Reviewed By Bonnie McGregor

② Text Book version

DRILLING MUD PLUMES FROM OFFSHORE DRILLING OPERATIONS: IMPLICATIONS FOR CORAL SURVIVAL

E.A. Shinn, J.H. Hudson, D.M. Robbin and Carol K. Lee

U.S. Geological Survey, Fisher Island Station, Miami Beach, Florida 33139

(305) 672-1784

Running Head: Offshore Drilling Mud Plumes

This is the
draft of Vathens GOM report.
Only name changed

Drilling Mud Plumes from Offshore Drilling Operations:

Implications for Coral Survival

E.A. Shinn, J.H. Hudson, D.M. Robbin and Carol K. Lee

Abstract

Drilling mud plumes from seven different offshore platforms operated by five major oil companies were sampled by divers in the northern Gulf of Mexico to determine amount of suspended solids at different distances downstream from the source. Each plume was sampled at six downstream locations above thermocline at depths ranging from 0.1 to 6.5 m using 10-liter Niskin bottles attached to a horizontal graduated 100 m-long line. Samples were taken 1, 6, 12, 24, 48, and 96 m horizontally from the source. Sampling was done at six platforms during normal drilling operations, and one was sampled during a bulk discharge. Five platforms were sampled without the operator's knowledge.

Suspended solids in samples taken 1 m from the point of discharge ranged from a high of 80 mg/liter to a low of 17 mg/liter with the average from seven platforms at 31 mg/liter. Six m from the source, the average was 6 mg/liter, representing an average 5-fold dilution over a distance of 5 m. At 96 m, suspended solids concentration was approximately 1 mg/liter above background, which averaged 2.07 mg/liter.

The purpose of sampling was to obtain data for comparison with modified 96-hour bioassay results of tests performed on seven species of reef-building corals. The concentrations of whole-used-drilling mud used in the bioassay tests were equivalent to 11, 150 and 479 mg/liter solids. Of the seven species, two (*Montastrea annularis* and *Agaricia agaricites*) were killed by the 479 mg/liter concentration and none was killed by the 150 and 11 mg/liter concentrations. The results of the present study suggest that all seven species of corals could have survived at least 96 hours within 1 m of the discharge pipe and probably much longer as close as 24 m from the source.

Introduction

The purpose of this paper is to describe and quantify suspended solids in plumes of drilling mud resulting from the drilling of exploration and production wells from offshore platforms in the Gulf of Mexico. Although the results of the work may be useful in the evaluation of pollution effects on all marine organisms, such as Neff *et al.* (this volume), the study was targeted specifically on the effects of drilling mud on hermatypic (reef-building) corals. The study was considered necessary for several reasons.

Concern in the United States over the possible effects of drilling mud on corals was articulated during the early 1970's with the announcement of lease sale numbers 26 and 34, both of which included lease blocks near the Flower Gardens coral reef approximately 177 kilometers off the Texas coast. The Flower Gardens had been the subject of intensive biological (Bright and Pequegnat, 1974), geological (Edwards, 1971; Bright and Rezak, 1976), as well as paleontological (Poag, 1972) studies.

Soon after the Flower Gardens sale, concern intensified with the MAFLA (Mississippi, Alabama, Florida) sale number 32 in 1973. The MAFLA sale included the Florida Middlegrounds. Although not a true coral reef, the Florida Middlegrounds is the site of both soft and hard coral growth on a pre-existing Tertiary age limestone. Water depth over the coral-populated Middlegrounds is approximately 25 m, whereas the surrounding coral-free bottom lies under approximately 37 m of water.

Shortly after the MAFLA sale, concern shifted to the Pacific coast. Tanner and Cortez Banks were offered for petroleum exploration in lease sale 35 in 1975. Although coral reefs do not occur along the Pacific coast, Tanner Bank does support colonies of the jewel coral, *Allopora californica*. Therefore, the Bureau of Land Management (BLM), charged with the responsibility of protecting corals, required a pre-drilling permit survey and insisted that drilling mud and cuttings be barged away to deeper water. Through negotiations between the U.S. Geological Survey's Conservation Division and BLM, it was agreed that the company involved (Shell Oil Company) would be allowed to discharge cuttings and mud at the drill site, provided, however, that a monitoring study be conducted.

In 1977 Atlantic Richfield Company drilled a C.O.S.T. Well in Lower Cook Inlet, Alaska. Although not a coral area, BLM regulations required a study of drilling mud and cuttings discharges. In addition to determining suspended solids levels at different distances downstream from the platform, as was done in the Tanner Bank study, bioassays on fish eggs, fish fry, and crabs were also conducted.

The above lease sales resulted in a number of studies and publications on the effects of drilling muds and cuttings:

1) The Flower Gardens sale stipulated a monitoring study, which was conducted by Texas A & M researchers (Bright and Rezak, 1976).

2) The MAFLA sale stipulated studies by SUSIO (State University System of Institute of Oceanography). SUSIO produced three reports (listed in the bibliography).

3) The Tanner Bank sale resulted in a 1.9 kg publication by Meek and Lindsey (1978). The results of that study are summarized in this volume.

4) The ARCO C.O.S.T. Well drilling in Cook Inlet, Alaska, resulted in a publication of a hardbound book by Dames and Moore (1978).

Recently, several expensive but unpublished investigations have been conducted for industry by universities and private consulting firms. Few, however, have been specifically related to effects of drilling mud on corals. The first study to address drill mud effects on corals was by Thompson and Bright (1977), in which various drilling mud additives, as well as whole mud, were applied to corals in static aquaria tests. Due to problems inherent in closed laboratory systems and the large dosages of specific toxic components used, the results have little application to the real world. For this reason, the USGS Conservation Division sponsored a second study by Thompson. The second program, completed in 1978 and published in 1979, employed only whole used drilling mud collected from the mud pit of an offshore platform, where drilling was at a depth of 4,200 m.

|← Thus, material in the form in which it is actually discharged into the environment was utilized. Although laboratory experiments were conducted, probably the most meaningful tests were carried out in the field on a coral reef off south Florida. The results of the field study are also published in this volume. Seven species of reef-building corals were placed in small sealed aquaria containing plastic water pumps to keep test mud in suspension. The tests lasted 96 hours, and three concentrations of drilling mud were used. The drill mud suspension was replaced every 24 hours to insure that corals were continuously exposed to known concentrations.

Three dilutions were prepared from a 4.8-kg mud containing 476,000 mg/ℓ solids. The test dilutions were 10,000:1, 3,160:1 and 1,000:1, in addition to controls. By calculation, these dilutions are equivalent to 47.6, 151 and 476 mg/ℓ suspended solids. Actual measurement by millepore filtration (Thompson, personal communication), however, gave values of 11, 150 and 479 mg/ℓ solids, the significant difference being at the higher dilution, (i.e., lower concentration). The disparity between calculated and measured concentrations is thought to be caused by a combination of experimental error and the observed adhesion of material to bacterial scum on the walls of the test aquaria.

[illegible] to those species [illegible] that [illegible] test them

ignore comment on p. 16

Thompson's (1979; this volume) studies showed that of the seven common species tested, two, *Montastrea annularis* (massive star coral) and *Agaricia agaricites* (lettuce coral), were killed at the higher level of suspended solids, i.e., 479 mg/ℓ (≈calculated mg/ℓ solids). No corals were killed at the two lower concentrations of 150 and 47.6 mg/ℓ. *Acropora cervicornis* (staghorn coral) was killed in one of two tests during exposure to the highest concentration. The reason why it survived one test and not the other is not completely understood.

Behavioral responses were noted in some corals even at the lowest concentration; therefore, the study may be criticized because a no-response level was not determined. Determining a minimum response level, however, would be difficult, because even controls often respond erratically during experimental testing, and some subjectivity is inherent in determining the state of polyp response. A second criticism of the Thompson bioassays is the short 96-hour testing time (the standard time for acute bioassays); therefore, it is difficult to predict long-term effects from the results of that study.

In this paper we determine the concentration of suspended solids at various distances from the source so that the concentrations tested by Thompson may be put into proper perspective.

Methods

Drilling mud plumes from seven offshore platforms in the northern Gulf of Mexico were sampled between August 14 and 21, 1979 (Fig. 1). A 50-ft (15.2-m) trawler (M/V SEA ANGEL), chartered in Miami, was maintained as base ship. Actual sampling was accomplished from a small outboard-powered rubber boat carrying divers (the authors and a photographer).

Sampling Method

Previous studies (Meek and Lindsey, 1978; Ayers *et al*, this volume; Dames and Moore, 1978) indicated that the maximum rate of dilution takes place very near the point of discharge. Sampling efforts were therefore concentrated close to the vicinity of discharge. To insure accurate water quality samples, a 100-m-long polyethelene line was equipped with six clips for attachment of 10-ℓ Niskin water bottles. Clips were placed so that when the line was attached to the discharge pipe, Niskin bottles could be placed precisely at 1, 6, 12, 48, and 96 m from point of discharge. On several occasions, additional line was needed for attachment to the platform because discharge points were seldom in the same location. Some discharges flowed from hoses several m above the water surface, and others emanated from submarine pipes placed five to seven m below the surface. Regardless how the line was attached, it was always situated so that samples could be taken at the predetermined distances from source, with one notable exception. At the Tenneco platform, West Cameron, Block 643, the combination of discharge location and current direction required that the premeasured line be attached to a platform member downstream of the discharge point, resulting in sampling locations of 1, 10, 22, 34, 58 and 106 m from source. Locations of all discharge points sampled are shown in Figure 2. Current direction, indicated by the plumes, date and current speed are also included in Figure 2.

not shown in Table
how was the
depth measured ?

The first two platforms (Shell/Progress, Mississippi Canyon, Block 311 and Exxon, Mississippi Canyon, Block 293) were sampled after contacting and obtaining permission from the drilling superintendent. The remaining platforms, however, were sampled by a "hit-and-run" method without permission of the superintendent, a time-saving move which also removed any possibility that operators might cut off or reduce flow rates.

The hit-and-run method was as follows: the area (Fig. 1) was cruised until a platform with an operating drilling rig was sighted. Most of the dozens of platforms encountered were either production platforms without rigs, or production platforms where tubing was being set or some other activity was in progress that did not require drilling mud. Those that were drilling were easy to spot, both by the rotating drill pipe and visible mud plume.

After spotting a drilling operation, the SEA ANGEL would cruise to within a few hundred m of the platform and drop off the outboard-powered rubber boat with its four-person team. One person took underwater photographs, another attached the measured sampling line, and the third attached and triggered the six Niskin bottles. The fourth person operated the rubber boat, picked up divers and Niskin bottles, and took current speed measurements using a simple propeller-type current meter. The entire operation generally was accomplished in less than 30 minutes, usually before attention of the operators was attracted. Underwater photographs in Figure 3 show the significant sampling procedures.

Weather conditions during the entire period were ideal. Seas were calm and wind was variable both in direction and velocity. Water currents were tidal and did not appear to be related to wind speed or direction.

The combination of calm winds and seas, a persistent current, and a thermocline at approximately seven m resulted in almost horizontal mud plumes. The turbid water was swept away from the source (as shown in Fig. 2) and was never observed to sink below seven m, even after traveling several hundred m downcurrent. Figure 4 schematically shows a typical plume and sampling locations. Cuttings were always observed to settle almost vertically. No attempt was made to collect cuttings.

Sampling was always directed at the worst case. In other words, the divers searched for the zone of maximum turbidity, then triggered the closure of the Niskin bottle. Since the floating polyethelene line tended to trail out and track with the plume, it became a simple matter to push the line and sampling bottles into the most turbid part of the plume before triggering the samplers. The distance from source for each sample was constant, except for that of the Tenneco platform mentioned earlier.

