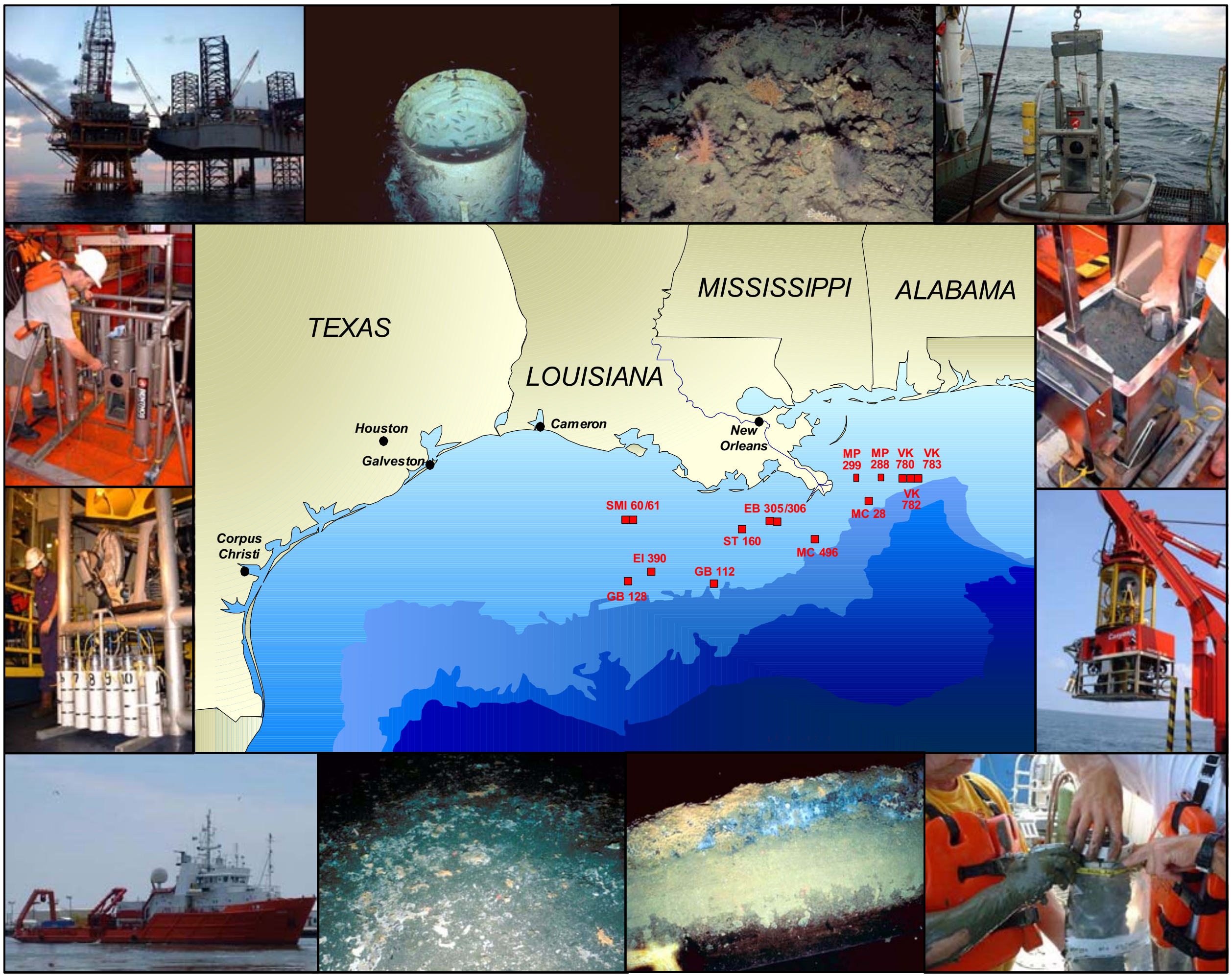
Final Report

GULF OF MEXICO COMPREHENSIVE SYNTHETIC BASED MUDS MONITORING PROGRAM

VOLUME I: TECHNICAL

October 2004



Prepared for

SBM Research Group

Submitted to

James P. Ray
Shell Global Solutions U.S.
Westhollow Technology Center
3333 Highway 6 South
Houston, Texas 77082
Telephone: (281) 544-6165

Prepared by

Continental Shelf Associates, Inc.
759 Parkway Street
Jupiter, Florida 33477
Telephone: (561) 746-7946

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TABLE OF CONTENTS

Page

VOLUME I: TECHNICAL

TABLE OF CONTENTS
(Continued)

Page

TABLE OF CONTENTS
(Continued)

Page

VOLUME II: TECHNICAL

TABLE OF CONTENTS
(Continued)

Page

TABLE OF CONTENTS
(Continued)

Page

TABLE OF CONTENTS
(Continued)

Page

VOLUME III: APPENDICES

TABLE OF CONTENTS
(Continued)

LIST OF TABLES

LIST OF TABLES
(Continued)

LIST OF TABLES
(Continued)

LIST OF TABLES
(Continued)

LIST OF TABLES
(Continued)

LIST OF TABLES
(Continued)

LIST OF TABLES
(Continued)

LIST OF TABLES
(Continued)

LIST OF TABLES
(Continued)

LIST OF FIGURES

LIST OF FIGURES
(Continued)

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LIST OF FIGURES
(Continued)

LIST OF FIGURES
(Continued)

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(Continued)

LIST OF FIGURES
(Continued)

LIST OF FIGURES
(Continued)

LIST OF PHOTOS

LIST OF PHOTOS
(Continued)

LIST OF PHOTOS
(Continued)

LIST OF ACRONYMS

AAS	atomic absorption spectrometry
ANOVA	analysis of variance
API	American Petroleum Institute
ASTM	American Society for Testing and Materials
BI	biotic index
BVA	Barry A. Vittor & Associates, Inc.
CAS	Columbia Analytical Services, Inc.
CC	Chesapeake Cultures
CL	clay
CNESS	chord-normalized expected species shared
CRM	certified reference material
CSA	Continental Shelf Associates, Inc.
CTD	conductivity/temperature/depth
CV	coefficient of variation
CVAAS	cold vapor atomic absorption spectrometry
DGPS	differential global positioning system
DISC	discretionary
DIW	deionized water
DO	dissolved oxygen
DP	dynamic positioning
DQO	data quality objective
EI	Eugene Island
ELG	Effluent Limitation Guideline
EW	Ewing Bank
FAAS	flame atomic absorption spectrometry
FF	far-field
FIT	Florida Institute of Technology
GB	Garden Banks
GC/MS	gas chromatography/mass spectrometry
GFAAS	graphite furnace atomic absorption spectrometry
GIS	geographic information system
HSD	Honest Significant Difference
IASPSO	International Association for the Physical Sciences of the Ocean
ICP-MS	inductively-coupled plasma-mass spectrometry
ID	internal diameter
IO	internal olefin
JCPDS	Joint Committee on Powder Diffraction Studies
KD	Kuderna-Danish
LAO	linear alpha olefin
LARS	launch and recovery system
LGL	LGL Ecological Research Associates, Inc.
LPIL	lowest practical identification level
LSA	logarithmic series alpha
MC	Mississippi Canyon
MDL	method detection limit
MDS	multidimensional scaling
MF	mid-field
MMS	Minerals Management Service

LIST OF ACRONYMS
(Continued)

MP	Main Pass
MS/MSD	matrix spike/matrix spike duplicate
MSL	Battelle Marine Sciences Laboratory
NAD	North American Datum
NADAS	navigation and data acquisition system
NESS	normalized expected species shared
NF	near-field
NIST	National Institute of Standards and Technology
NIVA	Norwegian Institute of Water Research
NOAA	National Oceanic and Atmospheric Administration
NPDES	National Pollutant Discharge Elimination System
NRC	National Research Council
OBM	oil based mud
OMZ	oxygen minimum zones
PAO	poly alpha olefin
PFTBA	perfluorotributylamine
QA/QC	quality assurance/quality control
RF	response factor
RIS	recovery internal standards
ROV	remotely operated vehicle
RPD	redox potential discontinuity
RSD	relative standard deviation
RTR	ratio-to-reference
SBF	synthetic based fluid
SBM	synthetic based mud
SD	standard deviation
SE	standard error
SICL	sitly clay
SIS	surrogate internal standards
SMI	South Marsh Island
SOP	standard operating procedure
SPI	sediment profile imaging
SRM	standard reference material
ST	South Timbalier
TMS	tether management system
TOC	total organic carbon
TPH	total petroleum hydrocarbons
USBL	ultra short base line
USDOI	U.S. Department of the Interior
USEPA	U.S. Environmental Protection Agency
UTM	Universal Transverse Mercator
UV	ultraviolet
VK	Viosca Knoll
WBM	water based mud

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REPORT ORGANIZATION

This report is organized into three volumes. The first volume consists of the Executive Summary, introductory chapters, and the synthesis of the project findings. Volume I is composed of the following:

	EXECUTIVE SUMMARY
Chapter 1	INTRODUCTION
Chapter 2	SITE SELECTION AND DESCRIPTION
Chapter 3	FIELD METHODOLOGY
Chapter 4	SYNTHESIS AND INTEGRATION
Chapter 5	REFERENCES*

The second volume consists of the technical support for the project findings. Volume II is composed of the following:

Chapter 6	GEOPHYSICAL DATA
Chapter 7	NANNOFOSSILS, SEDIMENTOLOGY, AND VISUAL CUTTINGS ANALYSIS
Chapter 8	THE ORGANIC CHEMISTRY OF SYNTHETIC BASED FLUID RESIDUES AND TOTAL PETROLEUM HYDROCARBONS IN SEDIMENTS
Chapter 9	METALS AND REDOX CHEMISTRY IN SEDIMENTS
Chapter 10	SEDIMENT TOXICITY
Chapter 11	SEDIMENT PROFILE IMAGING
Chapter 12	MACROINFAUNA
Chapter 13	REFERENCES*

Volume III contains the appendices. These are the following:

Appendix A	LOCATIONS OF SAMPLING SITES
Appendix B	HYDROGRAPHIC DATA FOR SAMPLING CRUISES 1 AND 2
Appendix C	ANALYTICAL RESULTS FOR NANNOFOSSIL ANALYSIS, GRAIN SIZE ANALYSIS, AND VISUAL CUTTINGS ANALYSIS FOR SAMPLING CRUISES 1 AND 2
Appendix D	TOTAL PETROLEUM HYDROCARBON AND SYNTHETIC BASED FLUID CONCENTRATIONS FOR SAMPLING CRUISES 1 AND 2
Appendix E	TRACE METAL, TOTAL ORGANIC CARBON, AND QUALITY ASSURANCE/QUALITY CONTROL DATA FOR THE SCREENING CRUISE AND SAMPLING CRUISES 1 AND 2; VERTICAL PROFILES FOR SEDIMENT CORES FOR CONCERNATIONS OF ALUMINUM, BARIUM, TOTAL ORGANIC CARBON, SYNTHETIC BASED FLUID, IRON, AND MANGANESE FOR SAMPLING CRUISES 1 AND 2; SEDIMENT PROFILE DATA (O_2, pH, and Eh) FOR SAMPLING CRUISES 1 AND 2; AND PORE WATER DATA FOR SAMPLING CRUISES 1 AND 2
Appendix F	SEDIMENT TOXICITY
Appendix G	SEDIMENT PROFILE IMAGE DATA
Appendix H	BENTHIC INFAUNAL DATA
Appendix I	PREVIOUS PROJECT REPORTS

* Chapters 5 and 13 contain all references cited in both Volumes I and II.

EXECUTIVE SUMMARY

The need to drill increasingly difficult deepwater and deviated wells, coupled with the economic and safety advantages of ocean discharge of cleaned cuttings, has led the offshore oil and gas industry to develop synthetic based drilling muds (SBMs). Synthetic based muds are drilling muds in which synthetic materials are the carrier fluid. They are designed to be less toxic and degrade faster in marine sediments than oil based drilling muds while providing similar technical advantages in drilling difficult wells.

The U.S. Environmental Protection Agency (USEPA) regulates discharges to water from offshore operations. In 1996, USEPA recognized SBMs as a new class of drilling muds and began reviewing cuttings treatment technologies and the environmental impacts of drill cuttings disposal options. The review provided input for the development of Effluent Limitation Guidelines (ELGs), which include technology-based limitations for the discharge of cuttings generated during drilling with SBMs. In addition to the requirements of the ELGs, a USEPA Region 6 National Pollutant Discharge Elimination System (NPDES) general permit requires operators to either conduct seabed surveys at each location where cuttings drilled with SBM are discharged or, alternatively, participate in a joint industry seabed survey study according to a plan submitted for approval to USEPA Region 6. The Gulf of Mexico Comprehensive Synthetic Based Muds Monitoring Program, documented in this report, meets the latter requirement. The study was sponsored by the SBM Research Group (composed of offshore operators and mud companies), the U.S. Department of Energy, and the Minerals Management Service. The objective of this study was to assess the fate and physical, chemical, and biological effects of SBM cuttings discharged from offshore platforms on the benthic environment of the Gulf of Mexico continental shelf and slope.

Four cruises were conducted during the project. Study sites were selected to ensure that all discharges of cuttings were completed prior to the cruises. A Scouting Cruise was performed in June 2000 to evaluate the suitability of ten candidate SBM cuttings discharge sites on the central Gulf of Mexico continental shelf. A Screening Cruise was conducted in August 2000, and geophysical data were collected at eight sites to evaluate the potential presence of substantial cuttings piles. Five of these sites were visited previously during the Scouting Cruise. The remaining three sites were located on the continental slope. Sediment samples were collected at each site and analyzed for a small number of physical, chemical, and biological parameters to document the presence and distribution of SBM cuttings accumulations on the bottom and evaluate the general characteristics of the benthic communities.

Eight sites were surveyed during Sampling Cruises 1 and 2 in May 2001 and May 2002, respectively. Four sites were located on the continental shelf in water depths from 37 to 119 m, and four were located on the continental slope in water depths from 338 to 556 m. Sediment sampling was performed in three zones around each discharge site: near-field (0 to 100 m from the discharge site), mid-field (100 to 250 m from the discharge site), and far-field reference (3,000 to 6,000 m from the discharge site). Surficial sediments were collected at each station for analysis of physical, chemical, and biological parameters. Benthic macroinfauna were counted and identified, and laboratory sediment toxicity tests were conducted on sediments collected at selected sites.

To address the objective of the program, four questions were investigated:

- What is the distribution of SBM cuttings in sediments around the drillsites?
- Are there changes over time in the distributions and concentrations of chemical components of SBM cuttings?
- What physical and chemical changes in sediments are attributable to SBM cuttings accumulations?
- What effects on the benthic community are attributable to SBM cuttings accumulations?

DISTRIBUTION AROUND DISCHARGE SITES

Evidence of drilling discharges was detected at all eight sites. Water based muds and cuttings and SBM cuttings were discharged at each site, and it was not possible to determine if the cuttings detected in the sediments were SBM cuttings. Physical evidence of cuttings in sediments depended primarily on the time since the last cuttings discharge at a site. Cuttings were visible in all near-field zones. Elevated concentrations of barium (Ba) (a tracer of drilling mud), the synthetic chemical (synthetic based fluid [SBF]), and total petroleum hydrocarbons (TPH) were detected in sediments from the near-field and mid-field zones at the sites; however, the distributions of the materials were patchy. Concentrations at far-field stations generally represented background levels. There was a sharp decrease in concentrations of cuttings and chemicals in sediments with distance from the discharge sites, which indicates that drill cuttings solids, especially from SBM cuttings, are deposited close to the discharge site. Most cuttings appeared to be deposited within 100 to 250 m of the discharge site at both continental shelf and continental slope water depths.

Near-field Ba concentrations at the sites were not related to the elapsed time since the last well was drilled or the total number of wells drilled, indicating that the main determinant of Ba concentrations in near-field sediments may be the local current regime and sediment transport. Based on Screening Cruise observations, near-field sediment concentrations of other metals associated with drilling muds were within the range of concentrations for uncontaminated marine sediments. Metals ratios indicated that much of the finer-grained sediments near platforms were from terrigenous (i.e., land-based) sources.

The differences between the concentrations of TPH and SBF in near-field sediments were greater than the differences in far-field sediments. This indicated that the near-field sediments contained hydrocarbons in addition to those counted as SBF, which were defined analytically as C_{16} to C_{18} range hydrocarbons. The presence of additional hydrocarbons not counted as SBF was attributed to factors such as variable concentrations of C_{20} range hydrocarbons in base fluids from different manufacturers, the presence of recent biogenic hydrocarbons in sediments, and changes in the gas-chromatographic fingerprint of sediment hydrocarbons as biodegradation progresses. Gas-chromatographic traces showed that the additional TPH in near-field sediments was not due to the presence of crude oil or petroleum distillate products.

TIME TRENDS

Concentrations of monitored components of SBM cuttings in sediments tended to decrease or return to background values with time after the last cuttings discharge (Figure ES-1). Possible mechanisms of decrease of SBF concentrations with time in surface sediments included microbial biodegradation (breaking down of materials by microorganisms) and burial by natural sediment deposition or bioturbation (reworking of sediments by marine organisms).

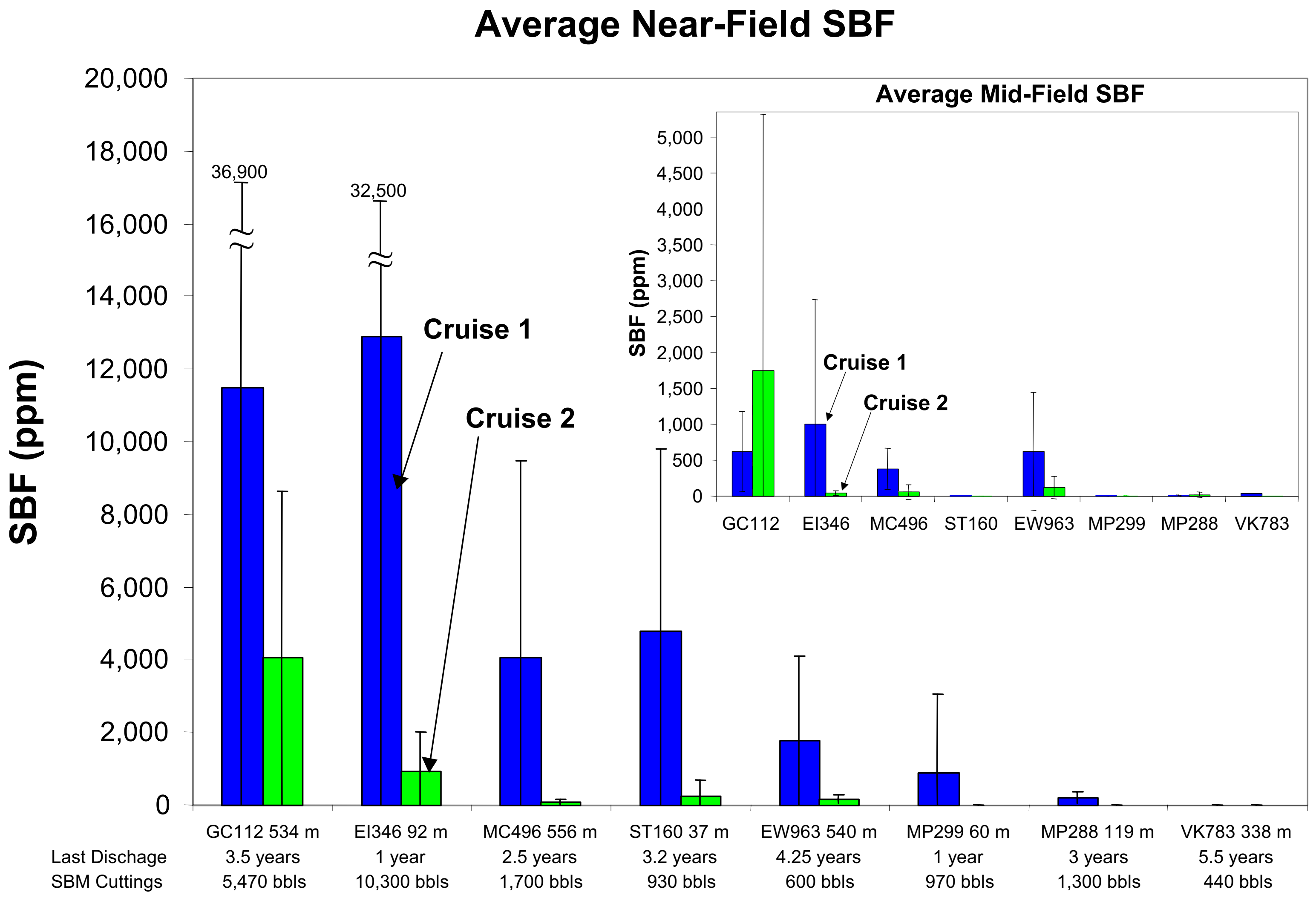


Figure ES-1. Average synthetic based fluid (SBF) base chemical concentrations at all sites for Sampling Cruise 1 (blue columns) and Sampling Cruise 2 (green columns). The error bars show one standard deviation of the measurements at a site and zone.

PHYSICAL AND CHEMICAL DISTURBANCE

A combination of visual, geophysical, and chemical/physical measurements at a total of 15 discharge locations in the Gulf of Mexico indicated that SBM cuttings do not accumulate in large piles, as has been observed in the North Sea for discharges of oil based drilling muds and cuttings. This is reasonable because the North Sea generally has larger reservoirs with many more wells drilled at a single location, compared to the Gulf of Mexico where there are smaller reservoirs with fewer wells at single site. Also, discharges in the North Sea often were shunted to near the seabed, while discharges in the Gulf of Mexico occur near the sea surface at most sites, providing for greater water column dispersion and broader distribution on the seabed.

In general, there was more sand in near-field sediments than in mid-field sediments, and far-field sediments generally contained the least sand and most fine-grained sediments, suggesting that drill cutting solids were deposited in the near-field zone and, to a lesser extent, in the mid-field zone. In general, grain-size distributions were more variable at the continental shelf sites than at the continental slope sites.

Measurements of oxygen, total organic carbon, reduction/oxidation potential, and manganese in sediments, signs of possible SBM cuttings-related organic enrichment, indicated such enrichment near the discharge locations. There was evidence of recovery or decrease over time in the severity of disturbance in the sediments near the discharge locations during the year between the two Sampling Cruises.

BIOLOGICAL DISTURBANCES

Sediment toxicity, which was determined in the laboratory using a standard compliance sediment bioassay utilizing survival of a non-indigenous, coastal benthic amphipod, *Leptocheirus plumulosus,* was restricted to a few locations near the drilling discharges; most of the sediments in the near-field and mid-field (<250 m) were not toxic. Amphipod survival exceeded 75% in all far-field samples at continental shelf and continental slope sites, and therefore these sediment samples were not considered toxic. Of the samples collected within 250 m of the continental shelf and continental slope discharge locations, 73% and 56%, respectively, had amphipod survival exceeding 75% and were considered not toxic. At sites where multiple samples had survival less than 50%, sediment toxicity and SBF concentration were correlated. Changes in sediment chemical composition or physical properties due to cutting deposition were probably responsible for most of the toxicity.

There were substantial differences in the benthic communities at the three sites examined. However, the communities of organisms observed at different zones within a given site were generally similar. At two of the three sites examined, the abundance of organisms in different zones was similar. At the site with the highest SBF concentrations of the three biological study sites, the abundance and diversity of the benthic community were reduced within 250 m of the site center. There was evidence of recovery in the time between the two Sampling Cruises at this site. Near- and mid-field sediments at the other two sites (with lower SBF concentrations) had only moderately disturbed benthic community structure, compared to the corresponding far-field samples. Variability of all benthic community parameters such as diversity and evenness was greatest in the near-field zone and generally much lower in the far-field zone. In the near-field zone, this variability was probably due to variations in sediment textures and patchy distributions of cuttings.

For the three sites where sediment chemistry, benthic faunal community structure, and sediment toxicity were measured, a sediment quality triad analysis was performed to develop an integrated assessment of drill site sediment conditions. This analysis clearly showed reduced sediment quality in the near-field compared to the mid-field. However, the triad analysis showed clear evidence of recovery over the 1-year period between the Sampling Cruises. At two of the three sites analyzed, minimal changes in ecological parameters used in the triad analysis suggested that the habitat quality of the sediments had not been seriously degraded by a long history of discharges at those sites.

In summary, this study was conducted with a diverse set of approaches to assess the fate and effects of discharged SBM cuttings at continental shelf and continental slope sites in the Gulf of Mexico. Key findings of the study are

- no large, multi-meter thick cuttings piles, such as those seen in the North Sea, were detected at any of the 15 sites visited in this study;
- discharges were deposited in a patchy distribution limited to the vicinity of the discharge location (<250 m);
- in general, sediment quality and biological communities were not severely affected, and impacts were limited to the vicinity of the discharge (<250 m); and
- where impacts were observed, progress toward physical, chemical, and biological recovery appeared to occur during the 1-year period between the two Sampling Cruises.

Chapter 1
INTRODUCTION

Alan D. Hart
Continental Shelf Associates, Inc.
and
Jerry M. Neff
Battelle Memorial Institute

Since the mid-1970's, the U.S. Environmental Protection Agency (USEPA) has expressed concern about the possible adverse environmental effects of discharging used water based drilling muds (WBMs) and drill cuttings to the ocean. In response to these concerns, the oil and gas industry and government agencies, particularly the Minerals Management Service (MMS), have funded research and monitoring studies in an effort to determine the environmental effects of ocean discharges of WBMs and cuttings. In general, the findings of these studies have shown that WBMs and cuttings have minimal and short-lived effects, most of which are on organisms living on the bottom where the cuttings accumulate and some drilling mud solids settle. Oil based muds (OBMs) have been used to deal with difficult down-hole problems during well drilling. In the U.S., these muds and associated cuttings are not permitted for offshore disposal. Most domestic offshore drilling is performed with WBMs, and OBMs are used only in conditions where WBMs are inadequate. Situations that require usage of non-aqueous fluids include

- water sensitive formations;
- wells drilled to depths where heat and pressure would degrade the performance of WBMs; and
- deviated wells requiring greater drilling fluid lubricity.

In the last decade, a variety of synthetic based drilling muds (SBMs) have been developed in an effort to provide the oil and gas industry with an environmentally acceptable alternative to OBMs. These SBMs are distinguished by the use of a synthetic based fluid (SBF) instead of water or oil. This SBF may be a hydrocarbon, ether, ester, or acetal. Synthetic hydrocarbons include normal paraffins, linear alpha olefins (LAOs), poly alpha olefins (PAOs), and internal olefins (IOs). The goal of these formulations is to offer excellent operational qualities (e.g., high lubricity, low reactivity, etc.) with the added benefits of low toxicity and environmental impact (e.g., Candler et al., 1993; Park et al., 1993; Burke and Veil, 1995; Friedheim and Conn, 1996; Veil et al., 1996; Churan et al., 1997). These muds generally are considered readily biodegradable and have a low aquatic toxicity. Perhaps the most important feature of the SBMs is that they are prepared synthetically and as such are well characterized and free from substantial impurities. The different organic liquid phases of SBMs actually are composed of several congeners of the particular SBF organic compound type with different chain lengths, and possibly branching and positions of double bonds. Unlike crude and refined petroleum—which are extremely complex, multicomponent mixtures—SBFs are simple (in terms of composition) and their compositions can be predicted based on the synthesis scheme used by the manufacturer. Because SBFs have low toxicity and high biodegradability, cuttings generated with SBMs have been permitted for offshore discharge. Since 2002, the concentrations of SBF adhering to the cuttings have been limited to 6.9% and 9.4% for IO and ester based mud systems, respectively (USEPA, 2001a).

1.1 STUDY OBJECTIVES

The Gulf of Mexico Comprehensive Synthetic Based Muds Monitoring Program was carried out in response to a permit requirement for dischargers of cuttings drilled with SBM to 1) conduct seabed surveys at each location where cuttings drilled with SBM are discharged or 2) participate in a joint industry seabed survey study according to a plan approved by USEPA Region 6 (USEPA, 2001c). This study was funded by a consortium known as the SBM Research Group (which is composed of offshore operators and mud companies), the U.S. Department of Energy, and the MMS.

The program had an overall objective of assessing the fate and effects (physical, chemical, and biological) of discharged cuttings drilled with SBM ("SBM cuttings") at continental shelf (<300 m depth) and continental slope (>300 m depth) Gulf of Mexico sites. The results of this assessment will provide

- USEPA with scientific data upon which to base effluent limitations for the discharge of SBM cuttings; and
- the oil and gas industry with scientifically valid data for the environmental assessment of the discharge of SBM cuttings.

There are four specific subobjectives for the study:

1) determine the thickness and areal extent of SBM cuttings accumulations on the seafloor and the magnitude of SBF concentrations in sediments near discharge sites representative of Gulf of Mexico conditions at both continental shelf (<300 m depth) and continental slope (>300 m depth) discharge sites;

2) determine the temporal behavior of SBM base fluid concentrations in sediments near discharge sites representative of Gulf of Mexico conditions at both continental shelf (<300 m depth) and continental slope (>300 m depth) discharge sites;

3) document the physical-chemical conditions in sediments in areas where SBM base fluids are present and compare these conditions with conditions in reference sediments distant from SBM cuttings discharges; and

4) determine whether a zone of biological effect has developed related to the discharge of SBM cuttings, and if detectable, determine its dimensions.

1.2 BACKGROUND

1.2.1 Offshore Drilling with SBMs in the Gulf of Mexico

SBMs were first developed as environmentally acceptable replacements for OBMs in the North Sea. The first offshore use of an SBM was in the Norwegian Sector of the North Sea in 1990, followed by wells drilled with SBMs in the United Kingdom Sector in 1991 and in the Gulf of Mexico in 1992 (Friedheim and Conn, 1996; Fechhelm et al., 1999). By 1994, more than 170 wells had been drilled in the North Sea with SBMs (Friedheim, 1994). Approximately 20% of the wells drilled in Federal waters of the Gulf of Mexico in the mid- to late 1990's were drilled with an SBM (Meinhold, 1999). Nearly all the other wells in the Gulf were drilled with WBMs. As exploratory and development drilling in the Gulf of Mexico has moved to deep water (>1,000 ft or 300 m), use of SBMs has increased. By 1999, about 75% of all wells drilled in deep water in the Gulf of Mexico were drilled at least in part with SBMs (USEPA, 1999). The percentage is expected to rise to 90% in the near future. During the last few years, between 500 and 800 wells have been drilled with SBMs in the Gulf of Mexico.

During the years 2000 to 2007, between 170 and 275 wells per year have been or will be drilled in deep water in the Gulf of Mexico (U.S. Department of the Interior [USDOI], MMS, 2000). Deepwater wells usually are drilled with a combination of drilling muds. Typically, WBMs are used for the upper portions of a well, with a changeover to an SBM below the 16-in. or 13-in. casing points at a depth below the seafloor of 2,000 m or more. Returns of WBMs and cuttings from the upper portion of the well often are discharged directly to the seafloor before the casing is set and the riser is installed. SBMs are returned to the platform for cleaning (removal of cuttings) and recycling into the drilling operation. The removed SBM cuttings may be discharged to the ocean from the platform.

1.2.2 Composition of SBMs

Drilling muds are an essential component of the rotary drilling process used to drill for oil and gas on land and in offshore environments. The most important functions of drilling fluids are to transport cuttings to the surface, balance subsurface and formation pressures preventing a blowout, and cool, lubricate, and support part of the weight of the drill bit and drill pipe. National Pollutant Discharge Elimination System (NPDES) permits allow bulk discharges of WBMs, but not SBMs, to Federal waters of the Gulf of Mexico (USEPA, 1999).

Drill cuttings are particles of crushed rock produced by the grinding action of the drill bit as it penetrates into the earth. Drill cuttings range in size from clay-sized particles to coarse gravel and have an angular configuration. Their chemistry and mineralogy reflect that of the geologic strata being penetrated by the drill. Drill cuttings contain small amounts of liquid and solid drilling mud components, in addition to formation solids. Current NPDES permits allow discharge of cuttings produced with WBMs or SBMs but not with OBMs (USEPA, 1999). Prior to the implementation of the current Effluent Limitation Guidelines (ELGs), SBM cuttings discharged into the Gulf of Mexico contained an average of 12 ± 4.8 weight percent adhering SBF (Annis, 1997).

The base fluid or continuous phase of an SBM is a water-insoluble synthetic organic chemical. SBMs also contain barite, clays, emulsifiers, water, calcium chloride ($CaCl_2$), lignite, and lime. Water or a saline brine (usually containing $CaCl_2$), at a concentration of 10% to 50%, is dispersed into the synthetic chemical phase to form a water-in-organic phase emulsion with water droplets less than 1 µm in diameter (Hudgins, 1991; Norwegian Oil Industry Association Working Group, 1996). This emulsion is called an invert emulsion because water is dispersed in the organic phase, and formation solids that come in contact with the non-aqueous based fluids become oil-wet.

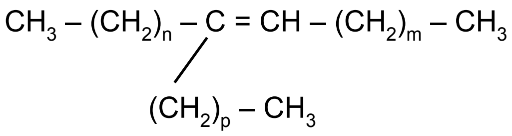
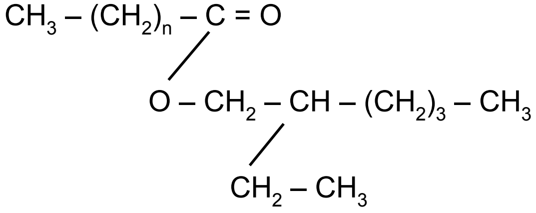
Polymerized olefins are used most frequently today in the Gulf of Mexico as SBFs in SBMs. Polymerized olefins include LAOs, PAOs, and IOs (Friedheim and Conn, 1996). Esters, the first type of SBM used offshore, were used frequently in the past. IOs and LAOs are used most frequently today for drilling in deep waters of the Gulf of Mexico. PAOs and esters were used frequently in the past but rarely are used today (Neff et al., 2000). Six of the eight platforms monitored in this study had wells drilled with IO SBMs; for the two remaining platforms, LAO SBM and ester SBM were used at one site each.

LAOs are produced by polymerization of ethylene. Each LAO molecule has a single double bond in the alpha position (between the first and second carbon in the chain) (Table 1-1). LAOs have molecular weights of 112 (C_8H_{16}) to 260 ($C_{20}H_{40}$) and are practically insoluble in water. Typical LAO mixtures used in SBMs are LAO C_{14}/C_{16} (a blend of $C_{14}H_{28}$ and $C_{16}H_{32}$ LAOs) and LAO C_{16}/C_{18}. In a typical LAO, about 28% of the molecules contain branches; most branches are methyl groups ($-CH_3$) (Rabke et al., 1998).

PAOs are manufactured by oligomerization of LAOs (Friedheim and Conn, 1996). Depending on the chain length of the LAOs and the nature of the oligomerization reactions, PAOs can be produced with varying degrees of branching and carbon chain lengths (Lee, 1998). In a typical PAO SBM, more than 90% of the molecules have branches (Rabke et al., 1998). The PAO fluid may contain a mixture of several PAOs from C_8H_{16} to $C_{30}H_{62}$ and sometimes to $C_{40}H_{82}$ (Vik et al., 1996a; Rabke et al., 1998). The average PAO is $C_{20}H_{42}$, with a molecular weight of 282.6 and an aqueous solubility less than 1 µg/L.

IOs are formed by isomerization of LAOs in the presence of heat and a suitable catalyst. Isomerization shifts the double bond from the alpha position to a position between two internal carbons (Friedheim and Conn, 1996; Lee, 1998) (Table 1-1). Commercial IOs usually have a chain length of 16 ($C_{16}H_{32}$) or 18 ($C_{18}H_{36}$) carbons and usually contain more than 20% internal branching (Vik et al., 1996a; Rabke et al., 1998). LAOs and IOs often are used in blends, designed to achieve a balance among the physical properties important to the drilling operation (e.g., viscosity, pour point, flash point, etc.).

Table 1-1. Names and chemical structures of several synthetic based chemicals of the types used in the Gulf of Mexico (From: Neff et al., 2000).

Type	Chemical Structure
Synthetic Hydrocarbons	
Linear Alpha Olefin (LAO)	$CH_3 - (CH_2)_n - CH = CH_2$
Poly Alpha Olefin (PAO)	 $CH_3 - (CH_2)_n - C = CH - (CH_2)_m - CH_3$ $(CH_2)_p - CH_3$
Internal Olefin (IO)	$CH_3 - (CH_2)_m - CH = CH - (CH_2)_n - CH_3$
Other Synthetic Based Chemicals	
Ester	 $CH_3 - (CH_2)_n - C = O$ $O - CH_2 - CH - (CH_2)_3 - CH_3$ $CH_2 - CH_3$

Esters are formed by the reaction of a carboxylic acid with an alcohol under acidic conditions (Norman, 1997). The ingredients of esters used in SBMs include fatty acids (carboxylic acids) with 8 to 24 carbons and alcohols with different chain lengths. The alcohol used most frequently for ester SBM muds used in the Gulf of Mexico is 2-ethylhexanol ($C_8H_{18}O$, molecular weight 130.2). The fatty acids usually are derived from natural vegetable or fish oils. They also can be made by oxidation of the terminal double bond of LAOs (Friedheim and Pantermuehl, 1993). An example of an ester used in SBMs is a mixture of C_8 through C_{14} fatty acids esterified with 2-ethylhexanol. The original Petrofree SBM system consisted of a mixture of five homologous fatty acid esters, of which the main component was 2-ethylhexyl dodecanoate (Schaanning et al., 1996). A typical ester has a molecular weight of 396.4 and the chemical formula $C_{26}H_{52}O_2$ (Vik et al., 1996a). Esters are somewhat polar and so are somewhat more water-soluble than other SBFs of comparable molecular weights. Chain length and branching of the fatty acids and alcohol can be modified to optimize viscosity, pour point, and hydrolytic stability (Friedheim and Pantermuehl, 1993; Norman, 1997). Esters also may be mixed with synthetic hydrocarbons (LAO, PAO, or IO) in an SBM to attain some particular drilling performance characteristic.

The SBM base chemical usually constitutes about 50% to 90% by volume of the fluid portion of the SBM (Rushing et al., 1991) and about 20% to 40% of the mass of the mud (Kenny, 1993). The major ingredients are similar for all SBM systems (Figure 1-1). All SBM systems contain emulsifiers, wetting agents, thinners, weighting agents, and gelling agents. Relative proportions of the different ingredients vary depending on the SBM type and the chemistry, geology, and depth of the formation being drilled.

Water (usually in the form of a concentrated $CaCl_2$ brine) is emulsified in the SBM base material. The synthetic/water volume ratio is varied in response to down-hole conditions and usually ranges from 55/45 to perhaps as high as 96/4 (McKee et al., 1995; Friedheim and Patel, 1999); a typical synthetic base chemical/water volume ratio is 70/30 (Rushing et al., 1991). The brine promotes dehydration of shales in the formation being drilled. It is dispersed in the oil phase to form an inverted emulsion (a water-in-SBM emulsion). The solids in the SBM, including formation solids (cuttings), are “SBM-wet.”

Emulsifiers, which often are metal soaps of fatty acids, are added to the SBMs to aid in forming and maintaining the inverted emulsion. Wetting agents are added to ensure that the solids in the muds are SBM-wet. Wetting agents include polyamines, fatty acids, and oxidized tall oils. Lime is added to make calcium soaps that aid in emulsification of water in the SBMs. Rheology modifiers and organophilic clays are added to aid in suspending drill cuttings in the mud.

Barite (barium sulfate) is used to increase the density of the drilling mud, counteracting formation pressure, which prevents a blowout. The amount of barite added to the mud usually increases as the depth of the well increases and formation pressure increases. A typical 11.5 lb/gal. (1,378 kg/m^3) SBM may contain about 230 lb/barrel (bbl) (660 kg/m^3) barite (Friedheim and Patel, 1999). Barite has an extremely low solubility in seawater and so is used frequently as a conservative tracer of the dispersion and fate of discharged drilling fluids (Hartley, 1996).

