure	Neff et al. 1980
	Crassostrea gigas spat	Static SPP changed daily	100% survival after 96-h exposure	Neff et al. 1980

Table C-1. Summary of Results of Acute Drilling Fluid Bioassays on Marine Organisms (Continued)

Test Material	Test Organism	Test Conditions	Results (LC50)[b]	Reference
Used spud mud	Crangon septemspinosa (sand shrimp) Gammarus locusta (amphipod) Mytilus edulis (blue mussel) Nereis virens (sand worm) Fundulus heteroclitus (killifish)	SW, 31-33 ppt, 7-12°C Static MAF Flow-through LSP	>100% MAF >100% LSP (Gammarus only)	Gerber et al. 1980
18 used drilling fluids from an exploratory platform in Mobile Bay. Note: This was an experimental drilling fluid, not intended for ocean disposal.	Palaemonetes pugio (grass shrimp) intermolt (Stage C)	Sw, 10 ppt, ‘O”c Static with daily replacement of media, LSP	30% mortality or greater in 96-h exposure at 1,000 ppm for 7 of 18 drilling fluids assayed. Mortality was 100% in 96 h for drilling fluid XVIII.	Conklin et al. 1980
5 used drilling fluids (most toxic in initial collection of 18 samples	Palaemonetes pugio	Sw, 10 ppt, 20°C Static with daily replacement of media, LSP	363 to 739 ppm	Conklin et al. 1980
Most toxic drilling fluid sample (XVIII) from above collection	Mysidopsis bahia (mysid or opossum shrimp) 1-42 days old (entire life cycle)	Sw, 10 ppt, 20°C	(4-d) 161 ppm (7-d) 116 ppm (14-d) 85 ppm (21-d) 77 ppm (28-d) 59 ppm (35-d) 57 ppm (42-d) 50 ppm	Conklin et al. 1980
Diesel-based drilling fluid plus cuttings. Components by percent weight: barite, 6.5% bentonite, 22.0% diesel, 64.7%	Crassostrea virginica (oyster) 70-120 mm	SW, 4.4-16.5 ppt, 27-29°C Solutions changed 3 times per day 1,000-2,000 ppm 200-500 ppm 80-120 ppm	 50% mortality after 6 d of exposure 50% mortality after 7 d of exposure 50% mortality in both controls and treatment organisms after 14 d of exposure	Cabrera 1968

Table C-2. Summary of Studies on Sublethal Effects of Drilling Fluids on Marine Organisms

Test Material	Test Organism	Test Conditions	Results	Reference
Drilling fluid-2 (density, 1.4 g/ml; pH, 11) and Drilling fluid-3 (density, 1.51 g/ml; pH, 11)	Homarus americanus (American lobster)	Activity of walker leg chemosensory neurons was examined after either a 3-5 min or 4-8 d exposure to 10 mg/l or 100 mg/l drilling fluid. Mussel extract and L-glutamate, chemical stimuli known to activate lobster chemoreceptors, were used to elicit responses of nerve bundles following exposure.	Short-term exposure to 10 mg/l drilling fluid-2 caused interference in 57% of previously unexposed lobsters. No interference of chemoreceptors in lobsters previously exposed to drilling fluids for 4-8 d and then exposed again (3-5 rein). Short-term exposure to 10 mg/l drilling fluid caused interference in 18% of lobsters not previously exposed and In 44% of the 4-8-d drilling fluid-treated lobsters. Short-term exposure to 100 mg/1 drilling fluid-3 caused interference in 50% of unexposed lobsters and 38% of 4-8-d drilling fluid-treated lobsters.	Derby and Atema 1980
Lignosulfonate drilling fluid	Planktonic larvae of ❑acrobenthic communities	SW, 27.5%, 28.0°C. Continuous-flow SW. Treatments included 0.2 cm cover of drilling fluid over sand, 1:10 and 1:5 mud to sand mixture. 8 replicates/treatment; 8 wk of colonization.	Numbers of Annelida and Coelenterata colonizing treatment aquaria were significantly less than controls. Numbers of Corophium acherusicum (arthropod) were significantly reduced only by drilling fluid cover over sand. Numbers of molluscs were not significantly affected by mud-sand mixtures or by mud cover.	Tagatz et al. 1980
Used high-density, medium-density, and sea water lignosulfonate drilling fluids	Mytilus edulis (blue mussel)	96-h exposure to MAF of several drilling fluids. Rates of filtration, respiration, and ammonia excretion measured.	Low correlation of physiological parameters and concentration of MAF. Control mussel respiration rates were significantly different from lower MAF concentrations	Gerber et al. 1980
Used low-density lignosulfonate drilling fluid	Crangon septemspinosa (sand shrimp) Carcinus maenas (green crab) Homarus americanus (American lobster)	96-h exposure toMAF of low-density lignosulfonate drilling fluid . Levels of energy metabolism enzymes, G6PdH, and AAT measured.	In all treatments, controls were significantly different from animals exposed to the lowest MAF concentration used.	Gerber et al. 1980
Used high- and medium-density lignosulfonate drilling fluids and spud mud	Nereis virens (sand worm)	96-h exposure to MAF of low-density lignosulfonate drilling fluid. Levels of energy metabolism enzymes, G6PdH, and AAT measured. Exposed to MAF and LSP.	Enzyme activity rates for exposed worms in 100% MAF decreased by 50% compared to controls, and decreased by more than 50% in the LSP treatment. Little effect on enzyme activities was observed for worms exposed to spud mud MAF or LSP.	Gerber et al. 1980
Used high-density lignosulfonate drilling fluid	Nereis virens (sand worm)	96-h exposure period followed by deputation period of 96 h.	Worms exposed to 100%MAF for 96 h had decreased enzyme activities but normal enzyme activity rates returned when the organisms were transferred to clean SW.	Gerber et al. 1980