Shipboard Methods (Filtration)

Water samples were returned to the base ship and quickly transferred to collapsible clear plastic containers. Later, and always during the same day as sampling, the samples were transferred to a 10-ℓ plastic pressure cylinder. Air from a Scuba tank equipped with a regulator set for 30 psi was used to force water from the pressure cylinder through a 142-mm-diameter polycarbonate filter with a pore diameter of 0.4 μm. The effluent, which was always clear, was collected and measured with a 1-ℓ graduated cylinder. A 1-ℓ portion was stored for future reference prior to filtration. In practice, two to eight ℓ were filtered to maximize accuracy. Filtrate volume is shown in Table 2. Most samples were between seven and eight ℓ. The filtration apparatus was supplied by ECOMAR, and the methods are the same as those of Meek and Lindsey (1978).

After filtration, the filters with adhering filtrate were folded and stored in test tubes with screw caps. A control sample, taken upstream of the drilling mud plume, was also filtered at each platform. The routine was to filter the samples in sequence from closest to source to most distant from source. The control was filtered last. The apparatus was rinsed once with sea water between each sample; thus, there is the possibility of low level contamination which was not considered significant for a study of this nature. A photograph of the apparatus in use is shown in Figure 3D.

Laboratory Methods

Filter disks were vacuum-dried in the test tubes and weighed on a precision balance after removal from the containers. The average weight of blank filter disks was determined by weighing 10 disks and calculating the average (Table 1). The average weight was 143.6 mg, and the range of variation of the 10 disks was 3.3 mg, or an error of 2.3 percent. The weight of suspended solids in mg/ℓ was calculated by subtracting the weight of a filter disk from the combined weight of filter disk and filtrate and then dividing the filtrate weight by the volume (in liters) of sample filtered. The raw data and results, expressed as mg/ℓ, are shown in Table 2. It should be noted that the filters and sediment were not rinsed in distilled water prior to drying and weighing. Thus, some sea salts are included and may explain why our controls are approximately 1 mg heavier than previously published control values.

Analytical Methods

X-Ray Diffraction

After weighing, each filter was cut in half and the material removed for X-ray diffraction analysis to determine, qualitatively, the mineral content. Each sample was first resuspended in triple-distilled water using an ultra-sonic probe. The resuspended sediment was then filtered through silver filters for X-ray diffraction analysis. The following Table (Table 3) lists the minerals in the approximate order of their concentration in the sample.

Emission Spectrography

Three of the seven series of samples (B, D, E) and a sample from the Mississippi River were analyzed quantitatively for barium and chromium. The other four series were not run for economic reasons. The following Table (Table 4) lists the content of barium and chromium. Note that these analyses were performed on material on the remaining half of the filter after X-ray analysis. The weight of material analyzed is provided in Table 4.

Results and Discussion

Suspended Solids

Table 5 shows current speed and suspended solids concentration, expressed as mg/ℓ, both in plume and control samples. Average values for six platforms are listed at the bottom. The 1-m average includes data from all seven platforms. The remaining six stations at Tenneco, West Cameron, Block 643, also shown on Table 5, are not included in the averages because sampling distances differ from those of the other six platforms.

Averaging was necessary to produce a consistent profile of downstream dilution because reversals occur in almost all sampling sequences. Reversals ~~are~~ were undoubtedly induced during sampling due to the visual difficulty of determining the zone of maximum turbidity. Furthermore, discharges often pulsated, causing breaks of clear water within the plumes. Although attempts were made to avoid sampling such breaks, they nevertheless must have influenced filtrate variations.

In addition to the reversals, one should note that the controls were occasionally heavier by as much as 1.52 mg. Although it is not fully understood why some controls contained more suspended solids than the 96-m sample (three out of seven were heavier than the 96-m sample), several explanations are possible: (1) plankton tended to avoid the plumes, thus less plankton are included in the downstream samples than in the upstream controls; (2) the fluid portion of mud discharge was devoid of plankton; or (3) the weight of the filter disks varied by as much as 3.3 mg (Table 1). Probably the latter factor is the correct explanation, although all three factors may have contributed to the anomalously high values of the three control samples.

One of the seven platforms, Exxon/Progress, South Timbalier, Block 172, was discharging bulk drilling fluid when sampled. An enormous plume extending several km attracted our attention to this platform. A column of mud was flowing from a pipe approximately 20 cm in diameter about 3 m above the surface. A petroliferous odor was noted, and a scum which clung to the divers and smeared face masks was present on the surface along with droplets of oil, which floated to the surface several m downcurrent along our sampling line. Although the volume of discharge is not known, the flow was great enough to completely obscure any underwater visibility beneath and downstream of the platform. Surprisingly, the effluents were among the lowest measured (Table 5). Maximum concentration 1 m from source was only 17.33 mg/ℓ and an even lower value of 7.99 mg/ℓ only 6 m from source. At 12 m from source, however, concentration increased to 16.10 mg/ℓ, followed by a drop to less than 8 mg/ℓ at 48 m, and another increase to 11.31 mg/ℓ at 96 m. Although it is difficult to explain why concentrations were generally low during this bulk discharge, the presence of reversals may be more easily explained. There are two explanations: (1) the entire area was so turbid from the discharge that divers could not visually detect the areas of maximum concentration, and (2) the mud pits may have been substantially diluted with sea water prior to and during discharge. X-ray diffraction of six samples from this location showed quartz to predominate over barite (Table 3). This suggests that the mud pits had become contaminated with sand and thus were being flushed to clean out the sand.

One reoccurring observation was the drastic reduction in underwater visibility caused by very low concentrations of suspended solids. Concentrations of only 10 mg/ℓ 1 m from source reduced visibility to only a few cm. When this water was transferred to the clear containers prior to filtration, however, it appeared almost as clear as drinking water. Mississippi River water provided a similar observation. Although the river looked extremely turbid and contained 41 mg/ℓ solids, the water appeared reasonably clear when viewed in a 10-ℓ container on shipboard. It is interesting that Mississippi River water taken near the town of Venice, Louisiana, contained approximately twice the suspended solids as that measured during the bulk dump at Exxon/Progress, South Timbalier, Block 172, but only about half that observed during normal drilling 1 m from source at Tenneco, West Cameron, Block 643.

The averaged data from six platforms (Table 5) are believed to represent the average discharge from typical well drilling operations in the Gulf of Mexico and probably elsewhere. Averaging of data from several plumes or repeated sampling of the same plume are probably the only ways of obtaining a progressive dilution profile. A single series of samples almost invariably contains reversals. The significant aspect of the dilution profile (Fig. 5) is the five-fold dilution that occurs over a distance of only 5 m between the 1- and 6-m sample. From that point on to the 96-m station, however, the rate of dilution tapered off at a much reduced rate. The average concentration at 96 m for six platforms is only 3.58 mg/ℓ, or 1.58 mg/ℓ above average background. The data from Tenneco, West Cameron, Block 643, are also shown in Figure 5 as a dashed line. As pointed out earlier, these data were not included in the averages (solid line in Fig. 5), because the sampling distances from source were not the same. It is interesting to note that these values are 24 times less Thompson's (1979; this volume) middle concentration of 151 mg/ℓ and 75 times less than the highest concentration used in his bioassays.

Qualitative X-Ray Diffraction Analysis

The purpose of the present study was to determine suspended particulate concentration and its relation to sedimentary effects on corals. Therefore, the results of chemical analyses presented here are, by necessity, rather superficial. Other authors in this volume treat the subject much more thoroughly.

The data presented in Table 3 for the most part support our observation that, aside from cuttings, there was little separation of mud plume components within 96 m of source. We had thought that barite, which has a high specific gravity, might tend to separate preferentially from the plume. In only one case (Exxon, Block 643, Mississippi Canyon) did the barite level decline with distance (Table 3). At this locality, barite was replaced by quartz at the 96 m location.

In other series, such as at Tenneco, Block 643, West Cameron, and Exxon/Progress, Block 172, South Timbalier, quartz was the principal ingredient in almost every sample, regardless of distance from source. The predominance of quartz at the Exxon/Progress location supports our suggestion that the purpose of the observed bulk discharge was to clean sand from the mud pits. Another explanation for the high quartz content is that the well had not yet reached a depth where large amounts of barite are needed. Normally, barite is not added until the depth of potential geo-pressuring, which might cause blowouts, is reached. The authors had no way of knowning drilling depth at the time of sampling because of the hit-and-run sampling method.

Calcite was present in many samples (Table 3). The source is probably the calcite cement, which is the natural binding agent for many sandstones in this area.

Quantitative Emission Spectrography

Quantitative data from three series are shown in Table 4. The data tend to support the above contention that there is little separation of mud components by settling. Except for samples B5 and B6 (Table 4), there was no significant reduction of barite with distance from source. The minor reduction that did occur is probably the result of analytical method, because the amount of sample was so low (see Table 4).

Relatively high levels of chromium were observed in both the B and D series (Table

4). Its source is probably the ferrochrome lignosulfate, which is added as an emulsifier. Others in this volume point out that the chromium is chemically bound up with other materials and is therefore relatively insoluble in sea water. The amount of chromium (190 ppm) in the Mississippi River sample is thought to be of natural origin since this is within the range for natural clays.

Controls

Barite and quartz, in addition to clay minerals, were present in trace quantities in all control samples. Although these minerals may be ~~are~~ normally present in sea water in trace quantities, we believe that a combination of contamination and sea water is the source. The pressure cylinders and tubing used during filtration were rinsed only once between samples, and sea water was used as the rinsing agent. Meek (personal communication) found barite in control samples using the same equipment, even though the system was flushed with distilled water.

[illegible] platform.
[illegible] controlled as
[illegible] amount of drilling
[illegible] water
[illegible] changed [illegible]

(Text continues on page 14.)

Environmental Implications

The data resulting from this study, except those from the Exxon/Progress platform, are thought to represent average values for normal exploratory drilling. Although all but one was a production platform, the quantity and composition of drilling muds used were probably the same as those used on temporary exploratory platforms. One location (Exxon/Eugene Island, Block 315) was indeed an exploratory well being drilled from a three-legged jackup rig (see Fig. 2). The values from this platform are in the same range (in fact, are slightly lower) as those in plumes from production wells (Table 5).

If the average mg/ℓ solids data shown in Table 5 and Figure 5 are compared with the bioassay results of Thompson (1979; this volume), it becomes evident that the bioassay dosages were much too high to have realistic application to environmental conditions near drilling operations. The average concentration of solids 1 m from the source was found to be less than the calculated mg/ℓ solids of the low level dose used by Thompson but almost three times more if compared with his measured values. At six m from source, the average level of suspended solids was found to be more than seven times less than the (calculated level of suspended solids) lowest level tested by Thompson. Griffin (1974) found that natural levels of suspended solids in a nearshore coral area of the Florida reef tract reached 5 mg/ℓ during windy weather, when bottom sediment was stirred into suspension by waves. Griffin (personal communication) also measured 40 mg/ℓ solids in a boat wake in John Pennekamp State Park off Key Largo, Florida. Three hours later the concentration had dropped to 14 mg/ℓ. Background values outside the 20-m-wide wake were 3 mg/ℓ. Thus, suspended solids in the wake of a typical tug-and-barge combination three hours after /passage were about twice the average amount the authors found six m from the discharge pipe of the offshore drilling platforms. Such boat wakes can be observed in the Pennekamp Park area along the Intracoastal Waterway almost every day of the week. It could be also be concluded that the average values of drill mud plumes

96 m downstream (1.51 mg/ℓ above background) are less than those observed under natural windy conditions in coral areas of the Florida reef tract.

Although behavioral effects of corals were noted in Thompson's (1979; this volume) experiments, i.e., polyp retraction, no corals died in the lower dose concentration test, nor were there mortalities at the intermediate dose level (150 mg/ℓ). All of the species tested by Thompson except *Dichocoenia stokesii* showed marked behavioral response to the highest dose level (476 mg/ℓ), and two species, *Montastrea annularis* and *Agaricia agaricites*, were killed after 65 hours. At the same concentration, *Acropora cervicornis* died in one 96-hour test but not in a second 96-hour test. It would appear that this species was near the borderline between life and death and that some minor variation in experimental procedure was sufficient to cause death. Behavioral responses were also noted in the two lower concentration tests.