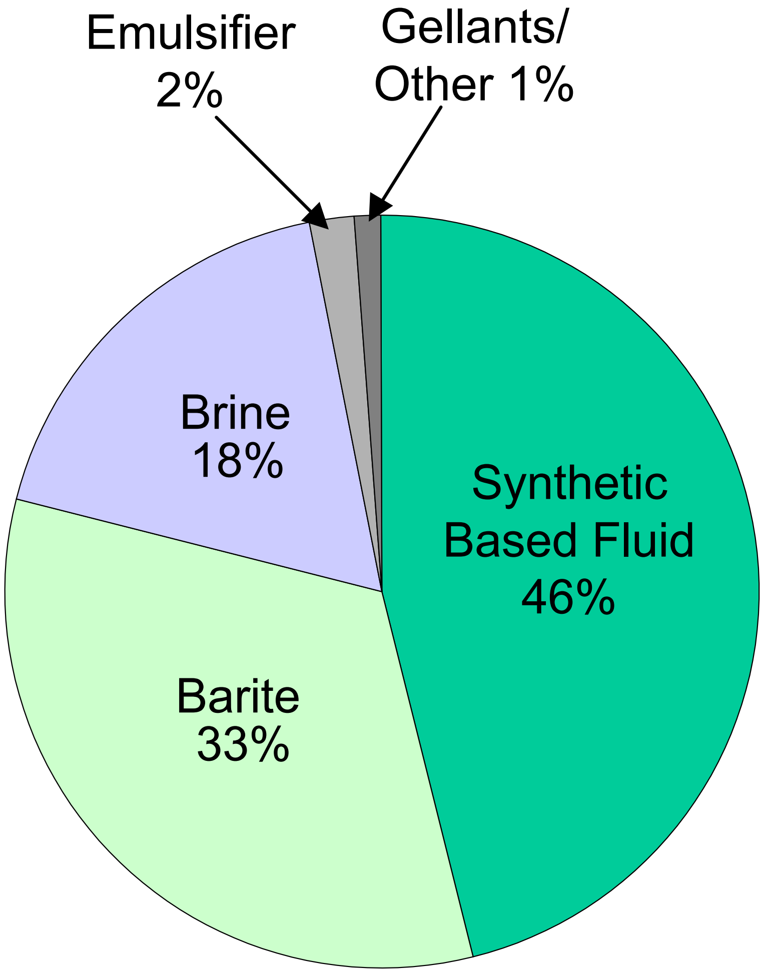


Figure 1-1. Example of synthetic based mud composition. Contributions of constituents are shown on a weight percentage basis.

Several metals are present in WBMs, OBMs, and SBMs. Most metals are present in drilling muds and cuttings at concentrations similar to those in uncontaminated marine sediments. However, a few metals may be present in some drilling muds at concentrations substantially higher (>100-fold) than natural concentrations in sediments; these include barium, chromium, lead, and zinc (Table 1-2). Most of the chromium is associated with chrome and ferrochrome lignosulfonates, used frequently in the past as a clay deflocculent in WBMs. The other metals are associated with dispersed cuttings and the solid additives (barite and clays), not the continuous phase (water, oil, or synthetic), in drilling muds. Metals concentrations in whole WBMs and OBMs are roughly similar (Table 1-2), depending mainly on the quality of barite and clays used to formulate the muds. No data are available for the metals concentration in SBMs, but concentrations should be similar to those in OBMs. Aluminum and barium in drilling muds are from clays and barite, respectively. Most of the metals detected in drilling muds and cuttings are present primarily as trace impurities in barite, bentonite clay, or sedimentary rocks (drill cuttings). Most of these trace metals in barite and drill cuttings are primarily in the form of insoluble sulfide salts (Kramer et al., 1980; Leuterman et al., 1997; Wilhelm, 2001). These metal sulfides have a limited mobility in the environment and low bioavailability to marine plants and animals. Metals associated with drilling muds or formation clays may be adsorbed to the clay surface or incorporated in the aluminosilicate lattice. The adsorbed metals are exchangeable, but those in the clay lattice are not. The ELGs set an upper limit on the concentrations of mercury and cadmium in drilling mud barite of 1 mg/kg and 3 mg/kg, respectively. The ELGs were set to control concentrations of these metals and indirectly control concentrations of other metals in drilling muds. The USEPA has included these ELGS in the current NPDES permits for the Gulf of Mexico.

Table 1-2. Comparison of the concentrations of metals in water based drilling muds and a typical oil based drilling mud (From: Fillio et al., 1987; Neff et al., 1987). Concentrations are mg/kg dry wt (ppm).

Metal	Water Based Mud	Oil Based Mud
Aluminum	10,800	52,000
Barium	720 – 449,000	487,000
Cadmium	0.16 – 54.4	0.39 – 12
Chromium	0.1 – 5,960	190 – 1,350
Iron	0.002 – 27,000	76,300
Lead	0.4 – 4,226	100 – 290
Mercury	0.017 – 10.4	Not Reported
Zinc	0.06 – 12,270	160 – 2,100

SBM base materials are synthesized in such a way as to avoid inclusion of aromatic hydrocarbons. This was done because aromatic hydrocarbons are considered to be major contributors to the toxicity of WBMs and OBMs (Neff et al., 1987; Kingston, 1992). Because the base materials do not contain aromatic hydrocarbons, the complete SBM systems usually do not contain aromatic hydrocarbons (Meinhold, 1999). However, crude oil may contaminate the mud, introducing aromatic hydrocarbons, when drilling through hydrocarbon-bearing formations. SBM cuttings may not be discharged if they contain free oil, as determined by both static sheen and reverse phase extraction tests.

1.2.3 Discharge Practices for SBMs in the Gulf of Mexico

Current NPDES permits for the Gulf of Mexico allow discharge to Federal waters of SBM cuttings if they meet regulatory effluent limits. The permits do not allow ocean discharge of bulk SBMs.

SBM containing cuttings is passed through shale shaker screens to remove coarse cuttings and then is sent to cuttings dryers for final processing prior to discharge (Figure 1-2). The cuttings, containing small amounts of adhering drilling mud solids, may be discharged to the ocean through a discharge pipe opening just above or below the sea surface. Occasionally, MMS requires that the cuttings be shunted to just above the bottom for disposal in order to protect critical habitats that are at shallower depths.

In the Gulf of Mexico, most SBMs are processed through two or more shale shakers with different mesh size screens; cuttings dryers often are used to remove additional fine-grained cuttings. Even after processing, cuttings discharged to the ocean contain small amounts of adhering SBM. This is the route by which SBMs reach the ocean.

The amount of SBM retained on cuttings following processing by current technology is highly variable. It depends on the grain size of the cuttings particles, the type of SBM, the efficiency of the cuttings processing equipment, and geologic characteristics of the formation being drilled (Annis, 1997). As a general rule, if comparable cuttings-cleaning equipment is being used, the amount of SBM adhering to cuttings increases as cuttings particle size decreases and SBM viscosity increases.

Several studies have been performed on the concentration of SBMs or WBMs on processed cuttings discharged to the ocean. Annis (1997) evaluated 738 SBM cuttings samples and reported that the average retention of synthetic base material on cuttings was 12.0 ± 4.8 weight percent, with the processing technology available in the mid-1990's. Cuttings dryers have been developed recently that allow operators to process cuttings to meet USEPA concentration limits for SBM on cuttings of 6.9% for IO and 9.4% for esters.

1.2.4 Fate of SBM Cuttings Discharges to the Continental Shelf and Slope of the Gulf of Mexico

When discharged to the ocean, SBM cuttings containing more than about 5% adhering SBM solids tend to clump together in discrete masses that settle rapidly to the bottom (Brandsma, 1996; Delvigne, 1996). Water cannot easily penetrate the hydrophobic mass of cuttings, so the cuttings do not disperse efficiently.

Growcock et al. (1994) estimated the dispersibility of several SBMs by mixing an SBM sample with seawater and allowing the solids to settle for 10 minutes before measuring organic matter (representing the SBM base chemical) in the aqueous phase. The relative dispersibility of different drilling mud systems, measured this way, was as follows:

> Ester > Di-Ether > Linear Alkyl Benzene > PAO > Low Toxicity Mineral Oil

This order of decreasing dispersibility correlates fairly well with increasing hydrophobicity of the organic phase of the muds, as indicated by estimated average log octanol/water partition coefficients (log K_{ow}). IOs and LAOs, the most commonly used synthetics in the Gulf of Mexico today, should lie between esters and PAOs in dispersibility.

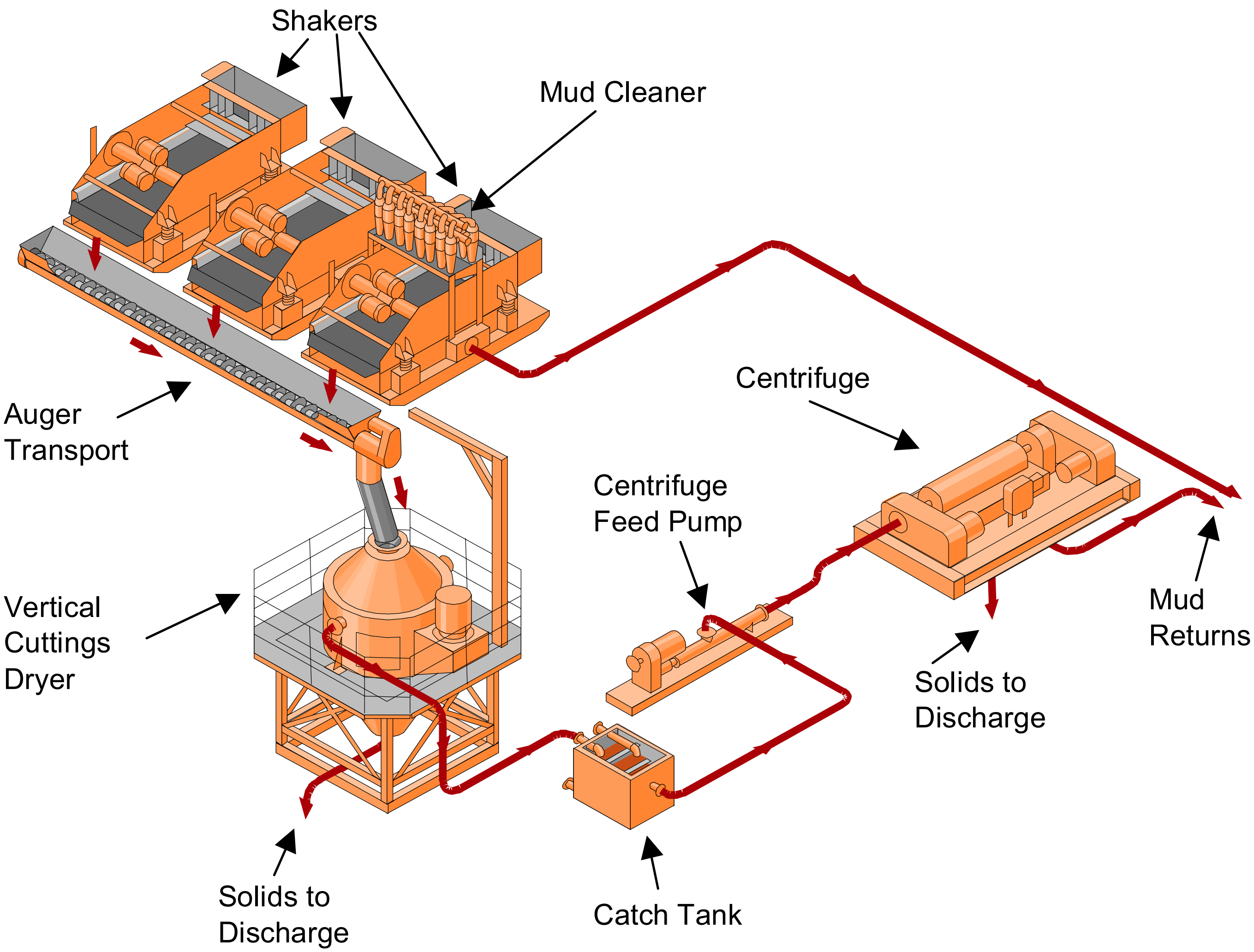


Figure 1-2. Solids control system used for drilling with synthetic based mud. (Figure used with permission of M-I, L.L.C., a Smith/Schlumberger Company.)

Getliff et al. (1997) reported that low viscosity SBMs, such as LAO SBMs, allow better separation of the drilling fluid from the cuttings on the shale shaker screens than can be accomplished with high viscosity muds. Cuttings with low concentrations of adhering SBM have a lesser tendency than cuttings containing high concentrations of SBM to clump, and dispersion is greater as the SBM cuttings settle through the water column. When cuttings containing 5% LAO or less (measured by retort analysis) were discharged from a platform in the Amoco Arkwright Field in the North Sea, they dispersed in the water column and no cuttings pile accumulated on the bottom.

Thus, SBMs, particularly esters and low viscosity LAOs and IOs, may be somewhat more dispersible than OBMs in seawater. Higher dispersibility allows the SBM cuttings to disperse and dilute in the water column as the cuttings settle to the bottom, decreasing the concentration and increasing the areal extent of cuttings accumulation on the seafloor. Increasing the dispersibility of SBM cuttings may decrease the magnitude of biological effects in sediments. Effective dispersion of SBM cuttings in the water column is not likely to have biologically significant adverse effects on water column organisms. WBMs and WBM cuttings, which do disperse in the water column, do not cause adverse effects in water column organisms (National Research Council, 1983; Neff, 1987).

Because most SBM cuttings do not disperse efficiently in the water column following discharge, they settle rapidly through the water column and accumulate on the bottom near the platform discharge site (Neff et al., 2000). Cuttings discharged near the sea surface, particularly in deep water, tend to disperse more than those shunted to near the bottom. The effect of shunting is to decrease the area of the seafloor over which cuttings accumulate and to increase the mass of cuttings deposited as a cuttings pile near the wellsite (Kennicutt et al., 1996).

SBM cuttings accumulations are expected to be smaller as water depth increases because of greater dispersion. The fate of SBM cuttings was monitored near a drilling template at the Pompano II site in Mississippi Canyon Block 28 (MC 28) in 565 m of water south of the Mississippi River in the northern Gulf of Mexico (Gallaway et al., 1998; Fechhelm et al., 1999). Discharges from the rig included 7,700 bbl of WBM cuttings, 5,150 bbl of SBM cuttings, and an estimated 7,695 bbl of Petrofree LE (an SBM base material containing 90% LAO and 10% ester), which was associated with the cuttings.

The seafloor near the drilling template was surveyed with a remotely operated vehicle (ROV). There was a thin layer of cuttings spread in a patchy distribution on the seafloor near the drilling template. Maximum cuttings accumulations appeared to be 20 to 25 cm thick in some locations. The largest deposits of large, chunk-like cuttings were detected a short distance southwest of the template. These cuttings accumulations probably were derived from direct drilling returns to the sea bottom during initial drilling with WBMs before the riser was installed. There was no clear gradient of SBM cuttings concentrations with distance in the small radius (<90 m) around the template in which samples were collected.

There was no evidence of cuttings piles of the sizes reported for the United Kingdom Sector of the North Sea (Hartley et al., 2003). In the North Sea, there are generally larger reservoirs with many more wells drilled at a single location compared to the Gulf of Mexico. In the Gulf of Mexico, the reservoirs are smaller with fewer wells at a single site. In the North Sea, discharges were often shunted to near the seafloor, and discharges in the Gulf of Mexico generally occur at or near the sea surface.

Drilling fluid and cuttings discharges at the Pompano II site occurred between May 1996 and March 1997 and again in February and March 1998. Sediment samples were collected at different distances and directions from the template for analysis of SBM base chemicals in July 1997 and March 1998. The highest concentration of LAO in surficial (0 to 2 cm) sediments collected in July 1997 was 165,000 mg/kg at a location 75 m northeast of the drilling site. The LAO concentration in surficial sediment at the same site was 198,000 mg/kg in March 1998 after completion of the second round of drilling. Concentrations in surficial sediments at other locations within about 100 m of the drilling template ranged from 89 to 47,000 mg/kg.

In 1997, LAO concentrations in subsurface (2 to 5 cm) sediments were lower than those in surficial sediments at all but one station (along the most heavily contaminated northeast transect). In March 1998, LAO concentrations in subsurface sediments from several stations were equal to or higher than those in surficial sediments from the same stations. These results suggest that SBM cuttings mixed downward into the site sediments in the year after the first drilling activities. Average LAO concentrations in the 2 to 5 cm layer of sediments were 782 mg/kg in 1997 and 1,000 mg/kg in 1998.

This study showed that SBM cuttings are distributed heterogeneously in surface and subsurface sediments around deepwater drilling sites. This extremely uneven distribution of cuttings on the bottom is caused by clumping of the hydrophobic SBM-coated cuttings. They are more likely to settle through the water column as large clumps of solids than are WBM cuttings, which are hydrophilic and have a greater tendency to disperse. The sediment samples containing the highest concentrations of SBM base chemical apparently are “pure” SBM cuttings with little or no admixture of bottom sediments. The locations of discrete SBM cuttings accumulations on the bottom are controlled by the direction and velocity of water currents at different depths in the water column. At the Pompano II site, bottom currents were toward the southwest; therefore, muds and cuttings used during initial spudding of the wells settled to the southwest of the template. However, SBM cuttings discharged from the drilling rig passed through a zone of mid-water currents moving toward the northeast. Most of the discharged cuttings accumulated to the northeast of the platform. An estimated area of 6,700 m^2 (the area of a circle with a radius of 46 m) of sediments (nearly 65% of which was northeast of the template) contained 10,000 mg/kg or more of LAO at the time of the July 1997 and March 1998 surveys.

Candler et al. (1995) monitored the accumulation and fate of a PAO SBM in sediments near a platform in 131 m of water in the Gulf of Mexico. Field surveys were performed 9 days, 8 months, and 24 months after completion of drilling. Accumulation of the SBM in sediments was monitored as total petroleum hydrocarbons (TPH) and barium. There was a good correlation between concentrations of the two SBM tracers. SBM (as indicated by TPH) and barium were very unevenly distributed in sediments near the platform over time. Shortly after drilling, highest SBM concentrations in sediments were 100 m north of the platform (38,470 mg/kg); only four sediment samples collected immediately after, 8 months after, and 24 months after drilling contained more than 10,000 mg/kg SBM. Surface sediments containing more than 1,000 mg/kg SBM were located 50, 100, and 200 m north, 50 and 100 m south, 25 and 50 m to the west, and 25 m to the east of the discharge site 9 days after completion of drilling. After 8 months and 2 years, sediments containing more than 1,000 mg/kg SBM were restricted to within 50 m of the drilling site. Between 9 days and 2 years after drilling, SBM and barite concentrations decreased in sediments collected from more than 25 m from the discharge and fluctuated erratically in sediments 25 m from the discharge site. The total estimated area of seafloor contaminated with 1,000 to 10,000 mg/kg SBM decreased by 86% from 43,984 m^2 shortly after drilling to 5,891 m^2 2 years later.

Studies in the North Sea, Gulf of Mexico, and offshore Australia and Ireland show that SBM cuttings accumulate in a very irregular pattern in sediments around a drilling rig (Neff et al., 2000). The observed footprint, maximum thickness, and SBM concentration in the cuttings accumulation around the platform seem in most cases to be less than those predicted by Brandsma (1996) for OBM cuttings discharges, in part because the modeling does not account for seafloor dispersion mechanisms, all of which tend to reduce high initial sediment SBF or oil based fluid concentrations. Highest concentrations of SBMs in sediments often are lower than the concentration of SBMs in the cuttings at the time of discharge, suggesting that some SBM desorbs from the cuttings during their fall through the water column (Getliff et al., 1997). Sometimes, however, SBM base chemical concentrations in sediments are as high as or higher than reported average concentrations on discharged cuttings, suggesting either that some cuttings are discharged containing high concentrations of adsorbed SBM or, more likely, that some sediment samples represent undiluted clumps of cuttings. Gallaway et al. (1998) observed clumps of cuttings on the seafloor near the drilling template for the Pompano II prospect in more than 500 m of water.

1.2.5 Bioavailability and Toxicity of Synthetic Based Cuttings in Sediments

As discussed previously, because SBM cuttings are “oil-wet,” they do not disperse as readily as WBM cuttings in the water column following ocean discharge. They tend to clump, with large clumps settling rapidly to the seafloor. The tendency for cuttings to clump increases as the concentration of SBM on the cuttings increases. Prior to issuance of the latest NPDES general permit in February 2002, SBM cuttings discharged to the Gulf of Mexico usually contained about 10% SBM base chemical. The current general permit limits concentrations of SBM base chemical on cuttings to 6.9% (IOs) or 9.4% (esters); as discussed above, modern cuttings processing technology enables operators to meet this limitation.

SBM cuttings particles, because they settle so rapidly, are not persistent in the water column. Therefore, they are unlikely to cause serious adverse biological effects in water column organisms. However, because they settle rapidly, SBM cuttings are likely to accumulate on the seafloor near the platform to a greater extent than WBM cuttings, even in deep water (Fechhelm et al., 1999). Thus, environmental effects of SBM cuttings discharges, if they occur, are most likely to be restricted to the seafloor in a small area under and down current from the discharge.

Biological effects of SBM cuttings on benthic communities are expected to be similar to or somewhat greater than those of WBMs and WBM cuttings. The minimal effects of WBMs and WBM cuttings on benthic ecosystems are well documented (National Research Council, 1983; Neff, 1987). The mass of SBMs discharged to the ocean per well is much less than the mass of WBMs discharged per well because the drilling fluid itself is not discharged and cuttings are processed to remove drilling mud before discharge (Veil and Daly, 1999). In most cases, the total amount of cuttings produced while drilling with SBMs is significantly less than when drilling with WBMs because SBMs increase the stability of the well bore and reduce the amount of washout (increase in well bore diameter due to sediment instability).

The toxicities of most WBMs and SBMs are low, unless they contain petroleum hydrocarbons (Neff, 2002b), so they probably represent only a small direct toxic threat to marine organisms living on or in sediments near the platform. However, SBM cuttings may harm benthic communities by increasing sediment anoxia through microbial biodegradation if SBM cuttings concentrations in sediments are high enough (Olsgard and Gray, 1995). WBMs and WBM cuttings usually do not cause sediment anoxia because they contain only low concentrations of biodegradable organic chemicals. However, both WBM and SBM cuttings also may harm benthic communities by burial and smothering, or they may alter sediment texture, rendering the local benthic environment less suitable for some species of benthic fauna and better for others (Neff, 1987). Thus, biological effects of SBM cuttings discharges are comparable to those of WBM and WBM cuttings discharges and are likely only in the immediate vicinity (within 50 to 100 m) of platforms, where the cuttings are likely to accumulate.

In many countries that are developing offshore oil and gas resources, discharge permits require performance of toxicity tests with drilling fluid ingredients and whole drilling fluids (Jones et al., 1996). Two types of toxicity tests may be performed: water column tests and solid-phase (sediment) tests, which are intended to assess potential risks from drilling fluid discharges to pelagic and benthic organisms, respectively. The USEPA requires testing of whole drilling discharge fluids, and, because SBM cuttings settle rapidly to the seafloor, has determined that water column toxicity of SBM cuttings is likely to be low. In addition to the water column toxicity test with the mysid *Mysidopsis bahia*, the USEPA requires a solid-phase test to evaluate the potential environmental impacts of SBM cuttings discharges.

In the solid-phase test required by the USEPA for SBMs, survival of benthic amphipods, *Leptocheirus plumulosus,* is measured during a 96-hour exposure to sediments containing SBM cuttings from each drilling project (American Society for Testing and Materials [ASTM], 1992). The operator also performs 10-day solid phase tests with *L. plumulosus* and SBM base chemicals on an annual basis. The ratio of the median lethal concentration (LC_{50}) of SBM cuttings to the LC_{50} of a $C_{16/18}$ IO base chemical must be equal to or greater than 1 (i.e., the discharged cuttings must be less toxic than the base fluid).

The mean LC_{50} for several tests with *Leptocheirus* and IO C_{16}/C_{18} SBM base chemical in sediment using the protocol recommended by the USEPA was 3,480 mg/kg (coefficient of variation [CV] 36%) (Neff et al., 2000). The mean LC_{50} of a diesel fuel run concurrently was 534 mg/kg (CV 19%). Thus, SBMs are much less toxic than diesel OBMs.

A concern about SBM base chemicals, particularly in North Sea countries, is that they may bioaccumulate in tissues of marine organisms, possibly tainting demersal marine animals of commercial value (Rushing et al., 1991; Vik et al., 1996a). Demersal fishes are able to bioaccumulate petroleum hydrocarbons from OBM cuttings (Payne et al., 1989; Stagg and McIntosh, 1996).

However, the structure and physical properties of the olefinic synthetic base chemicals suggest that they have a low bioavailability to marine organisms (Neff et al., 2000). Olefins of the sizes found in SBM base chemicals are relatively large linear chains that do not permeate membranes efficiently. They have high log K_{ow}s, above 6.4 for LAOs and above 9 for IOs (ERT Ltd., 1994; McKee et al., 1995), indicating extremely low aqueous solubility and low potential to bioaccumulate. Bioaccumulation of highly hydrophobic chemicals, such as SBM olefins, occurs very slowly, if at all. Equilibration in marine animals may require more than a year of continuous exposure (Hawker and Connell, 1985, 1986). This is longer than the life span of most benthic organisms. Olefins, which are readily biodegraded by aerobic microorganisms, probably are readily metabolized in the tissues of marine animals, producing acetate, which is an important organic nutrient for all tissues. Therefore, it is unlikely that bioaccumulation of SBM base chemicals represents an environmentally important risk to marine organisms in the vicinity of offshore SBM cuttings discharges. SBM esters are slightly water-soluble and usually have log K_{ow}s below about 1.7 (Growcock et al., 1994). They should be bioavailable; however, their close resemblance to natural fatty acid esters in tissues indicates that they probably are metabolized rapidly or incorporated into tissue lipid stores.

Schaanning et al. (1996) added marine polychaete worms *Hedeste (Neries) diversicolor* to Norwegian Institute of Water Research (NIVA) simulated seabed sediment chambers containing sediments contaminated with two esters, one IO, one LAO, or a mineral oil base chemical. Three doses of each organic drilling mud phase were used: 0.42, 4.33, and 19.0 mg/cm^2 of sediment surface. These loadings are comparable to those observed on the seafloor near an SBM cuttings discharge. After about 160 days, no worms survived in one ester treatment, having succumbed to low oxygen concentrations caused by rapid microbial degradation of the ester. In the other ester treatment, the worms contained high concentrations of esters in their tissues. The tissue esters were different from those in the base chemical formulation and resembled those in the tissues of worms from control chambers. The authors concluded that they probably were natural fatty acid esters, possibly synthesized from the SBM esters. Thus, they showed that there was no net bioaccumulation of ester SBM base chemicals by the worms.

At the end of the 6-month exposure period, worms exposed to sediments containing an IO SBM base chemical contained 2.37 to 49.5 mg/kg wet weight IO in their tissues. Worms exposed to the LAO contaminated sediments contained 3.56 to 7.77 mg/kg LAO. However, a comparison of the SBF/barium ratio in exposure sediments and whole worm tissues revealed that all or most of the SBF did not appear to be assimilated into the worm tissues. The majority was in the digestive tract of the worms, with possibly a small amount of SBF bioaccumulated by the worms during 6 months of exposure to contaminated sediments. This study shows that SBM base chemicals have a very low bioavailability to marine organisms, and there is little or no risk that these chemicals will bioaccumulate to potentially harmful concentrations in tissues of benthic animals or be transferred through marine food chains to important fishery species.

1.3 STUDY DESIGN

A stepwise approach was employed for the study design for the Gulf of Mexico Comprehensive Synthetic Based Muds Monitoring Program. After an initial selection of potential study sites, a Scouting Cruise was conducted. The purpose of the Scouting Cruise was to conduct a preliminary survey of a wide range of sites on the continental shelf using physical methods to 1) assess the extent of cuttings accumulations; 2) assess the suitability of each study site for further sampling during the program, i.e., identify potential obstacles that would hinder or preclude sampling; and 3) gather information about the sites that could be used to guide further sampling operations. An ROV survey was conducted around the discharge location at ten selected continental shelf study sites. The purpose of this ROV survey was to evaluate the magnitude of any cuttings accumulations that may have been present compared to accumulations that have been observed in the North Sea and to attempt to assess the distribution of cuttings. Other factors that could affect future sampling at the platform, such as pipeline placement, also were noted. To identify and survey the potential cuttings accumulations, the ROV was equipped to collect sector-scanning sonar, video, and altimeter data. Sector-scanning sonar was used to detect and determine the areal extent of the cuttings accumulations based on acoustic signature. The ROV altimeter was available to determine the vertical relief of the cuttings accumulations. Video data were collected to document visually detectable differences in substrate texture and vertical relief. The results of the Scouting Cruise were used in the process to select continental shelf study sites for the subsequent Screening Cruise.

After the data collected during the Scouting Cruise were evaluated, the potential study sites for the remainder of the program were selected. A Screening Cruise then was conducted to 1) provide a detailed mapping of the cuttings accumulations at each platform; 2) assess sediment SBF concentrations and sediment physical-chemical conditions at all eight sites; 3) test and refine the proposed field and laboratory methods; and 4) make preliminary biological and sediment-toxicity assessments at the continental shelf sites. To provide a detailed mapping of the cuttings accumulations at each platform during the Screening Cruise, an ROV was equipped with instrumentation to simultaneously collect high resolution swath bathymetry and side-scan sonar data. A map of the seafloor around the discharge point was developed based on the results of the high resolution swath bathymetry data to evaluate accumulations of cuttings from the discharge. The ROV also was equipped with a videocamera for visual observations. At three sediment sampling stations at each platform, a sediment profile imaging (SPI) system was deployed to obtain information concerning redox potential discontinuity (RPD) depth, sediment texture, cuttings, and macroinfauna. Temperature and salinity also were profiled at each study site. At each of the eight sites, six samples were collected for physical and chemical measurements of sediment conditions. Three of these samples were collected at random locations near the platform or subsea template, and three were collected at random reference locations. Samples were collected for redox profiling measurements, grain size and mineralogy, SBF and TPH, metals (aluminum [Al], arsenic [As], barium [Ba], cadmium [Cd], chromium [Cr], copper [Cu], iron [Fe], lead [Pb], mercury [Hg], nickel [Ni], vanadium [V], and zinc [Zn]), total organic carbon (TOC), and carbonate. Six infaunal samples and six sediment toxicity samples were collected at each of the continental shelf sites for preliminary biological and sediment toxicity analyses. In addition, sediment cores were collected at each of the eight sites and were vertically sectioned into 1- to 2-cm (or other appropriate) increments, and the sections were analyzed separately for grain size, metals, and SBF to investigate vertical layering and thickness of the cuttings accumulation. At three continental slope sites and four continental shelf sites, an additional sediment sample was collected at a discretionary location. The sample was located in suspected cuttings accumulations that had been previously identified during the mapping effort to confirm the presence of cuttings. At one continental slope site, the Pompano II subsea drilling template in MC 28, three additional samples were collected at locations sampled during a previous survey (Gallaway et al., 1998; Fechhelm et al., 1999).

Based on the data acquired during the Screening Cruise, several decisions were made concerning the two Sampling Cruises. The boundaries of three sampling strata ─ near-field, transition (mid-field), and far-field zones ─ were designated as <100 m, 100 to 250 m, and 3,000 to 6,000 m, respectively. Three continental slope study sites and three continental shelf study sites were designated as primary study sites, and the remaining two study sites (one continental slope site and one continental shelf site) were designated secondary study sites. Based on the results from the Screening Cruise, sediment samples were analyzed for nannofossils instead of mineralogy.

Sampling during the two Sampling Cruises is summarized in Table 1-3. At the primary study sites, sediment samples were collected at six locations within each of the three zones (sampling strata) during each Sampling Cruise. These sediment samples were analyzed for hydrocarbons (SBFs and TPH), metals, grain size, TOC, and the presence of cuttings (visual analysis by trained mud loggers). Samples of pore water also were collected and analyzed for metals at two sediment sampling locations at each primary study site. At the primary continental shelf study sites, samples for analysis of macroinfauna and sediment toxicity were collected. An additional core was collected at each primary study site during Sampling Cruise 1 and analyzed

Table 1-3. Summary of sampling at sites* during the two Sampling Cruises.

Parameters	Continental Shelf Study Sites				Continental Slope Study Sites			
	Primary			Secondary	Primary			Secondary
	EI 346	MP 288	MP 299	ST 160	EW 963	GC 112	MC 496	VK 783
Hydrographic Profile	X	X	X	X	X	X	X	X
Sediment Profile Imaging	X	X	X	X	X	X	X	X
Redox Profiles in Sediments	X	X	X	X	X	X	X	X
Synthetic Based Fluids/Total Petroleum Hydrocarbons	X	X	X	X	X	X	X	X
Grain Size	X	X	X	X	X	X	X	X
Nannofossils	X	X	X	X	X	X	X	X
Sediment Metals	X	X	X		X	X	X	
Pore Water Composition	X	X	X		X	X	X	
Total Organic Carbon	X	X	X	X	X	X	X	X
Visual Cuttings Analysis	X	X	X	X	X	X	X	X
Infauna	X	X	X					
Sediment Toxicity	X	X	X		2	2	2	
Radionuclides		1				1	1	1

* Study site designations were based on lease block containing the surface drilling location.
X = Sampling conducted during Sampling Cruises 1 and 2.
1 = Sampling conducted during Sampling Cruise 1 only.
2 = Sampling conducted during Sampling Cruise 2 only.

EI = Eugene Island.
EW = Ewing Bank.
GC = Green Canyon.
MC = Mississippi Canyon.
MP = Main Pass.
ST = South Timbalier.
VK = Viosca Knoll

for selected radionuclides to 1) determine sediment accumulation rates; 2) determine sediment mixing rates from biological and physical processes; and 3) identify the presence and thickness of layers of SBM cuttings. SPI images were collected at 12 locations at each primary study site. Sampling at the two secondary study sites was similar to that at the primary study sites, but the suite of analyses was not as extensive. Sediment samples were collected at 18 locations—6 locations in each of the three zones. These samples were analyzed for hydrocarbons (SBFs and TPH), grain size, mineralogy, TOC, and the presence of cuttings. SPI images were collected at 12 locations at each secondary study site. The sampling during Sampling Cruise 2 was the same as during Sampling Cruise 1, except sediment samples were not collected for analysis of radionuclides and samples for sediment toxicity were collected at the primary continental slope study sites.

Chapter 2
SITE SELECTION AND DESCRIPTION

Alan D. Hart
Continental Shelf Associates, Inc.

The selection of study sites for the two Sampling Cruises was a stepwise process. The first step was to identify potential study sites from the available sites in the Gulf of Mexico. Representatives of industry and the MMS collaborated on this initial identification. A Scouting Cruise then was conducted to collect preliminary information at ten continental shelf water sites. The information gathered during the Scouting Cruise was evaluated with other information about the SBM discharges, geographic location, and water depth to determine a short list of continental shelf water sites to be sampled during a Screening Cruise. Continental slope sites, which had been identified based on information collected from the operators and drilling mud companies, also were sampled. The results of this survey then were evaluated with all of the other available information to identify the eight study sites that were sampled during the two Sampling Cruises.

2.1 INITIAL SELECTION OF POTENTIAL CANDIDATE STUDY SITES: DESCRIPTION OF THE SITE SELECTION PROCESS

To begin the identification of potential study sites, drilling mud company records were used to build the initial database of Gulf of Mexico wells where SBM drilling and cuttings discharges had occurred. These data included the operator, block, spud/completion dates, water depth, type of drilling fluid, and estimates of discharge quantities. This original database included approximately 360 wells and side tracks in 165 blocks. The initial database was reduced to 71 wells by adding several constraints. Sites in the northwestern Gulf of Mexico were excluded to maximize available sampling time by minimizing boat transit time. Sites within a 25-mile radius of the mouth of the Mississippi River were excluded to avoid masking of drilling activity related effects by river discharges. Sites in greater than 700 m of water were excluded, and sites older than approximately 3 years were excluded. Sites without adequate descriptive data also were excluded.

The 71 wells were mapped using geographic information system (GIS) software to allow visualization of well locations and important selection criteria. These maps were used to aid site selection during project team meetings. The set of potential study sites was further reduced to a short list of sites (Table 2-1), primarily based on the type of drilling fluid used and the amount of SBM cuttings discharged. For these short-listed sites, the operators were contacted to verify the existing data on each well, describe future drilling plans, and supply additional logistical and safety data.

Table 2-1. Continental shelf platform short list.

Block	Platform	Water Depth (m)	Volume SBM Cuttings (bbl)	Number of Wells	First Well (year)	Last Well (year)	SBM Type
Eugene Island 331 "A"	Yes	73	45				IO
Eugene Island 331 "B"	Yes						
Eugene Island 346	No	92	1,374	19	1977	2002	IO
Eugene Island 390	No	113		6	1984	1998	IO
Ewing Bank 305/306	Yes	81		25	1980	2001	IO
Garden Banks 127	Yes	204	1,110				IO
Garden Banks 128	Yes	183	1,805	11	1994	2002	IO
Green Canyon 89	Yes	232	945				IO
Main Pass 288	Yes	119	98	23	1968	1997	IO
Main Pass 289 "B"	Yes	64					IO
Main Pass 289 "C"	Yes						IO
Main Pass 299 "BB"	Yes	83	900	450	1962	2002	IO
Main Pass 310 "A"	Yes	27	25				IO
Main Pass 310 "JA"	Yes	27	88				IO
South Marsh Island 60/61	Yes	38	60	14	1966	2000	IO
South Timbalier 148 Well A-7 Well A-9	Yes	34	1,395	2			LAO Novadrill IO
South Timbalier 149	No						
South Timbalier 160	Yes	37	883	21	1962	2001	IO
Viosca Knoll 780	Yes	210	916	10	1986	1998	IO
Viosca Knoll 782	No	290		1	1996	1996	IO
Viosca Knoll 783	No	338	920	13	1984	1996	Ester

IO = Internal olefin.
LAO = Linear alpha olefin.
SBM = Synthetic based mud.

A meeting of the site selection subgroup was held to rank the short-listed sites after receiving feedback from the operators. Several selection criteria were considered to make the ranking, including type of SBM, discharge volume, and age of the well or wells. IO SBF was, and still is, by far the most common type of base fluid in use in the Gulf of Mexico. The sites selected for study were drilled primarily with IO SBF. This reflects the predominant drilling practice in the Gulf of Mexico. The predominance of sites drilled with IO SBF also reflects the practical consideration that other constraints on the site selection process made it highly likely that otherwise suitable sites would have been drilled with the predominant drilling fluid system. Some of the selected sites included the discharge of ester-base SBF cuttings because of the specific limits for ester-based SBMs in the recently promulgated USEPA SBM ELGs. Sites with higher volumes of SBM cuttings discharges were preferred. Recently drilled sites were preferred to study the speed of seabed recovery. Sites where drilling was planned during the study were excluded because fresh SBM cuttings on the seabed would eliminate the ability to study the amount of recovery that occurred between cruises. Sites distant from other drilling operations were preferred to reduce the influence of other discharges. Sites outside the <40 m hypoxic zone that occurs in late summer in certain parts of the Gulf of Mexico were preferred because there was a concern that anoxia would influence the benthic fauna and possibly affect recovery rates. Based on the resulting ranking, a set of continental shelf sites was selected for sampling during the Scouting Cruise.

2.2 SCOUTING CRUISE

Data collection during the Scouting Cruise was conducted from 3 to 8 June 2000 as described in Chapter 3. The following discussion summarizes the observations at the candidate study sites.