Table C-2. Summary of Studies on Sublethal Effects of Drilling Fluids on Marine Organisms (Continued)

Test Material	Test Organism	Test Conditions	Results	Reference
Used high-, medium-, low-density ligno-sulfonate drilling fluids	Mytilus edulis (blue mussel)	96-h exposure to several drilling fluid MAFa. Levels of energy metabolism enzymes, G6PdH, and AAT measured. Temperature 10-11"C.	All enzyme activities in organisms exposed to MAF were 2 to 2.5 times the enzyme activities in control organisms.	Gerber et al. 1980
Used low-density lignosulfonate drilling fluid	Mytilus edulis (blue mussel)	30-d exposure to 50 mg/l (50,000 ppm) suspension of drilling fluid. Flow-through system at 13-15°C, 31-33 ppt.	Growth rate reduced by 54% after 10 to 20 d of exposure. 34% growth rate reduction for the period from 20 to 30 days of exposure. No reduction in days 1-10.	Gerber et al. 1980
Use high-density lignosulfonate drilling fluid	Fundulus heteroclitus (killifish)	96-h exposure to MAF and LSP. Energy metabolism enzymes, G6PdH, and AAT measured.	AAT. activities slightly decreased (30%, MAF; 26%, LSP) while G6PdH increased (3X, MAF; 2X, LSP) with increased concentration of MAF or LSP. The MAF was slightly more toxic than the LSP treatment for killifish.	Gerber et al. 1980
Used drilling fluid collected from active rig. Note: This drilling fluid was known to contain hazardous concentrations of sodium bichromate and was not intended for ocean disposal	Mysidopsis bahia (mysid) Crassostrea virginica (oyster) Arenicola cristata (polychaete) and benthic recolonization organisms	SW, 6-22 ppt, 12-26°C. Continuous-flow of unfiltered seawater and drilling fluid added to test containers. Dilutions corresponded to nominal concentrations of 10, 30, and 100 ppm. Final concentrations at day 100 were higher due to a gradual buildup of drilling fluid in containers.	Myaids were not acutely affected. After 10 days exposure: 10% mortality at 10 ppm, 17% at 30 ppm and 100 ppm. Oyater shell growth significantly inhibited at nominal concentrations of 30 and 100 ppm. 75% mortality of polychaetes exposed to 100 ppm after 100-d exposure; 64% mortality at 30 ppm; 33% mortality at 10 ppm. No significant difference in macrofaunal colonization was detected in total species harvested between treatments. Two mollusc species present in numbers exceeding controls at 10 and 30 ppm were virtually eliminated in 100 ppm concentration. Drilling fluid-exposed oysters concentrated Ba 30 times that of controls, Cr 15 x that of controls, and Pb 3 x that of controls.	Rubinstein et al. 1980
Used high-density lignosulfonate drilling fluid	Modiolus modiolus (mussel)	SW, 26-30 ppt, 10-14"C Static LSP, media changed every 4 d.	No mortalities occurred in 14 d of exposure at 3% concentration. Secretion of byssua threada was severely inhibited in 3% concentration but near normal behavior was exhibited by mussels exposed to 1% mixture. Pumping rates of mussels exposed to 3% mixture were reduced.	Houghton et al. 1980

Table C-3. Summary of Studies on Bioaccumulation of Heavy Metals from Drilling Fluids in Marine Organisms