[illegible] the species [illegible] died [illegible] species [illegible] listed

It seems reasonable to conclude that all the common corals tested by Thompson (1979; this volume) could survive 96 hours of exposure as close as 1 m from the discharge pipe during normal drilling operations. Whether or not these corals could survive indifinitely at the lower levels found farther from the discharge pipe has not been determined. If the effect of drilling mud on coral is purely mechanical, rather than chemical, then its effects should be no different than that of natural sediment of similar grain size. Given this condition, the reader is reminded that the concentration of natural sediment in natural coral areas of the Florida Keys (Griffin, 1974) is often several times greater than the amounts actually measured in drilling mud plumes 96 m from source.

The above discussion is addressed only to the conditions associated with normal drilling. During bulk dumping, however, which can occur several times during drilling, followed by a mass dump at termination of drilling, suspended solids levels can greatly exceed the levels reported here. Ayers *et al.* (this volume) noted the following levels during a controlled dump of 1,000 bbls per hour: 1,426,675 mg/ℓ at the source, 32 mg/ℓ at 60 m, 51 mg/ℓ at 152 m, 24 mg/ℓ at 376 m, and 9 mg/ℓ at 498 m. In their study, background levels were reached at 1,564 m. Although these are probably the highest levels yet reported, it can be noted that at 60 and 152 m from source, the concentration of suspended solids (32 mg/ℓ and 51 mg/ℓ, respectively) is near the lower dose level tested by Thompson (1979). These levels are also approximately nine times less than the highest concentration used by Thompson, in which only two of the seven species tested were killed. The point can be made, therefore, that all the species tested by Thompson could easily survive 96 hours 60 m or farther from source during a bulk dump. According to Ray and Meek (personal communication), bulk dumps seldom last more than a few hours. Therefore, chronic levels which persist during the one to four months required to drill typical offshore wells would be more important to coral survival than the occasional short-lived bulk discharges.

This study suffers, as do most other drilling mud studies, from lack of knowledge concerning the mud's chemical composition. No attempt has been made to assess toxicity of dissolved chemicals in the fluid phase of drill mud in this study. It is assumed, however, that dissolved components were present in the mud used by Thompson and that the suspended solids serve as an index of concentration, both of solids and the dissolved phase, an assumption that may not always hold true. In addition, because of the "hit-and-run" sampling method used, the concentration of solids in the mud before it entered the environment is not known. However, because of the extremely high rate of dilution that occurs between one and six m from source, it seems certain that even greater dilution occurs before the plume has traveled 1 m from source, if not within the discharge pipe itself. Drilling muds prior to discharge generally contain hundreds of thousands of mg/ℓ suspended solids, or greater, as described by Ayers *et al.* (this volume).

Although this study was conducted around platforms in greater than 60 m of water, where there were no living corals, the question of coral smothering nevertheless should be discussed. If wells were drilled in shallow water, for example, 6 to 15 m and very near or on a coral reef, what would happen? Would nearby corals be smothered and killed in an accumulation of drilling mud?

The authors believe that nearby corals almost directly under a drilling platform could be smothered by cuttings, but it is very unlikely that these corals could be smothered by drilling mud. Drilling mud, it should be remembered, is very fine-grained, much too fine to settle permanently on a coral reef. Geologists and sedimentologists agree that coral reefs do not grow in areas where fine-grained sediment can accumulate and, indeed, the natural sediment is invariably coarse-grained. Following Hurricane Donna in the Florida Keys (personal observation; Ball *et al.*, 1967; Shinn, 1976), carbonate mud from Florida Bay and the inner reef tract produced milky sediment-laden water that flowed seaward and persisted over the reef tract for several weeks. Similar observations were made during Hurricane Betsy in 1965 by Perkins and Enos (1968). Figure 6 shows lime mud in suspension over Carysfort Reef in the Key Largo Coral Reef Marine Sanctuary following Hurricane Betsy. The concentration of this fine-grained mud is thought to have been on the order of 50 to 100 mg/ℓ. Griffin (personal communication) has measured over 100 mg/ℓ on the Florida reefs for short periods during winter storms.

w fine? silt or grain-size

Carbonate mud was temporarily observed to settle and accumulate in reef areas where the normal sediment was very coarse-grained. Within a few weeks, this sediment was resuspended and removed by normal day-to-day wave and tidal currents. In their study of coral banding and growth rates, Hudson *et al.* (1976) did not observe reduction of growth rate of *Montastrea annularis* for the year in which Hurricane Donna struck, nor were any growth rate effects observed for any of the other years in which hurricanes crossed the Florida reefs. Hurricane effects, as noted by Ball *et al.* (1967) and Shinn (1976), were restricted to physical damage resulting from direct wave and current forces during the storm when wind velocities often exceeded 175 miles/hour.

These observations indicate that during normal day-to-day conditions, fine-grained sediment, whether it be natural carbonate mud or drilling mud, would not settle in coral reef areas. Only during unusually calm periods, seldom lasting more than a few days, could such fine-grained sediment accumulate, and then it would be quickly removed when normal conditions returned. Such accumulation would be in the sediment pockets and not on the live corals, which, because of their topography, are more current swept.

Because of high energy conditions associated with reef growth, sedimentation of drilling mud is not likely. Hudson (this volume) describes attempts by Texas A & M researchers to coat M. *annularis* with large doses of drilling mud in 3 m of water on a Florida reef. A thick slurry of whole drilling mud was repeatedly applied from a plastic bag held a few cm from the coral surface by a diver. Observations (by the senior author) and Hudson (this volume) showed that a combination of wave-generated currents and the actions of the corals themselves removed the sediment within ½ hour.

On the basis of this study and other observations cited above, the authors contend that aside from local accumulation of cuttings, drilling mud from drilling operations is not a major threat to coral reefs. Indeed, the concentrations we have measured appear insignificant compared to the volume of fine-grained sediment put into suspension by boat traffic and storms in the Florida reef tract. Drilling mud may have, on the other hand, a drastic effect on coral reefs if it should contain high levels of dissolved toxins. This study did not assess the toxicity of the liquid phase, but it is assumed that present regulations prevent addition of highly toxic biocides and other such ingredients to drilling mud if the mud is to be discharged into the water.

Conclusions

1) Sampling of drilling mud plumes from seven different platforms in the Gulf of Mexico yielded suspended solids concentrations ranging from 10.21 to 79.78 mg/ℓ at a location 1 m from source, to concentrations ranging from 1.39 to 11.31 mg/ℓ 96 m from source. The average was 31.37 at one m and 6.29 mg/ℓ six m from source. The average at 96 m was 3.58 mg/ℓ. Average background level was 2.07 mg/ℓ.

2) Maximum dilution rate~~d~~ occurred within six m of source.

3) Assuming that the muds are similar, a comparison of the suspended solids data with the experimental bioassay data of Thompson (1979) suggests that all the species tested could survive 96 hours within one m of source during normal drilling techniques, that is, the average concentration at one m of source was 14 times less than the concentration required to cause mortality in 96 hours. At one platform, the value was only six times less.

4) At 96 m from source, the concentration of suspended solids was 132 times less than that required to cause mortality in 96-hour bioassays using similar mud.

Acknowledgments

Funding for field and laboratory work was provided by the Branch of Marine Oil and Gas Operations of the USGS Conservation Division.

The authors thank Captain Roy Gaensslen of the M/V SEA ANGEL for navigating us safely from Miami to the northern Gulf of Mexico and back. Appreciation is also extended to Steve Earley for the underwater photography, as well as technical assistance in the field. Additional thanks go to the N.A.G.T. (National Association of Geology Teachers) USGS scholarship program which made Carol Lee available for this project.

Dr. Oiva Joensuu and Mr. Robert Glaccum of the University of Miami's Rosenstiel School provided the chemical consultation and analyses presented here. Ms. Barbara Lidz provided additional consultation and editing of the manuscript.

Unused Filter Disks (mg)
142.1
141.1
144.2
146.0
144.8
146.2
146.5
142.0
143.3
143.2
1439.4

Range 141.1-146.5 mg
Average 143.6 mg
Standard Deviation 1.9
Variance 3.3
95% Confidence Interval 3.8

Table 1

Company, Block and Area	Sample	Particulates plus Filter Paper (mg)	Filtrate Volume (ℓ)	Particulates (mg)	Particulate Concentration (mg/ℓ)
Shell/Progress, 311, Mississippi Canyon	A1	444.6	7.830	301.0	38.44
	A2	229.5	7.860	85.9	10.90
	A3	203.7	7.945	60.1	7.56
	A4	206.8	7.940	63.2	7.96
	A5	161.7	7.825	18.1	2.31
	A6	157.0	7.905	13.4	1.70
	Control	166.5	7.880	22.9	2.91
Exxon, 293, Mississippi Canyon	B1	311.4	7.925	167.8	21.17
	B2	154.1	7.980	10.5	1.32
	B3	157.3	8.000	13.7	1.71
	B4	157.9	7.815	14.3	1.83
	B5	165.9	7.925	22.3	2.81
	B6	154.4	7.755	10.8	1.39
	Control	166.5	7.880	22.9	2.91
Exxon/Progress, 172, South Timbalier	C1	278.3	7.740	134.7	17.40
	C2	207.5	8.000	63.9	7.99
	C3	266.1	7.610	122.5	16.10
	C4	200.0	7.935	56.4	7.11
	C5	205.8	7.940	62.2	7.83
	C6	233.6	7.945	90.0	11.30
	Control	156.0	7.860	12.4	1.58
Tenneco, 643, West Cameron	D1	430.8	3.600	287.2	79.78
	D2	408.1	7.600	264.5	34.80
	D3	266.7	7.640	123.1	16.11
	D4	162.1	3.335	18.5	5.55
	D5	161.2	7.990	17.6	7.20
	D6	147.6	2.000	4.0	2.00
	Control	156.7	7.965	13.1	1.64
Texaco, 313, Eugene Island	E1	251.2	6.210	107.6	17.33
	E2	178.9	8.050	35.3	4.38
	E3	155.4	8.050	11.8	1.46
	E4	147.0	3.510	3.4	0.97
	E5	182.0	7.990	38.4	4.81
	E6	164.4	8.000	20.8	2.60
	Control	163.3	7.900	19.7	2.49
Exxon/Atwood Oceanic, 315, Eugene Island	F1	224.0	7.920	80.4	10.20
	F2	212.9	7.925	69.3	8.74
	F3	216.4	7.955	72.8	9.15
	F4	202.5	8.015	58.9	7.35
	F5	202.0	7.850	58.4	7.44
	F6	159.4	7.945	15.8	1.99
	Control	160.7	7.880	17.1	2.17
Chevron, 341, Eugene Island	G1	421.2	7.880	277.6	35.23
	G2	178.4	7.905	34.8	4.40
	G3	167.8	7.915	24.2	3.06
	G4	185.9	7.940	42.3	5.33
	G5	170.6	7.930	27.0	3.40
	G6	163.3	7.950	19.7	2.48
	Control	156.7	7.995	13.1	1.64
	Mississippi River	513.9	7.920	370.3	46.76

Mass of filter disk = 143.6 mg.

Table 2.

A SERIES, SHELL/PROGRESS, BLOCK 311, MISSISSIPPI CANYON

A1 (1 m)
barite
quartz
montmorillonite
mica/illite
kaolinite/chlorite
plagioclase
microcline
calcite

A2 (6 m)
barite
quartz
montmorillonite
mica/illite
kaolinite/chlorite
plagioclase
microcline
calcite

A3 (12 m)
barite
quartz
montmorillonite
mica/illite
kaolinite/chlorite
plagioclase
microcline
calcite (trace)

A4 (24 m)
barite
quartz
montmorillonite
mica/illite
kaolinite/chlorite
microcline
plagioclase
calcite

A5 (48 m)
barite
quartz
kaolinite/chlorite
mica/illite
plagioclase
microcline
calcite

A6 (96 m)
barite
quartz
mica/illite
kaolinite/chlorite
plagioclase
calcite

Control (Surface)
barite
calcite
quartz
plagioclase
microcline
kaolinite/chlorite
mica/illite
montmorillonite?