2.2.1 Ewing Bank 305/306

The drilling rig and drilling discharges were located in Ewing Bank (EW) 305, but the bottom holes of some wells were in EW 306. Water depth at the site was 81 m (266 ft), and underwater visibility was approximately 4 m (13 ft). At the time of the survey, there was a platform with an adjacent drilling or jack-up rig at EW 305. Mud discharge had recently occurred from the drilling operation from a submerged discharge pipe located between the two structures and approximately 6 m (20 ft) below the surface. Sediment near the base of the two structures consisted of cuttings and mud occasionally covered with a discontinuous white filamentous layer (probably the sulfur-oxidizing bacteria *Beggiatoa* spp.) (Photos 2-1 and 2-2). Numerous small mounds comprising suspected discharged muds and cuttings were observed on the seafloor under the point of discharge (Photo 2-3). Mounds ranged in relief from 0.3 to 0.6 m (1 to 2 ft). Similar cuttings and muds were observed accumulated near the base of the platform and rig legs (Photo 2-4) and on top of near-bottom horizontal cross-members. Due to ongoing discharge activity and survey area limitations, it is uncertain if natural substrate was observed during survey operations at this site.

2.2.2 South Timbalier 160

Water depth at South Timbalier (ST) 160 was 40 m (131 ft), and underwater visibility was approximately 2 m (6.6 ft). There was a multiple platform structure at this site. The bottom near the given drillsite location was relatively level. A large depression surrounding a suspected drill hole was observed. Sector-scanning sonar showed that the suspected drill hole penetrated approximately 4 m (13 ft) below the surrounding surface sediment. Variable colored sediment was observed adjacent to the suspected drill hole. A discontinuous layer of white filamentous material (?*Beggiatoa* spp.) and pieces of grout were observed in association with the suspected drill hole (Photos 2-5 and 2-6). Natural substrate at the site appeared to be soft mud.

2.2.3 South Marsh Island 60/61

Water depth at South Marsh Island (SMI) was 38 m (125 ft), and underwater visibility was approximately 2 m (6.6 ft). There was a four-platform structure at the discharge location joined together by aerial catwalks. The seafloor at the survey site was relatively level with an occasional mound or depression (Photo 2-7). The sources of the observed alterations in the substrate topography were not obvious. Relatively small patches of white filamentous material (?*Beggiatoa* spp.) were observed within the survey area. There were no definitive indications of drill muds or cuttings in the survey area. Sediments consisted of sand/mud with some shell fragments and coarse debris (Photo 2-8).

Photo 2-1 - Coarse dark sediment near the base of the Ewing Bank 305 platform consisted of cuttings and mud covered with a white filamentous layer (probably the sulfur-oxidizing bacteria *Beggiatoa* spp.).

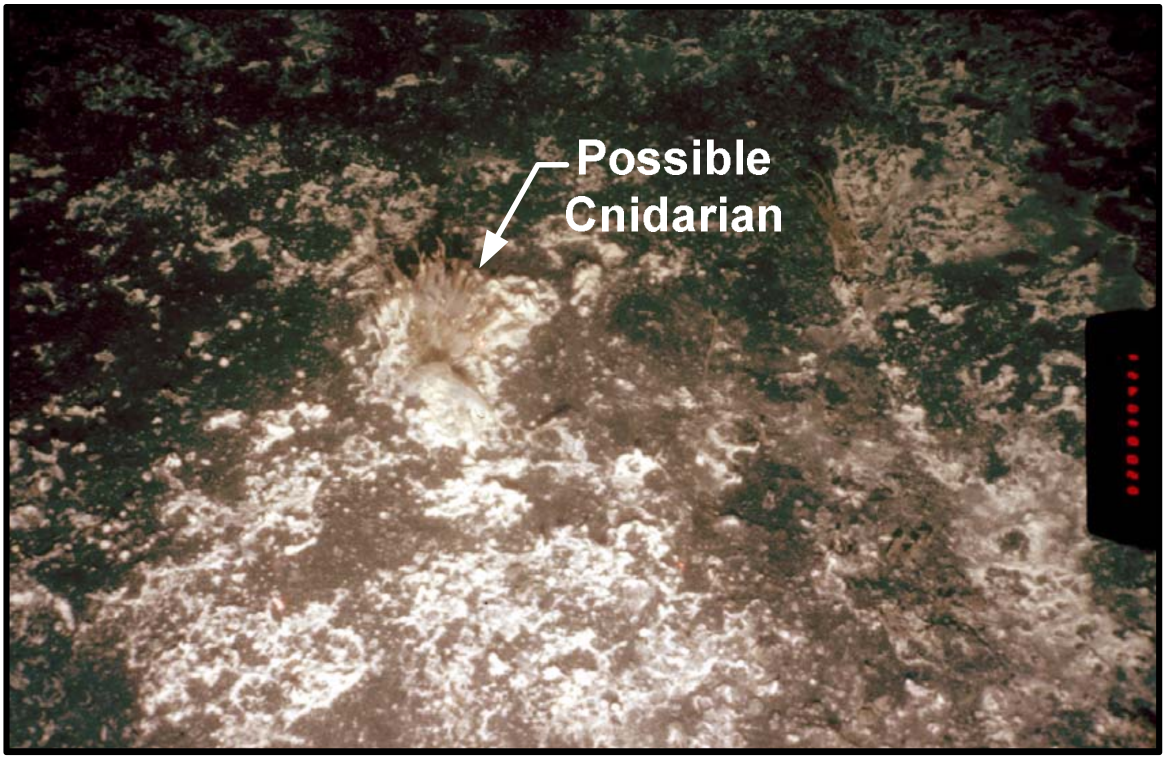


Photo 2-2 - Coarse dark sediment near the base of the Ewing Bank 305 platform consisted of cuttings and mud covered with a discontinuous white filamentous layer (probably the sulfur-oxidizing bacteria *Beggiatoa* spp.). Unidentified biota (probably cnidarians) are visible in the photograph.

Photo 2-3 - Small mound along south side of the Ewing Bank 305 platform. Sediment appears to be composed of muds and coarse cuttings.

Photo 2-4 - Muds and cuttings accumulation near the base of a Ewing Bank 305 platform leg. Vertical relief of the accumulation was approximately 0.3 to 0.6 m (1 to 2 ft).

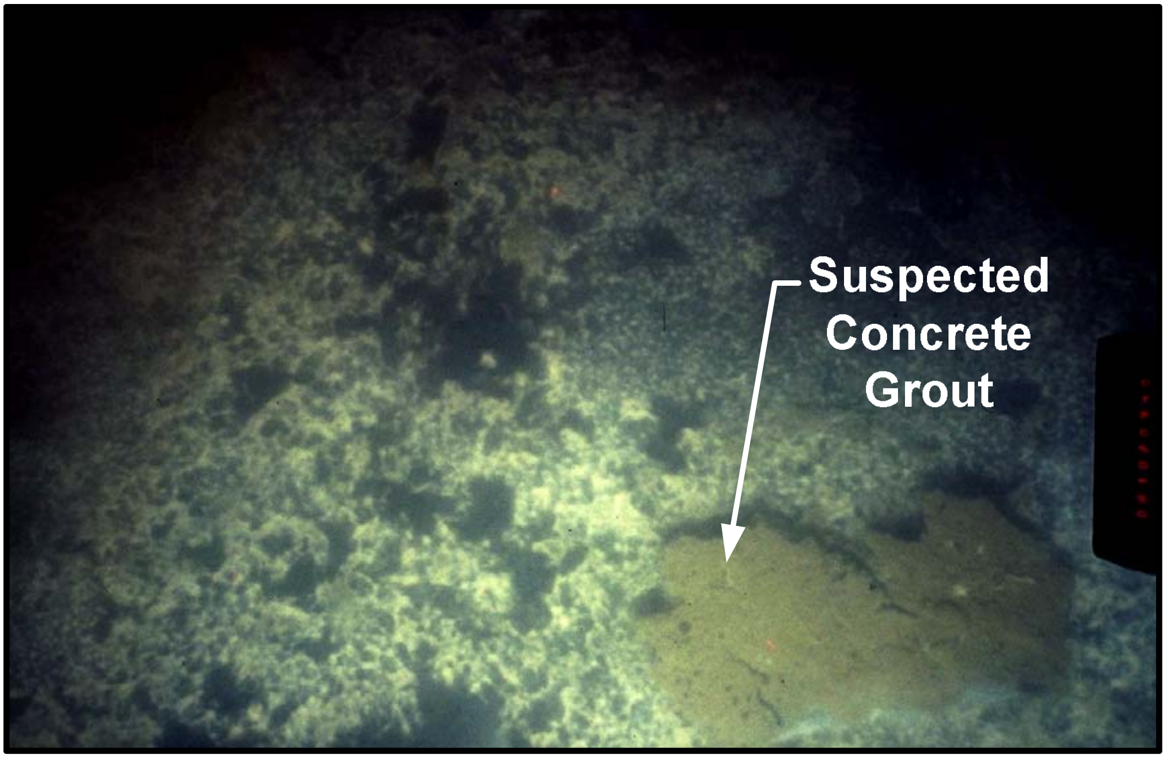


Photo 2-5 - Discontinuous white filamentous mat (?*Beggiatoa* spp.) overlying dark sediment at South Timbalier 160. A piece of suspected concrete grout is present in the right foreground.

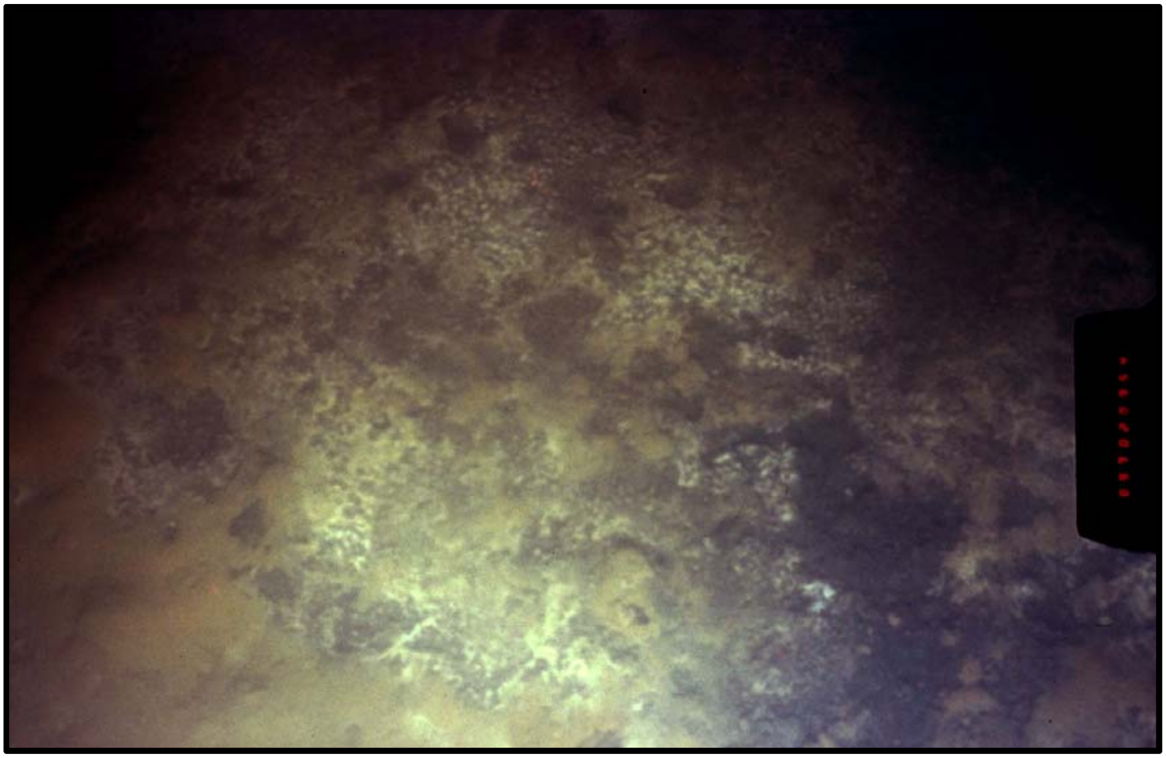


Photo 2-6 - Variable colored sediment at South Timbalier 160. White filamentous mat (?*Beggiatoa* spp.) was visible overlying the darker sediment.

Photo 2-7 - Small disturbance in the relatively level bottom topography observed at South Marsh Island 61 Platform "F." Sediment color variation and small patches of white filamentous mat *(?Beggiatoa* spp.) were associated with the substrate disturbance.

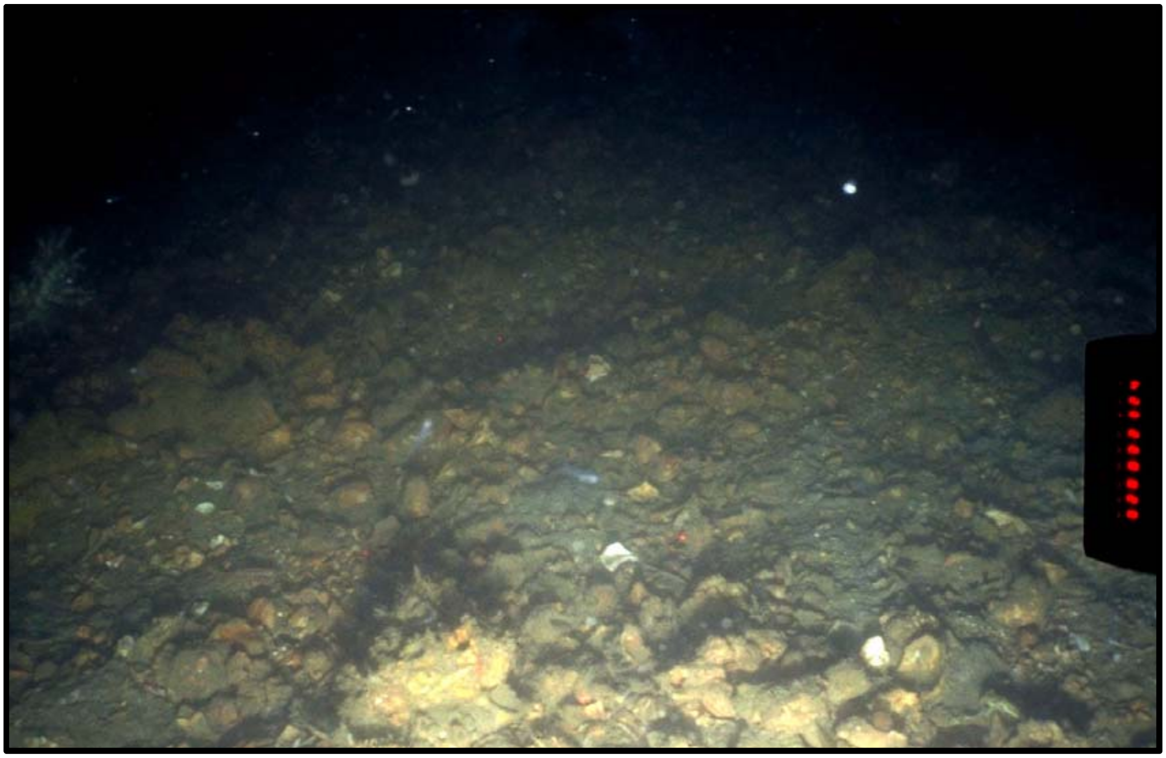


Photo 2-8 - Coarse sediment including barnacle and mollusk shell debris observed in close proximity to South Marsh Island 61 Platform "F."

2.2.4 Garden Banks 128

Water depth at Garden Banks (GB) 128 was 183 m (600 ft), and underwater visibility was greater than 10 m (33 ft). The structure at this site consisted of a single platform. The bottom near the drillsite was relatively level with some scouring near the platform base. Suspected cuttings and a surficial discontinuous layer of white filamentous material (?*Beggiatoa* spp.) were observed in and on the sediments in close proximity to the south side of the platform structure (Photo 2-9). Accumulations of suspected muds and cuttings were observed on top of substructures at the base of the platform (Photo 2-10). A surficial layer of a brownish filamentous material (possibly pigmented *Beggiatoa* spp.) was observed to be associated with some of these accumulations (Photo 2-11). Depths of the accumulations on the platform substructure were variable, ranging from approximately 0.3 m (1 ft) to a slight dusting. Heaviest accumulations were observed along the south side of the platform (Photo 2-12). Natural substrate at the site appeared to be soft mud.

2.2.5 Eugene Island 390

Water depth at Eugene Island (EI) 390 was 113 m (370 ft), and underwater visibility was approximately 9 m (30 ft). There were no platform or rig surface structures at this site. A wellhead structure projecting above the seafloor was observed during survey operations (Photo 2-13). The natural substrate at the given drillsite location consisted of irregular hard bottom outcrops with vertical relief of 1 to 6 m (3 to 20 ft) (Photo 2-14). Soft substrate, probably a veneer, consisting of sand/silt was observed between the rock outcrops. A fractured veneer of grout overlying sediment was observed in close proximity to the wellhead structure (Photo 2-15). A surficial discontinuous layer of white filamentous material (?*Beggiatoa* spp.) also was observed on sediments near the wellhead structure and at hard bottom locations with variable accumulations of discharge material. The hard bottom with a partial covering of discharged material was observed predominantly to the northeast of the wellhead structure (Photo 2-16).

2.2.6 Viosca Knoll 783

Water depth at Viosca Knoll (VK) was 338 m (1,110 ft), and underwater visibility was approximately 5 m (16.4 ft). There were no platform or rig structures at this site. There were no visual indications of drill muds or cuttings in the survey area. The only visual indication of drilling activity in the survey area was a few observations of debris (Photo 2-17). The bottom near the given drillsite location was relatively level with occasional mounds and depressions (Photo 2-18). The observed mounds and depressions in the substrate appeared to be biologically maintained. Sediment within the survey area consisted of mud.

2.2.7 Viosca Knoll 782

Water depth at VK 782 was 290 m (950 ft), and underwater visibility was approximately 5 m (16.4 ft). There were no platform or rig structures at this site. The bottom near the given drillsite location was relatively level with the exception of two large depressions. Debris was observed at both of the large depressions (Photo 2-19). There were no visual indications of drill muds or cuttings in the survey area. Sediment within the survey area consisted of mud (Photo 2-20).

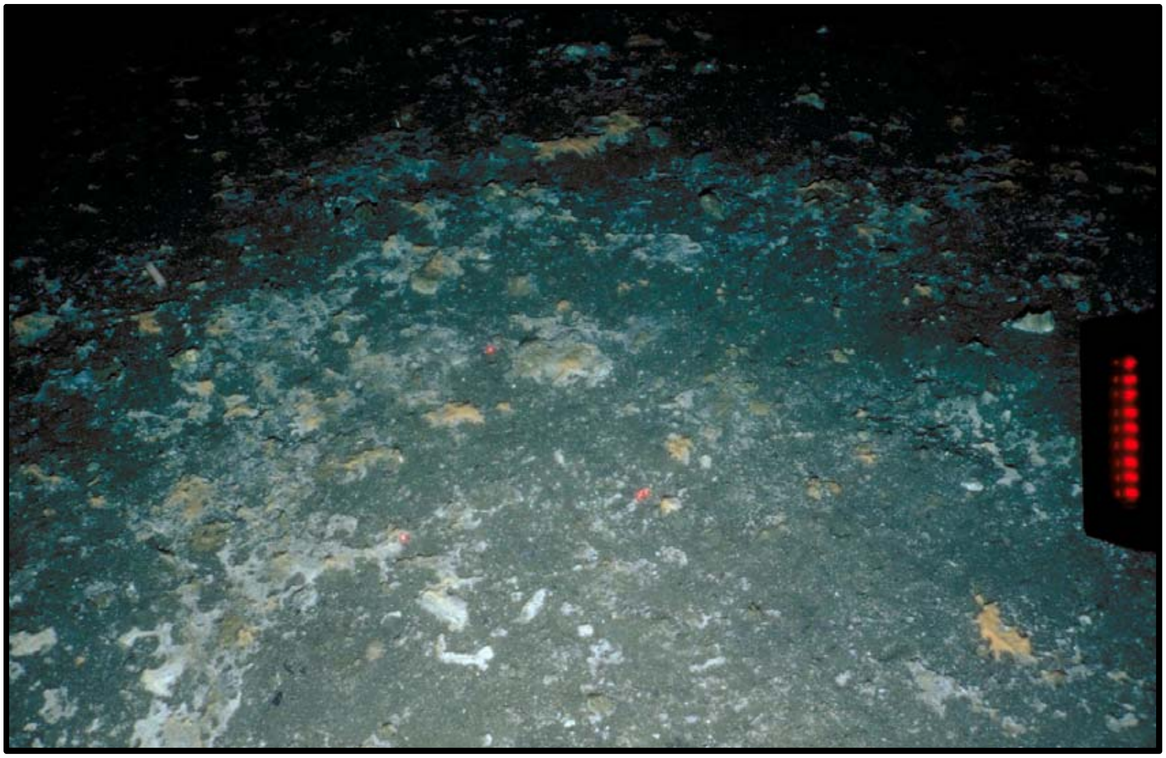


Photo 2-9 - Suspected cuttings and surficial discontinuous layer of white filamentous material (?*Beggiatoa* spp.) in and on the sediments in close proximity to the south side of the Garden Banks 128 platform structure.

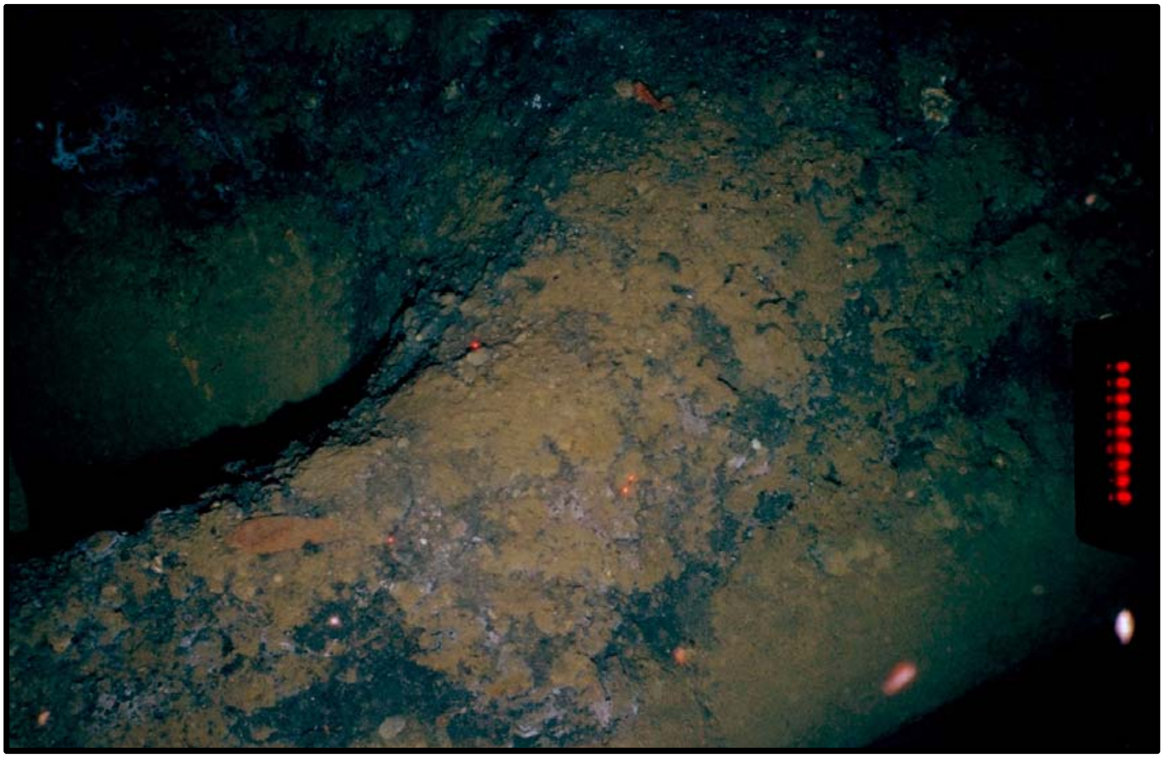


Photo 2-10 - Accumulation of suspected mud and cuttings on top of substructures at the base of the Garden Banks 128 platform structure.

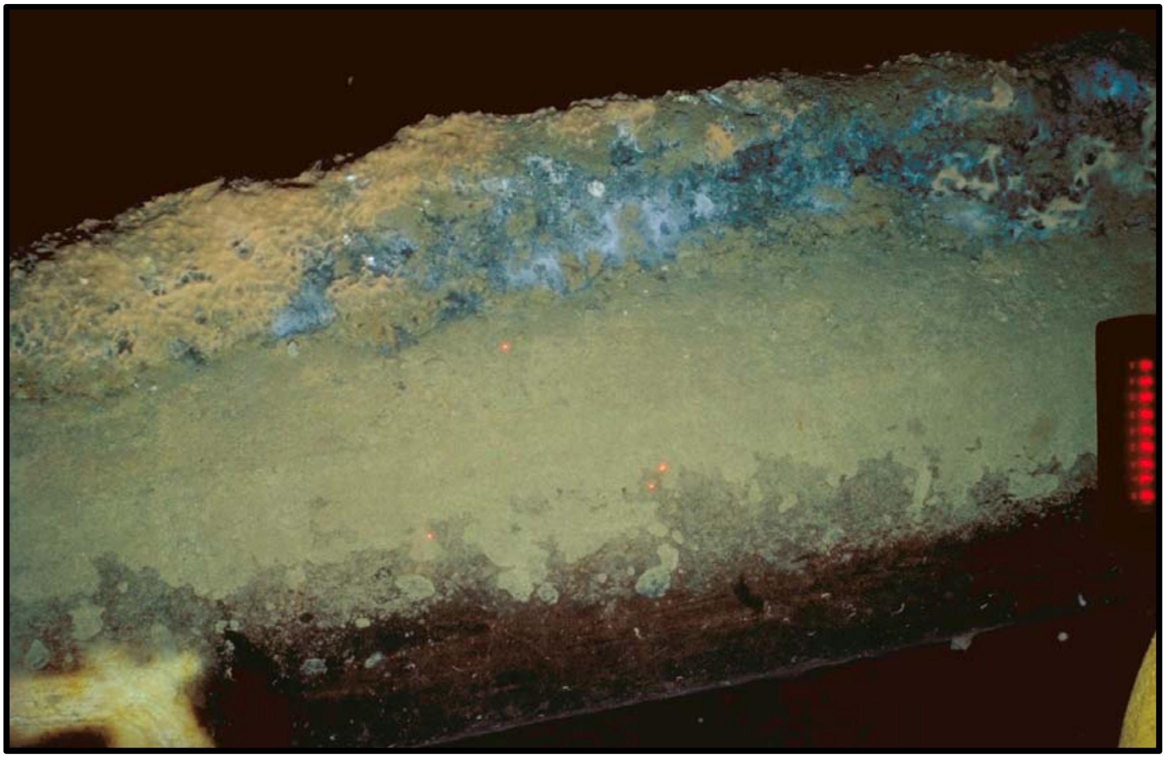


Photo 2-11 - Accumulation of suspected mud and cuttings on substructures of the Garden Banks 128 platform structure. A surficial layer of a brownish filamentous material (possibly pigmented *Beggiatoa* spp.) was present on the mud and cuttings accumulation.

Photo 2-12 - Heavy accumulation of mud and cuttings along the south side of the Garden Banks 128 platform.

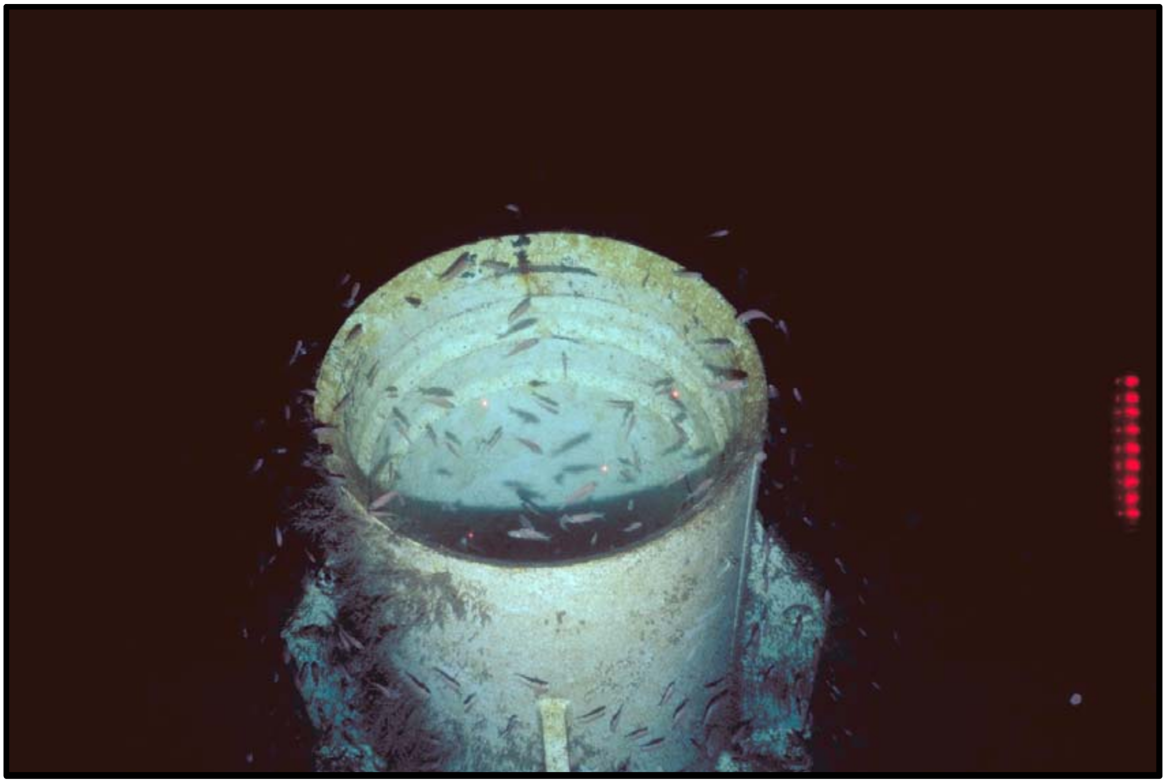


Photo 2-13 - Temporarily abandoned wellhead structure projecting above the seafloor at Eugene Island 390.

Photo 2-14 - Irregular hard bottom outcrops with vertical relief of 1 to 6 m (3 to 20 ft) observed during survey operations at Eugene Island 390. Visually dominant biota included soft corals and antipatharians (black coral).

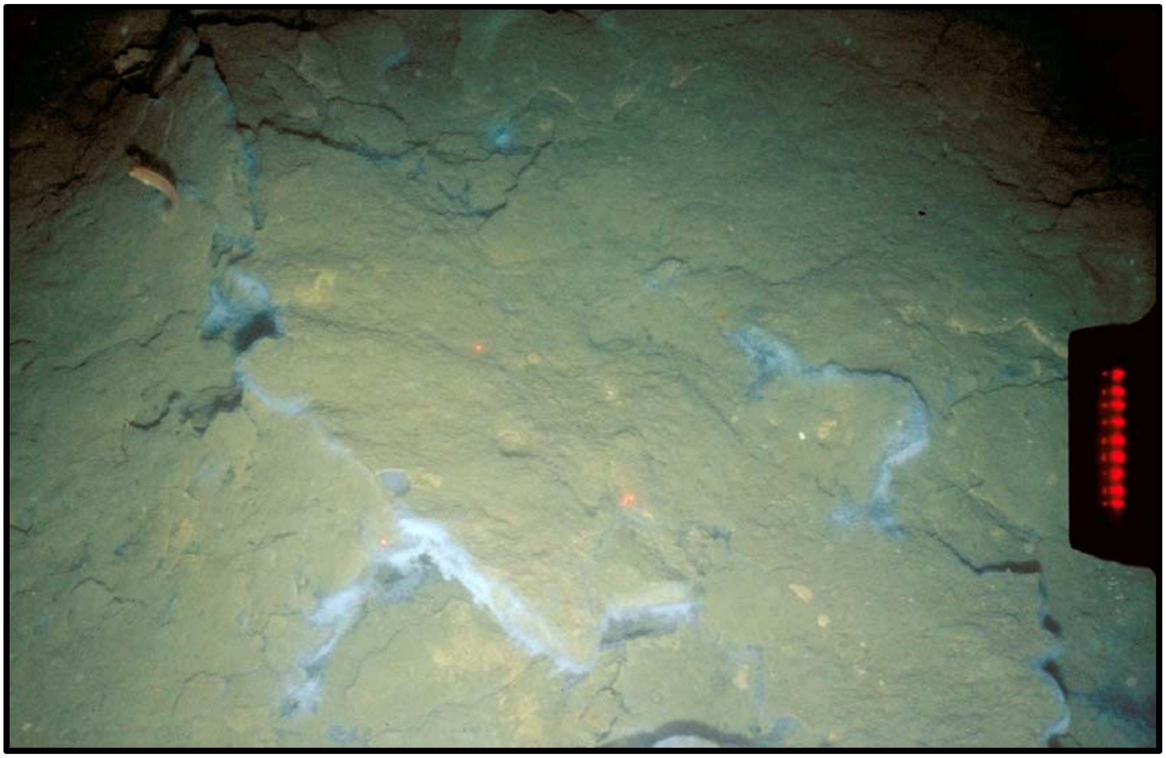


Photo 2-15 - A fractured veneer of concrete grout overlying sediment in close proximity to the Eugene Island 390 wellhead structure. A surficial layer of white filamentous material (?*Beggiatoa* spp.) was visible along the fracture lines.

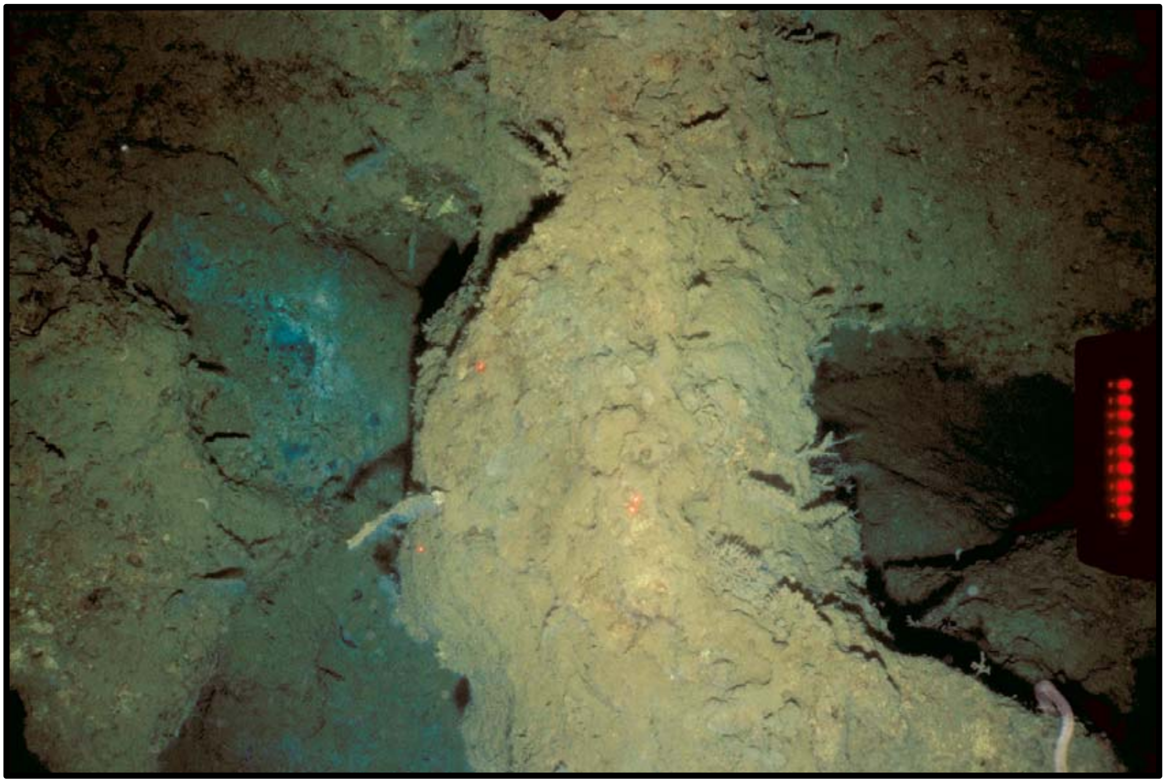


Photo 2-16 - Hard bottom with a partial covering of discharge material northeast of the Eugene Island 390 wellhead structure.

Photo 2-17 - Debris at Viosca Knoll 783. Associated biota included anemones, hydroids, and crabs.

Photo 2-18 - The bottom near the Viosca Knoll 783 drillsite location was relatively level with occasional biologically maintained mounds and depressions.

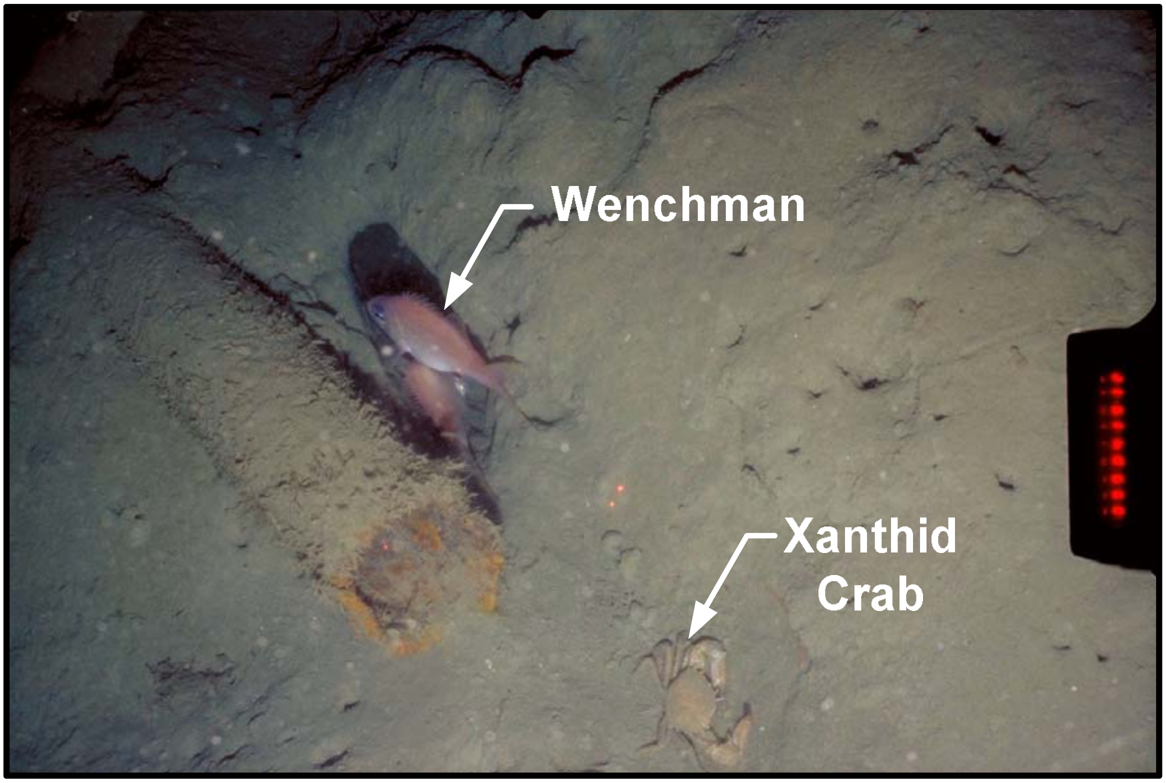


Photo 2-19 - Debris at one of the large depressions observed at Viosca Knoll 782. Pictured biota include a pair of wenchman (*Pristipomoides aquilonaris*) and a xanthid crab.

Photo 2-20 - Grapsoid crab on mud bottom at Viosca Knoll 782.