Test Material	Test Organism	Test Conditions	Results	Reference
Heated synthetic mud: barite, attapulgite of bentonite clay, Q-Broxin--ferrochrome lignosulfonate, aluminum stearate, plant starch	Placopectin magellanicus (sea scallop)	SW, 32 ppt, 5°C, 1.0 g/1, circulating; media changed every 2 d; fed daily; 28-d exposure.	Mean Cr concentration in kidney rose from 1.74 µg/g, dry to 4.35 µg/g, dry. Significant difference between exposed and control kidney concentrations of Cr. Cr concentrations in slow adductor muscle in teat organisms did not differ significantly from those of controls. After l-d exposure mean concentration of Ba increaaed from 1.0 µg/g, dry to 55 µg/g, dry. Over balance of test, mean increased to near 100 µg/g while controls remained below 10 µg/g.	Lisa et al. 1980
Used low-density lignosulfonate drilling fluid	Placopectin magellanicus (sea scallop)	SW, 32 ppt, 8°C, 1.0 g/1, circulating; media changed every 2 d; fed daily; 15-d deputation.	After 27 d of exposure, mean Cr concentrations in the kidneys was 2.94 µg/g, dry (1.4 µg/g controls). Deputation until day 42 showed Cr concentration to continue to rise in both test and control organisms. Ba concentrations in the kidneys were highly variable. In exposed organisms concentrations varied over 3 orders of magnitude and did not represent a significant increase over controls.	Liss et al. 1980
Ferrochrome lignosulfonate (Q-Broxin)	Placopectin magellanicus (sea scallop)	SW, 32 ppt, 5°C; 0.03, 0.1, 0.3, 0.5, 1.0 g FCLS/1 SW, circulating; media changed every 2 d; 14-d exposure, 14-d depuration.	0.03 g FCLS/1 produced an increase in Cr concentration greater than that produced in any tests with whole muds. Higher dosages of FCLS produced somewhat greater Cr concentrations, though no significant concentration differences were noted in doses tested. Dosage of 1.0 g produced significant mortality in test population.	Lisa et al. 1980
Used CLS lignosulfonate drilling fluid	Rangia cuneata (marsh clam)	96-h exposure to 62,500 ppm LSP of drilling fluid; media not changed.	Mean Cr concentration in drilling fluid-exposed clams rose within 24 h to 5 times controls and remained at this level for exposure period. Majority of accumulated Cr was apparently associated with gut contents, as a 24-h deputation period resulted in a significant reduction in Cr concentration. However, levels did not return to those in controls.	McCulloch et al. 1980

Table C-3. Summary of Studies on Bioaccumulation of Heavy Metals from Drilling Fluids in Marine Organisms (Continued)

Test Material	Test Organism	Test Conditions	Results	Reference
Used CLS lignosulfonate drilling fluid	Rangia cuneata (marsh clam)	16-d exposure to 100%MAF (10% drilling fluid to SW by volume); media not changed.	Cr uptake followed a sigmoidal pattern. Cr concentration in clam tissues nearly doubled during first 2 d, remained constant to day 8, then rose again during remaining 8 d. Maximum Cr concentration in tissues was 19 ppm. Clams returned to clean seawater rapidly released nearly half the accumulated Cr in 24h. 11 ppm Cr remained in tissues for remainder of n-d deputation period.	McCulloch et al. 1980
Used medium-density lignosulfonate drilling fluid	Rangia cuneata (marsh clam)	96-h exposure to 50% MAF (5% drilling fluid to SW by volume); media not changed.	Tissue Cr concentration rose to maximum of 15.3 ppm in 2 d, then remained constant. Clams returned to clean seawater released approximately half the accumulated Cr in 4 d. Concentration of Pb increased to 13 ppm after 3 d of exposure. Half of accumulated lead was released after clams returned to clean SW. Control concentration 10.5 and 8 ppm Cr and Pb, respectively.	McCulloch et al. 1980
Used medium-density lignosulfonate drilling fluid	Crassostrea gigas (Pacific oyster) spat	96-h exposure to several concentrations of SPP; exposure media renewed daily.	Between O and 40% SPP, tissue Cr concentration increased in nearly linear fashion from leas than 1 to 8 ppm. Large mortalities occurred among apat exposed to 40% and 80% SPP. Cr concentration was 18 and 33 ppm, respectively.	McCulloch et al. 1980
Used medium- and high-density lignosulfonate drilling fluids	Crassostrea gigas (Pacific oyster) spat	14-d exposure to 20-40% MAF.	Tissue Cr concentrations were 2-4 times higher than those in unexposed spat.	McCulloch et al. 1980
		40% MAF of high-density lignosulfonate drilling fluid.	Control organisms contained 1.81-3.08 ppm Pb. Concentration of Pb decreased in high-density lignosulfonate drilling fluid-exposed organisms but increased from 1.81 to 4.26 ppm after 10 d of exposure to medium-density lignosulfonate drilling fluid.	McCulloch et al. 1980
			No indication of Zn uptake during exposure up to 10 d of MAF of medium- or high-density lignosulfonate drilling fluid.	McCulloch et al. 1980
Spud mud	Crassostrea gigas (Pacific oyster) spat	96-h exposure to several concentrations of SPP.	Little or no accumulation of Cr.	McCulloch et al. 1980
		10-d exposure to 100% MAF.	Irregular accumulation of Pb to maximum amount of 3.4 ppm. Little or no tendency to release accumulated Pb after 10-d deputation in clean SW. No significant accumulation of Zn during 10-day exposure.	McCulloch et al. 1980