B SERIES, EXXON, BLOCK 293, MISSISSIPPI CANYON

B1 (1 m)
barite
quartz
montmorillonite
kaolinite/chlorite
mica/illite
plagioclase
calcite
microcline

B2 (6 m)
barite
quartz
montmorillonite
mica/illite
kaolinite/chlorite
plagioclase
microcline

B3 (12 m)
barite
quartz
montmorillonite
kaolinite/chlorite
mica/illite
plagioclase
calcite
microcline

B4 (24 m)
barite
quartz
kaolinite/chlorite
plagioclase
mica/illite
montmorillonite
calcite
microcline

B5 (48 m)
barite
quartz
kaolinite/chlorite
plagioclase
mica/illite
montmorillonite
calcite
microcline

B6 (96 m)
quartz
barite
kaolinite/chlorite
mica/illite
montmorillonite
calcite
plagioclase
microcline

Table 3.

B SERIES, EXXON, BLOCK 293, MISSISSIPPI CANYON

Control (Surface)
barite
calcite
quartz
plagioclase
microcline
kaolinite/chlorite
mica/illite
montmorillonite?

C SERIES, EXXON/PROGRESS, BLOCK 172, SOUTH TIMBALIER

C1 (1 m)
quartz
barite
montmorillonite
mica/illite
kaolinite/chlorite
plagioclase
microcline
calcite (trace)

C2 (6 m)
quartz
barite
montmorillonite
mica/illite
kaolinite/chlorite
plagioclase
microcline
calcite

C3 (12 m)
quartz
barite
montmorillonite
kaolinite/chlorite
mica/illite
plagioclase
microcline
calcite (trace)

C4 (24 m)
quartz
barite
montmorillonite
mica/illite
kaolinite/chlorite
plagioclase
microcline
calcite

C5 (48 m)
quartz
barite
mica/illite
kaolinite/chlorite
montmorillonite
plagioclase
microcline
calcite

C6 (96 m)
quartz
barite
montmorillonite
mica/illite
kaolinite/chlorite
plagioclase
microcline
calcite

Control (Surface)
quartz
barite
mica/illite
kaolinite/chlorite
montmorillonite
microcline
plagioclase
calcite?

D SERIES, TENNECO, BLOCK 643, WEST CAMERON

D1 (1 m)
quartz
barite
kaolinite/chlorite
mica/illite
montmorillonite
plagioclase
calcite
microcline

D2 (10 m)
quartz
barite
mica/illite
montmorillonite
kaolinite/chlorite
plagioclase
calcite
microcline

D3 (22 m)
quartz
barite
montmorillonite
kaolinite/chlorite
mica/illite
plagioclase
calcite
microcline

Table 3 (continued).

D SERIES, TENNECO, BLOCK 643, WEST CAMERON

D4 (34 m)
quartz
barite
kaolinite/chlorite
mica/illite
plagioclase
microcline
calcite (trace)
montmorillonite

D5 (58 m)
quartz
barite
kaolinite/chlorite
mica/illite
montmorillonite
plagioclase
microcline
calcite

D6 (106 m)
quartz
barite
mica/illite
kaolinite/chlorite
montmorillonite
plagioclase
calcite
microcline

Control (Surface)
barite
kaolinite/chlorite
quartz
plagioclase
microcline
mica/illite
montmorillonite
calcite?

E SERIES, TEXACO, BLOCK 313, EUGENE ISLAND

E1 (1 m)
montmorillonite
kaolinite/chlorite
quartz
mica/illite
barite
plagioclase
microcline
calcite

E2 (6 m)
quartz
barite
kaolinite/chlorite
mica/illite
montmorillonite
plagioclase
calcite (trace)
microcline

E3 (12 m)
quartz
barite
kaolinite/chlorite
mica/illite
montmorillonite
plagioclase
microcline
calcite (trace)

E4 (24 m)
kaolinite/chlorite
mica/illite
quartz
barite
montmorillonite
plagioclase
microcline
calcite

E5 (48 m)
quartz
barite
plagioclase
kaolinite/chlorite
mica/illite
montmorillonite
microcline
calcite

E6 (96 m)
calcite
barite
quartz
kaolinite/chlorite
plagioclase
mica/illite
microcline
montmorillonite

Control (Surface)
quartz
barite
kaolinite/chlorite
mica/illite
montmorillonite
plagioclase
calcite
microcline

Table 3 (continued).

MISSISSIPPI RIVER

quartz
mica/illite
montmorillonite
kaolinite/chlorite
plagioclase
microcline

Table 3 (continued).

F SERIES, EXXON/ATWOOD OCEANIC, BLOCK 315, EUGENE ISLAND

F1 (1 m)
barite
quartz
calcite
kaolinite/chlorite
plagioclase?
microcline?

F2 (6 m)
barite
quartz
calcite
kaolinite/chlorite

F3 (12 m)
barite
quartz
kaolinite/chlorite
mica/illite
montmorillonite?
microcline?
plagioclase?
calcite

F4 (24 m)
barite
quartz
kaolinite/chlorite
calcite
montmorillonite?

F5 (48 m)
barite
quartz
kaolinite/chlorite
calcite
montmorillonite

F6 (96 m)
barite
quartz
kaolinite/chlorite
calcite
plagioclase?

Control (Surface)
barite
quartz
plagioclase
microcline
calcite
kaolinite/chlorite
mica/illite
montmorillonite?

G SERIES, CHEVRON, BLOCK 341, EUGENE ISLAND

G1 (1 m)
quartz
montmorillonite
kaolinite/chlorite
mica/illite
barite
plagioclase
calcite
microcline?

G2 (6 m)
quartz
montmorillonite
kaolinite/chlorite
mica/illite
barite
plagioclase
calcite
microcline

G3 (12 m)
montmorillonite
quartz
kaolinite/chlorite
mica/illite
barite
plagioclase
calcite
microcline

G4 (24 m)
quartz
montmorillonite
kaolinite/chlorite
mica/illite
barite
calcite
plagioclase
microcline

G5 (48 m)
quartz
kaolinite/chlorite
mica/illite
montmorillonite
plagioclase
microcline
calcite

G6 (96 m)
montmorillonite
kaolinite/chlorite
mica/illite
quartz
barite
plagioclase
calcite
microcline?

Control (Surface)
barite
kaolinite/chlorite
quartz
calcite
plagioclase
mica/illite
microcline?
montmorillonite?

Table 3 (continued).

Sample	$BaSO_4$ (%)	Cr (ppm)	Weight (mg) of Material Analyzed
B1	31.0	820	108.1
B2	23.0	1100	15.8
B3	15.5	1100	17.8
B4	24.5	460	17.8
B5	9.0	190	19.6
B6	5.1	220	5.0
D1	25.0	2100	201.6
D2	12.5	910	190.8
D3	16.0	1100	103.6
D4	8.5	560	14.1
D5	16.0	1100	12.1
D6	22.0	1200	25.8
Control	14.0	550	4.0
E1	7.2	180	91.0
E2	8.0	180	28.2
E3	5.0	220	14.0
E4	5.5	310	6.4
E5	5.1	110	33.6
E6	1.6	90	12.2
Control	9.8	90	12.2
Mississippi River	1.0	190	253.8

Table 4

Location:			Particulate Concentration (mg/l) per sample:							Current	
			Distance from Source (m)								
Area	Block	Company	1 m	6 m	12 m	24 m	48 m	96 m	Control	(cm/s)	Date
Mississippi Canyon	311	Shell/Progress	38.44	10.91	7.56	7.96	2.31	1.70	2.91	26*	08/14/79*
		sample number	A1	A2	A3	A4	A5	A6			
		water depth (m)	0.2	0.3	0.6	0.9	1.5	0.9	0.2		
		time	1015	1016	1019	1021	1022	1025	1130*		
Mississippi Canyon	293	Exxon	21.17	1.32	1.71	1.83	2.81	1.39	2.91	26*	08/14/79*
		sample number	B1	B2	B3	B4	B5	B6			
		water depth (m)	6.1	6.7	7.6	6.1	4.6	3.0	0.2		
		time	1715	1716	1717	1720	1722	1725	1130*		
South Timbalier	172	Exxon/Progress	17.40	7.99	16.10	7.11	7.83	11.31	1.58	24	08/15/79
		sample number	C1	C2	C3	C4	C5	C6			
		water depth (m)	all samples were taken 0.3 to 0.6 m below the surface								
		time	1525	1528	1529	1532	1534	1536	1545		
Eugene Island	313	Texaco	17.33	4.38	1.46	0.97	4.81	2.60	2.49		08/21/79
		sample number	E1	E2	E3	E4	E5	E6			
		water depth (m)	3.0	3.6	4.2	4.6	4.9	6.1	0.2		
		time	1215	1217	1220	1224	1226	1230	1220		
Eugene Island	315	Exxon/Atwood Oceanic (jackup)	10.21	8.74	9.15	7.35	7.44	1.99	2.17	32	08/21/79
		sample number	F1	F2	F3	F4	F5	F6			
		water depth (m)	0.3	0.3	0.6	0.6	0.9	1.5	0.2		
		time	1400	1403	1406	1409	1411	1415	1407		
Eugene Island	341	Chevron	35.23	4.40	3.06	5.33	3.40	2.48	1.64	26	08/21/79
		sample number	C1	C2	G3	G4	G5	G6			
		water depth (m)	0.3	0.3	0.3	0.6	0.9	1.8	0.2		
		time	1600	1603	1606	1609	1612	1615	1603		
			1 m	10 m	22 m	34 m	58 m	106 m	Control		
West Cameron	643	Tenneco	79.78	34.80	16.11	5.55	2.20	2.00	1.64	44	08/19/79
		sample number	D1	D2	D3	D4	D5	D6			
		water depth (m)	0.3	0.4	0.5	0.7	1.0	1.0	0.2		
		time	1615	1618	1620	1623	1625	1628	1618		
			1 m	6 m	12 m	24 m	48 m	96 m	Control		
AVERAGE			31.37	6.29	6.51	5.09	4.77	3.58	2.07	30	

* Taken only once for the two adjacent stations.

Table 5

References

Ball, M.M., E.A. Shinn, and K.W. Stockman, 1967. The geologic effects of Hurricane Donna in south Florida. J. Geol. 75: 583-597.

Bright, T.J. and L.H. Pequegnat (eds.), 1974. Biota of the West Flower Garden Bank. Gulf Publishing Co., Houston, Tex. 435 p.

Bright, T.J. and R. Rezak, 1976. A biological and geological reconnaissance of selected topographical features on the Texas continental shelf. Submitted to Bureau of Land Management, New Orleans, by College of Geosciences, Texas A & M Univ., College Station, Tex. BLM Contract No. 08550-CT5-4. 377 p.

Dames and Moore, 1978. Drilling Fluid Dispersion and Biological Effects Study for the Lower Cook Inlet C.O.S.T. Well. Conducted for Atlantic Richfield Co. 309 p.

Edwards, G.S., 1971. Geology of the West Flower Garden Bank. Texas A & M Sea Grant Pub. TAMU-SG-71-215, Dec. 1971. 198 p.

Griffin, G.E., 1974. Dredging in the Florida Keys: Case history of a typical dredge-fill project in the northern Florida Keys-- Effects on water clarity, sedimentation rates and biota. Harbor Br. Fdn. Pub. No. 33. 67 p.

Hudson, J.H., E.A. Shinn, R.B. Halley, and B. Lidz, 1976. Sclerochronology-- A tool for interpreting past environments: Geol. 4: 361-364.

Meek, R.P. and J.E. Lindsey, 1978. Tanner Bank Mud and Cuttings Study. Conducted for Shell Oil Co., April 1978. 495 p.