2.2.8 Main Pass 288

Water depth at Main Pass (MP) 288 was 119 m (390 ft), and underwater visibility was approximately 1 to 2 m (3.3 to 6.6 ft). The structure at this site consisted of a single platform. The bottom near the given drillsite location was relatively level. Some anthropogenic debris (i.e., a tractor tire and tugboat bumper) was observed during survey operations. Accumulations of suspected discharges were observed along the northeast base of the platform (Photo 2-21). A layer of white filamentous material (?*Beggiatoa* spp.) occasionally was observed covering portions of the suspected discharge accumulations (Photos 2-22 and 2-23). Natural sediments surrounding the platform consisted of sand/silt with shell fragments (Photo 2-24).

2.2.9 Viosca Knoll 780

Water depth at VK 780 was 210 m (690 ft). The structure at this site consisted of a single platform. The bottom near the drillsite was relatively level with some anthropogenic debris (e.g., a 55-gallon drum and grating). Accumulations of suspected discharged material were observed along the northeast platform legs and on top of substructures at the base of the platform (Photo 2-25). Depths of the accumulations on the platform substructure were variable, ranging from approximately a few inches to a slight dusting. Heaviest accumulations were observed along the near-bottom structural cross-members on the northeast side of the platform (Photos 2-26 and 2-27). Natural substrate at the site appeared to be soft mud (Photo 2-28).

2.2.10 Main Pass 299

Water depth at MP 299 was 60 m (197 ft). The structure at this station consisted of a single platform. The bottom near the given drillsite location was relatively level. Debris and suspected grout were observed in a 1-m (3.3-ft) depression near the platform. There were no visual indications of discharge accumulations within the survey area. A surficial layer of white filamentous material (?*Beggiatoa* spp.) occasionally was observed covering portions of sediment north of the platform structure (Photo 2-29). Sediments surrounding the drillsite area consisted of sand and mud with some coarse calcareous debris in close proximity to the platform (Photo 2-30).

2.3 SCREENING CRUISE

The results of the Scouting Cruise were reviewed in conjunction with other data such as discharge records, geographic location, and water depth to determine a set of continental shelf study sites to be sampled during the Screening Cruise. The Screening Cruise was conducted from 26 July to 7 August 2000. The continental shelf study sites sampled during the Screening Cruise were

- EW 305;
- GB 128;
- MP 288;
- MP 299; and
- VK 780.

In addition, three candidate continental slope study sites were sampled during this cruise:

- Green Canyon (GC) 112;
- Mississippi Canyon (MC) 28; and
- MC 496.

Photo 2-21 - Accumulation of suspected discharges along the northeast base of the Main Pass 288 platform. White filamentous mat (?*Beggiatoa* spp.) is visible overlying portions of the darker sediment.

Photo 2-22 - Accumulation of suspected mud and cuttings near the base of a Main Pass 288 platform diagonal support. White filamentous mat (?*Beggiatoa* spp.) is conspicuously visible adjacent to the platform support structure.

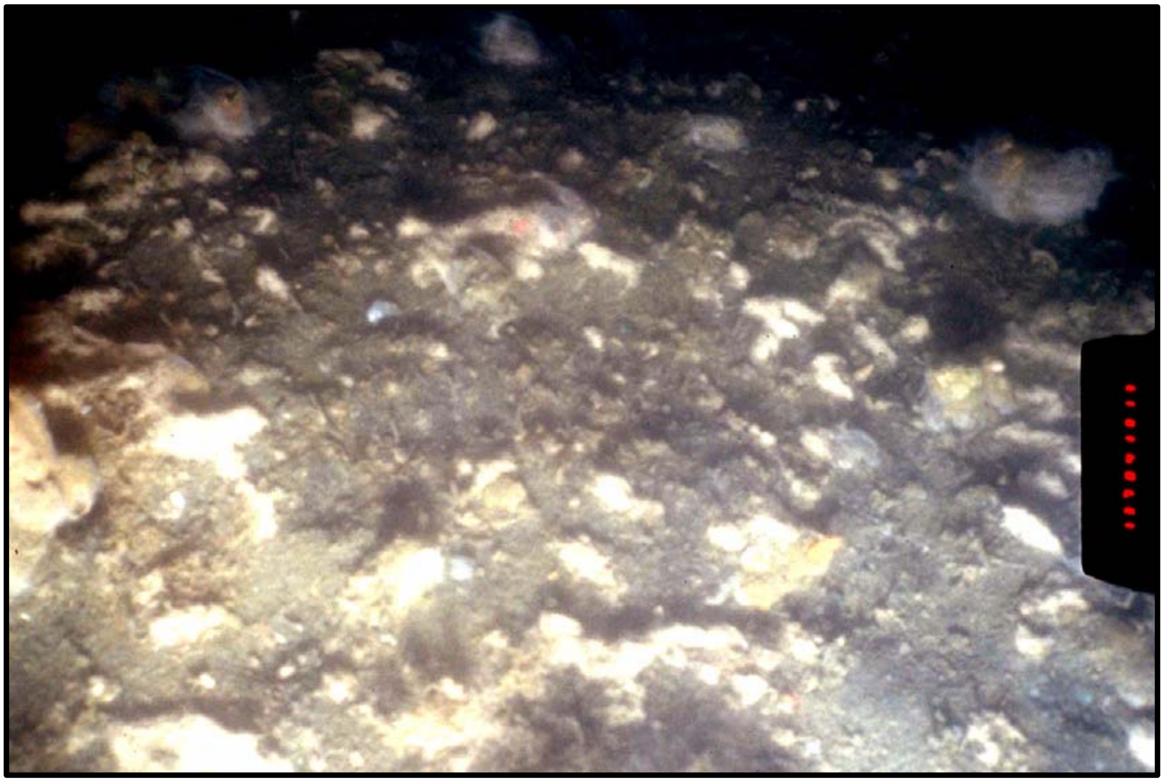


Photo 2-23 - Coarse dark sediment including barnacle and mollusk shell debris was observed in close proximity to the Main Pass 288 platform. Discontinuous white filamentous mat (?*Beggiatoa* spp.) was visible overlying portions of the near-platform sediment.

Photo 2-24 - Natural sediments surrounding the Main Pass 288 platform consisted of sand/silt with shell fragments.

Photo 2-25 - Accumulation of suspected discharge material along the northeast Viosca Knoll 780 platform. Depths of the observed accumulation ranged from approximately a few inches to a slight dusting.

Photo 2-26 - Suspected discharge material at the base of the Viosca Knoll 780 platform.

Photo 2-27 - Suspected discharge material observed at the Viosca Knoll 780 platform. Parthenopid crabs were visible on the suspected discharge material.

Photo 2-28 - Sea star *Anthenoides piercei* on mud bottom at Viosca Knoll 780.

Photo 2-29 - A surficial layer of a white filamentous material (?*Beggiatoa* spp.) on coarse substrate at Main Pass 299.

Photo 2-30 - Sediment in close proximity to the Main Pass 299 platform consisted of sand and mud with some coarse calcareous debris.

Early in the Screening Cruise, problems arose in attempting to collect sediment samples in the near-field at EW 305 due to the presence of a very hard clay layer. An alternate site, VK 783, was substituted for EW 305 as a study site.

As previously discussed in Chapter 1, one of the objectives of the Screening Cruise was to provide preliminary information on pre-selected study sites that were to be sampled during the two Sampling Cruises. Part of this evaluation was to confirm that sufficient samples would be collected during the two Sampling Cruises to determine if meaningful differences occurred spatially and temporally. To this end, a series of power curves (Cohen, 1977) were prepared and evaluated. Examples of these curves are presented in Figures 2-1 to 2-3. In these curves, the level of differences that can be detected is plotted against sample sizes at a particular power level. For convenience, several power levels were plotted on the same graph. These curves were examined to determine the sample size necessary to detect spatial and/or temporal differences. For example, the power curve for SBF concentration (Figure 2-1) indicates that, based on the variability of the entire set of SBF concentrations measured in samples collected during the Screening Cruise, a real change in mean SBF concentrations by a factor of 16 ($10^{1.2}$) would be detected with a power (probability of detecting a real difference) of 95% by comparison of two sets of six samples each. At sample sizes greater than six, the detectable difference in concentration decreases (i.e., the measurement sensitivity increases) only gradually for even large increases in sample size. As a result, the Sampling and Analysis Plans for Sampling Cruises 1 and 2 adopted a sample size of six samples in each stratum (near-field, mid-field, and far-field) as being an optimum balance between measurement sensitivity and cost.

After the data collected during the Screening Cruise were evaluated to finalize the study sites for the two Sampling Cruises and prior to Sampling Cruise 1, additional drilling at three sites was scheduled. To accommodate the objectives of the project, these sites were replaced with alternate study sites. The study sites for the two Sampling Cruises are presented in Table 2-2 with a summary of their respective SBM drilling history.

Table 2-2. Summary of SBM drilling at the study sites for Sampling Cruises 1 and 2.

Site	Water Depth (m)	SBM Type	Number of SBM Wells	SBM Cuttings Discharges (bbl)	Last SBM Cuttings Discharge
Eugene Island 346	92	IO	3	10,328	April 2000
Main Pass 288	119	IO	4	1,309	March 1998
Main Pass 299	83	LAO	3	966	April 2000
South Timbalier 160	37	IO	1	929	February 1998
Viosca Knoll 783	338	Ester	1	436	November 1995
Ewing Bank 963	535	IO	3	598	January 1997
Green Canyon 112	536	IO	4	5,470	December 1997
Mississippi Canyon 496	556	IO	1	1,674	October 1998

IO = Internal olefin.
LAO = Linear alpha olefin.
SBM = Synthetic based mud.

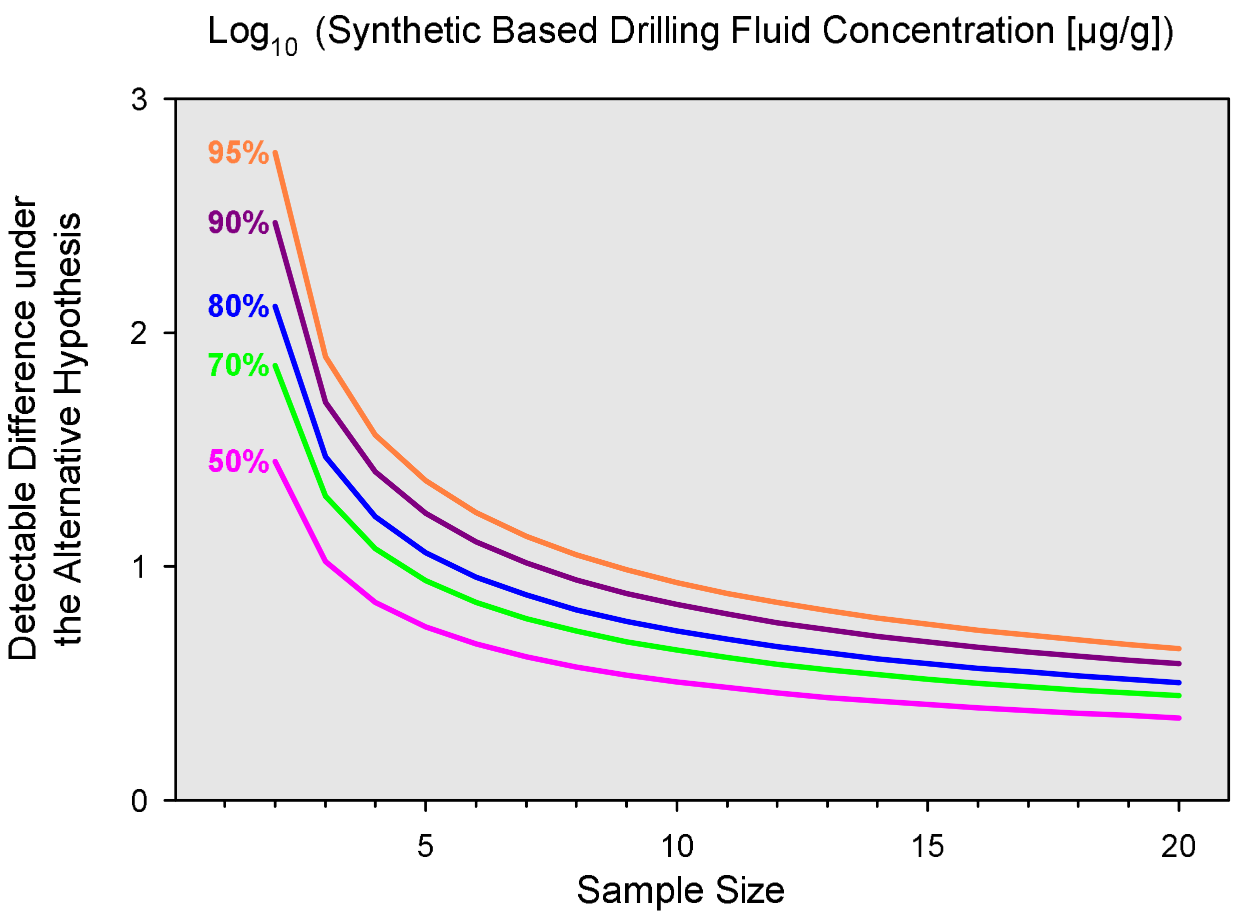


Figure 2-1. Power curves for synthetic based fluid concentration (log base 10 transformation) computed based on Screening Cruise data.

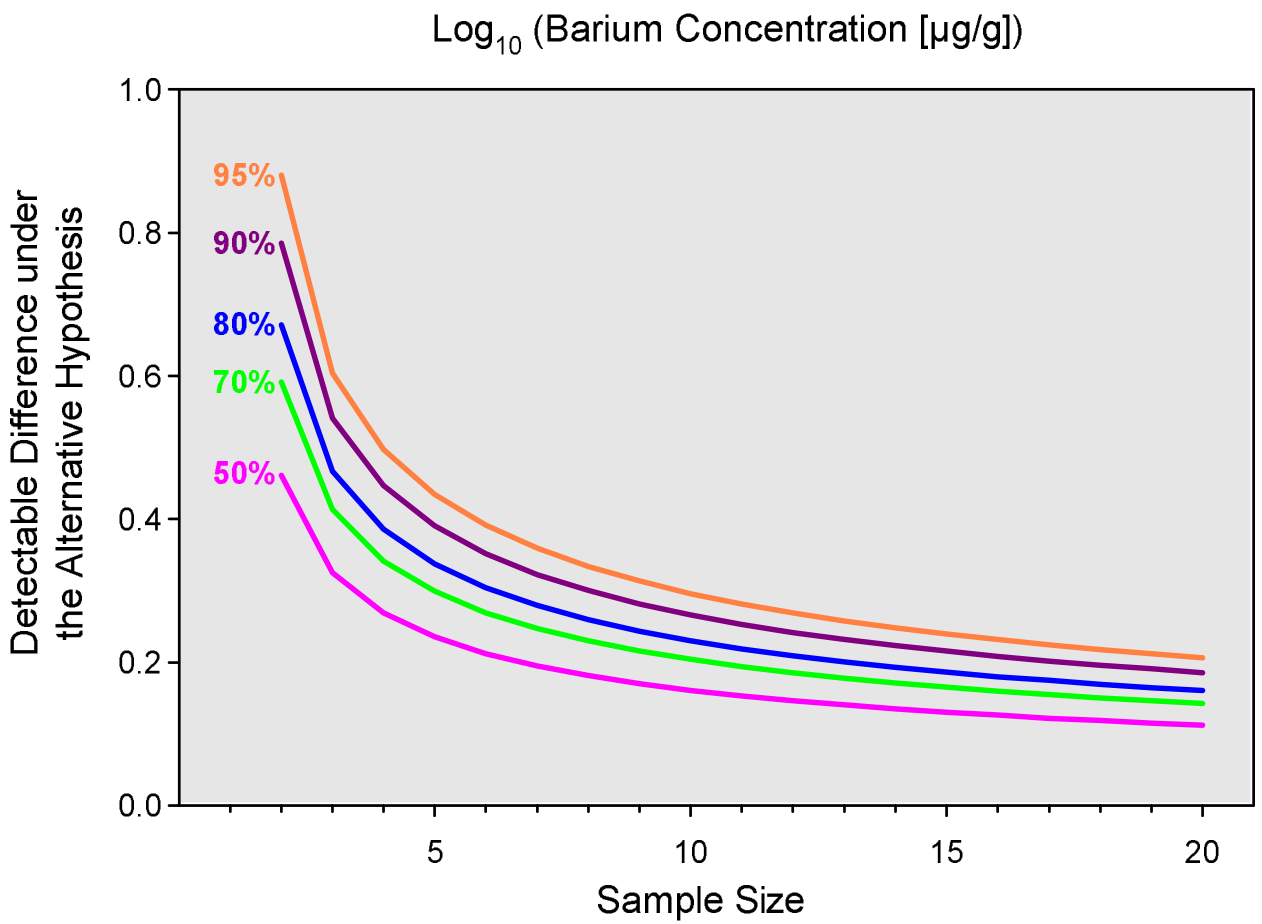


Figure 2-2. Power curves for barium concentration (log base 10 transformation) computed based on Screening Cruise data.

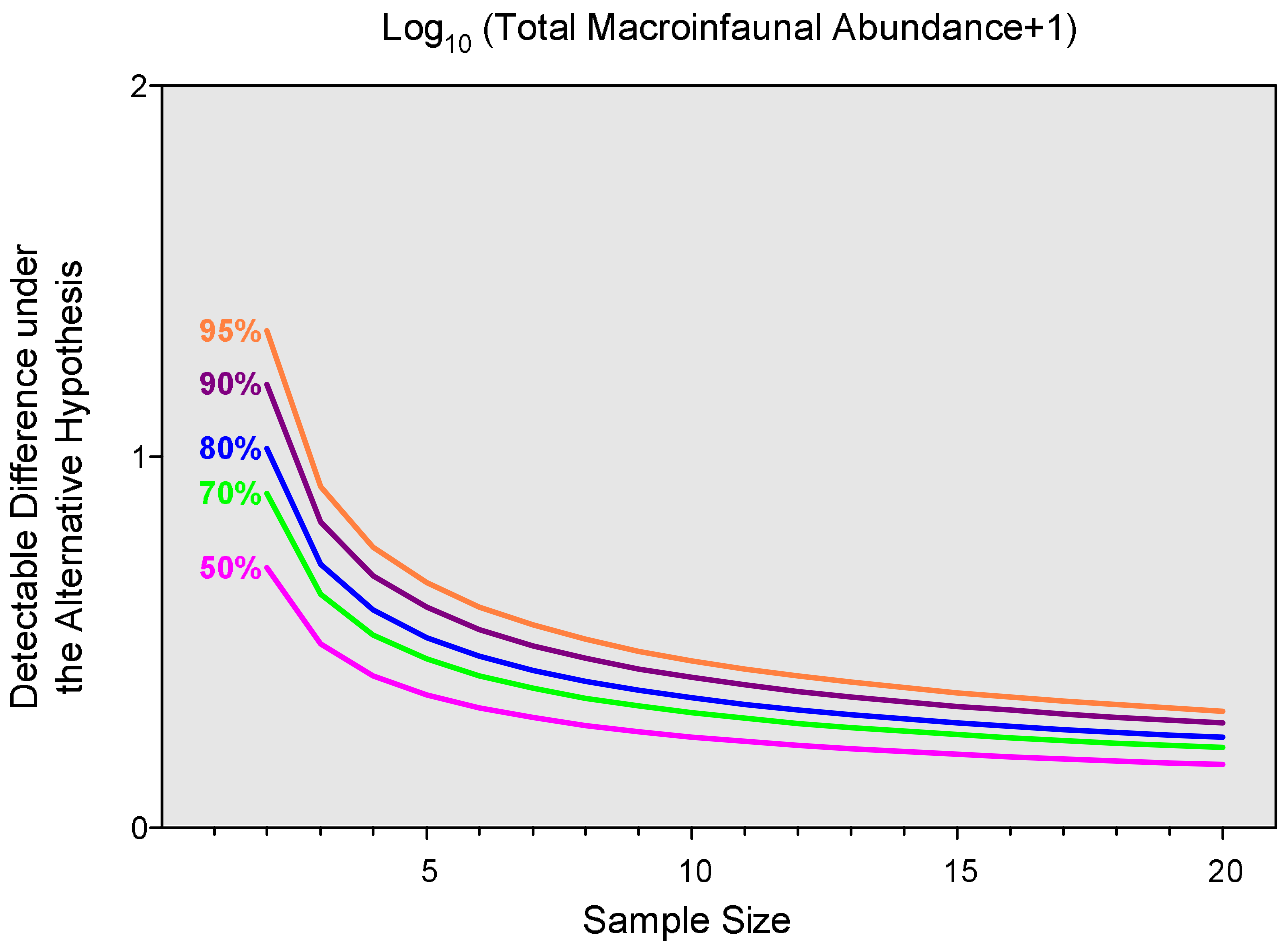


Figure 2-3. Power curves for total macroinfaunal abundance (log base 10 transformation) computed based on Screening Cruise data.

Chapter 3
FIELD METHODOLOGY

Stephen T. Viada
Continental Shelf Associates, Inc.

As discussed in Chapter 1, four field surveys were conducted during this program. These surveys were the Scouting Cruise, Screening Cruise, Sampling Cruise 1, and Sampling Cruise 2, and this chapter presents the field methodology that was used during each of these surveys.

3.1 SCOUTING CRUISE

The Scouting Cruise was conducted from 3 to 8 June 2000. This cruise was designed to provide preliminary information on potential study sites on the Gulf of Mexico continental shelf (<300 m [<984 ft] water depth). Acoustic and visual observations were made to 1) locate and assess the extent of cuttings accumulations; 2) assess the suitability of each study site for further sampling during the program; and 3) design the final sampling strategy. An ROV was used to collect video and acoustic data from seafloor areas around drillsites where SBM cuttings were discharged. Data collected during this cruise were used to select study sites to be sampled during the subsequent Screening Cruise (Section 3.2).

3.1.1 Study Sites

Ten sites were surveyed during the Scouting Cruise. Table 3-1 provides a list of these sites and corresponding water depths (sites are listed chronologically in the order they were visited during the cruise). Figure 3-1 shows the relative locations of the sites.

Table 3-1. Sites visited during the Scouting Cruise. Geodesy is North American Datum 27.

Lease Block Designation	Water Depth (m)	Site Center Latitude	Site Center Longitude
Ewing Bank 305/306	81	28°39'57" N	089°58'10" W
South Timbalier 160	40	28°34'49" N	090°20'17" W
South Marsh Island 60/61 “F”	38	28°40'15" N	090°58'15"W
Garden Banks 128	183	27°52'31" N	091°59'11" W
Eugene Island 390	113	28°00'26" N	091°40'53" W
Viosca Knoll 783	338	29°13'44" N	087°56'53" W
Viosca Knoll 782	290	29°14'17" N	087°58'28" W
Main Pass 288	119	29°14'23" N	088°24'34" W
Viosca Knoll 780	210	29°14'14" N	088°06'30" W
Main Pass 299	60	29°15'26" N	088°46'23" W

Figure 3-1. Location of sites surveyed during the Scouting Cruise.

3.1.2 Survey Vessel and ROV

The SEA HORSE I, a 46-m (150-ft) supply boat, was used as the main support platform for the Scouting Cruise. A medium-sized open frame ROV arm was used for investigations of the study sites. The ROV system was equipped with a system-specific launch and recovery system (LARS) and tether management system (TMS) for stabilizing operations near platform structures (Photo 3-1). The ROV system was controlled from the vessel using a 1,500-m armored main umbilical cable that supported the TMS. The ROV and TMS were deployed from the vessel as a single unit. After the latched ROV and TMS were lowered to within 20 m of the seafloor, the ROV was unlatched and maneuvered freely at the end of its 122-m neutrally buoyant tether. The ROV was equipped with auto depth, heading, and altitude capabilities, enabling the pilot to select and automatically maintain the vehicle at a specific heading, depth, and/or height off the bottom.

All of the equipment and instrumentation used for data collection was mounted on the ROV. A Simrad MS900 color imaging sonar system was used during the cruise to reconnoiter the bottom topography within the survey area. The color imaging sonar system provided 1) long range (100 m), high resolution, acoustic navigation; 2) object or obstacle detection; and/or 3) avoidance capability. This subsystem was the primary tool for detecting irregular or anomalous topographic features, especially in near-bottom low visibility conditions encountered during this cruise. The ROV was outfitted with video and 35-mm still cameras, mounted directly on the ROV frame and on a pan and tilt unit. The video and still cameras on the pan and tilt unit were adjusted to collect photographic data within the same field of view.

Videocameras included two high resolution (450 lines), medium light sensitive, Super VHS color units. One camera was configured with a wide-angle lens and mounted on the forward portion of the ROV frame for ROV piloting and general observations. The other videocamera was mounted on the pan and tilt unit and configured with a close-up lens and remote focus control for close range observations. This video system provided both high resolution and high quality color imagery for interpreting sediment characteristics. Four 150-watt quartz halogen underwater lamps provided video lighting. Two lamps were mounted on the pan and tilt unit, and two were mounted on the ROV frame. The ROV was outfitted with a Photosea 1000 still camera and strobe for 35-mm still photography. The camera was loaded with 30-ft rolls of film providing a 250-exposure capacity. The system was equipped with an LED data chamber that placed a data cell showing date, time, and photograph number on each frame of the still camera film. The still camera and strobe were triggered manually from the topside controller by a scientist who viewed the imagery from the videocamera that had the same field of view. The camera system was powered by a nicad battery pack that carried enough charge for approximately 500 flashes. Segments (tails) of each film roll were developed on board to assure proper data quality (i.e., exposures and film advance).

The ROV also was outfitted with a five-function manipulator arm. The manipulator arm was used to mechanically disturb sediment for texture verification and perform various other physical tasks.

Photo 3-1 - Triton remotely operated vehicle (ROV) with launch and recovery system (LARS) and tether management system (TMS) used during the Screening Cruise.

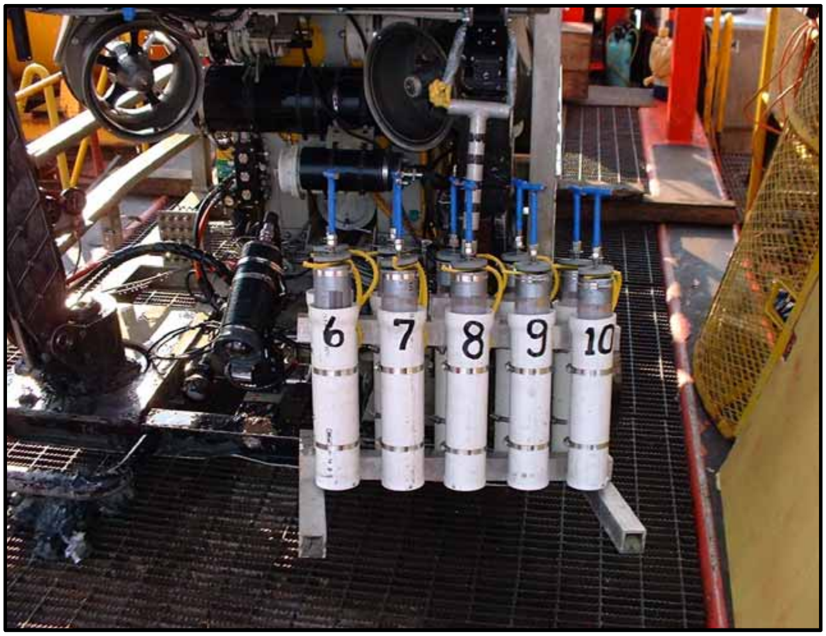


Photo 3-2 - Sampling gear (acrylic cores and carrier rack) used for the collection of discretionary sediment samples from the remotely operated vehicle during the Screening Cruise.

3.1.3 Navigation, Positioning, and Tracking

Navigation for this project was conducted using the Universal Transverse Mercator (UTM) grid. The UTM grid is most appropriate for scales of 1:250,000 and larger. The UTM coordinates are measured in meters (or feet) east and north from two perpendicular reference baselines. North American Datum (NAD) 27 was used as the local reference datum for this study. The UTM coordinates were converted to latitude and longitude for the figures presented in this chapter.

The vessel navigation system consisted of a Magnavox Model 300 differential global positioning system (DGPS) receiver coupled with a Starlink Model MRB-2A beacon receiver. Differential corrections were acquired using Coast Guard beacons, which broadcast real-time GPS differential corrections. The primary Coast Guard beacon station was at English Turn, Louisiana. The navigational system with differential correction had an accuracy of ±2 m. A complete duplicate backup DGPS system was carried on board in the event the primary system malfunctioned.

Continental Shelf Associates, Inc.'s (CSA's) navigation and data acquisition system (NADAS), a modular computer software and hardware package, was used to interface the various data collection sensors with the DGPS positioning system. The foundation of the system was Coastal Oceanographics Hypack for Windows software. The NADAS was used for vessel guidance, data logging, and real time vessel track plotting via both a primary display on the navigator's computer and a secondary display monitor placed in front of the vessel's helmsman.

A Ferranti ORE Trackpoint II ultra short base line (USBL) acoustic underwater tracking system was used to accurately and precisely track the position of the ROV. This system was used in conjunction with CSA's NADAS. The Trackpoint II system consisted of a topside deck unit connected to an underwater transceiver fixed to an articulating mount. A battery-powered transponder beacon, mounted on the ROV, was used to transmit and receive an acoustic signal. The transceiver received the acoustic signal from the responder, converted the signal to digital form, and sent it to the topside deck unit. The topside deck unit used its internal software to compute the range, bearing, and depth of the ROV relative to the transceiver. Offsets were input to determine these parameters relative to the navigation antenna on the vessel. Range, bearing, and depth were relayed to CSA's NADAS, producing a real-time display of the precise position of both vessel and ROV with respect to true north and each other. The transceiver had built-in accelerometers to compensate for vessel motion due to sea conditions. The navigational system was calibrated with visits to a known benchmark placed on or identified at each site during the cruise. The positional error for the trackpoint system was 2% of the water depth.

3.2 SCREENING CRUISE

The Screening Cruise was conducted from 26 July to 7 August 2000. This field effort was designed to provide preliminary information on preselected study sites in the Gulf of Mexico. Four continental shelf (37 to 119 m [121 to 390 ft] water depth) study sites and four continental slope (>300 m [>984 ft] water depth) study sites were sampled. An ROV was used to conduct acoustic side-scan sonar and bathymetric mapping surveys to assess the extent of cuttings accumulations and locate stations for discretionary sediment sampling. Sediment samples were collected from randomly selected stations at each site.

3.2.1 Study Sites

Eight primary sites and one alternate site were surveyed during the Screening Cruise. The nine sites, their site designations ("continental shelf" or "continental slope"), and their water depths are presented in Table 3-2. Sites are listed chronologically in the order they were visited. Figure 3-2 shows the relative locations of the sites. Sampling locations are shown in Appendix A, Figures A-1 to A-9. An example of the sampling location figures is shown in Figure 3-3.

Table 3-2. Sites visited during the Screening Cruise. Geodesy is North American Datum 27.

Lease Block	Site Designation	Water Depth (m)	Site Center Latitude	Site Center Longitude
Ewing Bank 305	Shelf	81	28°39'57" N	089°58'10" W
Garden Banks 128	Shelf	183	27°52'31" N	091°59'11" W
Main Pass 288	Shelf	119	29°14'23" N	088°24'34" W
Main Pass 299	Shelf	60	29°15'26" N	088°46'23" W
Viosca Knoll 780	Shelf	210	29°14'14" N	088°06'30" W
Green Canyon 112	Slope	534	27°51'19" N	091°58'15" W
Mississippi Canyon 496	Slope	556	28°27'02" N	089°22'26" W
Mississippi Canyon 28	Slope	558	28°55'59" N	088°34'30" W
Viosca Knoll 783 (alternate site)	Slope	338	29°13'44" N	087°56'53" W

3.2.2 Survey Vessel and ROV

The DP (dynamic positioning) ROVSV MERLIN, a 200-ft supply vessel, was used as the primary support vessel for the Screening Cruise. A Triton XL 100 ROV, equipped with a system-specific LARS and TMS (as described in Section 3.1.2), was used during seafloor mapping operations and for discretionary sediment collection. The ROV was equipped with automatic depth, heading, and altitude capabilities to enable the vehicle to maintain a specified heading, depth, and/or height (altitude) off the bottom. A Simrad 900-D digital imaging sonar system, attached to the ROV frame, was used to reconnoiter the bottom topography within the survey area and provided a long range (100 m) high resolution acoustic navigation and object or obstacle detection and/or avoidance capability. A Reson SeaBat 8101 multibeam bathymetric processor, also mounted on the ROV frame, was used during the ROV seafloor mapping survey (Section 3.2.4). The ROV was outfitted with video and 35-mm still cameras for navigation and photodocumentation of seafloor features and discretionary sediment sampling efforts. The videocameras varied in resolution and light sensitivity. One camera was configured with a wide-angle lens and was mounted on the forward portion of the ROV frame for ROV piloting and general observation. The second videocamera was mounted on a pan and tilt unit and configured with a close-up lens and remote focus control for close range observations. The second video system provided both high resolution and high quality color imagery for interpreting sediment characteristics. Four 150-watt quartz halogen underwater lamps provided video lighting. Two lamps were mounted on the ROV frame, and two were mounted on the pan and tilt unit. The ROV also was outfitted with a multifunction manipulator arm that was used to collect and retrieve sediment and biological samples from discretionary stations at each study site.

Figure 3-2. Location of sites surveyed during the Screening Cruise.

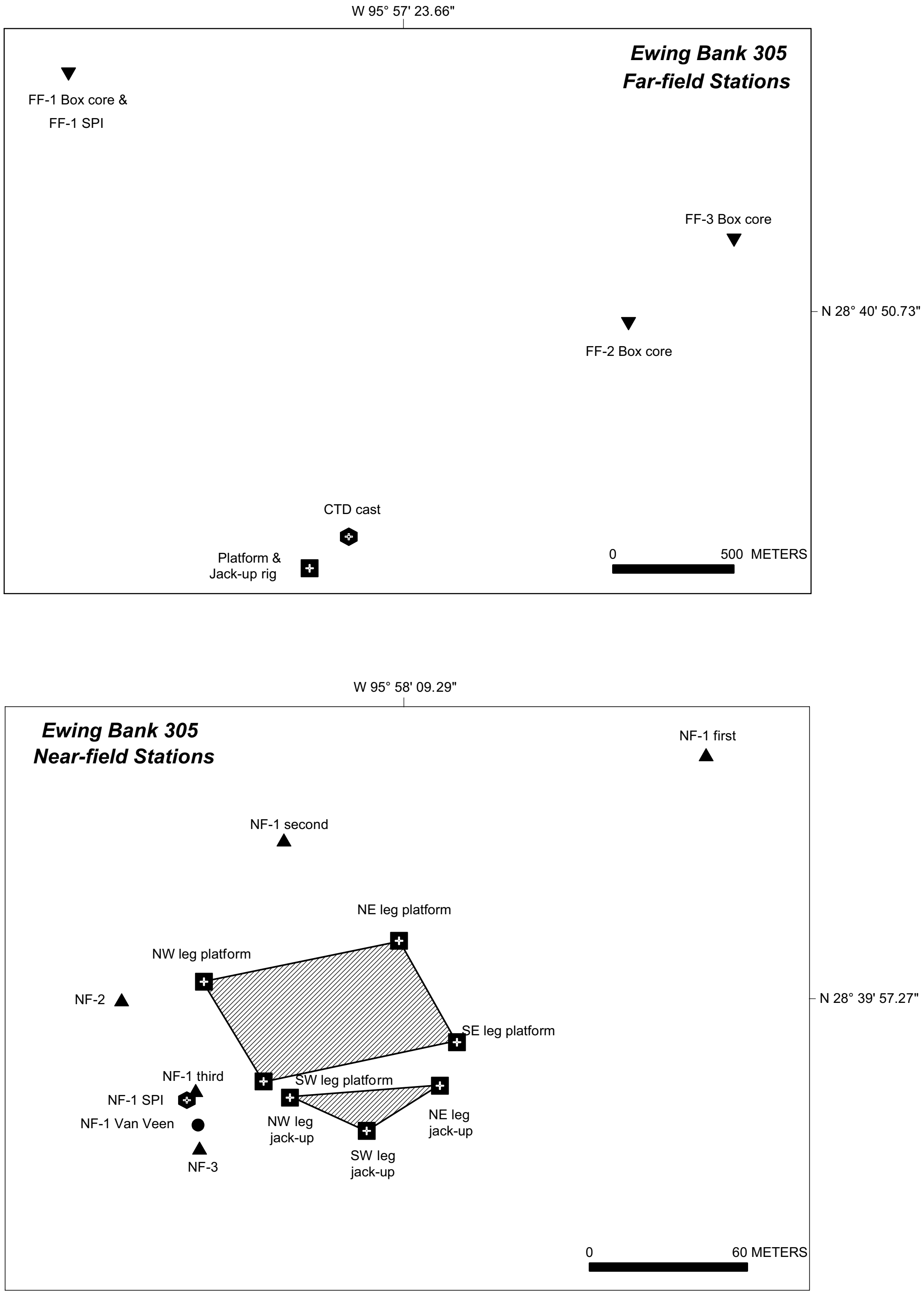


Figure 3-3. Locations of stations sampled during the Screening Cruise in Ewing Bank 305 relative to the platform and jack-up rig.

3.2.3 Navigation, Positioning, and Tracking

As described in Section 3.1.3, the survey vessel's navigation system consisted of a Magnavox Model 412 DGPS receiver, coupled with a Starlink Model MRB-2A beacon receiver. CSA's NADAS was used to interface the various data collection sensors with the DGPS positioning system.

A Sonardyne USBL acoustic underwater tracking system was used in conjunction with CSA's NADAS to accurately track the position of in-water sampling devices (i.e., the ROV, box core, and SPI camera), with respect to the survey vessel. The Sonardyne system consisted of a topside deck unit that was connected to an underwater hydrophone. The hydrophone was fixed to a retractable, through-hull mount. A battery powered responder beacon mounted on the in-water sampling devices was used to transmit and receive an acoustic signal. The hydrophone received the acoustic signal from the responder, converted the signal to digital form, and sent it to the topside deck unit. The topside deck unit used its internal software to compute the range, bearing, and depth of the ROV relative to the hydrophone. Offsets were input to determine these parameters relative to the navigation antenna on the vessel. Range, bearing, and depth were relayed to CSA's NADAS, which provided a real-time display of the precise position of the vessel and ROV with respect to true north and each other. The Sonardyne system was properly calibrated with visits to known benchmarks previously identified at each site during the Scouting Cruise.

3.2.4 ROV Seafloor Mapping Survey

An ROV seafloor mapping survey was conducted over a 500-m x 500-m area surrounding each study site center in an effort to locate potential accumulations of drilling muds/cuttings. A minimum of seven parallel transect lines was established to provide adequate overlapping coverage of each study site. Transect lines were set up on north-south or east-west headings with 60-m line spacing. ROV altitude was maintained at approximately 15 m. The Reson SeaBat 8101 multibeam processor simultaneously collected high resolution swath bathymetry data and side-scan sonar data. The on-board Isis Data Acquisition and Presentation System enabled a real-time review of the SeaBat data collected at each study site for determining potential targets for ROV discretionary sediment sampling. The resolutions of the swath bathymetry data and the side-scan sonar data were 1 and 2 m, respectively.

3.2.5 Hydrographic Profiles

A Sea-Bird Electronics SEACAT recording water quality profiler (conductivity, temperature, depth [CTD] probe) was used to collect hydrographic data daily at each study site. Water column values for temperature, salinity, and depth were logged continuously from near-surface to near-bottom depths. Temperature was recorded in °C, salinity in parts per thousand (ppt), and depth in meters. Prior to each profile, the CTD probe was checked for calibration and attached to the side of the SPI camera frame with its dissolved oxygen probe positioned slightly above the base of the frame. This ensured that the deepest oxygen measurements would be obtained very close to the seafloor. Results of the hydrographic profiles are presented in Appendix B.