Table C-3. Summary of Studies on Bioaccumulation of Heavy Metals from Drilling Fluids in Marine Organisms (Continued)

Test Material	Test Organism	Test Conditions	Results	Reference
Used SW CLS drilling fluid	Palaemonetes pugio (grass shrimp)	7-d exposure to 25-100% MAF (2.5-10% drilling fluid to SW by volume).	Uptake was dose-dependent. Maximum concentration of Cr (23.71 ppm) was 100 times higher than the exposure concentration (0.25 ppm). No attempt to differentiate between Cr adsorbed to exoskeleton, in gill cavity, and in digestive tract from Cr actually assimilated in tissues.	Carr et al. 1980
Used SW CLS drilling fluid	Palaemonetes pugio (grass shrimp)	4-d exposure to static 75% MAF followed by 4-d deputation period in clean SW.	Cr accumulated rapidly to levels 2 orders of magnitude above ambient Cr exposure concentrations within 48 h. In deputation Cr rapidly released with concentrations reduced to control levels in 96 h.	Carr et al. 1980
Used SW CLS drilling fluid	Penaeus aztecus (brown shrimp) Portunus spinicarpus (crab)	SW, 28-35 ppt, 22-23°C. 7-d exposure to several concentrations of SSP.	Both crustaceans showed a linear dose-dependent uptake of Cr with one exception. P. aztecus exposed to highest concentration (20,000 ppm) accumulated less Cr than shrimp exposed to 10,000 ppm. Maximum Cr concentrations in tissues of P. aztecus and P. spinicarpus were 5 and 3 times the controls, respectively.	Carr et al. 1980
Used SW CLS drilling fluid	Penaeus aztecus (brown shrimp)	SW, 28 ppt, 22-23°C. 4-d exposure to 2,000 ppm SSP followed by 14-d deputation in clean SW.	Time-dependent accumulation of chromium during 96-h exposure. Cr concentration in tissues dropped to control levels within 72 h after return to clean SW.	Carr et al. 1980
Used SW CLS drilling fluid	Neanthes virens (sand worm)	Sw, 35 ppt, 10°C. 4-d exposure to 100,000 ppm MAF followed by 4-d deputation in clean SW.	Accumulated Cr was 4 times that found in control animals. Little of accumulated Cr released during 96-h deputation.	Carr et al. 1980
Medium-density lignosulfonate drilling fluid	Mytilus edulis (blue mussel)	7-d exposure to drilling fluid with Cr concentration of 1.4 ppm.	Tissue Cr concentration increased from 1 ppm to 6.6 ppm.	Page et al. 1980
Ferrochrome lignosulfonate drilling fluid	Mytilus edulis (blue mussel)	7-d exposure of FCLS solution with initial Cr concentration of 0.7 ppm.	Tissue Cr concentration increased from 1 ppm to 12.5 ppm.	Page et al. 1980
Ferrochrome lignosulfonate drilling fluid	Mytilus edulis (blue mussel)	7-d exposure of FCLS solution with initial Cr concentration of 6.0 ppm.	Tissue Cr concentration increased from 1 ppm to 63,9 ppm.	Page et al. 1980

Table C-3. Summary of Studies on Bioaccumulation of Heavy Metals from Drilling Fluids in Marine Organisms (Continued)

Test Material	Test Organism	Test Conditions	Results	Reference
Cr^{3+} solution	*Mytilus edulis* (blue mussel)	7-d exposure. Concentration of Cr^{3+} was 0.6 ppm.	Concentration of Cr in tissues increased 1 ppm to 49.5 ppm.	Page et al. 1980
XC-polymer drilling fluids	*Onisimus* sp. and/or *Boeckosimus* ap. (amphipods)	20-d exposure of amphipods to 5%, 10%, and 20% LSP drilling fluid to SW mixture.	Mean metal concentrations in unexposed amphipods were 0.3 ppm Cd, 3.0 ppm Cr, 9.7 ppm Pb, and 85.8 ppm Zn. Concentrations of all metals in exposed amphipods increased but no relationship between exposure concentrations and total metal concentrations in amphipods existed. Maximum amphipods were 1.5 ppm Cd, 5 ppm Cr, 20 ppm Pb, and 140 ppm Zn. Metals may have been contained in gut and not assimilated by the organism.	Tornberg et al. 1980