Perkins, R.D. and P. Enos, 1968. Hurricane Betsy in the Florida-Bahamas area-- geologic effects and comparison with Hurricane Donna. J. Geol. 76: 710-717.

Poag, C.W., 1972, Shelf-edge submarine banks in the Gulf of Mexico: Paleoecology and biostratigraphy. Trans., Gulf Coast Assoc. of Geol. Soc., 22nd Ann. Conv. Corpus Christi, Tex. Vol. 22: 267-288.

Shinn, E.A., 1976. Coral reef recovery in Florida and the Persian Gulf. Environ. Geol. 1: 241-254.

SUSIO. Proc., Marine Environmental Implications of Offshore Drilling, Eastern Gulf of Mexico. 1974, Conference Workshops, Jan. 31, Feb. 1, 2, 1974. St. Petersberg, Fla. 455 p.

SUSIO. Compilation and Summation of Historical and Existing Physical Oceanographic Data from the Eastern Gulf of Mexico, Final Report. Contract No. 08550-CT4-16, July 15, 1975.

SUSIO. Final Report on the Baseline Environmental Survey of the MAFLA Lease Areas, CY 1974. BLM Contract No. 08550-CT4-11, vol. 1-5, approx. 400 p. each.

Thompson, J. and T.J. Bright, 1977. Effects of drill mud on sediment clearing rates of certain hermatypic corals. Proc., 1977 Oil Spill Conf., New Orleans, La. p. 495-498.

Figure Captions

Fig. 1. Location map showing offshore platforms that were sampled and their relationship to Flower Gardens Reef.

Figure 2. Schematic layout of all seven platforms that were sampled, showing current direction (indicated by plume direction), date and current speed, expressed as cm/sec. An aerial plume was noted at Texaco Platform B, which was caused when dry drilling mud was pumped with compressed air from transport container to mud pit. The air plume was not sampled, because its contribution to the water column was thought to be insignificant compared to the liquid discharge.

Figure 3. (A) Diver attaching line to drilling mud and cuttings discharge pipe. Measured sampling line was then attached to line around pipe. (B) Drill mud discharge during normal drilling. Compare with A and note that cloud of drill mud is intermittent. (C) Diver with 10-liter sampler. Note attachment of sampler to measured line. (D) Filtration of samples aboard ship. Sample is pressurized to 30 psi in two vertical PVC chambers. Pressurized samples pass through filters in filter heads. Filtered fluid is collected in two plastic canisters below filter heads.

Figure 4. Schematic cross section of a typical sampling operation, showing sampling line attached to platform member and sampling bottle locations, indicated by dots on the line and "X's" showing distance from the source where samples were taken. Control sample was taken upstream from plume.

Figure 5. Dilution profile. Dark line shows average suspended solids from six platforms. Sampling locations shown by large black dots. Dashed line shows data from Tenneco Platform B, West Cameron, Block 643, where sampling distances had to be modified because of discharge location (see Fig. 2). Black squares show sampling locations. Note that although initial values were higher than the average of six platforms, downstream values fall below the average and also below the average control value.

Figure 6. (A) View of Carysfort Reef in Key Largo Coral Reef Marine Sanctuary

during normal weather conditions. Note corals around 30-m-high lighthouse. Photo taken in August, 1978. View is to the southwest. (B) Carysfort Reef several days after passage of Hurricane Betsy in September, 1965. Reef is enveloped in a sea of lime mud. Band at top of photo is clear water of the northward flowing Florida Current. View is to the east.

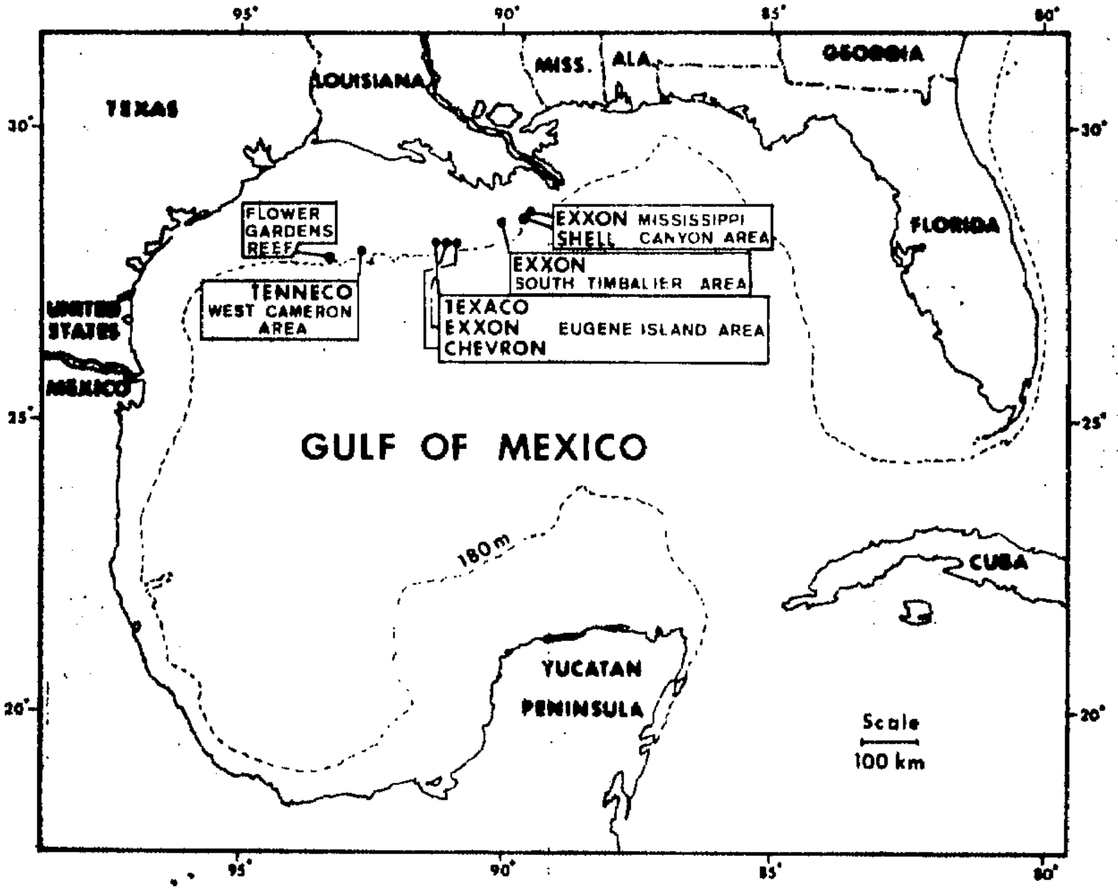
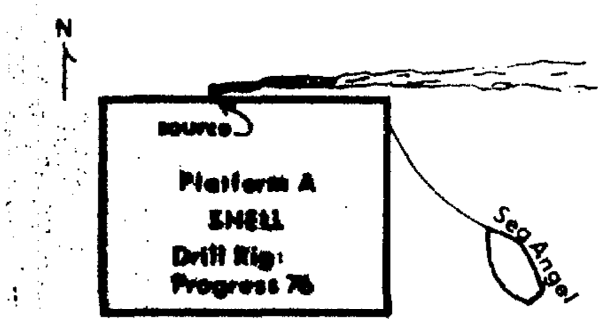
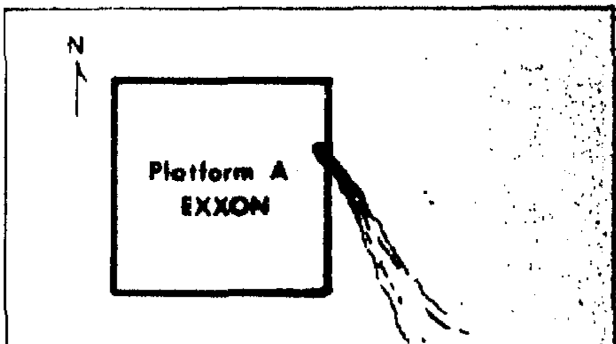

95°
90°
85°
80°
30°
25°
20°
TEXAS
LOUISIANA
MISS.
ALA.
GEORGIA
FLORIDA
UNITED STATES
MEXICO
FLOWER GARDENS REEF
TENNECO WEST CAMERON AREA
EXXON MISSISSIPPI
SHELL CANYON AREA
EXXON SOUTH TIMBALIER AREA
TEXACO
EXXON
CHEVRON
EUGENE ISLAND AREA
GULF OF MEXICO
180m
CUBA
YUCATAN PENINSULA
Scale
100 km

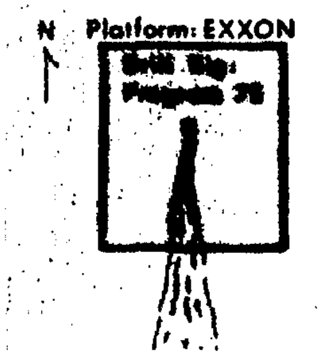
Fig.



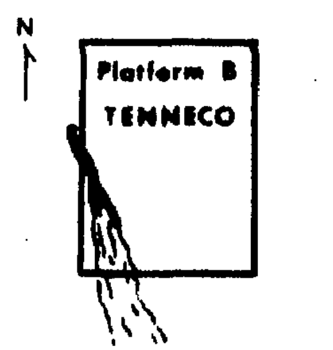
Location: Area - Mississippi Canyon, Block-311
Current Speed: 26cm/s Date: 8/14/79



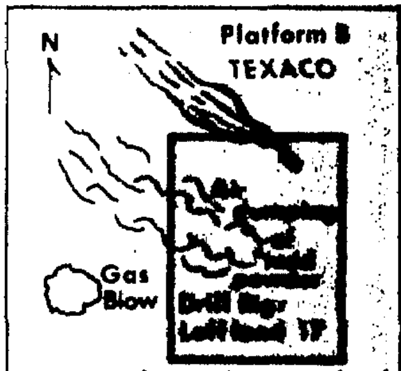
Location: Area - Mississippi Canyon, Block-293
Current Speed: 26cm/s Date: 8/14/79



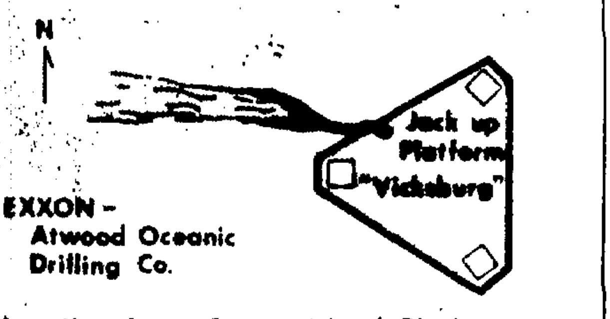
Location: Area - S. Timbalier, Block-172 Date: 8/15/79
Current Speed: 24cm/s



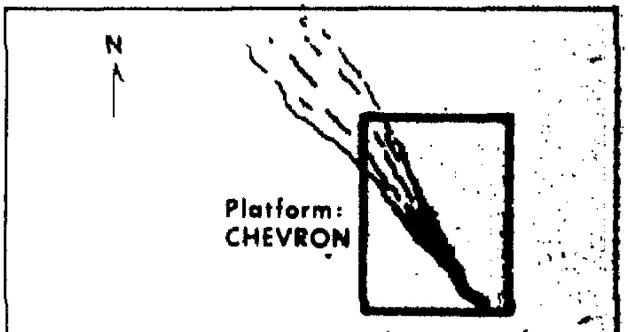
Location: Area - West Cameron, Block-643 Date: 8/19/79
Current Speed: 44cm/s