3.2.6 Sediment Collection

Sediment collection locations at each of the Screening Cruise study sites are shown in Appendix A, Figures A-1 to A-9. At each of the eight study sites, six sediment stations were sampled for physical and chemical measurements using a box core. Three of these stations were at random locations near the platform or template (near-field stations), and three were at random reference locations (far-field stations). Sediment samples were collected for redox profiling/dissolved oxygen measurements, and grain size, clay mineralogy, TPH, metals (Al, As, Ba, Cd, Cr, Cu, Fe, Hg, Ni, Pb, V, and Zn), TOC, and visual cuttings analyses. Six infaunal and sediment toxicity samples were collected at the four continental shelf sites and one continental slope site for preliminary biological and sediment toxicity analyses. In addition, two core samples collected at each of the eight sites were vertically sectioned in 2-cm increments, with the sections analyzed separately for grain size, metals, and TPH to investigate vertical layering of sediment samples collected near the drillsites. Continental Shelf Associates, Inc. (2000) presented these data (see Appendix I).

Additional sediment samples were collected at a discretionary location at seven study sites. These discretionary samples were collected in suspected cuttings accumulations identified during the ROV seafloor mapping effort (described in Section 3.2.4). At one continental slope site, the Pompano II subsea drilling template in MC 28, one sample was collected at a discretionary location, and two were collected at previously sampled locations. Tables 3-3 and 3-4 present summaries of sample and data collection for the continental shelf and continental slope study sites, respectively.

3.2.6.1 ROV Samples. The ROV was used to collect sediment samples from a selected "discretionary" area located at a suspected muds/cuttings accumulation at each of the eight study sites. The ROV was equipped with a carrier rack for holding 10 to 20 acrylic cores (depending on the study site to be sampled) (Photo 3-2). The acrylic cores had an inside diameter of 6.67 cm (2-5/8 in.) and height of 38.1 cm (15 in.) and were equipped with a top mounted "T" handle attached to a PVC one-way valve assembly. The "T" handle was designed to facilitate handling of the core tubes by the ROV manipulator arm during sediment collection. The one-way valve allowed water to be displaced during insertion of the core and created suction for keeping sediment in place within the core after collection.

Five acrylic cores were collected within a circle with a 1-m diameter at each of the discretionary sediment sampling stations. Sediment sampling parameters per suite of collected cores was as follows:

- TPH;
- metals and TOC;
- grain size;
- clay mineralogy (top 2 cm and vertical profile); and
- visual cuttings analysis and a redox/O_2 profile.

Field methods for sediment sample collection and processing are described in the following subsections.

Table 3-3. Summary of sampling for the Screening Cruise continental shelf study sites.

Near-field Sediment Sampling	• Box core samples at 3 stations • SPI penetrations at 2 stations
Near-field Hydrographic Profile	• Hydrographic (temperature and salinity) profile at 1 SPI near-field station at each site
ROV Mapping and Sediment Sampling	• ROV collected swath bathymetry and side-scan sonar data for detailed mapping of potential cuttings accumulations • Visual investigation of potential cuttings accumulations • ROV collected sediment at discretionary location of suspected cuttings accumulation • Video data collected during the visual investigation of potential cuttings accumulations
Far-field Sediment Sampling	• Box core samples at 3 stations • SPI penetration at 1 station
Samples/Analyses	• Redox profile at 7 sediment sampling locations • Grain size at 7 sediment sampling locations • Visual cuttings analysis at 7 sediment sampling locations • SPI images at 3 sediment sampling locations • SBF/TPH by GC-FID at 7 sediment sampling locations • Metals: (Ba, Fe, Al, and Mn) at 7 sediment sampling locations; Al, As, Ba, Cd, Cr, Cu, Fe, Hg, Mn, Ni, Pb, V, and Zn at selected locations • Clay mineralogy at 7 sediment sampling locations • TOC at 7 sediment sampling locations • Macroinfauna at 6 sediment sampling locations (outside platform footprint) • Sediment toxicity at 6 sediment sampling locations (outside platform footprint)

GC-FID = Gas chromatography-flame ionization detection.
Redox = Reduction-oxidation potential.
ROV = Remotely operated vehicle.
SBF = Synthetic based fluids.
SPI = Sediment profile imaging.
TOC = Total organic carbon.
TPH = Total petroleum hydrocarbons.

Table 3-4. Summary of sampling for the Screening Cruise continental slope study sites.

Near-field Sediment Sampling	• Box core samples at 3 stations • SPI drift transects at 2 stations
Near-field Hydrographic Profile	• Hydrographic (temperature and salinity) profile at 1 SPI near-field station at each site
ROV Mapping and Sediment Sampling	• ROV collected swath bathymetry and side-scan sonar data for detailed mapping of potential cuttings accumulations • Visual investigation of potential cuttings accumulations • ROV collected sediment at discretionary location of suspected cuttings accumulation • Video data collected during the visual investigation of potential cuttings accumulations
Far-field Sediment Sampling	• Box core samples at 3 stations • SPI drift transect at 1 station
Samples/Analyses	• Redox profile at 7 sediment sampling locations • Grain size at 7 sediment sampling locations • Visual cuttings analysis at 7 sediment sampling locations • SPI images at 3 sediment sampling locations • SBF/TPH by GC-FID at 7 sediment sampling locations • Metals: Ba, Fe, Al, and Mn at 7 sediment sampling locations; Al, As, Ba, Cd, Cr, Cu, Fe, Hg, Mn, Ni, Pb, V, and Zn at selected locations • Clay mineralogy at 7 sediment sampling locations • TOC at 7 sediment sampling locations • Macroinfauna at 6 sediment sampling locations at 1 of the continental slope sites

GC-FID = Gas chromatography-flame ionization detection.
Redox = Reduction-oxidation potential.
ROV = Remotely operated vehicle.
SBF = Synthetic based fluids.
SPI = Sediment profile imaging.
TOC = Total organic carbon.
TPH = Total petroleum hydrocarbons.

3.2.6.2 Box Core Samples. All sediment samples, except samples from the discretionary station and the two additional stations at MC 28, were collected using a precleaned, 0.12 m^2 Gray-O'Hara stainless steel box core sampler (Photo 3-3). The box core sampler was deployed using an electro-hydraulic winch with 3/8-in. diameter wire rope. When the box core was retrieved, the collected sample was visually inspected according to the standard operating procedure to determine that there was no forceful leakage of water and loss or disturbance of fine, surface layer sediments from the sample (Photo 3-4).

3.2.6.3 Sediment Subsampling and Sample Processing. Acceptable box core samples were subsampled using acrylic and Teflon® core tubes and a square, stainless steel sediment-partitioning core, depending on the study site, following the standard operating procedures in the Project Quality Assurance Plan. Acrylic and Teflon® core tubes had an inside diameter of 9.7 cm (3-13/16 in.) and height of 25.4 cm (10 in.). The stainless steel core had an opening of 20 cm x 20 cm, a height of 20.3 cm (8 in.), and a 5-cm-increment demarcation along the inside wall. The number of coring devices used to subsample box core sampling stations at continental shelf and continental slope sites was 6 and 3, respectively. The core tube type and sediment sampling parameter per box core sample for continental shelf sites were as follows:

- one Teflon® core tube for TPH, metals, TOC, and grain size;
- one acrylic core tube for clay mineralogy (top 2 cm), visual cuttings analysis, and redox/O_2 profile;
- one acrylic core tube for interstitial water and/or clay mineralogy vertical profile;
- two acrylic cores for macroinfauna; and
- one stainless steel core for sediment toxicity.

Core types and sediment sampling parameters per box core sample were the same for continental slope study sites, but without macroinfaunal and sediment toxicity samples. Each subsampling core was inserted vertically into the sediment sample through the top access doors of the box core sampler. All cores were thus placed in the collected sample prior to removing subsamples to prevent disturbance of the sediment surface by individual core removal (Photo 3-5). Excess water, if present, was siphoned from the box core sampler through a precleaned Tygon® hose prior to removal of the cores. The subsampling coring tubes were then extracted and individually processed. The top 2 cm from the core tubes provided adequate sediment (approximately 220 g wet weight) for TOC, metals, TPH, visual cuttings and clay mineralogy, and grain size analyses. Any clear (i.e., sediment-free) surface water overlying the subsample was decanted, and the flocculent layer, when present, was poured into a precleaned 1-L glass mixing bowl or appropriate container. Care was exercised to maintain vertical orientation of the coring tube. A rubber plunger was inserted up into the bottom of the coring tube, and a precleaned 2-cm high ring (of the same diameter and material as the tube) was held firmly in place on the top edge of the coring tube. The plunger then was pushed up, filling the ring with sediment. The portion of sediment in the ring then was sheared from the coring tube and transferred into the precleaned 1-L glass mixing bowl into which the flocculent layer was decanted. This material was homogenized and subdivided for the various analyses.

Photo 3-3 - Retrieval of the box core during the Screening Cruise.

Photo 3-4 - Visual inspection of the surface layer and integrity of a box core sample.

Photo 3-5 - Placement of Teflon® and acrylic core tubes within a box core sample.

Photo 3-6 - Collection of 2-cm subsurface samples from a Teflon® core tube.

The acrylic core tube used for redox/O_2 profiling and clay mineralogy and visual cuttings samples was perforated with sealed access holes at 1-cm increments along its length. Following redox/O_2 profiling, the top 2 cm of sediment was placed into a precleaned 1-L glass mixing bowl, homogenized, and subdivided.

At each station, a separate acrylic core tube was removed from the box core sample as an undisturbed vertical profile for clay mineralogy analysis. After removal, both ends of the core tube were capped, and the integrity of the sediment layering within the core tube was maintained (i.e., the tube was not tipped or inverted).

One Teflon® core tube from two stations at each site was vertically sectioned in 2-cm increments to provide subsurface sediment samples for metals, TPH, and grain size analyses at three sediment depth intervals (0 to 2, 4 to 6, and 8 to 10 cm [or other appropriate intervals identified in the field]) (Photo 3-6). Subsurface sediments were collected, processed, and stored in the same manner as the surface sediments described below. Intermediate sediment layers (2 to 4 and 6 to 8 cm) were discarded.

Subsamples for sediment toxicity analyses were collected from each box core sample using the stainless steel core. The top 5 cm of sediment removed from the core provided enough material (approximately 2 L) for duplicate sets of sediment toxicity samples. The partitioning core was inserted into the box core sample to the level of the top 5 cm scribed line. Clear (i.e., sediment free) surface water overlying the subsample was siphoned through a precleaned Tygon® hose and discarded. Any remaining flocculent layer was siphoned through the same Tygon® hose into the precleaned, 4-L sample container. A precleaned stainless steel scoop was used to remove the sediment from the partitioning core and place it into two sample containers. As holding time for sediment toxicity samples was 30 days, arrangements were made to ship samples to Battelle Marine Science Laboratories during the Screening Cruise to ensure the holding time was not exceeded.

Sediment from two acrylic core tubes was used for macroinfaunal analyses. Sediment from these coring tubes was combined and gently washed through a 0.5-mm mesh sieve (Photo 3-7). The material remaining on the sieve following washing was placed in a labeled container.

Sediment chemistry samples (SBF, TPH, metals, and TOC) were stored frozen at temperatures below 0°C. Other samples were stored under refrigeration at temperatures of 2°C to 4°C. Macroinfaunal samples were preserved with a solution of 5% buffered formalin and rose bengal stain.

3.2.6.4 Equipment Cleaning. All equipment used for collecting and processing sediment chemistry samples was cleaned prior to sampling operations. Sampling equipment included the box core sampler, Teflon® and acrylic core tubes, 2-cm rings, plungers, mixing bowls, utensils, and commercially precleaned sample containers.

The box core sampler was cleaned daily with phosphate-free soap and rinsed with seawater prior to sampling. Between stations, the sampler was cleaned with seawater. The plungers used to extract sediment from coring tubes also were washed with seawater between stations.

Photo 3-7 - Washing macroinfaunal samples through 0.5-mm wire mesh sieves.

Photo 3-8 - Sediment profile imaging (SPI) camera and frame. Sonardyne® beacon (yellow) shown mounted on SPI frame leg.

Cleaning procedure for Teflon® core tubes, 2-cm rings, mixing bowls, and utensils was as follows:

> *Initial wash* - conducted prior to sampling operations; equipment washed with phosphate-free soap and clean seawater and scrubbed with a nylon brush;
>
> *Water rinse* - conducted after each usage; equipment rinsed with clean seawater;
>
> *Acid wash* - equipment thoroughly soaked in a plastic bucket containing 10% to 20% solution of nitric acid;
>
> *Organic solvent wash* - equipment washed in a stainless steel bucket containing organic solvent (i.e., acetone or hexanes) to remove any organics; and
>
> *Water rinse* - equipment thoroughly rinsed with deionized water (DIW).

Acrylic core tubes and 2-cm rings were washed with phosphate-free soap and clean seawater, scrubbed with a nylon brush, and rinsed with DIW.

3.2.7 Field and Equipment Blank Collection Methods

Field and equipment blanks were collected for each sediment chemistry sample parameter (i.e., TOC, metals, and TPH). Equipment blanks were collected from the sediment coring tubes and/or sampling utensils for each parameter. TOC and metals equipment blanks were collected by pouring DIW through a precleaned coring tube or over a sampling utensil and into the appropriate sample bottle. TPH equipment blanks were collected by storing a precleaned Teflon® and/or acrylic coring tube in precleaned aluminum foil.

3.2.8 *Beggiatoa* Samples

Samples suspected to be the sulfur-oxidizing bacteria *Beggiatoa* spp. were collected from box core and ROV core sediment samples for identification. A quantity of white or pale red-orange filamentous mat, suspected to be the bacteria, was removed from surface layers of sediment, placed in labeled containers, and preserved with a mixture of filtered seawater, 2.5% glutaraldehyde, and 1.0% formalin.

3.2.9 Sediment Profile Imaging

A series of SPI photographs were collected at three sediment sampling stations at each study site. These photographs were obtained using a vertically oriented 35-mm still camera that was housed over a mirrored prism and designed to slide vertically within a support frame (hereafter termed SPI camera). A vertically oriented videocamera also was mounted on the support frame (Photo 3-8).

During each SPI camera transect, the camera array was alternately lowered to the seafloor and then lifted to a height of approximately 15 m. As the frame reached the seafloor, the sliding prism device would penetrate the seafloor sediment and trip the mechanical trigger for shutters on the still camera and videocamera. This would result in the exposures of two still photographs that showed the vertical layering of sediment against the front of the prism's glass face, and a segment of video to show still camera function and the seafloor surface. The SPI system was designed to provide information concerning RPD depth, sediment texture, cuttings, and macroinfauna.

Slide film for the 35-mm still camera was developed in the field using Jobo semi-automated equipment and freshly mixed E6 chemicals. Following film development, each slide was labeled with station designation and replicate (if applicable). Slides were checked against the field log to ensure that all stations were sampled.

During every sampling station deployment, the SPI system was checked to ensure proper penetration of prism and still camera flash in real time on deck via the video monitor. Any miss-fires or camera operating problems were corrected while on station. A complete back-up system was available in case the first system failed. All SPI video results were logged and recorded onto high band 8-mm videotape (Hi8-mm videotape).

3.3 SAMPLING CRUISE 1

Sampling Cruise 1 was conducted from 5 to 16 May 2001. Two Sampling Cruises were scheduled in this program and were designed to determine levels and spatial distributions of sediment SBF concentrations around eight selected drillsites. A comparison of data collected from Sampling Cruises 1 and 2 (scheduled approximately 1 year apart) provided information to evaluate temporal change(s) in the levels and distributions of sedimentological, chemical, and biological parameters in proximity to these drillsites.

3.3.1 Study Sites

Eight study sites, consisting of four continental shelf (37 to 119 m [121 to 390 ft] water depth) and four continental slope (>300 m [>984 ft] water depth) sites, were visited during Sampling Cruise 1. Three shelf sites were designated as primary sites and one as a secondary site, based on results derived from data collected during the previous Screening Cruise. Similarly, there were three primary continental slope sites and one secondary continental slope site. Positional coordinates of the study site centers, along with corresponding site designations and water depths, are listed in Table 3-5. The relative locations of these sites are shown on Figure 3-4. In addition, a site partially completed during the previous Screening Cruise within Ewing Bank (EW) 305 was visited during this cruise to collect samples to evaluate the sedimentological and chemical characteristics of a sediment layer from a near-field station that appeared to be dense clay and prevented the penetration of the box corer used during the previous cruise.

Table 3-5. Study sites visited during Sampling Cruise 1.

Site Name	Site Designation	Water Depth (m)	Number of Synthetic Based Mud Wells
Eugene Island 346	Shelf	92	4
Main Pass 288	Shelf	119	3
Main Pass 299	Shelf	83	3
South Timbalier 160	Shelf	37	1
Ewing Bank 963	Slope	535	2
Green Canyon 112	Slope	536	2
Mississippi Canyon 496	Slope	556	1
Viosca Knoll 783	Slope	338	1

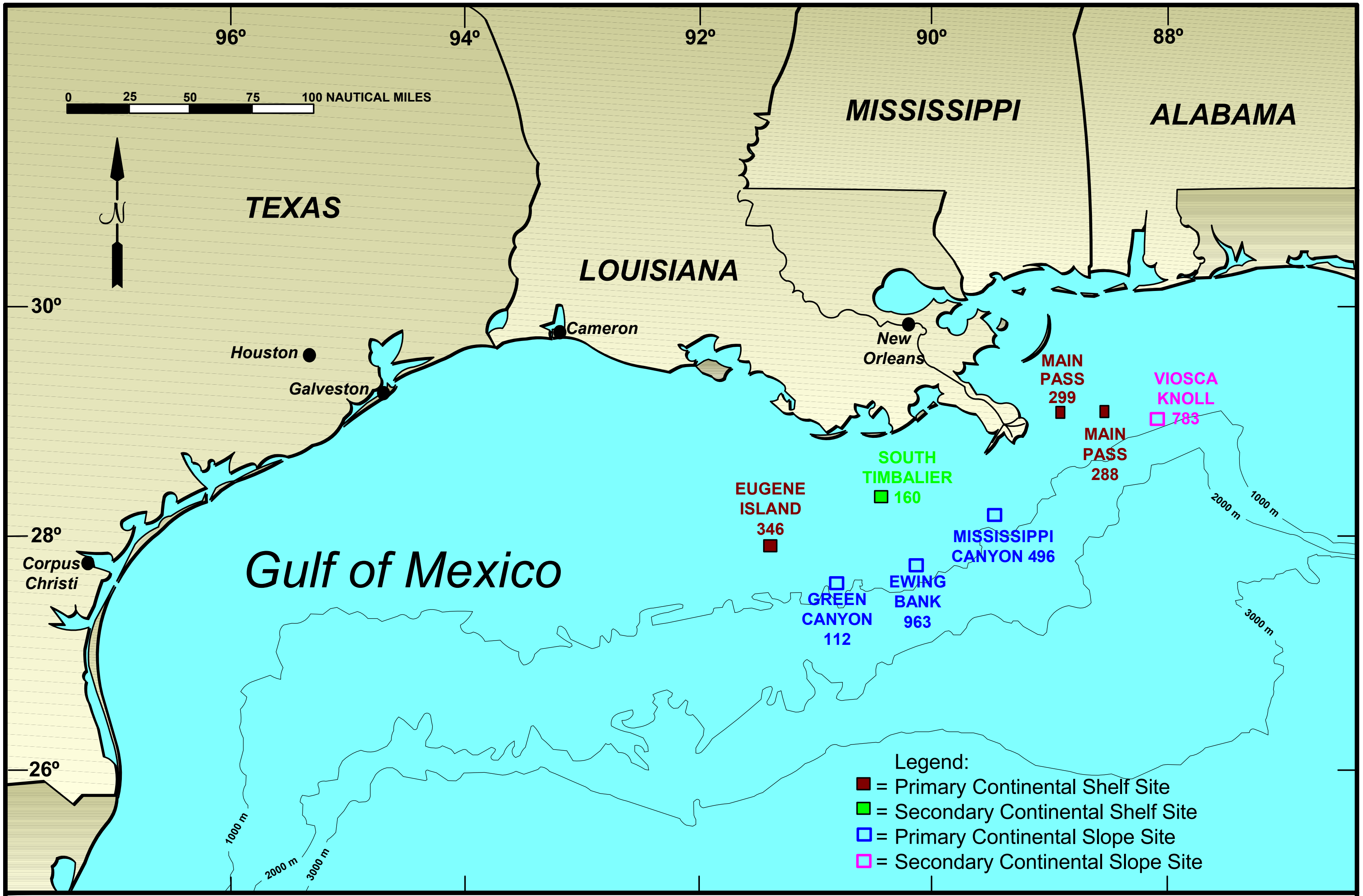


Figure 3-4. Location of sites surveyed for Sampling Cruise 1.

Samples and data collected at each study site included vertical hydrographic water column profiles, seafloor sediments, and photographic SPI images. Sampling stations were randomly selected within circular near-field, mid-field, and far-field zones positioned around each study site center. The near-field zone encompassed a circle extending from the site center or platform to 100-m, the mid-field zone ranged from the near-field zone to 250 m, and the far-field zone ranged from 3,000 to 6,000 m. Sampling locations for MP 299 are presented in Figures 3-5 (near-and mid-field) and 3-6 (far-field). Sampling locations at all study sites are presented in Appendix A, Figures A-10 to A-25.

3.3.2 Survey Vessel

The M/V BEAUREGARD, a 130-ft offshore supply vessel, was used as the primary support platform for Sampling Cruise 1. Three portable containers were secured on deck and used as a sediment chemistry laboratory and two storage containers. Deck-mounted handling gear for the deployment and retrieval of field sampling equipment consisted of a fixed, steel "A-frame," which was positioned just aft of the vessel's superstructure, and an electro-hydraulic winch, which was positioned athwartship to the A-frame.

3.3.3 Navigation, Positioning, and Tracking

As described in Section 3.1.3, the survey vessel's navigation system consisted of a Magnavox Model 412 DGPS receiver, coupled with a Starlink Model MRB-2A beacon receiver. CSA's NADAS was used to interface the various data collection sensors with the DGPS positioning system.

A Sonardyne® USBL acoustic underwater tracking system was used in conjunction with CSA's NADAS to accurately track the position of in-water sampling devices (i.e., the ROV, box core, and SPI camera) with respect to the survey vessel. This system and its application during the cruise are described in Section 3.1.3.

3.3.4 Hydrographic Profiles

One vertical water column profile was collected daily from a near-field station at each study site using a recording Sea-Bird Electronics SEACAT CTD probe. Field methods for hydrographic profiles are discussed in Section 3.2.5. Results of the hydrographic profiles are presented in Appendix B.

3.3.5 Sediment Collection

Seafloor sediments were collected at six near-field, six mid-field, and six far-field zone stations at each study site. The types of sediment samples collected at each site were a function of site designation (i.e., primary versus secondary site). In addition, sediment collected at one near-field and one far-field zone station at each site were subsampled in greater detail than other stations.

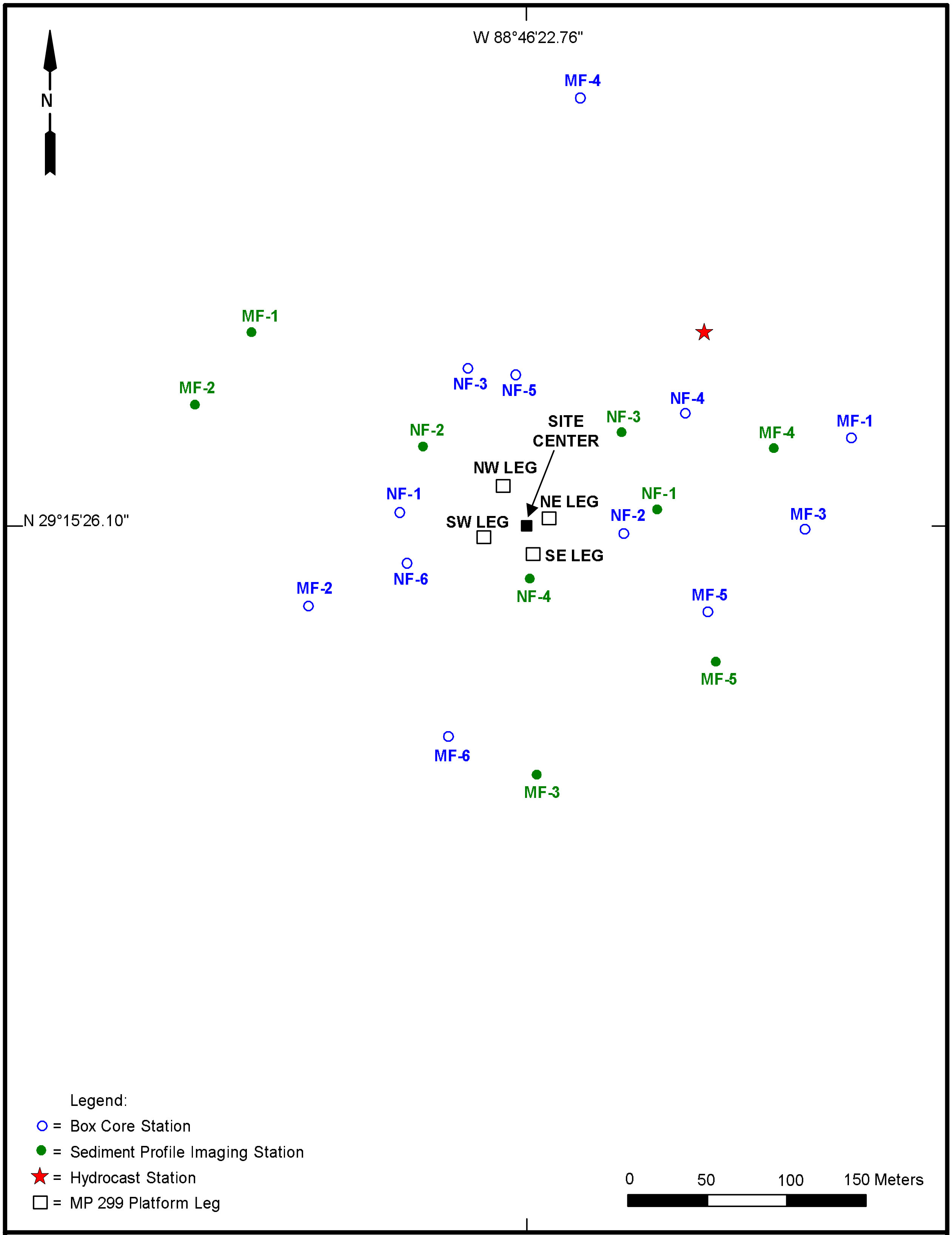


Figure 3-5. Main Pass (MP) 299 near- and mid-field sampling locations for Sampling Cruise 1.

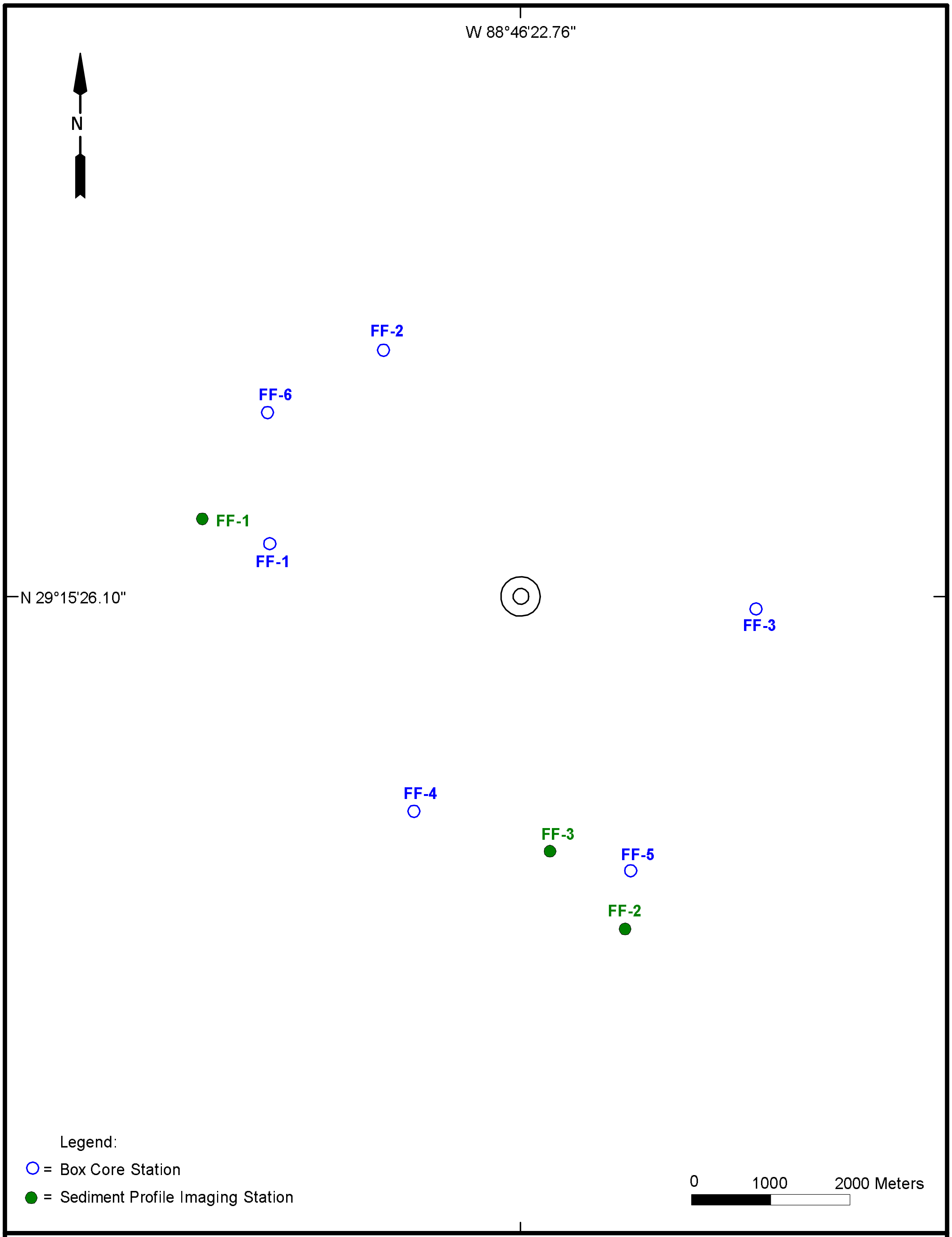


Figure 3-6. Main Pass 299 far-field sampling locations shown relative to near- and mid-field zones.

Sediment locations within each zone were randomly selected for each cruise independently. For the near-field and mid-field zones, a random northing and easting were generated over a range of values between the maximum and minimum northings and eastings, respectively. If this point was located in the zone, it was kept; if not, then another random point was generated. A similar strategy was used for generating random points in the far-field. Random points were generated within the area delineated as 3,000 to 6,000 m from the discharge location.

Sediment samples were collected with a stainless steel Gray-O'Hara-type box core sampler. Detailed box core sample collection, subsampling processing, sample preservation and storage, and cleaning procedures are discussed in Section 3.2.6. Sediment collected within the box core sampler at all sites was subsampled for the following analytical parameters:

- *in situ* redox (probe) measurements (Note: core samples for redox analyses were collected from most but not all box core samples);
- SBF;
- TPH;
- metals;
- TOC;
- visual cuttings;
- nannofossils; and
- grain size.

As discussed in Section 3.2.6, samples were removed from the top 2 cm of sediment (0 to 2 cm) from all acceptable box core samples for the aforementioned parameters (with the exception of *in situ* redox measurements that required an intact, full-depth core sample). An additional four subsurface layer samples for SBF, TPH, metals, and grain size analyses were collected from box core samples collected from one near-field and one far-field zone station at each site. At these stations, subsurface samples were collected from the following sediment layers: 0 to 2 cm; 2 to 4 cm; 4 to 6 cm; 6 to 8 cm; and a lower, selected, 2-cm layer that, whenever possible, represented background (i.e., visibly unimpacted) sediment. Selection of the lower subsurface sediment sample was made after examination of a 1-in. diameter core sample that was pulled from the box core sample and split in cross-section to reveal subsurface sediment layering.

Additional sediment samples were collected at primary continental shelf sites (MP 299, MP 288, and EI 346) for sediment toxicity and macroinfaunal analyses. At these sites, sediment toxicity samples, each consisting of an approximately 2 L volume of material, were collected from the 0 to 5 cm sediment layer. Macroinfaunal samples were derived from a 0.1-m^2 surface area of sediment that extended to a depth of approximately 30.5 cm.

Tables 3-6 and 3-7 present summaries of sample and data collection for the continental shelf and continental slope sites, respectively.

3.3.6 Sediment Profile Imaging

SPI methods are discussed in Section 3.2.9. The SPI camera system was deployed at 12 randomly selected stations within near-field, mid-field, and far-field zones at each study site to obtain vertical (cross-sectional) images of near-surface sediment layers.

Table 3-6. Summary of sampling for the Sampling Cruise 1 continental shelf sites.

Near-field Sediment Sampling	• Box cores at 6 stations, including 1 station subsampled for SBF/TPH, metals, and grain size at various depths in the sediment column • SPI at 4 stations
Near-field Hydrographic Profile	• Hydrographic (temperature and salinity) profile at 1 SPI near-field station at each site
Mid-field Sediment Sampling	• Box cores at 6 stations • SPI at 5 stations
Far-field Sediment Sampling	• Box cores at 6 stations, including 1 station subsampled for SBF/TPH, metals, and grain size at various depths in the sediment column • SPI at 3 stations
Samples/Analyses	• Redox profile at 18 stations • Grain size at 18 stations, with additional subsurface layer samples collected at 2 stations • Visual cuttings analysis at 18 stations • SPI images at 12 stations • SBF/TPH by GC-FID at 18 stations, with additional subsurface layer samples collected at 2 stations • Nannofossils at 18 stations • TOC at 18 stations
Additional Samples Collected at Primary Sites	• Infauna at 18 stations • Sediment toxicity at 18 stations • Metals (Ba, Fe, Al, and Mn) at 18 stations, with additional subsurface layer samples collected at 2 stations

GC-FID = Gas chromatography-flame ionization detection.
Redox = Reduction-oxidation potential.
SBF = Synthetic based fluids.
SPI = Sediment profile imaging.
TOC = Total organic carbon.
TPH = Total petroleum hydrocarbons.

Table 3-7. Summary of sampling for the Sampling Cruise 1 continental slope sites.

Near-field Sediment Sampling	• Box cores at 6 stations • SPI at 4 stations
Near-field Hydrographic Profile	• Hydrographic (temperature and salinity) profile at 1 near-field station at each site
Mid-field Sediment Sampling	• Box cores at 6 stations • SPI at 5 stations
Far-field Sediment Sampling	• Box cores at 6 stations • SPI at 3 stations
Samples/Analyses	• Redox profile at 18 stations • Grain size at 18 stations, with additional subsurface layer samples collected at 2 stations • Visual cuttings analysis at 18 stations • SPI images at 12 stations • SBF/TPH by GC-FID at 18 stations, with additional subsurface layer samples collected at 2 stations • Nannofossils at 18 stations • TOC at 18 stations
Additional Samples Collected at Primary Sites	• Metals (Ba, Fe, Al, and Mn) at 18 stations, with additional subsurface layer samples collected at 2 stations

GC-FID = Gas chromatography-flame ionization detection.
Redox = Reduction-oxidation potential.
SBF = Synthetic based fluids.
SPI = Sediment profile imaging.
TOC = Total organic carbon.
TPH = Total petroleum hydrocarbons.

3.4 SAMPLING CRUISE 2

Sampling Cruise 2 was conducted from 6 to 22 May 2002. This cruise was the second of two field efforts designed to determine and temporally compare levels and spatial distributions of sediment SBF concentrations around eight selected drillsites.

3.4.1 Study Sites

Study sites visited during Sampling Cruise 2 consisted of the same four continental shelf sites and four continental slope sites as were sampled during Sampling Cruise 1 (Table 3-5). The locations of these sites are shown in Figure 3-7.

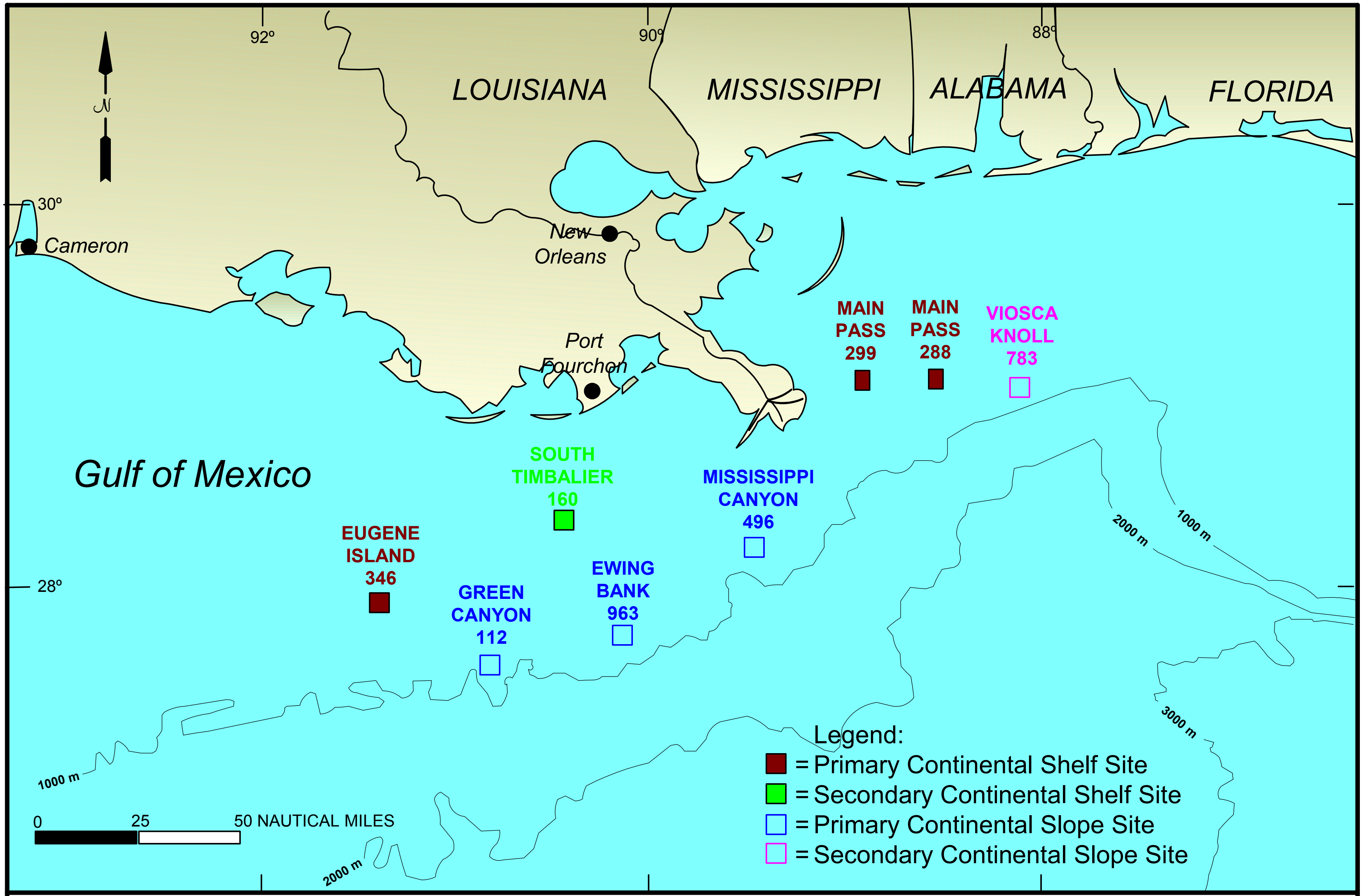


Figure 3-7. Location of sites surveyed for Sampling Cruise 2.

Samples and data collected at each study site included hydrographic profiles, seafloor sediments, and photographic SPI images. Sediments and SPI images were collected at randomly selected stations positioned within near-field, mid-field, and far-field zones centered around each drillsite. Sampling locations for this survey at MP 288 are shown in Figures 3-8 (near- and mid-field) and 3-9 (far-field). Sampling locations for all study sites are presented in Appendix A, Figures A-26 to A-41.

3.4.2 Survey Vessel

The R/V J.W. POWELL, a 142-ft oceanographic research vessel, was used as the primary support platform for this sampling effort. Two portable containers were secured on the main deck to serve as a laboratory for sediment sample chemistry processing, storage, and working space for vessel navigation and tracking equipment. Deck-mounted handling gear for the deployment and retrieval of field sampling equipment consisted of a hydraulic articulating "A-frame" positioned on the starboard side of the vessel, a diesel-powered, deep-sea coring winch positioned aft of the A-frame, and a hydraulic deck crane.

3.4.3 Navigation, Positioning, and Tracking

The vessel navigation system included a Leica Model 412 DGPS receiver coupled with a Starlink Model MRB-2A beacon receiver. As described in Section 3.1.3, CSA's NADAS was used to interface the various data collection sensors with the DGPS positioning system.

A Sonardyne USBL acoustic underwater tracking system was used in conjunction with CSA's NADAS to accurately track the position of in-water sampling devices (i.e., the ROV, box corer, and SPI camera), with respect to the survey vessel. This system and its application during the cruise are described in Section 3.1.3.

3.4.4 Hydrographic Profiles

One vertical water column profile was collected daily from a near-field station at each study site using a recording Sea-Bird Electronics SEACAT CTD probe. Field methods for hydrographic profiles are discussed in Section 3.2.5. These data are presented in Appendix B.

3.4.5 Sediment Collection

Overviews of samples collected at continental shelf and continental slope sites are shown in Tables 3-8 and 3-9, respectively. Sediment samples were collected with a stainless steel, Gray-O'Hara-type box core sampler. Detailed box core sample collection, processing, preservation, and storage procedures are discussed in Section 3.2.6.

Sediment collected within the box core sampler at each study site was subsampled for the following analytical parameters:

- *in situ* redox measurements;
- SBF;
- TPH;
- metals;
- TOC;
- visual cuttings;
- nannofossils; and
- grain size.

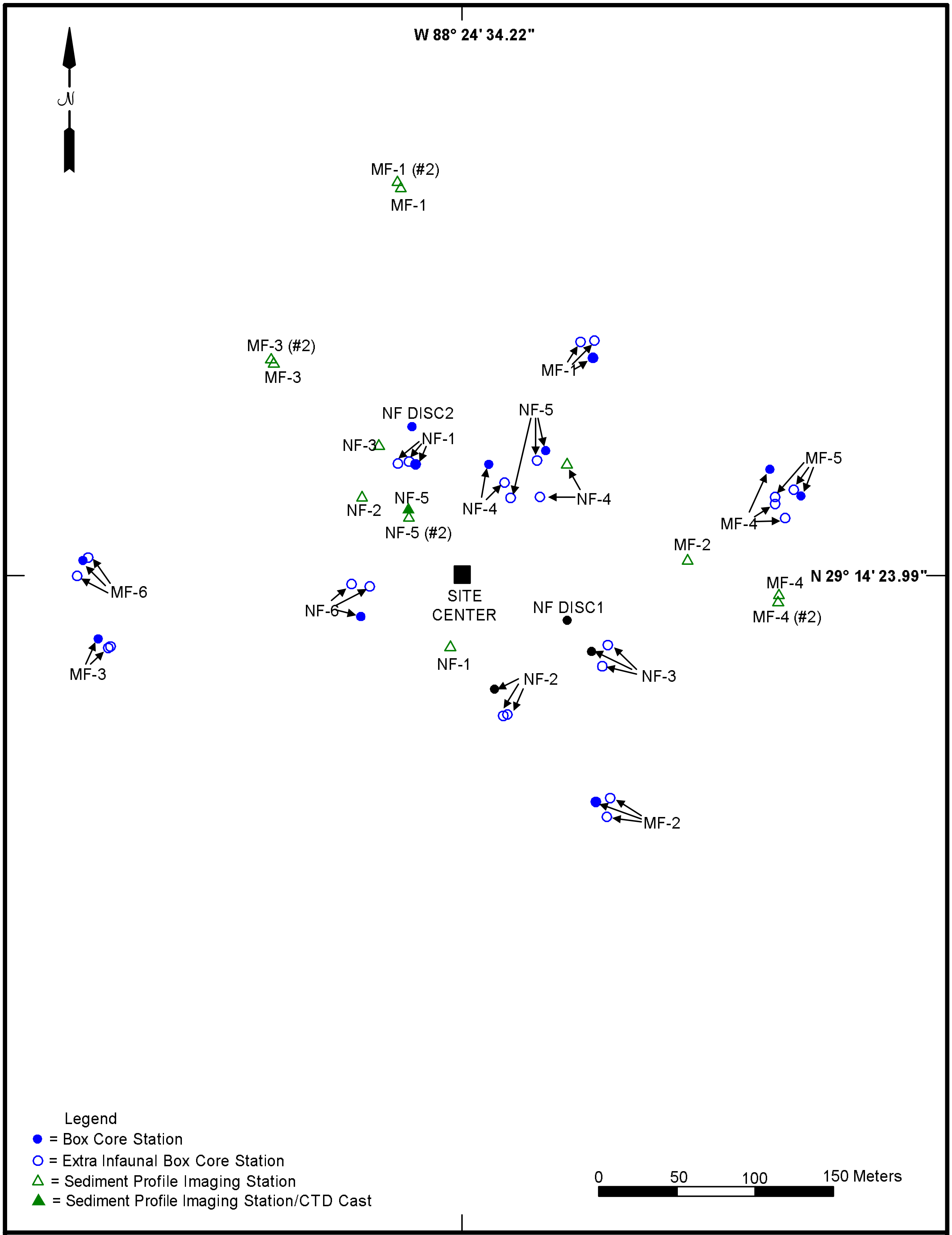


Figure 3-8. Main Pass 288 near- and mid-field sampling locations for Sampling Cruise 2.

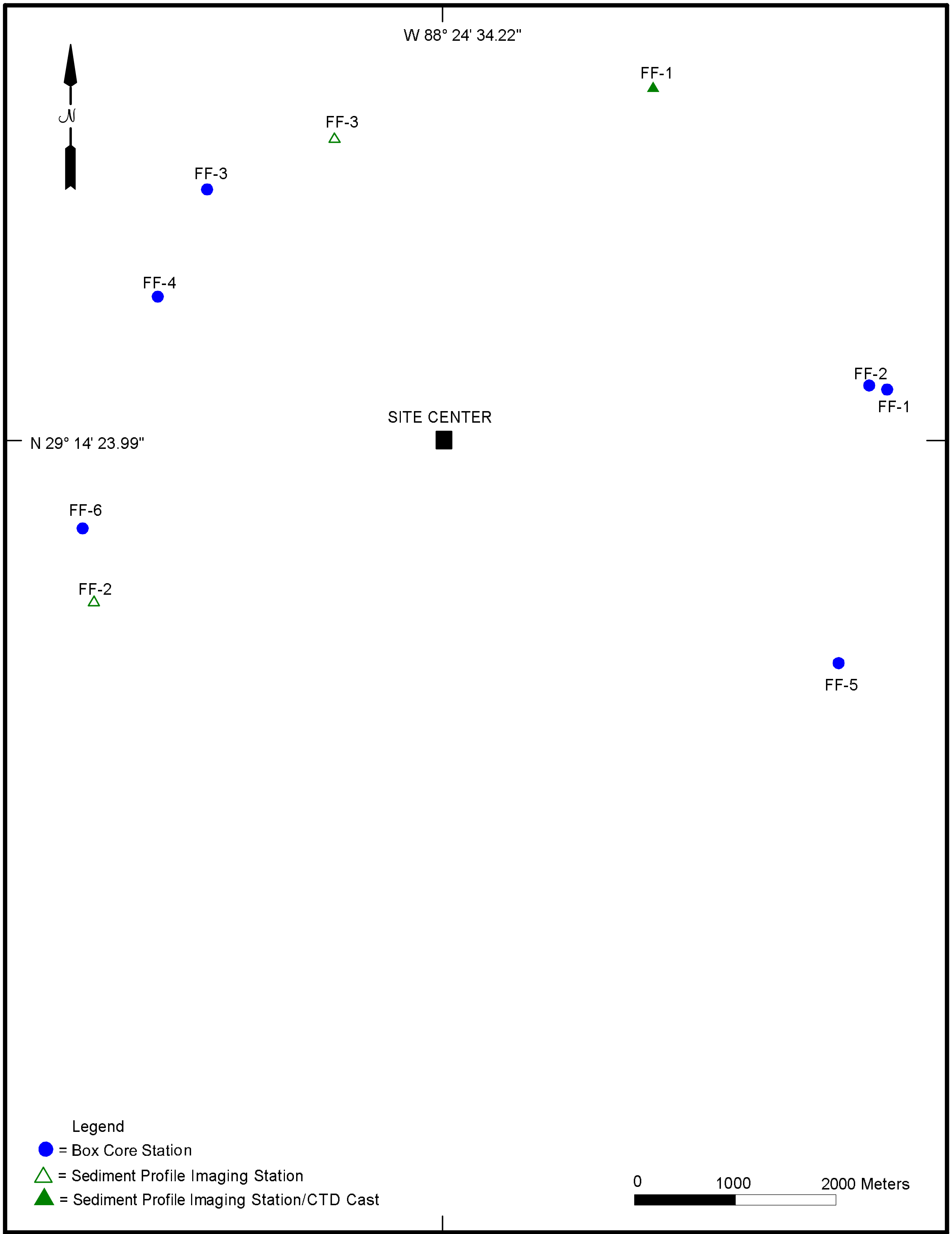


Figure 3-9. Main Pass 288 far-field sampling locations for Samping Cruise 2.

Table 3-8. Summary of sampling for the Sampling Cruise 2 continental shelf sites.

Near-field Sediment Sampling	• Box cores at 6 stations, including 1 station (NF-1) subsampled vertically for SBF/TPH, metals, grain size, and nannofossils • Box cores at two discretionary stations subsampled for SBF/TPH, metals, grain size, and nannofossils • Extra box cores (2) at the 3 primary sites for infauna • SPI at 5 stations
Near-field Hydrographic Profile	• Hydrographic (temperature and salinity) profile at 1 SPI station
Mid-field Sediment Sampling	• Box cores at 6 stations • Two additional box cores at the 3 primary sites for infauna • SPI at 4 stations
Far-field Sediment Sampling	• Box cores at 6 stations, including 1 station (FF-1) subsampled vertically for SBF/TPH, metals, grain size, and nannofossils • Extra box cores (2) collected at the 3 primary sites for infauna • SPI at 3 stations
Far-field Hydrographic Profile	• Hydrographic (temperature and salinity) profile at 1 SPI station
Samples/Analyses	• Redox profile at 18 stations • Grain size at 18 stations, with additional subsurface layer samples collected at two stations (NF-1 and FF-1) • Nannofossils at 18 stations, with additional subsurface layer samples at 2 stations (NF-1 and FF-1) • Visual cuttings analysis at 18 stations • SBF/TPH by GC-FID at 18 stations, with additional subsurface layer samples at 2 stations • TOC at 18 stations • SPI images at 12 stations • Hydrographic profiles for temperature, salinity, dissolved oxygen, and depth at 2 stations
Additional Samples Collected at Primary Sites	• Sediment toxicity at 18 stations • Two near-field discretionary stations subsampled for SBF/TPH, metals, grain size, and nannofossils • Metals (Ba, Fe, Al, and Mn) at 18 stations, with additional subsurface layer samples at 2 stations (NF-1 and FF-1) • Infauna at 18 stations (3 box core samples per station)

GC-FID = Gas chromatography-flame ionization detection.
Redox = Reduction-oxidation potential.
SBF = Synthetic based fluids.
SPI = Sediment profile imagery.
TOC = Total organic carbon.
TPH = Total petroleum hydrocarbons.

Table 3-9. Summary of sampling for the Sampling Cruise 2 continental slope sites.

Near-field Sediment Sampling	• Box cores at 6 stations, including 1 station (NF-1) subsampled vertically for SBF/TPH, metals, grain size, and nannofossils • Box cores at 2 discretionary stations subsampled for SBF/TPH, metals, grain size, and nannofossils • Box core at 1 station for SBM degradation at each site • SPI at 5 stations
Near-field Hydrographic Profile	• Hydrographic (temperature and salinity) profile at 1 SPI station at each site
Mid-field Sediment Sampling	• Box cores at 6 stations • SPI at 4 stations
Far-field Sediment Sampling	• Box cores at 6 stations, including 1 station (FF-1) subsampled for SBF/TPH, metals, grain size, and nannofossils • Box core at 1 station for SBM degradation at each site • SPI at 3 stations
Far-field Hydrographic Profile	• Hydrographic (temperature and salinity) profile at 1 SPI station at each site
Samples/Analyses	• Redox profile at 18 stations • Grain size at 18 stations, with additional subsurface layer samples collected at 2 stations (NF-1 and FF-1) • Nannofossils at 18 stations, with additional subsurface layer samples collected at 2 stations (NF-1 and FF-1) • Visual cuttings analysis at 18 stations • Sediment toxicity at 18 station at MC 496, EW 963, and GC 112 • SBF/TPH by GC-FID at 18 stations, with additional subsurface layer samples collected at 2 stations • TOC at 18 stations • SPI images at 12 stations • Hydrographic profiles for temperature, salinity, dissolved oxygen, and depth at 2 stations
Additional Samples Collected at Primary Sites	• Sediment toxicity collected at 18 stations • Two near-field discretionary stations subsampled for SBF/TPH, metals, grain size, and nannofossils • Metals (Ba, Fe, Al, and Mn) at 18 stations, with additional subsurface layer samples collected at 2 stations (NF-1 and FF-1)

GC-FID = Gas chromatography-flame ionization detection.
Redox = Reduction-oxidation potential.
SBF = Synthetic based fluids.
SBM = Synthetic based muds.
SPI = Sediment profile imagery.
TOC = Total organic carbon.
TPH = Total petroleum hydrocarbons.

With the exception of the redox samples, all samples for these parameters were subsampled from the top 2-cm layer of sediment (0 to 2 cm) in acceptable box core samples. Redox measurements required an intact, full-depth acrylic core sample. Subsurface (i.e., below the 0- to 2-cm sediment layer) samples for SBF, TPH, metals, grain size, and nannofossil analyses were obtained from box core samples collected from one near-field and one far-field zone station at each study site (NF-1 and FF-1) and at two preselected discretionary near-field stations that had been sampled during Sampling Cruise 1. The selection criterion for the discretionary stations was the presence of high relative levels of SBF in sediments, as determined from laboratory analyses. These stations were sampled to provide temporally comparative sediment chemistry and geology data in areas where high SBF concentrations were observed during Sampling Cruise 1. Samples from all NF-1 and FF-1 stations were collected from the 0- to 2-cm sediment layer and from the following four subsurface layers: 2 to 4 cm; 4 to 6 cm; 6 to 8 cm; and 8 to 10 cm. Samples at the discretionary stations (labeled DISC1 and DISC2 for identification) also were collected from the 0- to 2-cm, 2- to 4-cm, 4- to 6-cm, and 6- to 8-cm layers. The fifth subsurface sample was collected from, if possible, what appeared to be background (unimpacted) sediment. Its selection was made after an examination of a separate 1-in. diameter core sample that was extracted from the box core sample and split in cross-section to reveal subsurface sediment layering. Samples for sediment chemistry analyses (SBF, TPH, metals, and TOC) were stored frozen at temperatures below 0°C. Samples for grain size, nannofossils, and visual cuttings analyses were stored under refrigeration at temperatures of approximately 10°C to 12°C.

Sediment samples for sediment toxicity analyses were collected at the three primary continental shelf sites and the three primary continental slope sites. Sediment toxicity samples were collected from the 0- to 5-cm sediment layer within a cleaned, stainless steel form that was pressed into each box core sediment sample. Each sample consisted of approximately 2 L of material. Sediment toxicity samples were stored under refrigeration at 2°C to 6°C.

Sediment samples for macroinfaunal analyses were collected at the three primary continental shelf sites. Two additional samples at each station (labeled INF2 and INF3) were requested by the American Petroleum Institute (API) for this sampling effort. This required the collection of two additional box core samples in the vicinity of each macroinfaunal station. All macroinfaunal samples were collected from the 0- to 30.5-cm sediment layer within a stainless steel form of 1,012 cm^2 (surface volume) that was pressed into the box core sample. The collected sediment was sieved through 0.5-mm screens and transferred into suitable containers.

3.4.6 Sediment Profile Imaging

SPI methods are discussed in Section 3.2.9. The SPI camera system was deployed at 12 randomly selected stations at each study site. These included five near-field, four mid-field, and three far-field stations.

Chapter 4
SYNTHESIS AND INTEGRATION

Jerry M. Neff
Battelle Memorial Institute

4.1 INTRODUCTION

4.1.1 Regulatory Background

The major wastes generated during drilling of oil and gas wells are drilling muds (also called drilling fluids) and drill cuttings (National Research Council, 1983; Neff et al., 1987). There are three basic types of drilling muds: WBMs, OBMs, and SBMs. USEPA (1996) also identifies enhanced mineral oil-based drilling mud as a separate type of drilling mud. The focus of this report is on the environmental fates and effects of SBM, which USEPA (1996) defines as a drilling fluid in which a synthetic material is the continuous phase with water as the dispersed phase.

Drill cuttings are particles of crushed sedimentary rock produced by the action of the drill bit as it penetrates into the earth. Used drilling muds are reprocessed and recycled or disposed of by ocean discharge, reinjected, or hauled to shore to a landfill. Cuttings are processed to remove excess drilling mud and either disposed of by ocean discharge, reinjected, hauled to a landfill, or hauled to shore and processed for beneficial uses.

USEPA is responsible for regulating discharges of waste materials from drilling rigs and development/production platforms in U.S. Federal waters. USEPA regulates waste discharges from offshore exploration and production platforms by issuance of NPDES permits. These permits are intended to prevent unreasonable degradation of the receiving waters by limiting or prohibiting discharges of specific chemicals or waste types (pollutants).

USEPA never has permitted bulk discharges of OBMs or SBMs to State or Federal waters of the U.S. The high cost of these drilling muds, particularly SBMs, makes it economically feasible to return them to shore where they can be reprocessed and regenerated. USEPA usually permits bulk discharges of WBMs to Federal waters of the Gulf of Mexico unless the discharges contain “free oil” (do not pass bucket sheen test) or are toxic in required marine toxicity tests. Water based mud and SBM cuttings, but not OBM cuttings, usually are permitted for discharge to Federal waters unless they contain excessive amounts of oil.

The need to drill increasingly difficult deepwater and deviated wells, coupled with the economic and safety advantages of ocean discharge of cuttings, led to development of SBMs (Neff et al., 2000). Synthetic based muds are designed to be less toxic and degrade faster in marine sediments than OBMs but provide the technical advantages of OBMs in drilling difficult wells (Friedheim and Conn, 1996).

USEPA recognized SBMs as a new class of drilling muds in 1996 (USEPA, 1996) and began a process of reviewing the capabilities of cuttings treatment technology and the relative environmental impacts of all cuttings disposal options. The data collected in this process provided input for the development of the ELGs, which provided technology-based limits for the discharge of cuttings generated during drilling with SBMs (USEPA, 2001a). A subsequent NPDES general permit for the Central and Western Gulf of Mexico implemented the ELGs (USEPA, 2001c). In addition to the requirements of the ELGs, the NPDES permit requires operators to either conduct seabed surveys at each location where cuttings drilled with SBM are discharged or to participate in a joint industry study conducted according to a plan approved by USEPA Region 6 (USEPA, 2001c). This study, sponsored by the Synthetic Based Mud Research Group, the MMS, and the U.S. Department of Energy, satisfies the latter requirement.

4.1.2 Objectives of the Synthesis and Integration Discussion

The objective of the Gulf of Mexico Comprehensive Synthetic Based Muds Monitoring Program is to assess the fate and physical, chemical, and biological effects of discharge of drill cuttings generated during use of SBMs (also referred to in the following discussion as SBM cuttings) from offshore platforms to continental shelf (40 to <300 m) and continental slope (>300 m) waters of the Gulf of Mexico. The purpose of this chapter is to synthesize and integrate the results of the physical, chemical, and biological components of the program so that conclusions can be drawn about the relationships between physical and chemical disturbance of the seafloor near drilling waste discharge sites on the continental shelf and slope and characteristics of the benthic biological communities occupying those habitats.

This chapter will address the four subobjectives of this study through an integration of the results of the subsequent chapters of this report with results in current scientific reports and publications on the topics of interest. As described in Chapter 1, the four subobjectives of this study were to

1) determine the thickness and areal extent of SBM cuttings accumulations on the seafloor and the magnitude of SBF concentrations in sediments near discharge sites representative of Gulf of Mexico conditions at both continental shelf (<300 m depth) and continental slope (>300 m depth) discharge sites;

2) determine the temporal behavior of SBM base fluid concentrations in sediments near discharge sites representative of Gulf of Mexico conditions at both continental shelf (<300 m depth) and continental slope (>300 m depth) discharge sites;

3) document the physical-chemical conditions in sediments in areas where SBM base fluids are present and compare these conditions with conditions in reference sediments distant from SBM cuttings discharges; and

4) determine whether a zone of biological effect has developed related to the discharge of SBM cuttings, and if detectable, determine its dimensions.

4.2 DISTRIBUTION OF SBM CUTTINGS IN OFFSHORE SEDIMENTS NEAR DRILLSITES

4.2.1 History of Drilling Discharges from Drilling Discharge Study Sites

Synthetic based mud cuttings are composed of crushed rock, produced by the grinding action of the drill bit on the geologic formation being penetrated, and a small amount (historically about 10% to 15% by weight; Annis, 1997) of adhering SBM chemicals. The general NPDES permit for the western Gulf of Mexico, introduced in February 2002, requires that retention of synthetic base chemical (SBF) on cuttings not exceed 6.9% (for IOs) or 9.4% (for esters) (Rabke et al., 2003).

Drill cuttings range widely in size from clay-sized particles to coarse gravel. SBM cuttings containing more than about 5% synthetic chemical clump when discharged to the ocean and tend to settle rapidly to the seafloor near the discharge site (Delvigne, 1996; Neff et al., 2000). It is probable that the SBM cuttings discharged from the eight discharge sites monitored in this study contained more than 5% synthetic base chemical because discharges occurred prior to implementation of the 2002 NPDES permit.

The distribution and concentrations of SBM cuttings in sediments near offshore drillsites depend on the concentration of SBM on the cuttings, the mass and temporal pattern of cuttings discharges, water depth, and physical oceanographic conditions (water currents and turbulent mixing of the water column) at the discharge site. Following accumulation on the bottom, concentrations of SBM cuttings ingredients decrease slowly over time due to dilution by bed transport or burial and biodegradation of the organic components of the cuttings (Neff et al., 2000).

Drillsites within eight MMS lease blocks were surveyed during Sampling Cruises 1 and 2 in May 2001 and May 2002, respectively. There were no reported SBM cuttings discharges at any site between the two Sampling Cruises. Four sites were at continental shelf water depths (37 to 119 m), and four were in deeper continental slope waters (338 to 556 m) (Table 4-1). Prior to the field program, between 3 and 450 wells had been drilled in the blocks surveyed. Main Pass 299 is the most active 3-mile x 3-mile MMS lease block in the Gulf of Mexico. Wells have been drilled in MP 299 from 1962 to the present; the most recent well was spudded there in February 2003. More wells were drilled within 50 m of the study site center in MP 288 than within 50 m of the study site in MP 299, making the study site in MP 288 more active than that at MP 299 (Table 4-2). Drilling activity has been much less intense at the other drillsites monitored in this program.

Table 4-1. Drilling locations on the continental shelf and slope sampled during Sampling Cruises 1 (May 2001) and 2 (May 2002), respectively, as part of the Gulf of Mexico Comprehensive Synthetic Based Muds (SBM) Monitoring Program. Sites are ordered by water depth.

Site	Abbreviation	Water Depth (m)	SBM Type	SBM Wells Within 50 m of Site Center	Total Wells in Block
Continental Shelf					
South Timbalier 160	ST 160	37	IO	1	21
Main Pass 299	MP 299	83	LAO	3	450
Eugene Island 346	EI 346	92	IO	3	5
Main Pass 288	MP 288	119	IO	4	21
Continental Slope					
Viosca Knoll 783	VK 783	338	Ester	1	8
Ewing Bank 963	EW 963	535	IO	3	3
Green Canyon 112	GC 112	536	IO	4	7
Mississippi Canyon 496	MC 496	556	IO	1	5

IO = Internal olefin.
LAO = Linear alpha olefin.

Table 4-2. Summary of drilling and discharge history at the eight discharge sites monitored in this program. Data from: Minerals Management Service and industry sources.

Site	No. Wells Drilled	No. Wells Within 50 m	Last WBM Cuttings Discharge[a]	WBM Cuttings Discharge (bbl)[b]	Last SBM Cuttings Discharge[a]	SBM Cuttings Discharge (bbl)[b]
South Timbalier 160	21	1	2/98	2,817	2/98	929
Main Pass 299	450	15	4/97[c]	26,726	4/00[c]	966
Eugene Island 346	19	5	4/00[d]	7,639	4/00[d]	10,328
Main Pass 288	23	26	9/87	29,990	3/98	1,309
Viosca Knoll 783	13	1	12/95	5,045	11/95	436
Green Canyon 112	7	2	12/97	3,552	12/97	5,470
Ewing Bank 963	4	2	1/97	5,910	1/97	598
Mississippi Canyon 496	5	1	10/98[e]	2,980	10/98[e]	1,674

[a] Last reported cuttings discharge before start of monitoring program.

[b] Total cuttings discharge volume within 50 m of the drillsite.

[c] Wells spudded at Main Pass 299 on 3/2/02, 4/14/02, 5/13/02, 5/20/02, 2/1/03, 2/12/03, and 2/21/03 were more than 1 km from the study site center.

[d] Well spudded at Eugene Island 346 on 12/22/02 was more than 1 km from the study site center.

[e] Wells spudded at Mississippi Canyon 496 on 8/30/01 and 3/28/03 more than 1 km from the study site center.

Between one and four wells were drilled with SBM within 50 m of each study site center (Table 4-1). Esters, LAOs, or, most frequently, IOs, were the SBMs used, and most SBM use was for the most recent wells. Frequently, the large-diameter near-surface sections of wells are drilled with WBM, and the switch-over to SBM is made for deeper, more difficult sections of the well. At times, completed WBM wells are re-entered and deviated sections are drilled with SBM.

The drilling and discharge history is different for each site (Table 4-2). The date of the most recent WBM cuttings discharge within 50 m of the study site center ranged from September 1987 at MP 288 to April 2000 at EI 346. Total reported volumes of WBM cuttings discharged within 50 m of the study site centers ranged from 2,817 bbl at ST 160 to more than 25,000 bbl at MP 288 and MP 299.

Six of the study sites had SBM cuttings discharges within 50 m of the study site center that ranged from 436 to 1,674 bbl. Green Canyon 112 and EI 346 had much larger SBM cuttings discharges of 5,470 and 10,328 bbl, respectively. The time of the last reported SBM cuttings discharge before the start of the monitoring program ranged from November 1995 at VK 783 to April 2000 at MP 299 and EI 346.

4.2.2 SBM Cuttings in Sediments Near Drillsites

Four field cruises were performed as part of this monitoring program. A Scouting Cruise was performed to survey several candidate continental shelf drilling sites to identify the presence of cuttings accumulations on the bottom and evaluate the suitability of the sites for more detailed monitoring. Eight candidate continental shelf and continental slope sites were selected for further evaluation, and a Screening Cruise was performed to better characterize the distribution of drilling discharges and physical, chemical, and biological conditions in the sediments at different distances from these candidate monitoring sites. Three continental shelf and three continental slope sites were chosen as primary study sites for more detailed evaluation in two Sampling Cruises, based on the results of the Screening Cruise. The remaining two sites (one continental shelf site and one continental slope site) were designated as secondary study sites. Results of the Screening Cruise also were used to define the three sampling strata for the Sampling Cruises: near-field (<100 m from site center), mid-field (100 to 250 m from site center), and far-field (3,000 to 6,000 m from site center). The focus of this synthesis and integration discussion is on the results of the two Sampling Cruises to facilitate comparisons of the three sampling strata.

Sampling Cruise 1 was intended to document the distribution and concentrations of SBM cuttings components in sediments at different distances from the discharge sites and any physical and biological disturbance that was associated with the cuttings accumulations. Sampling Cruise 2 was intended to document the temporal change in cuttings ingredient concentrations and associated physical and biological disturbance to the benthic ecosystem.

Sampling locations at each site were randomly selected for each Sampling Cruise in the three zones or sampling strata (near-field, mid-field, and far-field). Far-field samples were intended to represent background conditions for the area. Because sampling locations were randomly selected within each zone, they should give a good indication of representative conditions in that zone. Comparisons can be made among the three zones at a site for a cruise or for the same zone at the time of the two cruises. However, data for a particular sampling station cannot be compared between cruises because of the random sampling site selection process used for each cruise.

As discussed above, it is highly likely that the upper 1,000 to 2,000 m of most wells were drilled with WBMs, possibly with some drilling mud returns directly to the seafloor. Synthetic based muds were used for drilling the deeper sections or for reentering and drilling deviated portions of 20 of the wells drilled at the eight sites. All the other wells were drilled with WBMs. Thus, at all study sites, but particularly at the continental shelf discharge sites, some of the mud and cuttings solids detected on the seafloor probably were from WBM and WBM cuttings discharges.

There are several ways to detect cuttings solids in surface sediments. Cuttings-contaminated sediments may have a different sediment grain size and mineralogy, higher metals (particularly Ba) concentrations, enhanced ultraviolet (UV) fluorescence (if petroleum products are present), and presence of unique mud and cuttings components (i.e., hydrocarbons, nannofossils from the geologic formations, and glass spheres, occasionally used in drilling muds). A unique indicator of the presence of SBM cuttings is the presence of the SBM base chemical in the sediments. These properties were examined in surficial sediment samples collected at several randomly-selected locations in the near-field, mid-field, and far-field around the drillsites.

Sediment Grain Size. Drill cuttings that settle near the discharge site, particularly in deep water, usually are silt-sized (≥63 μm) or larger, of variable mineralogy, and often have an angular or tabular configuration. However, some shales may swell and disaggregate, forming clay-sized particles in sediments. The texture of the discharged cuttings depends on the mineralogy of the formation being drilled, as well as the amount of drilling mud clay and barite adhering to the cuttings at the time of discharge. Therefore, the presence of cuttings particles in a sediment sample sometimes is indicated by different than expected (compared to reference) percent coarse sediments and by visual evidence of angular or tabular particles. Most surficial

sediments on the outer continental shelf and slope off the Mississippi River in the vicinity of the eight discharge sites are clays; drill cuttings can be identified by their larger size.
Table 4-3 is a summary of the observations from Sampling Cruise 1 on sediment grain size differences and visual identification of cuttings particles. Most surficial sediments near the eight sites monitored in this investigation were composed primarily of silty clay. The exception was sediments from some far-field stations at MP 288, which contained more than one-quarter sand. Sediment profile imagery collected at several of the sites during the Screening Cruise and Sampling Cruises 1 and 2 revealed that most surficial sediments at near-field stations were silt-clay; most surficial sediments from far-field stations were primarily clay. Surficial sediments collected on Sampling Cruises 1 and 2 from mid-field stations were nearly evenly divided between silt-clay and clay.

Table 4-3. Differences in mean sediment grain size with distance from drillsites and visual evidence of cuttings particles in sediments as indices of the accumulation of drill cuttings solids in sediments near the eight drillsites in the Gulf of Mexico. Data from: Continental Shelf Associates, Inc., 2002.

Location	Mean Grain Size Range (µm)	Grain Size Gradient	Cuttings Visible
South Timbalier 160			
NF	2.8 – 10.8	No	Yes (6/6)
MF	3.7 – 5.7	No	Yes (6/6)
FF	3.2 – 6.5	No	Yes (6/6)
Main Pass 299			
NF	1.6 – 5.8	No	Yes (6/6)
MF	2.6 – 9.7	No	Yes (6/6)
FF	2.3 – 3.4	No	Trace (6/6)
Eugene Island 346			
NF	3.1 – 25.7	NF > FF	Yes (6/6)
MF	1.8 – 13.1	MF > FF	Yes (6/6)
FF	3.2 – 4.2	FF < NF~MF	No
Main Pass 288			
NF	2.3 – 8.3	No	Yes (6/6)
MF	2.9 – 4.8	No	Yes (6/6)
FF	2.9 – 23	95% sand	Yes (1/6)
Viosca Knoll 783			
NF	2.9 – 4.9	No	Trace (6/6)
MF	2.4 – 4.4	No	Trace (6/6)
FF	0.76 – 3.2	No	Trace (6/6)
Green Canyon 112			
NF	1.4 – 12.2	No	Yes (5/6)
MF	1.4 – 5.4	No	Yes (3/6)
FF	1.4 – 4.6	No	Trace (3/6)
Ewing Bank 963			
NF	2.4 – 7.8	No	Yes (5/6)
MF	0.90 – 6.2	No	Yes (5/6)
FF	0.86 – 2.7	No	No
Mississippi Canyon 496			
NF	1.7 – 3.5	NF > FF	Yes (5/6)
MF	2.3 – 3.4	MF > FF	Yes (5/6)
FF	1.1 – 2.1	FF < NF~MF	Yes (4/6)

FF = Far-field; MF = Mid-field; and NF = Near-field.

There was some evidence, based on mean grain size range in sediments from near-field, mid-field, and far-field stations, of decreasing grain size with distance from all eight drilling waste discharge sites and strong evidence, as indicated by grain size gradient, at two sites at the time of Sampling Cruise 1 (Table 4-3). At all sites, one or more near-field sediment samples contained a larger mean grain size than any sediment samples from mid-field or, with one exception, far-field stations. The gradient was strongest at EI 346 and MC 496. This parameter proved to be a weak indicator of the presence of cuttings particles in surficial sediments, mainly because of the natural variability in sediment grain size, particularly at continental shelf locations. However, sediment grain size did provide some evidence of the presence of cuttings particles in near-field and mid-field sediments.

Cuttings Particles. Sediment particles visually resembling cuttings particles were detected in three or more (of six) surficial sediments from near-field and mid-field stations collected during Sampling Cruise 1 at all eight sites (Tables 4-3 and 4-4). Visible cuttings particles also were detected in far-field sediments from six of the eight drilling locations, usually at lower frequency than at near-field and mid-field stations. Many sediment samples contained only traces of cuttings particles. Visual identification of cuttings provides strong evidence of the widespread distribution of drilling waste solids in surficial sediments near offshore drillsites. Both WBM and SBM cuttings were discharged at all eight drillsites, and it is not possible to determine if the cuttings particles detected in sediments were from SBM cuttings.

UV Fluorescence. Only traces of UV fluorescence (a qualitative indicator of aromatic hydrocarbons) were observed in sediments near three discharge sits at the time of Sampling Cruise 1. Fluorescence was not detected in sediments from the other five sites or in sediments from any sites at the time of Sampling Cruise 2. Drill cuttings ordinarily do not contain aromatic hydrocarbons, so UV fluorescence is not a useful indicator of cuttings solids in sediments.

Nannofossils and Glass Spheres. Nannofossils of Holocene or greater age (characteristic of sedimentary strata encountered during drilling) or glass spheres (sometimes added to drilling mud) were present in sediments near six of the eight drillsites during Sampling Cruises 1 and 2 (Table 4-4). No nannofossils were found in sediments at MP 299 or in most sediments at EW 963 and ST 160. The absence of nannofossils in surficial sediments from these sites may be due to natural sediment deposition since the last cuttings discharge. Nannofossils were not found or were present in only trace amounts in far-field sediments at all eight sites. In most cases, abundance of nannofossils decreased with distance from the drillsites.

Glass spheres were observed in surficial sediments collected from near-field and mid-field stations at five sites (Table 4-4). They also were observed in trace amounts in surficial sediments at some far-field stations at five sites at the time of Sampling Cruise 1.

The sums of cuttings, fossil, and sphere indications in Table 4-4 gives an overall picture of the time-progression of the physical indicators. The sums in Table 4-4 show that the cuttings indications are decreasing over time but the spheres and fossils are not changing much. This is an indication of changes resulting from disaggregation of cuttings particles rather than burial or bed transport, because these latter processes would affect all indications equally.

Table 4-4. Summary of results of analysis of sediments for cuttings solids, anachronous nannofossils, and glass spheres (From: Chapter 7). Dark shading indicates sites where parameter was detected in more than half of the sediment samples; light shading indicates sites where parameter was detected in some, but less than half, of the samples.

Site	Indicator	Cruise 1			Cruise 2		
		NF	MF	FF	NF	MF	FF
Eugene Island 346	Cuttings	1	1	0	1	½	0
	Fossils	1	½	½	1	½	0
	Spheres	1	1	½	1	½	½
Main Pass 288	Cuttings	1	1	½	0	0	0
	Fossils	½	0	0	½	½	0
	Spheres	0	0	0	½	½	0
Main Pass 299	Cuttings	1	1	½	½	½	0
	Fossils	0	0	0	0	0	0
	Spheres	½	½	½	1	½	½
Ewing Bank 963	Cuttings	1	1	0	0	0	0
	Fossils	0	0	0	½	0	0
	Spheres	0	0	0	½	0	1
South Timbalier 160	Cuttings	1	1	1	0	0	0
	Fossils	½	0	½	0	0	0
	Spheres	0	½	0	½	½	½
Viosca Knoll 783	Cuttings	1	1	1	1	½	½
	Fossils	1	1	0	1	½	½
	Spheres	½	1	½	½	½	½
Green Canyon 112	Cuttings	1	½	½	0	0	0
	Fossils	1	½	0	½	½	½
	Spheres	0	0	½	½	0	½
Mississippi Canyon 496	Cuttings	1	1	1	0	0	0
	Fossils	1	½	0	1	½	0
	Spheres	1	½	½	½	½	½
Sum of cuttings indications		8	7.5	4.5	2.5	1.5	0.5
Sum of fossils indications		5	2.5	1	4.5	2.5	1
Sum of spheres indications		3	3.5	2.5	5	3	4

FF = Far-field.	0 = Indications in no samples.
MF = Mid-field.	½ = Indications in half or less of samples.
NF = Near-field.	1 = Indications in majority of samples.

Summary for Physical Indicators of Cuttings. The physical evidence indicates that some sediments near all eight drillsites contained drill cuttings solids. The evidence for cuttings was strongest for four sites: EI 346 in 92 m of water, MC 496 in 556 m of water, GC 112 in 536 m of water, and ST 160 in 37 m of water. Thus, at these sites, physical evidence of cuttings accumulation in surficial sediments could not be correlated simply with water depth, total number of wells drilled, number of wells drilled with SBM, or total volume of cuttings discharged (Table 4-2). The year of the most recent cuttings discharge before the May 2001 start of

Sampling Cruise 1 at these sites ranged from 1995 to 2000. Wells were drilled with SBM about 1 year before Sampling Cruise 1 at EI 346 and MP 299. There was strong physical evidence of cuttings accumulation in sediments near EI 346; evidence was weaker at MP 299. The largest number of wells was drilled and the largest volume of cuttings was discharged in MP 299, yet no nannofossils and only traces of glass spheres were detected in sediments near the drillsite (Table 4-4); cuttings were visible in near-field and mid-field sediments, but sediment grain size was fairly uniform throughout the area. It is probable that physical evidence of cuttings in sediments at MP 299 was weak because drilling depths were too shallow to produce nannofossils and the cuttings were fine-grained and did not contain significant amounts of glass spheres. In addition, MP 299 is near the mouth of the Mississippi River, and sediments from this source probably diluted and buried any cuttings particles derived from drilling discharges.