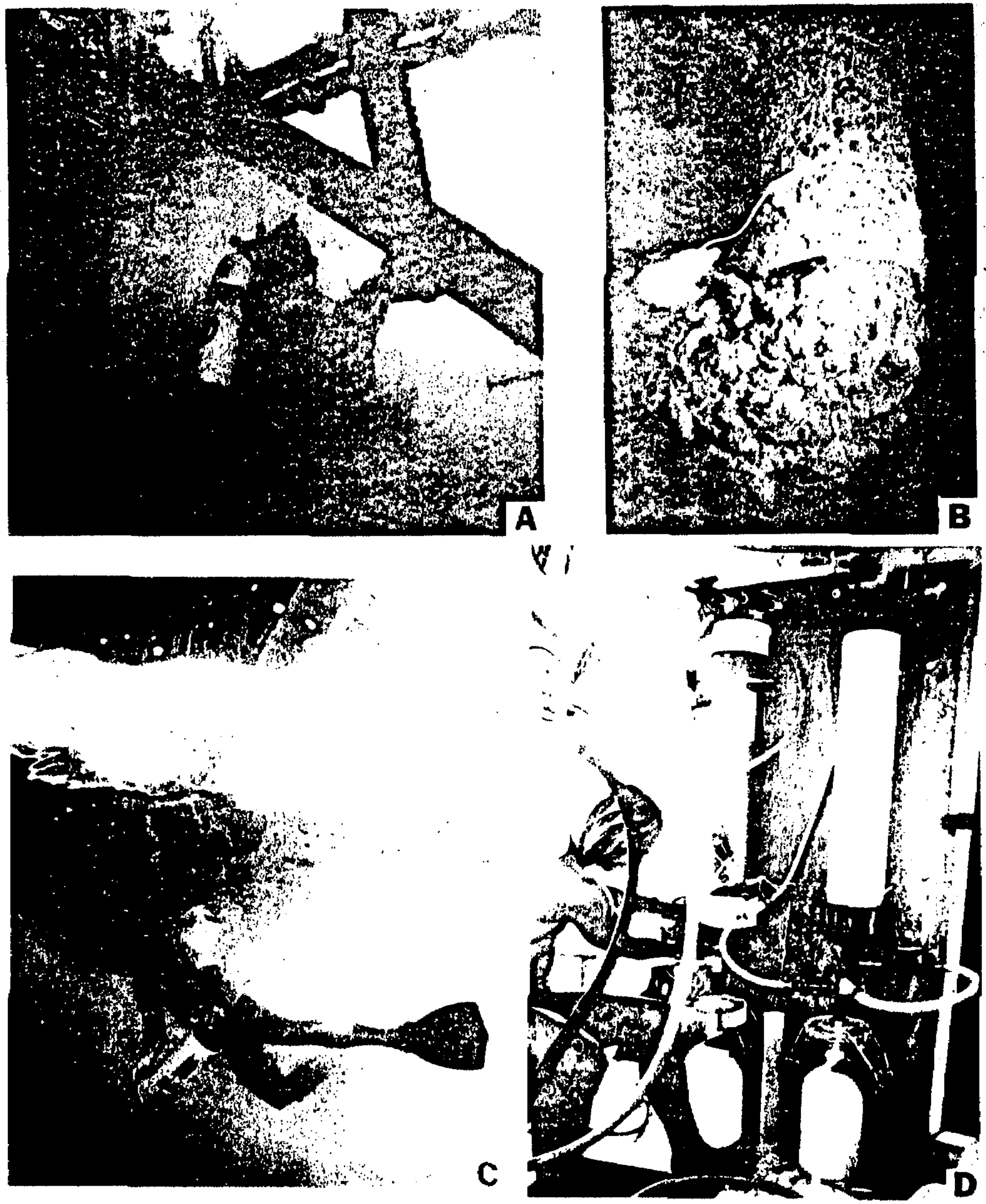
Location: Area - Eugene Island Block-313 Date: 8/21/79
Current Speed: NA

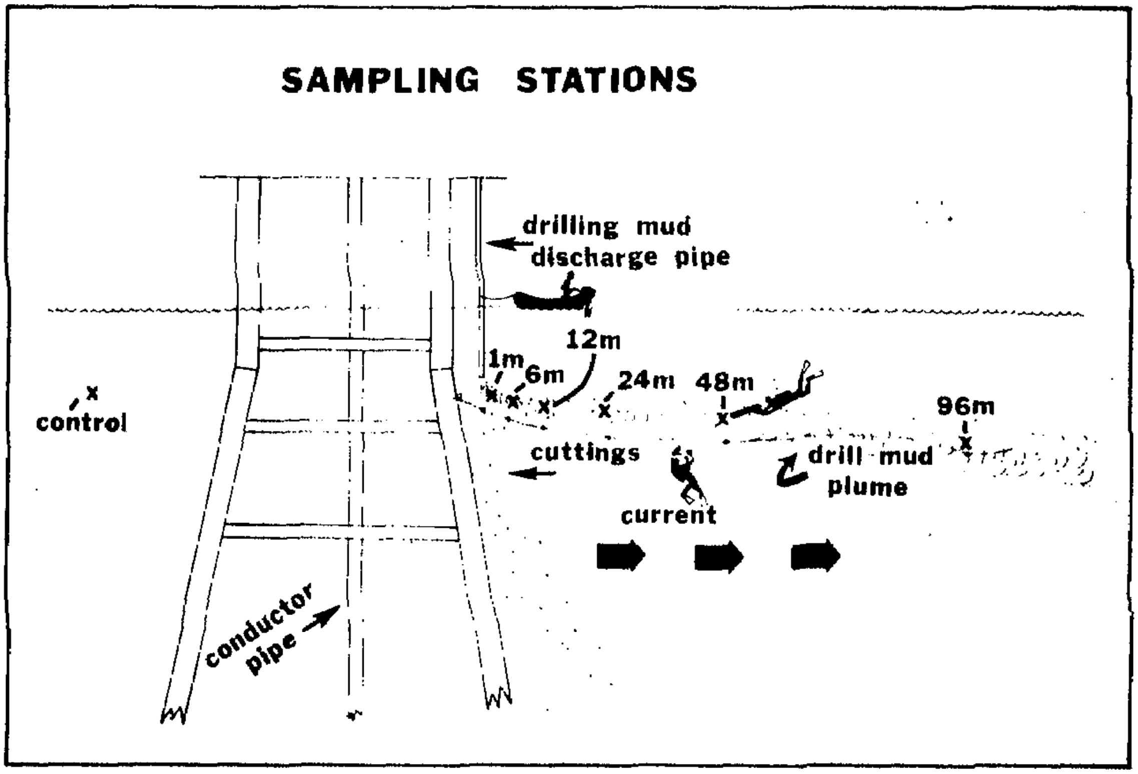


Location: Area - Eugene Island, Block-315
Current Speed: 32cm/s Date: 8/21/79

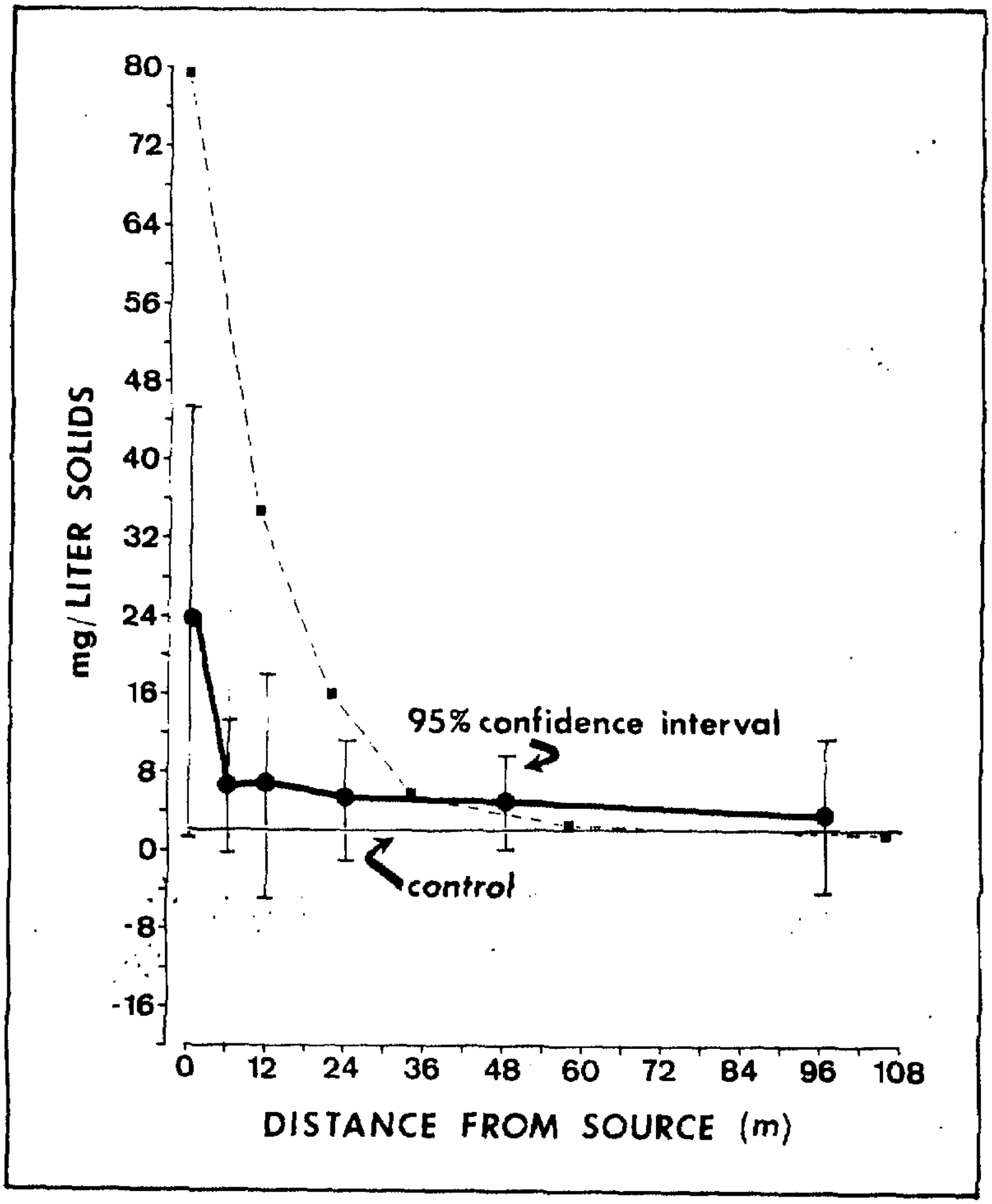


Location: Area - Eugene Island, Block-341
Current Speed: 26cm/s Date: 8/21/79


A
B
C
D



SAMPLING STATIONS


mg/LITER SOLIDS
80
72
64
56
48
40
32
24
16
8
0
-8
-16
95% confidence interval
control
0
12
24
36
48
60
72
84
96
108
DISTANCE FROM SOURCE (m)

Toxicity of Drilling Fluids on Corals

Principal Investigator: Eugene A. Shinn
U.S. Geological Survey
Fisher Island Station
Miami Beach, FL 33139

Objective: To determine potential effects of offshore drilling upon coral reefs

During oil- or gas-well drilling, a mixture of water and clays called drilling mud is circulated downhole through the drill bit and back to the surface for several operational purposes:
(1) lubricating and cooling the bit, (2) circulating cuttings to the surface for geological examination,
(3) forming a supportive wall or mud casing to the wall (generally called a mud cake), and
(4) preventing blowouts.

In recent years, the possible effects of drilling mud discharges during offshore operations have become an environmental concern. The deposition of drilling mud on corals first became an issue in the early 1970's when tracts were leased near a coral-capped salt dome known as the Texas Flower Gardens. Concern deepened in 1973 when tracts were leased and drilled on and near the Florida Middlegrounds, a coral-encrusted bedrock feature west of Tampa, Fla. The recent move to establish the Texas Flower Gardens as a national marine sanctuary has further stimulated environmental interest in the possible consequence of using drilling mud near corals.

Over the last few years, the environmental concerns have been the subject of research conducted by personnel of the Fisher Island Station, and the findings are presented below.

Toxicity of Drill Mud on Corals

Three years ago, Dr. Jack Thompson, then a Ph.D. candidate at Texas A&M University, performed experimental studies under the principal investigator to develop quantitative information on mud-coral interaction: Thompson (1979), Thompson and Bright (1980), and Thompson and others (1980). These experiments were conducted in the Fisher Island Station laboratories of USGS as well as offshore areas where numerous thriving coral reefs are found.

Seven species of corals were tested employing whole, used drilling mud (mud and cuttings) to determine the degree of exposure that corals can tolerate. The species chosen represent typical reef-building corals, some of which are also found at the Texas Flower Gardens.

The study concluded that of the seven species tested, concentrations of 476 mg/l suspended solids were required to kill three of the species during the 96-hr bioassay. Although behavioral effects were observed (such as polyp retraction), none of the seven species was killed at lower dosages of 150 and 11 mg/l. These findings raised the question, "At what distance from a drilling platform would these concentrations of suspended solids be found?" In addition, the question was posed, "Has drilling near a coral reef, such as at the Texas Flower Gardens, caused any negative effects on coral growth?" To answer the above questions, the principal investigator studied drill mud plumes from seven offshore platforms in the Gulf of Mexico and investigated past growth rates at the Flower Gardens Reef using a coral banding technique developed by Hudson and others in 1976.

Coral Banding in Florida and the Texas Flower Gardens

Hudson and Robbin (1980) conducted a two-part study to determine effects of drilling mud on the massive coral *Montastrea annularis*. The study involved determination of long-term effects on growth of this coral following short-term massive doses, and effects on the growth rate of the same species living at the Texas Flower Gardens Reef 200 km off the Texas coast, where drilling commenced nearby in 1975 (fig. 70).

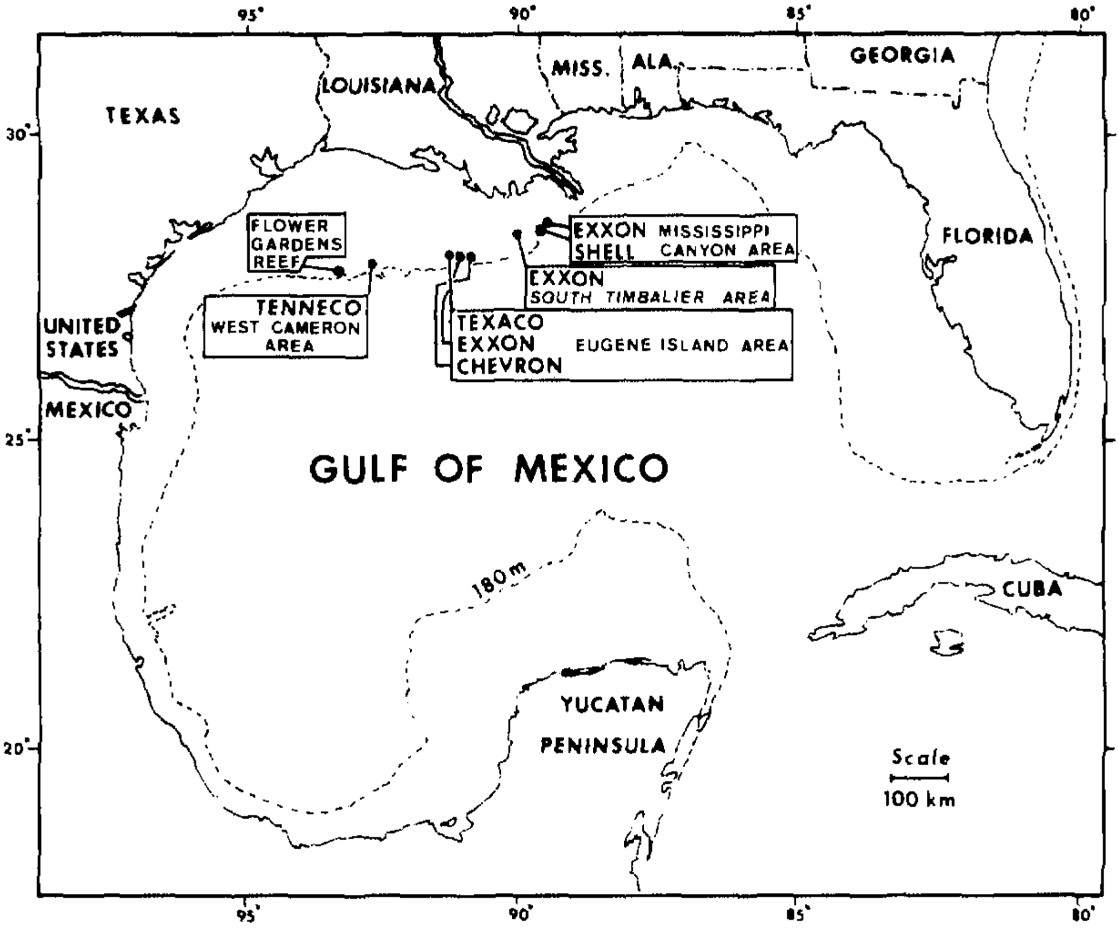


FIGURE 70.—Map of Gulf of Mexico showing location of *Flower Gardens Reef and offshore*

In the Florida study, performed in cooperation with a team of graduate students headed by Thomas Bright, live corals were dosed by divers four times every 2.5 hours. Drill mud was applied from a plastic bag in sufficient quantity to form a 2- to 4-mm-thick layer of mud over the living coral. Effects were monitored on a 24-hour basis using closed circuit underwater television and photography. All the corals removed the drill mud within 1 hour with the aid of normal wave surge. All specimens tested survived and were allowed to live on the reef for 6 months, at which time they were collected and examined in the laboratory. X-ray photographs of the coral, which contains tree-ringlike bands, showed that the growth rate associated with the period of heavy dosage was slightly reduced, even though barite (a common ingredient of drilling mud) was incorporated within the skeleton to levels as high as 1,200 ppm. Normal barite content is approximately 12 ppm.

The second phase of this study was conducted at the Texas Flower Gardens (fig. 71), where 12 large heads of *Montastrea annularis* in 20 m of water were core drilled. The cores were sliced and X-radiographs made to examine annual growth bands. Using this technique, measurements could be made of annual growth rates since 1900, as well as growth since 1975 when drilling commenced nearby. The location of wells drilled between 1974 and 1979 is shown in figure 71. In addition, sampling was possible of coral skeleton laid down during the period of drilling to analyze this material for barite and chromium. These analyses showed that (1) no change occurred in growth rate during the year drilling occurred, and (2) barite and chromium levels were no greater than those found in pre- and post-oil drilling coral bands.

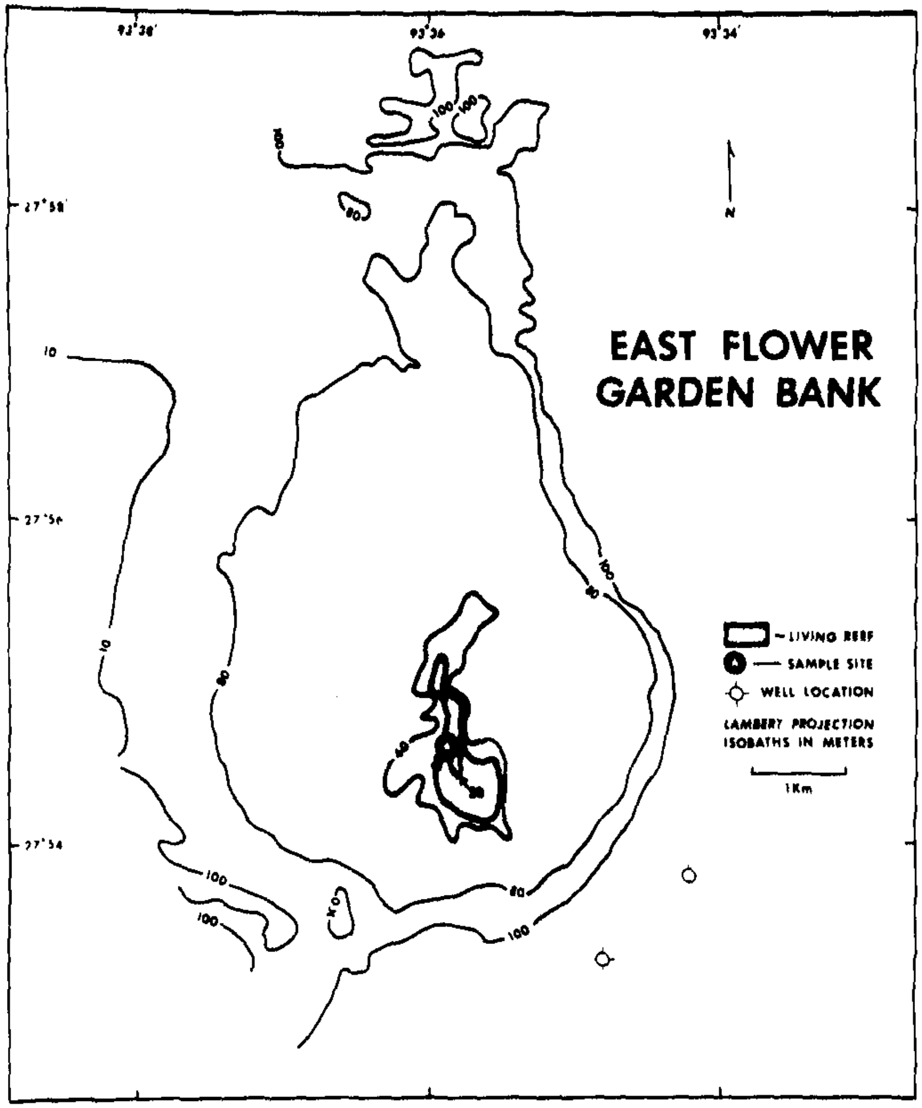


FIGURE 71.—Map of East Flower Garden Bank showing locations of living coral, sampling area, and nearby exploratory wells drilled between 1974 and 1979

Analysis of the growth bands did show, however, that a sudden reduction in growth rate had occurred in 1957, the reason for which is unknown. But Richard Rezak of Texas A&M University, who has been studying the reef under Bureau of Land Management (BLM) funding, suggested salt dome collapse. Rezak, in a personal communication to the principal investigator, pointed out that nearly all other salt domes in the areas contain grabens or down-faulted blocks on their crests, a phenomenon related to salt movement or dissolution. Further, an extensive brine seep near the base of East Flower Gardens Reef has been reported (Bright and others, 1980). Workers on a nearby Pennzoil platform have reported earth tremors that occassionally shake the platform (Rezak, personal communications to the principal investigator). The tremors are thought to be caused by minor faulting related to loss of salt from the dome beneath the coral reef. The reef possibly may have collapsed several meters in 1957 which lowered the corals to areas of lower light levels, thereby reducing the rate of growth. This hypothesis is supported by the observation that growth rates have never returned to pre-1957 levels (see fig. 72).