The last of four wells at EW 963, the location with the least evidence of drill cuttings in sediments, was drilled in January 1997. At the sites where the evidence of cuttings in sediments was strongest (EI 346, MC 496, and GC 112), the last well was drilled between December 1997 and April 2000. As discussed below, evidence of cuttings accumulation on the seafloor was stronger at the time of Sampling Cruise 1 than at the time of Sampling Cruise 2. Thus, the ability to observe physical evidence of cuttings in sediments depends primarily on the time since the last well was drilled and drill cuttings discharged. Cuttings may be dispersed by bed transport, buried by natural sediment deposition, or mixed down into the local sediments over time by bioturbation or gravity settling. Shales in cuttings weather rapidly due to hydration and swelling and quickly lose their identity as cuttings particles. Clumps of SBM cuttings probably also disaggregate following deposition through hydration and possibly synthetic material biodegradation.

Iron and Aluminum in Sediments Near Discharge Sites. Concentrations of Fe and Al in sediments were used primarily as indices of the presence in the sediments of drilling mud solids. Both Al and Fe are abundant in marine sediments, particularly fine-grained ones. Much of the Al is in clays (aluminosilicates). In oxidized sediments, Fe is present primarily as iron oxyhydroxide coatings on clay particles or associated with some natural heavy minerals; in reduced sediment layers, most of the Fe is present as iron sulfides, FeS (amorphous iron sulfide or mackinawite) under slightly reducing conditions or highly stable FeS_2 (pyrite) at low Eh (Cornwell and Morse, 1987; Cranfield, 1989). Much of the Fe and Al in continental shelf and slope sediments often is derived from riverine inflows, and concentrations of the two metals in sediments co-vary (Slomp et al., 1997). The concentration ratio of Fe to Al often is quite uniform in shelf and slope sediments of uniform grain size, mineralogy, and origin.

Accumulation of significant amounts of drill cuttings solids in sediments may alter this ratio. However, in sediments near the six primary discharge sites, Fe/Al concentration ratios were relatively uniform and did not vary much with distance from the discharge site. Aluminum concentrations in sediments near discharge sites varied by a factor of about 9, and Fe concentrations varied by a factor of about 4. However, mean Fe/Al ratios (the mean for all samples within a zone at each site and cruise) were relatively constant, ranging from 0.43 to 0.55, similar to the value of 0.53 for sediments from the Mississippi River (Trefry and Presley, 1982). This suggests that much of the fine-grained sediments near platforms is from terrigenous sources.

At EI 346, MC 496, EW 963, and GC 112, far-field sediments contained lower concentrations of Fe and Al than most mid-field and near-field sediments. The differences were greatest in sediments from EI 346. However, the Fe/Al ratios were similar at near-field, mid-field, and far-field locations. Iron and Al concentrations and Fe/Al ratios were similar at all MP 299 locations. Thus, the Fe and Al data provide an indication, though weak, of the presence of drilling solids in near-field and mid-field sediments at four of the six sites.

Barium in Sediments Near Discharge Sites. Barium concentrations vary widely in marine and estuarine sediments not obviously containing discharged oil well drilling fluids (rich in barite) (Neff, 2002a). Most of the Ba in deepwater marine sediments is present as fine-grained barite particles or inclusions in detrital aluminosilicates (clays) (Robin et al., 2003). Thus, coarse-grained carbonate and silicate sediments, such as those on Georges Bank (a fishing bank off the U.S. New England coast), often contain less than 100 ppm Ba, most of it associated with the silt-clay fraction (Neff et al., 1989). Fine-grained sediments rich in clay minerals, such as many sediments off Louisiana, may contain more than 1,000 ppm Ba. Based on the concentration ranges at far-field stations in the present investigation, apparent background sediment Ba concentrations are about 700 mg/kg in shelf sediments and perhaps a little higher in slope sediments.

The concentration of Ba (as barite: $BaSO_4$) often is very high in drilling muds and cuttings. Because of this and because barite is nearly insoluble in seawater and settles rapidly to the bottom, Ba often is used as a tracer of the fate of drilling mud and cuttings solids in sediments following their discharge to the ocean (Boothe and Presley, 1989; Hartley, 1996). However, it should be kept in mind that barite particles may behave differently than other drilling solids in the water column and sediments, so their distribution and concentrations in sediments may not reflect those of other drilling waste ingredients, particularly the clay and synthetic chemical components of SBMs.

Discharge of drilling fluids to the ocean during drilling of exploration and development wells results in the release of large amounts of barite to the ocean. The barite is deposited rapidly in sediments near the offshore platforms, often resulting in gradients of steeply decreasing Ba concentrations in sediments with distance from platforms (Boothe and Presley, 1985, 1989; API, 1989; Jenkins et al., 1989; Kennicutt et al., 1996; Neff et al., 2000).

In the present investigation, there was a clear, sharp, and statistically significant gradient of decreasing sediment Ba concentrations with distance from all the drillsites (Figure 4-1). There was not a statistically significant difference in Ba concentration in sediments between near-field and mid-field stations at three sites (MP 299, EI 346, and EW 963). At all sites, highest concentrations were in near-field sediments and lowest concentrations were in far-field sediments.

There was no relationship between mean or range of Ba concentrations in near-field sediments and either the time since last drilling or the number of wells drilled. The main determinant of Ba concentrations in near-field sediments may be local water current regimes and sediment transport.

The sediment Ba data do show that drilling mud/cuttings solids have accumulated in near-field and most mid-field sediments at the six primary shelf and slope sites. There is some indication of a small amount of excess Ba in far-field sediments at most sites, particularly GC 112 and EW 963, both slope sites. Similar results have been reported for several monitoring studies in the Gulf of Mexico (Neff, 2002b). Substantially elevated concentrations (compared to local background) of Ba in bulk sediments rarely extend farther than about 1 km from the discharge site, but small amounts of excess Ba may occur in sediments up to several kilometers from the discharge. Wide dispersal of barite probably is much greater from WBM and WBM cuttings discharges than from SBM cuttings discharges because WBMs tend to disperse in the water

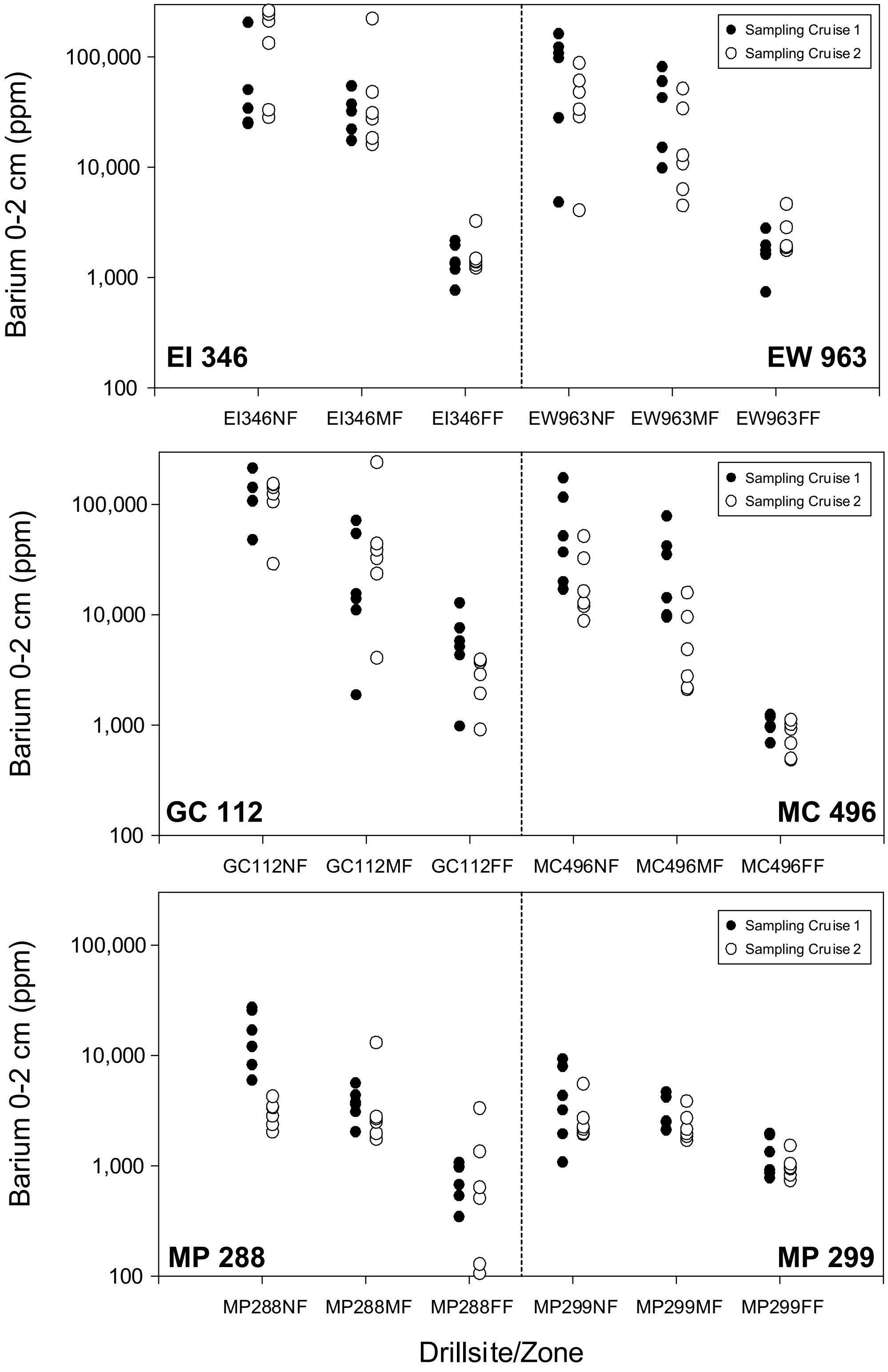


Figure 4-1. Barium concentrations in surficial sediments from near-field (NF), mid-field (MF), and far-field (FF) zones at three continental shelf and three continental slope sites in the Gulf of Mexico, sampled on Sampling Cruise 1 (May 2001) and Sampling Cruise 2 (May 2002).

column and the disaggregated fine-grained barite particles settle very slowly, allowing dispersal to considerable distances down-current from the discharge, particularly in deep water (Neff et al., 2000). SBM cuttings tend to clump upon ocean discharge and settle rapidly as large clumps near the discharge site. Thus, the excess Ba identified in many mid-field and some far-field sediments probably originated in WBM and WBM cuttings discharges.

Metal/Al concentration ratios often are used to identify anthropogenic contributions of metals to sediments (Windom et al., 1989; Weisbart et al., 2000). This approach is based on the assumption that much of the natural metals in sediments are associated with the clay mineral (aluminosilicate) phase of the sediment. Anthropogenic contributions should exceed the expected linear metal/Al ratio. As mentioned above, much of the natural Ba in continental shelf sediments is associated with clays and clay-sized barite particles. Therefore, Ba additions from drilling discharges should be reflected in an excess of Ba relative to Al in sediments near the discharge site. Barium concentration increases slightly with Al concentration in far-field sediments; however, there is no relationship or even a slight inverse relationship between Ba and Al concentrations in near-field and mid-field sediments (Figure 4-2). This relationship indicates that near-field and mid-field sediments are enriched in Ba relative to uncontaminated background sediments represented by the far-field sediments.

Other Metals in Sediments Near Discharge Sites. Nine metals (As, Cd, Cr, Cu, Hg, Ni, Pb, V, and Zn), as well as Ba, were analyzed in near-field and far-field sediments from three of the discharge sites during the Screening Cruise (see Chapter 9). In most cases, metals (except Ba) concentrations were similar in near-field and far-field surficial sediments at the three sites (Table 4-5). The range of Ba concentrations in near-field sediments exceeded the range in far-field sediments at all three sites. At one or more sites, concentrations of all ten metals were higher in one or more near-field sediment samples than in the single far-field sample for the same location. Although differences in Ba concentrations in near-field and far-field sediments were large, differences in metals concentrations between near-field and far-field sediments were small. This probably reflects the generally low, near-background concentrations of most metals in modern WBMs and SBMs, in which barite meets the criteria for Hg and Cd.

Table 4-5. Concentrations of metals in surficial sediments from near-field (NF) and far-field (FF) zones of three of the discharge sites. Samples were collected during the Screening Cruise and analyzed by Trefry et al. (Chapter 9) and summarized in the Post-Screening Cruise Data Report (Continental Shelf Associates, Inc., 2000). Concentrations are mg/kg dry wt.

Metal	Main Pass 299		Green Canyon 112		Mississippi Canyon 496	
	NF[a]	FF[b]	NF[a]	FF[b]	NF[a]	FF[b]
Arsenic	5.3 – 10	8.3	15 – 25	15	11 – 21	14
Barium	4,200 – 34,800	848 – 3,640	93,000 – 240,000	2,550 – 2,710	2,110 – 358,000	750 – 1,060
Cadmium	0.12 – 0.24	0.15	0.48 – 1.2	0.26	0.13 – 0.72	0.23
Chromium	59 – 87	93	44 – 174	66	17 – 70	77
Copper	19 – 25	20	37 – 54	26	20 – 89	27
Mercury	0.04 – 0.07	0.06	0.12 – 0.37	0.09	0.06 – 0.36	0.08
Nickel	14 – 33	29	19 – 35	41	6.0 – 30	31
Lead	18 – 52	26	17 – 50	32	27 – 77	30
Vanadium	98 – 164	136	68 – 167	156	10 – 136	139
Zinc	96 – 159	120	123 – 149	120	34 – 147	128

[a] Range for all samples.
[b] Only one far-field sediment sample was collected at each site.

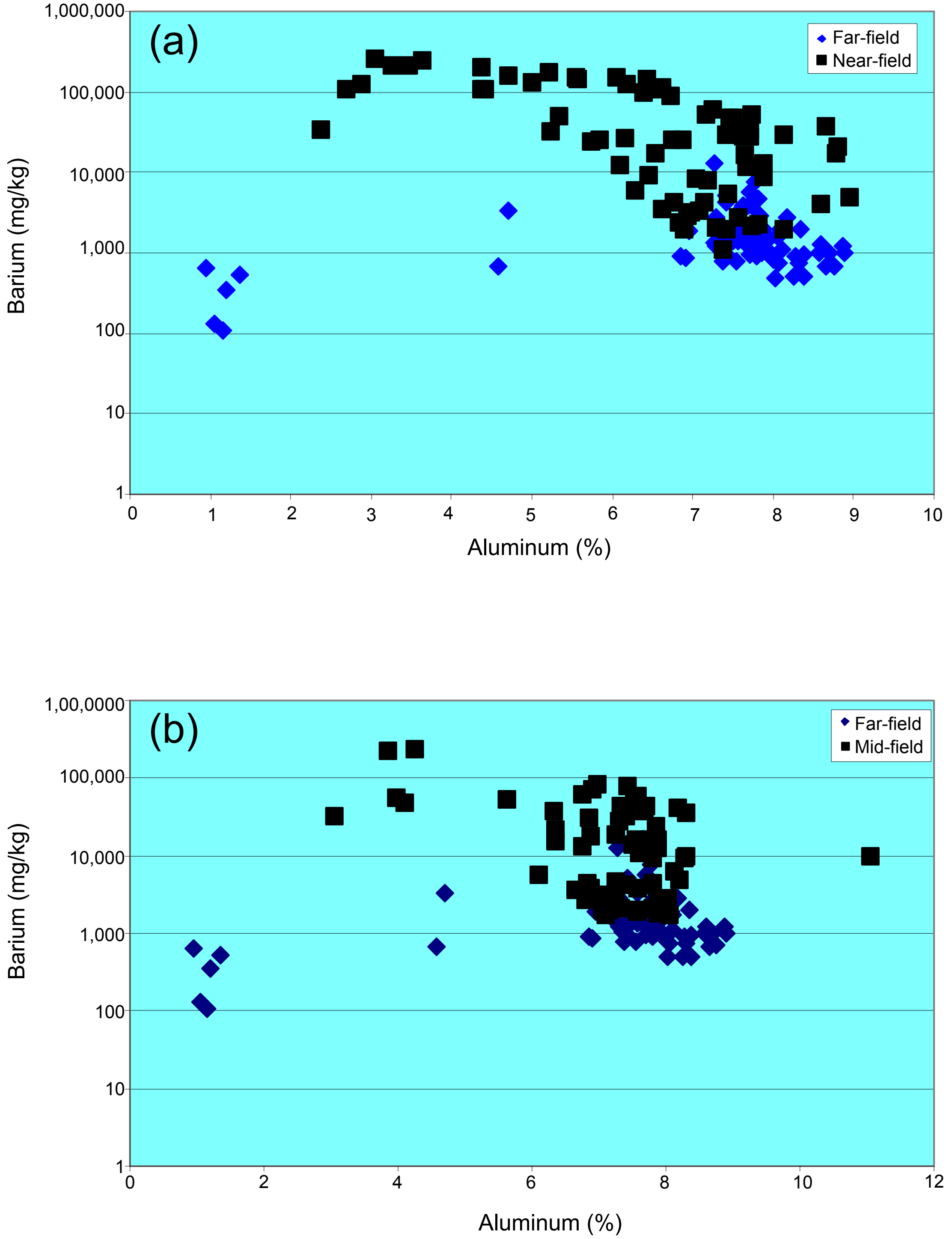


Figure 4-2. Relationship between barium and aluminum concentrations in (a) near-field and far-field and (b) mid-field and far-field surficial sediments from three continental shelf and three continental slope sites sampled on Sampling Cruise 1 (May 2001) and Sampling Cruise 2 (May 2002). Data from: Chapter 9.

These results show very little evidence that metals, other than Ba, associated with drilling wastes have accumulated to concentrations higher than natural background levels in sediments near the offshore drillsites. The metals most frequently present in drilling fluids at concentrations substantially (>100-fold) greater than natural concentrations in soils and sediments are Ba, Cr, Pb, and Zn (Table 4-6). The most abundant metal in most WBMs, Ba (an alkaline earth element like calcium and strontium), was discussed above. Barium is the only metal found consistently at higher concentrations in near-field than far-field sediments.

Table 4-6. Concentration ranges of metals in water based drilling fluids from different sources and in typical soils and marine sediments. Concentrations are mg/kg dry wt (ppm). Modified from: Neff et al. (1987).

Metal	Drilling Muds	Soils	Sediments
Barium	720 – 449,000	20 – 3,000	60 – 8,100
Chromium	0.1 – 5,960	1 – 1,500	10 – 200
Cadmium	0.16 – 54.4	0.4 – 50	0.1 – 1.0
Copper	0.05 – 307	1 – 300	8 – 700
Iron	0.002 – 27,000	---	20,000 – 60,000
Mercury	0.017 – 10.4	<0.01 – 4.6	0.05 – 3.0
Lead	0.4 – 4226	<10 – 70	6 – 200
Zinc	0.06 – 12,270	<5 – 300	5 – 400
Nickel	3.8 – 19.9	<5 – 200	2 – 1000
Arsenic	1.8 – 2.3	<0.1 – 93.2	2 – 20
Vanadium	14 – 28	---	10 – 500
Aluminum	10,800	---	10,000 – 90,000
Manganese	290 – 400	7 – 3,000	100 – 10,000

Concentrations of Cu, Pb, and Zn, although slightly higher in one or more near-field sediment samples than in the corresponding far-field sediment sample at one or more of the three discharge sites, are in the middle of the expected range of background concentrations for uncontaminated marine sediments (Table 4-6). Chromium concentration in a sediment sample from GC 112 is in the upper part of the range for background. Concentrations of Ni and V in all near-field and far-field sediments are in the lower or middle part of the range of background concentrations in marine sediments. These metals rarely are abundant in drilling muds. Cadmium concentration in one near-field sediment sample from GC 112 and MC 496 is in the upper part of the expected range for marine sediments. This Cd may be associated with drilling mud barite. Mercury concentrations in Gulf of Mexico shelf and slope sediments usually are below about 0.15 mg/kg (Neff, 2002b). Concentrations of Hg in some sediment samples from two continental slope sites are greater than 0.3 mg/kg. Insufficient data are available for Hg in deepwater sediments to determine if this concentration is within the normal range or represents excess Hg associated with drilling mud barite.

Synthetic Base Chemicals and Hydrocarbons in Sediments Near Discharge Study Sites. Prior to the 2002 Gulf of Mexico NPDES permit, separated cuttings generated during use of SBMs usually contain about 10% to 15% adhering SBM solids (Annis, 1997). When discharged to the ocean, these cuttings tend to clump and settle rapidly to the seafloor (Brandsma, 1996; Delvigne, 1996). Because they settle rapidly, SBM-contaminated cuttings accumulate near the discharge site, even in deep water. Most of the SBM cuttings solids are distributed in a heterogeneous fashion within a radius of a few hundred meters of the discharge site, with most solids concentrated in the direction of the mean (for all water depths) residual current flow.

In this study, TPH in sediment as measured by GC/MS was defined as those hydrocarbons between n-C_{10} and n-C_{36} that can be extracted and measured in the sediment samples. Practically, this measurement detected and quantified petroleum (including crude and most refined products such as diesel, residual fuels, and lubricating-range materials), synthetic based drilling fluid hydrocarbons, and certain biogenic (naturally occurring) hydrocarbons, e.g., plant waxes. Sediment that contained residues of SBF had a TPH value that reflected the SBF content plus any other petroleum or natural hydrocarbons found in the sediment outside that SBF carbon-range window.

SBM base chemical and TPH in sediments around the eight drillsites were measured by gas chromatography/mass spectrometry (GC/MS) (see Chapter 8). The TPH analysis included resolved alkanes between n-C_{10} and n-C_{36} including the SBM olefins and esters and was used mainly to validate the more specific SBM base chemical analyses. The TPH analysis measures biogenic and petrogenic/pyrogenic hydrocarbons, in addition to the SBM olefins and esters. Concentrations of TPH in far-field sediments (probably including biogenic hydrocarbons and petrogenic/pyrogenic mixtures from the Mississippi River outflow) at the eight sites surveyed for SBM base chemical during Sampling Cruises 1 and 2 ranged from <1 to 62 mg/kg.

As expected, concentrations of TPH were higher than those of SBM base chemical in sediments at most sites and zones at the time of both Sampling Cruises 1 and 2 (Figure 4-3). SBM base chemical was slightly more abundant than TPH in a single near-field sediment sample (of six replicates) collected at ST 160 and MP 496 at the time of Sampling Cruise 1. Mean concentrations of TPH and SBM base chemical decreased markedly with distance from all eight drillsites. Green Canyon 112 was the only site where any SBM base chemical was detected in far-field sediments at the time of Sampling Cruise 1; at the time of Sampling Cruise 2, three far-field sediment samples at ST160 contained 1.0, 1.1, and 2.5 mg/kg SBM base chemical and two far-field samples from MC 496 contained 1.1 and 2.0 mg/kg SBM base chemical. All these concentrations are just above the method detection limit of 1 mg/kg.

Highest concentrations of TPH and SBM base chemical were in near-field sediments at GC 112 (a slope site) and EI 346 (a shelf site) at the time of Sampling Cruise 1 (Figure 4-3). There was a nearly ten-fold decrease in concentrations of both TPH and SBM base chemical in near-field sediments at both sites between Sampling Cruises 1 and 2. Lowest concentrations in near-field sediments at the time of both Sampling Cruises were at VK 783 (drilled with ester SBM), MP 288 (drilled with IO SBM), and MP 299 (drilled with LAO). Thus, several factors, in addition to SBM olefin type, seem to influence SBM base chemical concentrations in near-field sediments. Internal olefins and LAOs biodegrade at similar rates in offshore sediments and so would be expected to have equal environmental persistence. However, esters degrade much more rapidly than olefins in sediments and therefore have a lower environmental persistence (Neff et al., 2000).

In most cases, particularly at near-field stations, the difference between TPH and SBM base chemical concentrations in sediments was greater than the background concentration of TPH at the far-field stations. This suggests that the SBM base chemicals were biodegrading to other hydrocarbons in sediments, or that small amounts of hydrocarbons (possibly including other mud ingredients and crude oil) in addition to the SBM base chemicals were discharged from the drilling facilities and accumulating in sediments near the drillsite. At most near-field and mid-field locations, the difference between TPH and SBM base chemical concentration was

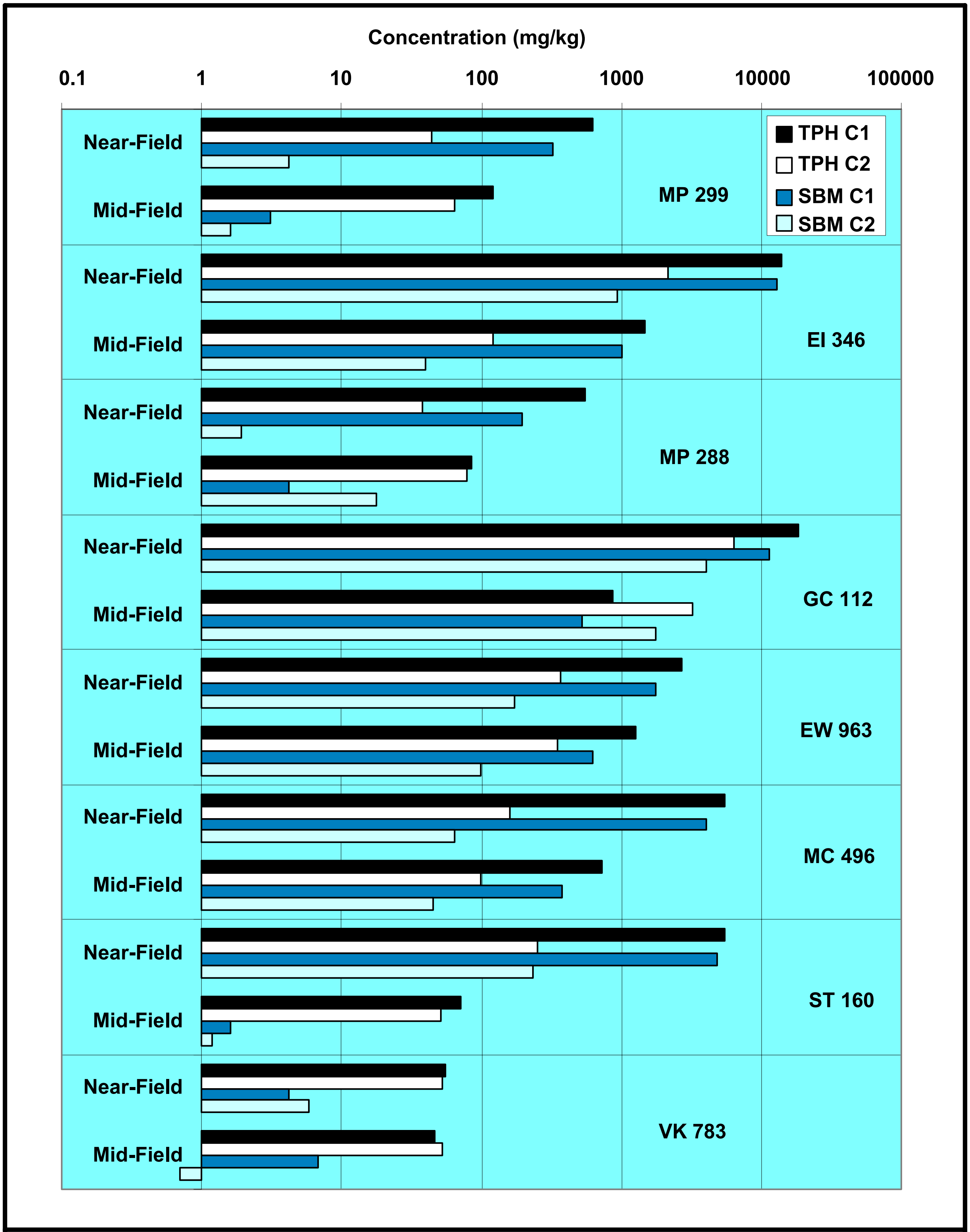


Figure 4-3. Mean concentrations of total petroleum hydrocarbons (TPH) and synthetic based mud (SBM) base chemical in near-field and mid-field sediments at eight continental shelf and continental slope SBM cuttings discharge sites. Data for Sampling Cruise 1 (May 2001) and Sampling Cruise 2 (May 2002) were combined. Data from: Chapter 8.

small (Figure 4-3), indicating that most of the TPH was SBM base chemical. Usually, the difference between TPH and SBF concentrations was much less in mid-field sediments than in near-field sediments; nearly all far-field sediments did not contain detectable concentrations of SBF, so differences were due almost exclusively to the presence of background TPH in the sediments.

There was not a close correlation between concentrations of TPH or SBF on the one hand and TOC on the other in sediments at any sites. Thus, TOC cannot be used as a measure of SBM accumulation in sediments.

The analytical data show convincingly that SBM base chemical does accumulate in surficial sediments near drillsites where SBM cuttings were discharged. SBMs accumulate primarily within 100 m (near-field) of the discharge, with small amounts dispersed to at least 250 m (mid-field). Little or no SBM base chemical was dispersed as far as the far-field sites, about 3,000 m from the discharges. Synthetic based fluid concentrations of 1.0 to 2.5 mg/kg (just above the method detection limit) were found in one or two far-field sediment samples collected during either Sampling Cruise 1 or Sampling Cruise 2 at ST 160 (a shelf site) and at MC 496 and GC 112 (both slope sites). These traces of hydrocarbons identified as SBMs may have been authentic SBMs or natural hydrocarbons that eluted in the same range as the SBM olefins. Laboratory blank samples did not contain detectable concentrations of hydrocarbons eluting in the SBM base chemical range, indicating that the SBM range hydrocarbons in a few far-field samples were from the sediments, not from laboratory contamination.

Synthetic based fluids and Ba were the best indicators of the presence of drilling waste solids in sediments. Although there was a good correlation between barium and SBM base chemical concentrations in sediments collected on Sampling Cruises 1 and 2 ($r^2 = 0.75$), many samples containing concentrations of SBM base chemical below the method detection limit (~0.1 mg/kg) were enriched in Ba (>1,000 mg/kg) (Figure 4-4). For example, a far-field sediment sample collected at GC 112 during Sampling Cruise 1 contained 12,800 mg/kg Ba and less than 0.1 mg/kg SBF. All sediments containing more than about 5 mg/kg SBM base chemical also contained more than 1,000 mg/kg Ba (the approximate upper limit background concentration), but Ba concentrations were highly variable. Mid-field surficial sediment samples collected at MP 299 and EI 346 on Sampling Cruise 1 both contained 5 mg/kg SBM base chemical but contained 4,670 mg/kg and 37,500 mg/kg Ba, respectively. Two mid-field sediment samples from GC 112 and EI 346, containing about 50 mg/kg SBM base chemical, also contained 14,000 and 223,000 mg/kg Ba, respectively.

There are three likely explanations for this apparent discrepancy, all of which may apply to varying degrees at the discharge sites. The first and most likely explanation is that much of the drilling waste discharged at the eight drilling locations monitored in this investigation was WBM and WBM cuttings. A much larger mass of barite is discharged during drilling with WBM than when SBMs are used because both bulk WBM discharges and continuous WBMs cuttings discharges are permitted during drilling in Federal waters with WBMs, whereas only SBM cuttings are permitted for discharge during drilling with SBMs. At all of the sites except EW 963, more wells were drilled with WBMs than with SBMs (Table 4-1). Thus, much of the excess Ba measured in sediments near the eight drillsites probably was derived from discharges of WBMs and WBM cuttings.

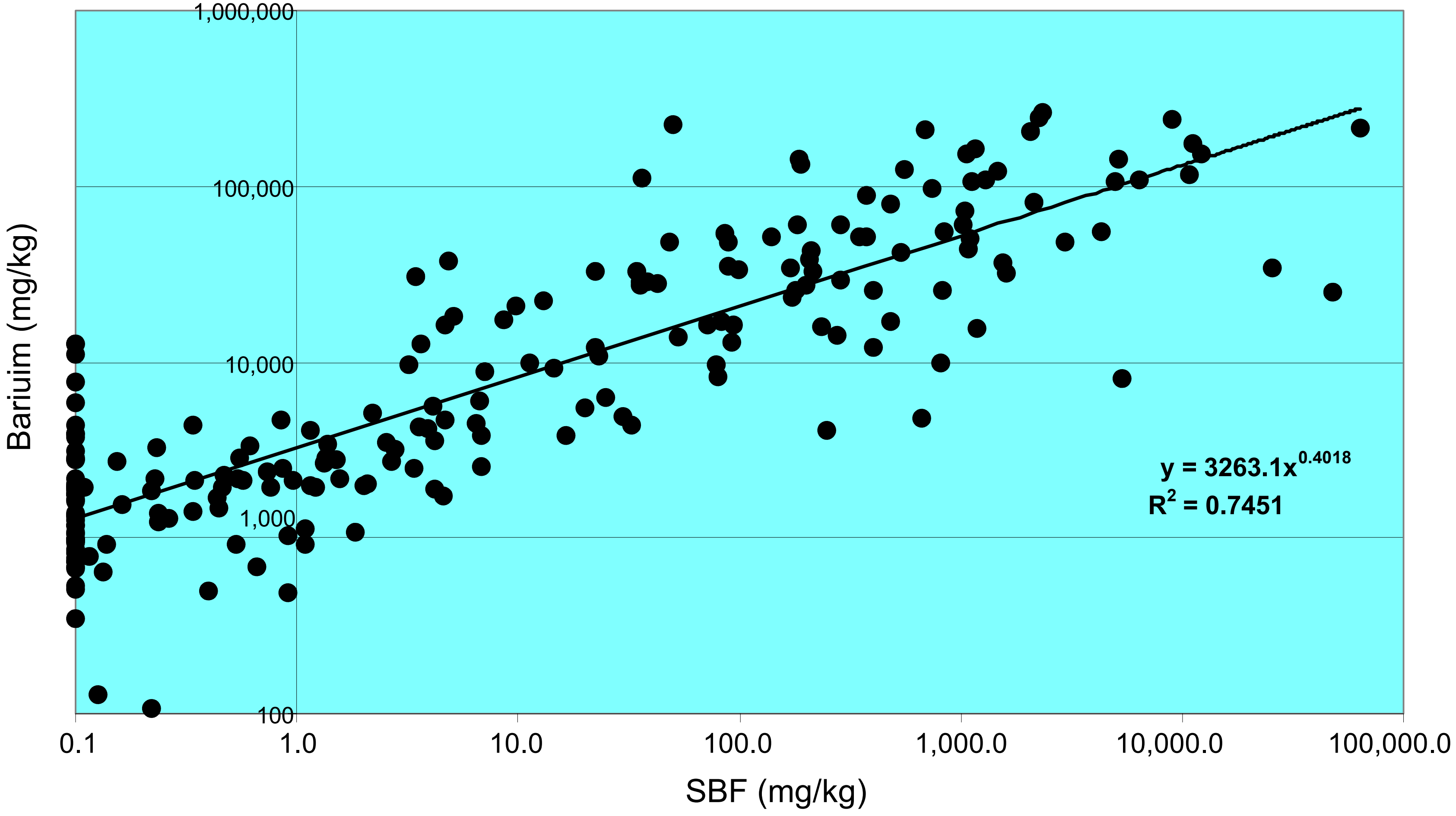


Figure 4-4. Regression of barium concentration against synthetic based fluid (SBF) base chemical concentration in sediments collected during Sampling Cruise 1 (May 2001) and Sampling Cruise 2 (May 2002) at six primary synthetic based mud cuttings discharge locations in the Gulf of Mexico. Barium concentration is log scale and regression equation and R^2 are included. Data from: Chapters 8 and 9.

Synthetic ingredients in SBMs are designed to be biodegradable. Esters are highly biodegradable and do not persist long in sediments; IOs and LAOs biodegrade more slowly but do biodegrade under both aerobic and anaerobic conditions in sediments (Neff et al., 2000). The time since the last SBM cuttings discharge before Sampling Cruise 1 ranged from about 1 year (at MP 299 and EI 346) to more than 4 years (at EW 963) and more than 5 years (at the secondary site VK 783, where ester SBM cuttings were discharged). Thus, considerable biodegradation of SBM base chemicals may have occurred in sediments at some sites before the initiation of sampling. Barite is not biodegradable and its solubility in seawater is so low that it is very persistent in both aerobic and anaerobic sediments.

Both SBM base chemicals and barite have very low solubilities in seawater. Olefinic SBM base chemicals probably have single-phase aqueous solubilities of about 1 µg/L or less; esters are somewhat more soluble. Because of their low aqueous solubilities and high affinities for the organic phase of sediments or cuttings (as indicated by log K_{ow}s >6.5), SBM base chemicals dissolve very slowly from sediments.

The solubility of barite in marine sediments and drill cuttings accumulations on the seafloor is very low and is controlled by sulfate concentration in sediment pore water (Monnin et al., 2001). As sediment oxygen is depleted by microbial degradation of organic matter, sulfate reducing bacteria use sulfate as an alternate electron source and generate sulfide that combines with and precipitates sediment metals (Hartley et al., 2003). If barite concentration in sediments is high, it can serve as a source of reducible sulfate for sulfate reducing bacteria (Ulrich et al., 2003), releasing dissolved Ba into the pore water (Phillips et al., 2001). Much of the Ba released into sediment pore water by the activity of sulfate reducing bacteria diffuses upward to the oxic layers of the sediment or into the overlying water column, where it precipitates with sulfate in the oxygenated water phase (Paytan et al., 2002). Thus, barite is highly persistent in marine sediments containing WBM or SBM cuttings. It is unlikely that differential solubility contributes significantly to the differential distribution of SBM base chemical and Ba in sediments near discharge sites.

However, the presence of synthetic organic chemicals (IO, LAO, or ester) and Ba in near-field and mid-field sediments at all eight sites is unequivocal evidence of accumulation of SBM cuttings solids in sediments near the platforms. Only traces of SBM chemical were detected in near-field and mid-field sediments at VK 783, where ester based SBM was used. Concentrations of TPH also were low in these sediments. The ester probably biodegraded in the 6 years between drilling and the field surveys.

4.2.3 Summary of SBM Cuttings Distribution Near Offshore Drillsites

Several lines of evidence were used to document the presence and concentrations of SBM cuttings solids in sediments in two zones (<100 m and 100 to 250 m) around eight offshore SBM cuttings discharge sites on the continental shelf and slope of the Gulf of Mexico (Table 4-7). Far-field stations served as site-specific reference locations for the measured parameters at each discharge site. However, cuttings particles were detected at greater than trace concentrations in far-field sediments at ST 160 (a continental shelf site) and MC 496 (a continental slope site) (Table 4-3). Excess Ba (>1,000 mg/kg) was present in one or more far-field sediment samples from all six primary discharge sites (Figure 4-1). This excess Ba may be natural (Ba concentrations up to at least 2,000 mg/kg are common in fine-grained, deepwater marine sediments [Neff, 2002a]), or more likely from previous discharges of WBM and WBM cuttings. The latter explanation is supported by the observation that SBM base chemical was detected in one to three far-field sediment samples from four sites. Thus, the evidence indicates that SBM cuttings settle and accumulate on the seafloor within about 3,000 m (the minimum distance to the far-field stations), with most deposition within 100 m of the discharge site at both continental shelf and slope water depths.

Table 4-7. Summary of evidence for the presence of synthetic based mud (SBM) cuttings in seafloor sediments in the near-field (<100 m) and mid-field (100 to 250 m) of eight drill cuttings discharge sites on the continental shelf and slope of the Gulf of Mexico. In most cases, evidence was indicated as a difference between the parameter value for near-field (NF), mid-field (MF), and far-field (FF) stations.