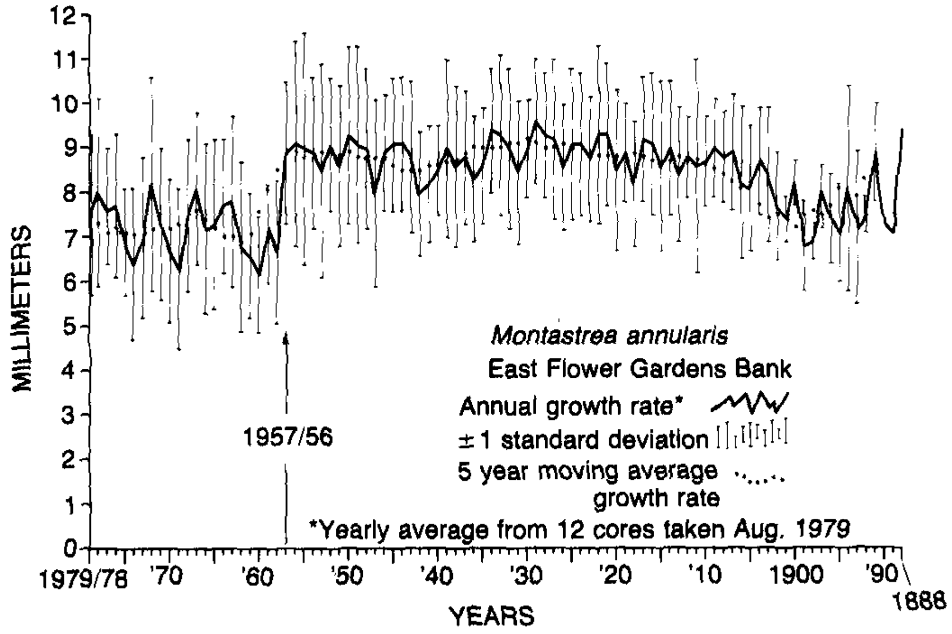


FIGURE 72.—Graph of average growth rate obtained from cases from 12 living corals

Drilling Mud Plume Study

To gain more insight into the concentration of suspended solids contained in drilling mud plumes, the principal investigator made a study of plumes from seven different platforms in the northern Gulf of Mexico. (See figure 70 for locations.) The study was conducted by attaching a line to or near the point of discharge. Water from the densest part of the near-horizontal plumes was collected in 10-liter bottles almost simultaneously from 1, 6, 12, 24, 48, and 96 m from the source. The collection operation, shown diagrammatically in figure 73, was usually accomplished in 30 minutes or less, often without attracting the operators' attention.

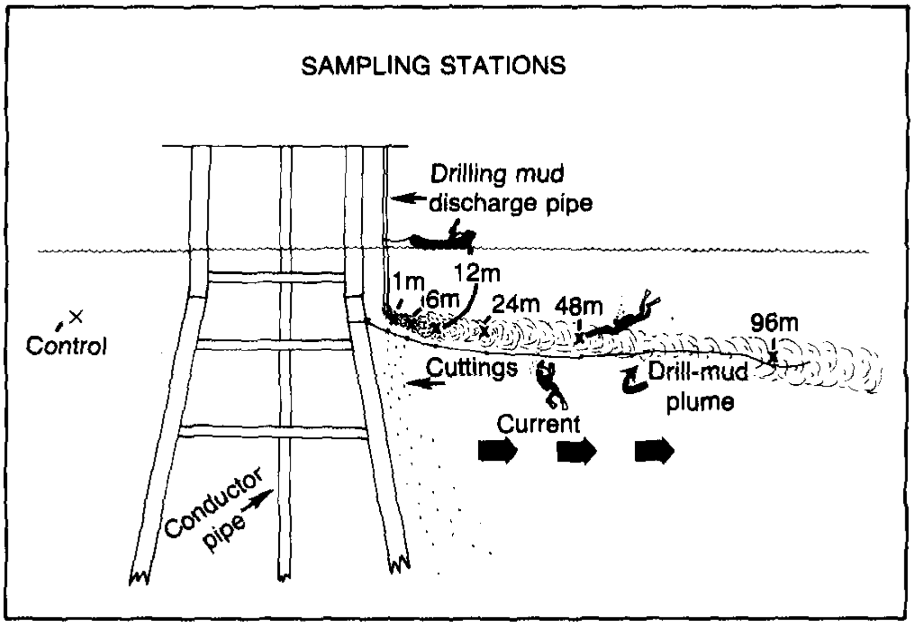


FIGURE 73.—Schematic drawing of plume sampling technique

Using air pressure, water samples were passed through a 0.4 mm pore size polycarbonate filter disk. The material filtered on the disk was later dried in the laboratory, weighed, and the amount expressed as mg/liter. The average concentration of suspended solids for six plumes is indicated by the bold line in figure 74. The dashed line shows concentration from the seventh platform, where the sampling intervals were slightly different.

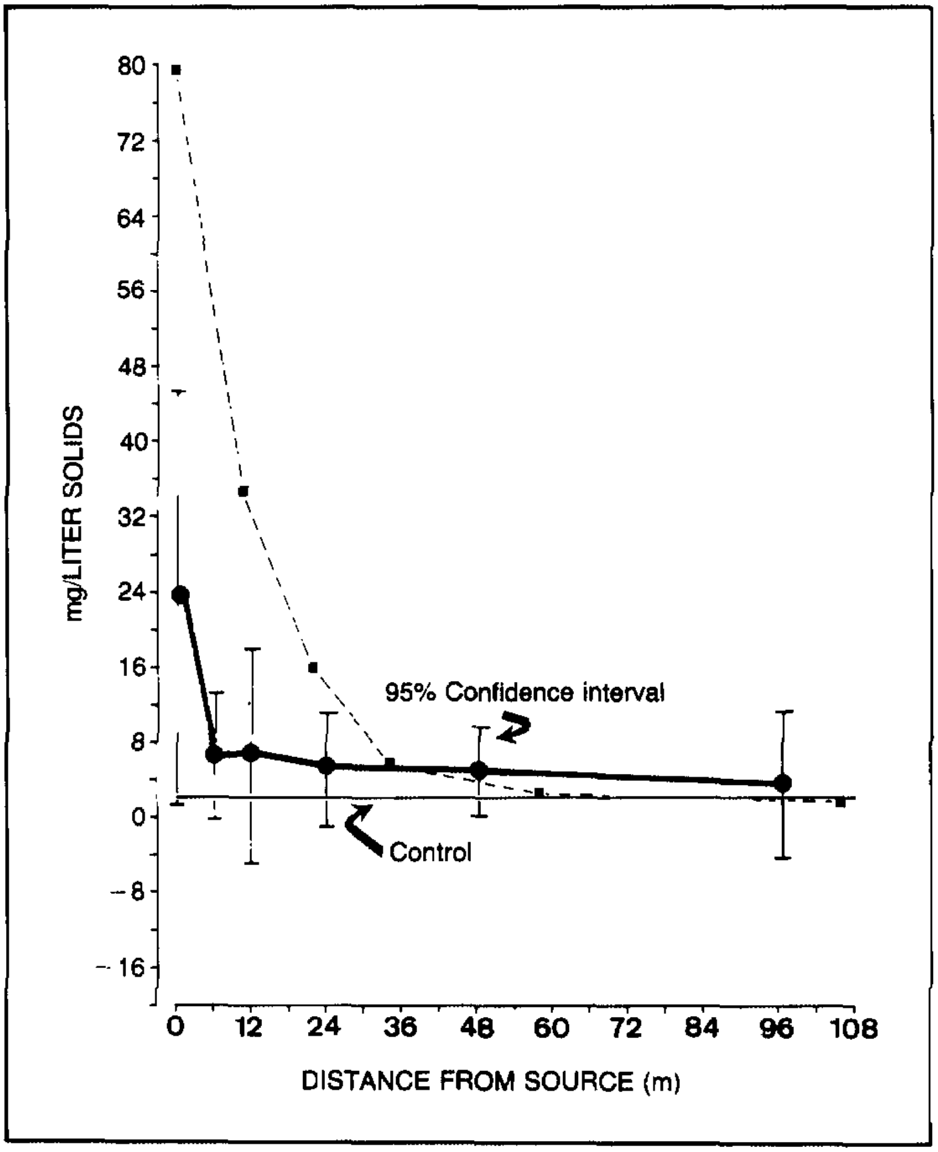


FIGURE 74.—Average of data from six separate plumes

The plumes examined were those that normally occur during exploratory drilling and such plumes may persist for several months, depending upon the time required to drill a well. Larger plumes occur several times during the drilling of a well when bulk discharges are necessary to remove sand from the mud pits or for other reasons. Such "dumps," which may involve more than 1,000 barrels, usually last 1 to 6 hours. Thus, the values reported in our study relate only to the chronic pollution resulting from exploratory drilling rather than from the more sudden, short-lived, high concentration bulk discharges.

The values shown in figure 74 should be compared with the concentrations used by Thompson, as well as those employed by others in bioassay studies. Apparently, most published studies have employed unrealistically high concentrations, and their results, therefore, may say little about effects in the real world. For example, note that the concentration found just 1 m from the discharge pipe was 80 mg/l and that the average was around 24 mg/l. Just 6 m from the source, the average value for six of the plumes was less than 8 mg/l. Between 48 and 96 m from the source, all seven plumes had been diluted to near background levels, even though the plumes could be seen to be continuing beyond for as much as 1,000 m.

Therefore, the average concentration just 1 m from the discharge pipe was approximately 14 times less than the concentration required to kill three of the seven species tested by Thompson and Bright (1980) and Thompson and others (1980). At 96 m from the source, the concentration was 132 times less than that required to cause coral mortality. Apparently, the plumes resulting from normal exploratory drilling should have a minor effect on coral growth, even within 100 m of source. Bulk discharging, however, might have a greater effect, but note that such dumps last only a few hours, and concentrations within 100 m of the source rarely approach the values that have been determined to kill corals in a 4-day test. Thus, even with high-concentration, short-lived dumps, the duration of impact may be too short to result in mortality, although growth rates might be temporarily reduced below normal. Corals 100 m from the source would unlikely experience the kind of extreme dosage that was experimentally applied in the study described by Hudson and Robbin (1980a). In addition, remember that coral reefs rarely grow in low-energy areas, where fine-grained drilling mud carbonate sand between coral heads is coarse due to frequent high energy, and drilling mud has not been able to accumulate there (Meyer and others, 1981).

A reasonable approach to more conclusive assessment to the effects of drilling on coral reefs would be to study areas where drilling has occurred directly on top of living coral reefs. Such areas exist in the Far East, such as the Samarang Field off Sarawak (Borneo) and the Nido and the Matinloc Fields near Palowan Island in the Philippines. Further studies will be made in such areas.

Reports and References

Bright, T. J., Powell, E. N., and Rezak, R., 1980, Environmental effects of a natural brine seep at the East Flower Garden Bank, northwestern Gulf of Mexico, *in* Geyer, R. A., ed., Marine Environmental Pollution, Hydrocarbons, v. 1, p. 292-316, Elsevier Scientific Pub. Co., Amsterdam.

Hudson, J. H., and Robbin, D. M., 1980a, Effects of drilling mud on the growth rate of the reef-building coral, Montastrea annularis, *in* Geyer, R. A., ed., Marine Environmental Pollution, Hydrocarbons, v. 1, p. 455-470, Elsevier Scientific Pub. Co., Amsterdam.

———, *1980b, effects of drilling mud on the growth rate of the reef-building coral*, Montastrea annularis: Research on Environmental Fate and Effects of Drilling Fluids, Lake Buena Vista, Fla., Proceedings, v. II, p. 1101-1119.

Meyer, D. B., Trefry, J. H., and Trocine, R. P., 1981, Geochemical assessment of the environmental impact of offshore drilling operations on the Texas Flower Gardens: Annual Mtg. of Florida Acad. of Sci., Abs., v. 44, suppl. 1, p. 44.

Shinn, E. A., Hudson, J. H., Robbin, D. M., and Lee, C. K., 1980, Drilling mud plumes from offshore drilling operations—implications for coral survival, *in* Geyer, R. A., ed., Marine Environmental Pollution, Hydrocarbons, V. 1, p. 471-496, Elsevier Scientific Pub. Co., Amsterdam.

Thompson, J. H., Jr., 1979, Effects of drilling mud on seven species of reef-building corals as measured in field and laboratory: Thesis, Texas A&M University, Department of Oceanography, College Station, Tex.

Thompson, J. H., and Bright, T. J., 1980, Effects of an offshore drilling fluid on selected corals: Research *on Environmental Fate and Effects of Drilling Fluids and Cuttings, Lake Buena Vista, Fla., Proceedings*, v. II, p. 1044-1076.

Thompson, J. H., Shinn, E. A., and Bright, T. J., 1980, Effects of drilling mud on seven species of reef-building corals as measured in the field and laboratory, *in* Geyer, R. A., ed., Marine Environmental Pollution, Hydrocarbons, v. 1, p. 443-453, Elsevier Scientific Pub. Co., Amsterdam.