Zone	Grain Size	Visible Cuttings	Fossils Spheres	Iron and Aluminum	Barium	Metals	SBF and TPH
South Timbalier 160							
NF	Slight	Yes	Slight	NA	NA	NA	Strong
MF	No	Yes	Slight	NA	NA	NA	Yes
Main Pass 299							
NF	Yes	Yes	Slight	No	Strong	Slight	Yes
MF	No	Yes	Slight	No	Strong	NA	Slight
Eugene Island 346							
NF	Yes	Yes	Yes	Slight	Strong	NA	Strong
MF	Yes	Yes	Slight	Yes	Strong	NA	Strong
Main Pass 288							
NF	Slight	Yes	Slight	Slight	Strong	NA	Slight
MF	No	Yes	Slight	Slight	Strong	NA	Slight
Viosca Knoll 783							
NF	Yes	Slight	Yes	NA	NA	NA	Slight
MF	Yes	Slight	Yes	NA	NA	NA	Slight
Green Canyon 112							
NF	No	Yes	Yes	Yes	Strong	Yes	Strong
MF	No	Yes	Slight	Yes	Strong	NA	Strong
Ewing Bank 963							
NF	Yes	Yes	No	Yes	Strong	NA	Strong
MF	No	Yes	No	Yes	Strong	NA	Strong
Mississippi Canyon 496							
NF	Slight	Yes	Yes	Slight	Strong	Yes	Strong
MF	Yes	Yes	Slight	Slight	Strong	Na	Strong

Yes = evidence present; No = no evidence; Slight = weak evidence; Strong = strong evidence; NA = not analyzed.
SBF = Synthetic based fluid.
TPH = Total petroleum hydrocarbons.

Grain size, nannofossils and spheres, and Fe/Al concentrations and ratios were only of limited use in detecting cuttings solids in sediments. These parameters, taken collectively, did provide evidence of cuttings solids in near-field sediments at all eight discharge sites and in mid-field sediments at all but ST 160 and MP 299. The presence of visible cuttings particles in sediments qualitatively identified cuttings solids in near-field and mid-field sediments at seven of the eight discharge sites. There were only traces of visible cuttings in near-field and mid-field sediments at VK 783, where there had not been WBM or SBM cuttings discharges since the end of 1995 and the amounts of cuttings discharged was small (Table 4-2).

There was an excess (compared to background concentrations) of Ba in near-field and mid-field sediments at the six primary discharge sites where Ba was measured (Table 4-7). This is strong evidence of the presence of drill cuttings solids in near-field and mid-field sediments but does not provide clues as to whether the cuttings solids were WBM or SBM cuttings. One or more concentrations of Cr, Hg, Pb, and Zn were slightly higher (compared to their concentrations in far-field sediments) in near-field sediments at one or more of the three sites where these metals were analyzed (Table 4-6).

SBM base chemical and TPH concentrations were elevated above those in far-field sediments in nearly all near-field sediments at the eight discharge sites (Figure 4-3 and Table 4-8). Strongest evidence for SBM cuttings accumulation was at the three sites where the largest volumes of SBM cuttings were discharged (10,328 bbl at EI 346, 5,470 bbl at GC 112, and 1,674 bbl at MC 496: Table 4-2). Synthetic chemical was not present at a concentration above the method detection limit in some near-field and mid-field samples from VK 783, where ester SBM was used. This may reflect the higher rate of biodegradation or dissolution of ester compared to olefin synthetic chemicals (Neff et al., 2000). However, this site received the smallest volume of SBM cuttings discharges, and discharges occurred more than 5 years prior to Sampling Cruise 1. The mean concentrations of SBM chemical and TPH in near-field sediments were less than 100 mg/kg at VK 783 and less than 1,000 mg/kg at MP 288 and MP 299. Highest mean concentrations in near-field sediments (>10,000 mg/kg) were at EI 346 (a shelf site) and GC 112 (a slope site).

Table 4-8. Summary of concentrations of synthetic based fluid (SBF) (internal olefin or linear alpha olefin) and total petroleum hydrocarbons (TPH) in sediments collected during Sampling Cruise 1 near eight drillsites. Sediment total organic carbon (TOC) concentrations are included for comparison (Data from: Chapters 8 and 9).

Zone	SBF (µg/g)		TPH (µg/g)		TOC (%)	
	Mean	Range	Mean	Range	Mean	Range
Main Pass 299						
NF	322	1.2 – 1,879	619	55 – 2,650	1.3	0.8-1.7
MF	3.1	<1 – 6.8	122	77 – 201	1.3	1.2-1.3
FF	<1	<1	11	<1 – 35	1.2	1.2-1.4
Eugene Island 346						
NF	12,900	178 – 47,500	13,900	280 – 48,000	2.8	0.8-6.0
MF	1,000	4.8 – 4,290	1,460	49 – 5,520	1.7	0.7-5.2
FF	<1	<1	17	13 – 21	0.9	0.8-1.1
Main Pass 288						
NF	196	6.7 – 404	551	118 – 1,020	1.4	1.3-1.6
MF	4.6	<1 – 16	85	9 – 157	1.4	1.3-1.5
FF	<1	<1	24	8 – 51	1.7	0.4-5.0
Green Canyon 112						
NF	11,500	37 – 63,300	18,200	324 – 99,800	1.6	0.6-3.8
MF	519	<1 – 1,180	867	40 – 1,990	1.4	0.9-2.1
FF	1.2	<1 – 2.2	35	29 – 46	1.1	0.7-1.2

Table 4-8. (Continued.)

Zone	SBF (µg/g)		TPH (µg/g)		TOC (%)	
	Mean	Range	Mean	Range	Mean	Range
Ewing Bank 963						
NF	1,750	43 – 6,410	2,670	114 – 9,800	0.9	0.4-1.9
MF	620	11 – 2,120	1,250	77 – 3,390	1.7	0.8-3.1
FF	<1	<1	3.6	<1 – 13	1.0	0.8-1.2
Mississippi Canyon 496						
NF	4,060	10 – 11,200	5,520	48 – 20,500	2.9	0.8-7.4
MF	379	79 – 817	725	228 – 1,090	1.6	1.2-2.2
FF	<1	<1	22	13 – 32	1.2	1.0-1.4
South Timbalier 160						
NF	4,790	499 – 14,200	5,460	853 – 14,600	1.0	0.7-1.7
MF	2.0	<1 – 6.8	71	61 – 93	0.8	0.7-0.8
FF	<1	<1	41	29 – 61	0.7	0.6-0.8
Viosca Knoll 783						
NF	4.4	<1 – 13	55	30 – 93	1.5	1.3-1.8
MF	7.1	<1 – 38	46	26 – 115	1.7	1.5-1.8
FF	<1	<1	39	26 – 57	1.7	1.5-1.8

FF = Far-field.
MF = Mid-field.
NF = Near-field.

The means and ranges of SBM base chemical and TPH concentrations were much lower, usually by a factor of 10 or more, in mid-field sediments than in near-field sediments at all but VK 783, where concentrations were low in all zones (Figure 4-3). Highest mean concentrations in mid-field sediments were at EI 346 and EW 963. Concentrations of SBM base chemical at EW 963 were only about twice as high in near-field sediments as in mid-field sediments.

Most mid-field sediments at all eight sites contained less than about 500 mg/kg SBM base chemical at the time of Sampling Cruise 1. Thus, there was a steep gradient of decreasing SBM base chemical with distance at most discharge sites. The steepest concentration gradients were at the two most heavily contaminated sites, EI 346 and GC 112. These sites had the largest SBM cuttings discharges, and discharges within 1 to 3 years of Sampling Cruise 1 (Table 4-2). Although the zone of SBM cuttings accumulation extends into the mid-field (100 to 250 m from the discharge source), the steep concentration gradient strongly implies that the outer limit of substantial cuttings accumulation occurs in or near the mid-field.

4.3 TEMPORAL CHANGES IN DISTRIBUTION AND CONCENTRATIONS OF SBM CUTTINGS IN SEDIMENTS

4.3.1 Loss of Cuttings Solids from Sediments

Monitoring studies in the Gulf of Mexico, North Sea, and offshore Australia and Ireland have shown that SBM cuttings accumulate in a very irregular pattern in sediments around the drillsite (Neff et al., 2000). Highest concentrations of SBM base chemical in sediments often are lower than the concentration of SBM base chemical in cuttings at the time of discharge, suggesting that some SBM base chemical desorbs from the cuttings during their fall through the water column (Getliff et al., 1997) or that the base chemical is diluted with natural sediments or is biodegraded rapidly following deposition (Neff et al., 2000). Sometimes, SBM base chemical concentrations in sediments are as high as or higher than reported average concentrations on discharged cuttings, suggesting either that some cuttings are discharged containing high concentrations of adsorbed SBM or that some sediment samples represent undiluted clumps of SBM cuttings.

In the present investigation, the samples with the highest concentrations from GC 112 and EI 346 contained 63,300 mg/kg (6.3%) and 47,500 mg/kg (4.7%) SBM base chemical, respectively. Typical SBM cuttings discharged to the Gulf of Mexico at the time of these discharges contained 10% to 15% SBM base chemical (Annis, 1997). Thus, these samples may have contained about 50% SBM cuttings. These sediment samples also contained 214,000 mg/kg (GC 112) and 24,800 mg/kg (EI 346) Ba, representing approximately 38.9% and 4.5% barite, respectively (assuming that Ba represents 55% of drilling mud $BaSO_4$). A typical SBM contains about 35% to 40% barite (Rushing et al., 1991). The sample from GC 112 probably was nearly straight SBM, while the sediment sample from EI 346 probably was SBM cuttings that had been diluted with natural sediments.

Concentrations of drill cuttings ingredients tend to decrease with time following deposition of SBM and WBM cuttings in sediments near offshore drillsites. Average concentrations in surface sediments decrease with time due to dispersion through bed transport, natural or bioturbated (biologically mediated) vertical mixing in the upper sediment column, burial and dilution by deposition of natural particulate matter, dissolution, and biodegradation. Dissolution affects concentrations in sediment of drill cuttings ingredients that are slightly soluble in sea water. Slightly soluble cuttings ingredients include barite (under sulfate-reducing conditions), a fraction of the metals adsorbed to barite and clay particles, and several organic drilling mud additives, such as lignosulfonates, emulsifiers, and lime. Esters are slightly water-soluble and may be lost by dissolution, but IO and LAO have very low aqueous solubilities.

Biodegradation probably is the main mechanism of loss of SBM base chemicals and emulsifiers. The different SBM base chemicals vary widely in biodegradability. Esters are most biodegradable, followed by different olefins. Mineral oil (an OBM base chemical) is the least biodegradable.

In the present investigation, temporal changes in the distribution and concentrations of discharged drilling wastes in sediments near offshore discharge sites can be documented semiquantitatively by observed changes in concentrations of Ba and SBM base chemical in sediments during the 1 year between Sampling Cruises 1 and 2. SBM base chemical concentration is the only unique indicator of the presence of SBM cuttings solids in sediments.

Barium seems to be a more conservative indicator of former cuttings discharges, so temporal changes in SBF/Ba concentration ratios between Sampling Cruises 1 and 2 provide a good indication of the rate of loss of SBM base chemical from site sediments (Figure 4-5). The mean concentration of SBM base chemical as a percentage of the mean concentration of Ba in near-field and mid-field sediments at all primary discharge sites, except MP 288, was higher at the time of Cruise 1 than at the time of Cruise 2. At mid-field stations at MP 288, the percentage of SBM base chemical increased from 0.11 to 0.43 between Sampling Cruises 1 and 2, due to the low SBM base chemical concentrations in most sediments and the presence of 93 mg/kg SBM base chemical in one mid-field sediment sample (of six) at the time of Sampling Cruise 2. If this one high value is not used, the percent SBF base chemical in

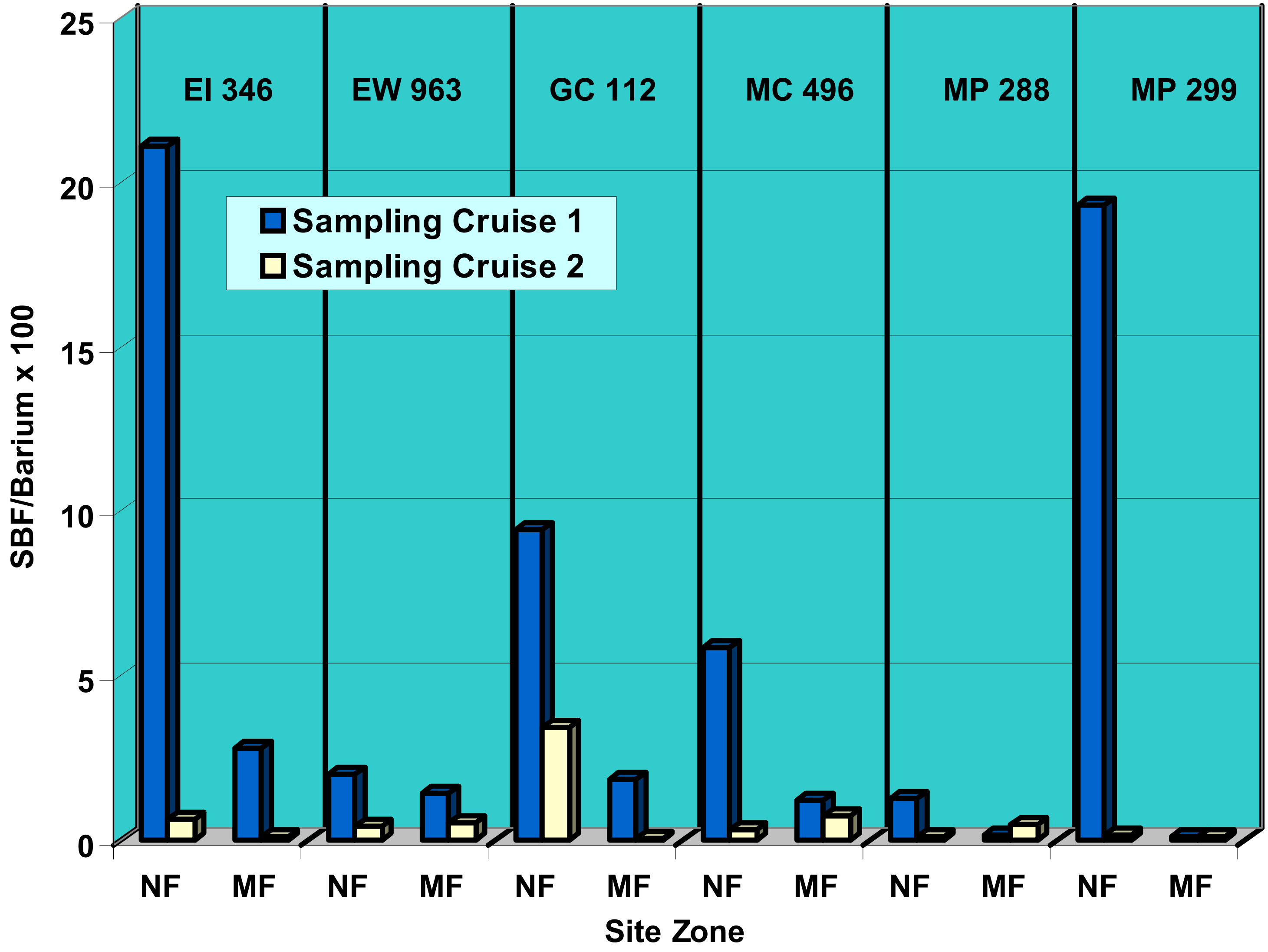


Figure 4-5. Mean concentration ratio of synthetic based fluid (SBF) to barium (times 100) in sediments collected during Sampling Cruise 1 (May 2001) and Sampling Cruise 2 (May 2002) at six primary synthetic based mud cuttings discharge sites in the Gulf of Mexico. Data from: Chapters 8 and 9.

mid-field sediments at MP 288 decreased from 0.11 to 0.06 between Sampling Cruises 1 and 2. Temporal changes in the SBF/Ba ratio provide strong evidence of a substantial decline in relative SBF concentrations in near-field and mid-field sediments at all primary discharge sites during the year between Sampling Cruises.

4.3.2 Cuttings, Nannofossils, and Glass Spheres

Cuttings particles were detected in a majority of near-field sediment samples collected at EI 346 and VK 783 on Sampling Cruises 1 and 2 (Table 4-4). Cuttings were not detected in near-field sediments from five of the other discharge sites at the time of Sampling Cruise 2, though they were at the time of Sampling Cruise 1. A few of the near-field sediments collected at MP 299 on Sampling Cruise 2 contained cuttings.

At the time of Sampling Cruise 1, most mid-field sediment samples from seven discharge sites contained cuttings particles. Less than half the mid-field sediments at GC 112 contained cuttings. A year later, at the time of Sampling Cruise 2, a few sediment samples each at EI 346, MP 299, and VK 783 contained cuttings. No cuttings were observed in sediments from the other mid-field stations.

Nannofossils and/or glass spheres were observed in most near-field sediment samples from EI 346, MP 299, VK 783, and MC 496 at the time of Sampling Cruise 2. Only a few near-field sediments from each of the other discharge sites contained nannofossils and/or glass spheres. A few mid-field sediment samples at all locations except EW 963 contained nannofossils and/or glass spheres. Most of the far-field sediment samples from EW 963 contained glass spheres, though the mid-field sediments from the same location contained none. A few far-field sediments at VK 783 and GC 112 contained nannofossils; far-field samples from all sites but MP 288 contained some glass spheres.

Although visual presence of cuttings particles, nannofossils, and glass spheres in sediments are weak indices of the presence of drilling discharges if considered individually, they provide strong qualitative evidence of the presence of drilling discharges if considered collectively. There was strong evidence of a decrease in the abundance of cuttings particles but not in the abundances of nannofossils and glass spheres in mid-field and far-field sediments at all discharge sites in the year between Sampling Cruises 1 and 2 (Table 4-4). Concentrations of cuttings seem to have decreased at near-field stations at all sites except EI 346 and possibly VK 783. Eugene Island 346 was the continental shelf site most heavily contaminated with SBM cuttings, so one would expect that these particles would remain visible in sediments longer at this site. Viosca Knoll 783 was the site where ester SBM was discharged. Nannofossils and glass spheres were still present at the time of Sampling Cruise 2 at nearly all sites where they were observed at the time of Sampling Cruise 1. These observations of the persistence of cuttings and other drilling-related particles show that the inorganic solids associated with cuttings are more persistent than the SBM base chemicals.

These observations of cuttings particles, nannofossils, and glass spheres have documented the presence of inorganic drill cuttings particles in all near-field (<100 m), most mid-field (100 to 250 m), and some far-field (3,000 to 6,000 m) sediments near eight SBM drillsites on the continental shelf and slope of the Gulf of Mexico. These particles may have been associated with either WBM or SBM cuttings discharged from the platforms. Cuttings, nannofossils, and glass spheres associated with WBM cuttings probably are dispersed over a wider area than those associated with SBM cuttings, because the latter, being “oil wet,” do not disperse effectively in the water column following discharge (Neff et al., 2000). Synthetic based mud cuttings, like OBM cuttings, also do not appear to disperse as much as WBM cuttings do following accumulation on the seafloor (Neff et al., 2000). Most of the large cuttings piles documented in the central and northern North Sea are composed of OBM cuttings; North Sea cuttings piles containing mainly WBM cuttings usually are much smaller and less persistent than OBM cuttings piles (Hartley et al., 2003).

4.3.3 Iron and Aluminum

Concentrations of Al and Fe tend to co-vary in marine sediments and in drilling muds and cuttings. However, drill cuttings discharged from the rigs apparently contained lower concentrations of Fe and Al than did local sediments. Concentrations of Fe and Al were lower in near-field and mid-field sediments than in far-field sediments at most discharge sites.

Mean concentrations of Fe in near-field and mid-field sediments increased between Sampling Cruises 1 and 2 at all discharge sites. Mean Al concentrations increased between Sampling Cruises 1 and 2 at three discharge sites. The increases in Fe and Al concentrations in sediments provide an indication that the clay-sized fraction of drill sediments near continental shelf and slope drillsites is increasing with time after the last discharge. This increase probably is caused by dilution of the drill cuttings solids (low Fe and Al) with natural fine-grained sediments (higher Fe and Al) being deposited continuously from the water column.

4.3.4 Barium

Barite solubility in sea water (naturally high in sulfate) is about 81 µg/L (48 µg/L as Ba) (Neff and Sauer, 1995). Drilling mud barite is stable and persistent in oxidized sediments but may dissolve slowly under reducing conditions, as discussed above. Thus, it is quite persistent in sediments near drill cuttings discharge sites. However, it can be dispersed and diluted over time by bed transport or burial.

Temporal decreases in Ba concentration in sediments near SBM cuttings discharge sites may be difficult to document because of the irregular, heterogeneous distribution of cuttings solids on the bottom. A large number of sediment samples would be required to fully characterize the temporal patterns of distribution and concentrations of barite in sediments even in a relatively small area, such as the near-field zone (100 m radius, 31,400 m^2). Because of the high variance in Ba concentrations in sediment samples, it often is difficult to statistically demonstrate a significant change in sediment Ba concentrations between two sampling times.

In the present investigation, Ba concentration was measured in six randomly located sediment samples in each of three zones around the six primary SBM cuttings discharge sites at two sampling times separated by 1 year (Table 4-9). Although there was an apparent decrease in mean Ba concentration in near-field sediments between Sampling Cruises 1 and 2 at five of the six sites, temporal changes in Ba concentrations at all sampling stations were statistically significant at only two of the sites, MP 288 and MC 496 (Table 4-9). Mean Ba concentrations decreased between Sampling Cruises 1 and 2 in both near-field and mid-field sediments from MP 299, MC 496, and EW 963. At MP 288, EI 346, and GC 112, mean Ba concentrations decreased in near-field sediments and increased in mid-field sediments between Sampling Cruises 1 and 2. Mean concentrations of Ba increased between Sampling Cruises 1 and 2 in far-field sediments at MP 288, EI 346, and EW 963 and decreased at the other three discharge sites. This could have been caused by bed transport and dispersal of cuttings away from the discharge site in the year between Sampling Cruises 1 and 2.

Table 4-9. Changes in concentrations of barium in surficial sediments near the six primary discharge sites in the Gulf of Mexico between Sampling Cruise 1 (May 2001) and Sampling Cruise 2 (May 2002) (From: Chapter 9).

Zone	Barium Concentration (mg/kg)				Statistical Interpretation
	Sampling Cruise 1		Sampling Cruise 2		
	Mean	Range	Mean	Range	
Main Pass 288					
NF	16,100	5,980 – 27,300	3,060	810 – 2,030	P<0.02 (Significant)
MF	3,750	2,040 – 5,620	4,130	1,750 – 13,100	
FF	760	350 – 1,070	1,010	110 – 3,340	
Main Pass 299					
NF	4,640	1,080 – 9,300	2,760	1,940 – 5,520	P>0.10 (Not Significant)
MF	3,030	2,110 – 4,670	2,370	1,710 – 3,860	
FF	1,300	780 – 1,980	1,010	740 – 1,530	
Eugene Island 346					
NF	65,100	24,800 – 205,000	152,000	28,400 – 263,000	P>0.06 (Not Significant)
MF	36,400	17,500 – 54,900	60,700	16,200 – 223,000	
FF	1,460	770 – 2,160	1,680	1,230 – 3,260	
Mississippi Canyon 496					
NF	69.300	17,100 – 174,000	22,400	8,850 – 51,700	P<0.01 (Significant)
MF	31,600	9,560 – 78,500	6,190	2,110 – 15,600	
FF	1,010	690 – 1,250	790	490 – 1,120	
Ewing Bank 963					
NF	87,300	4,830 – 162,000	43,800	4,070 – 87,900	P>0.21 (Not Significant)
MF	44,900	9,840 – 81,300	20,000	4,500 – 51,500	
FF	1760	740 – 2,790	2,470	1,770 – 4,640	
Green Canyon 112					
NF	121,000	47,900 – 214,000	118,000	29,000 – 154,000	P>0.95 (Not Significant)
MF	28,200	1,890 – 71,800	64,000	4,060 – 241,000	
FF	6,120	980 – 12,800	2,880	910 – 3,930	

FF = Far-field.
MF = Mid-field.
NF = Near-field.

The sediment Ba data confirm observations from other monitoring studies that drilling mud barite is persistent in sediments. Kennicutt et al. (1996) compared sediment Ba data from the Gulf of Mexico Offshore Monitoring Experiment (GOOMEX) study and an earlier API study (Boothe and Presley, 1985) at Matagorda Island 686, a shallow-water, high energy site off the Texas coast. In the 14 years between the sampling periods, all the excess Ba in sediments within about 125 m of the discharge had disappeared. Sediment Ba concentrations at distances greater than 125 m from the discharge did not change and probably represent background concentrations for the area. At deeper water depositional sites, there was little change in sediment Ba concentrations in the 5 to 10 years between surveys (Continental Shelf Associates, 1983; Kennicutt et al., 1996).

Candler et al. (1995) monitored the accumulation and fate of a PAO SBM and Ba in sediments near a platform in 131 m of water in the Gulf of Mexico. Field surveys were performed 9 days, 8 months, and 24 months after completion of drilling. Between 9 days and 2 years after drilling, SBM base chemical and Ba concentrations decreased in most sediments collected more than 25 m from the discharge and fluctuated erratically in sediments 25 m from the discharge site. Concentrations of PAO decreased more rapidly than Ba concentrations.

4.3.5 Synthetic Base Chemicals

As expected, concentrations of SBM base chemicals proved to be the best indicator of the presence and relative concentrations of SBM cuttings in sediments near the eight drill cuttings discharge sites. At all locations except VK 783, where ester based mud cuttings were used and more than 5 years had elapsed since the last discharge, near-field and some mid-field sediments contained high concentrations of SBM base chemicals and TPH at the time of Sampling Cruise 1 (Figure 4-3). Only a few far-field sediment samples contained detectable concentrations of SBM base chemical.

A year later, at the time of Sampling Cruise 2, mean absolute and relative concentrations of SBM base chemical in near-field and mid-field sediments at most discharge sites had declined (Figures 4-5 and 4-6). However, because of the large variance in concentrations of SBM base chemical in near-field and mid-field sediments at the time of the two Sampling Cruises, only a few of the differences in mean concentrations between Sampling Cruises 1 and 2 were statistically significant. Although not statistically significant at most sites when they are assessed individually, there is a clear trend of a decreasing mean and relative SBM base chemical concentration at near-field and mid-field zones between cruises at all sites except the mid-field zone of GC 112. However, the mean SBM base chemical concentration relative to the mean Ba concentration did decrease in the mid-field zone of GC 112, indicating that there was a loss of SBM base chemical from the sediments.

There was a substantial decrease in the lowest concentrations of SBM base chemical in near-field sediments between Sampling Cruises 1 and 2 at EI 346, MP 288, and ST 160 (Figure 4-6). Smaller decreases were evident at MC 496, MP 299, and VK 783. SBM base chemical concentrations in all replicate sediment samples collected during Sampling Cruise 2 at EW 963 and GC 112 were within the range of concentrations in sediment samples collected during Sampling Cruise 1 in the near-field of the same site. The largest differences were at EI 346, a heavily contaminated site. Thus, there is evidence of some decrease in concentrations of SBM base chemical in near-field sediments during the year between Sampling Cruises 1 and 2 at six of the eight discharge sites. The variability in concentrations of SBM base chemical in near-field sediments at all locations at both sampling times reflects the heterogeneity in the distribution of cuttings solids on the seafloor near the discharge sites and the probability of collecting a clump of cuttings solids in sediment samples collected at randomly-selected sampling locations.

A similar pattern of temporal change in SBM base chemical concentrations was apparent in mid-field sediments. The lowest sediment SBM base chemical concentration in samples from Sampling Cruise 2 was substantially lower than the range of concentrations in mid-field sediments from Sampling Cruise 1 at MC 496, MP 299, ST 160, and VK 783. The lowest concentration in mid-field sediments from Sampling Cruise 2 was slightly lower than the lowest concentration in mid-field sediments from Sampling Cruise 1 at EI 346, EW 963, and GC 112. At GC 112 and MP 288, one mid-field sediment sample collected during Sampling Cruise 2 contained more SBM base chemical than mid-field sediment samples collected during Sampling Cruise 1 at the same discharge locations. Thus, there was evidence of a decrease in the range of mid-field sediment SBM base chemical concentrations in the year between Sampling Cruises 1 and 2 at six of the eight discharge sites.

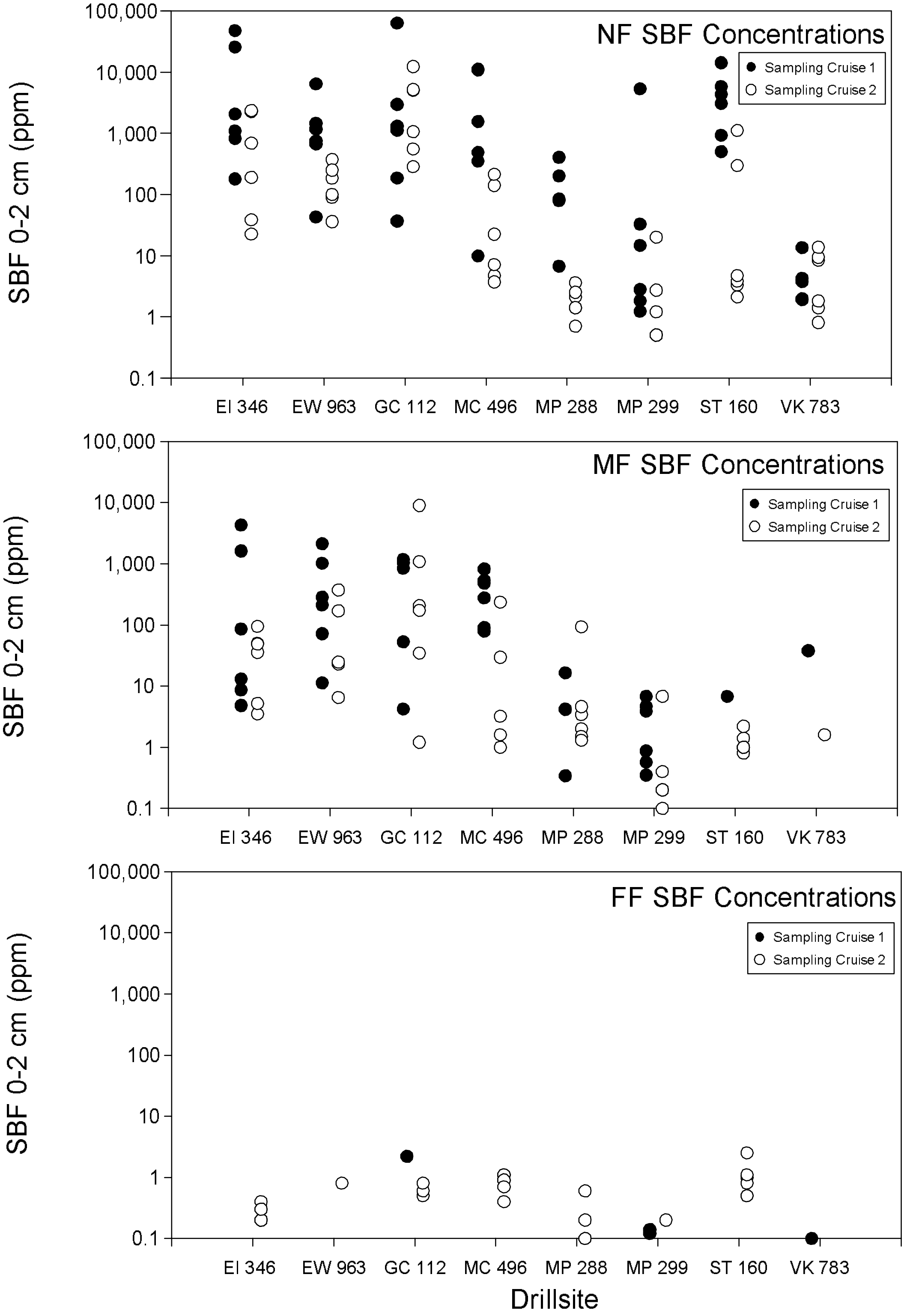


Figure 4-6. Synthetic based fluid (SBF) concentrations in near-field (NF), mid-field (MF), and far-field (FF) surficial sediments collected at eight discharge sites during Sampling Cruise 1 (May 2001) and Sampling Cruise 2 (May 2002). Values <1 ppm are included in plot but not detected records have been eliminated.

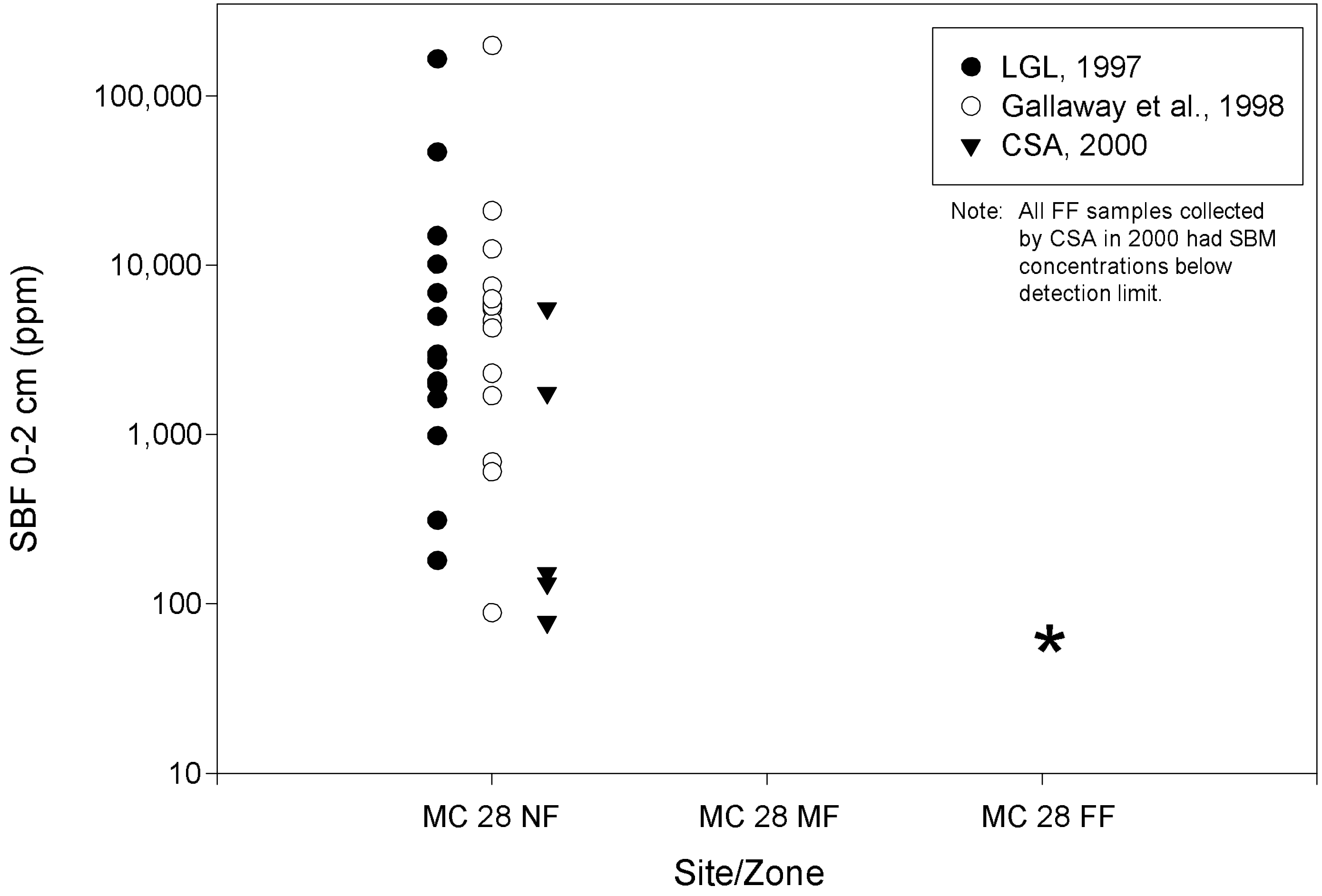
The weakest evidence for a decrease in sediment SBM base chemical concentration in the year between Sampling Cruises 1 and 2 was in the mid-field zone at GC 112, the most heavily contaminated slope site. The higher mean SBM base chemical concentration in mid-field sediments at the time of Sampling Cruise 2 was due to a single sample containing 8,991 mg/kg SBM base chemical. The mean concentration of SBM base chemical in the other five sediment samples was 299 mg/kg, about 60% of the mean concentration of SBM base chemical in mid-field sediments at the time of Sampling Cruise 1.

Four near-field surficial sediment samples were collected at GC 112 during the Screening Cruise in August 2000 and analyzed for SBM base chemical. Concentrations ranged from 752 to 22,368 mg/kg, in the middle of the range of SBM base chemical concentrations (37 to 63,300 mg/kg: mean 11,483 mg/kg) in near-field sediments collected at GC 112 on Sampling Cruise 1, showing that SBM base chemical has a very patchy distribution in sediments around this continental slope site. Because of the patchy distribution of SBM cuttings in sediments near GC 112, it is difficult to detect a temporal change in the distribution or concentration of SBM base chemical in surficial sediments with the limited number of near-field and mid-field sediment samples collected during Sampling Cruises 1 and 2 (12 per cruise).

Sediments near a platform in MC 28 in 558 m of water off the mouth of the Mississippi River were sampled in July/August 2000 during the Screening Cruise (Continental Shelf Associates, Inc., 2000; this report, Chapter 2). This site was not chosen for sampling during the Sampling Cruises because it was learned that the operator planned to drill another well at the site in the time interval between Sampling Cruises 1 and 2. The same site, the Pompano II prospect, was sampled earlier in 1996-97 and 1998 during the period when drilling was occurring (LGL Ecological Research Associates, Inc. [LGL], 1997; Gallaway et al., 1998; Fechhelm et al., 1999). Eight wells were drilled at MC 28 between March 1996 and March 1998. Discharges from the rig included 7,700 bbl of WBM cuttings, 5,150 bbl of SBM cuttings, and an estimated 7,659 bbl of Petrofree LE base chemical (an SBM base chemical containing 90% LAO and 10% ester) associated with cuttings. LGL sampled sediments at the site in July 1997, 4 months after the most recent drilling discharge and again in March 1998 just before completion of the final well. Although sampling methods used by LGL and CSA were different, it is possible to compare results for SBM base chemical in near-field sediments to determine the temporal trend of synthetics in sediments near the drilling template.

LGL surveyed the seafloor near (<90 m from the edge of the template) the drilling template with an ROV. They observed a thin veneer of cuttings dispersed over much of the bottom in a patchy distribution near the drilling template. Maximum cuttings accumulations appeared to be 20 to 25 cm thick in some locations. The largest deposits of large, chunk-like cuttings were detected a short distance southwest of the template. These cuttings accumulations did not contain high concentrations of SBM base chemical and probably were derived from direct drilling returns to the sea bottom during initial drilling with WBM before the riser was installed. There was no clear gradient of SBM cuttings concentrations with distance from the drillsite.

There was a definite trend of decreasing concentrations of LAO base chemical in near-field sediments between 1997/1998 and 2000 (Figure 4-7). Highest concentrations of LAO were detected in surficial (0 to 2 cm) sediments northeast of the drillsite (Figure 4-8). They probably were carried to the northeast from the drillsite by the prevailing mid-water ocean currents. The highest LAO concentration measured in 1997 was 165,000 mg/kg in surficial sediment from a location 75 m northeast of the template. In March 1998, surficial sediment from the same location contained 198,000 mg/kg LAO. In July 1997, LAO concentrations in surficial sediments from other locations near the drillsite ranged from 180 to 47,000 mg/kg; in March 1998, LAO



Note: All FF samples collected by CSA in 2000 had SBM concentrations below detection limit.

Figure 4-7. Surficial sediment synthetic based fluid (SBF) concentrations collected at Mississippi Canyon 28 (MC 28) grouped by sampling event and zone. The 1997 and 1998 survey collected samples only in the near-field (NF) zone. The 2000 survey collected samples in the NF and far-field (FF) zones. All FF concentrations were below the detection limit. Data from: LGL Ecological Research Associates, Inc. (LGL) (1997), Gallaway et al. (1998), and Continental Shelf Associates, Inc. (CSA) (2000).

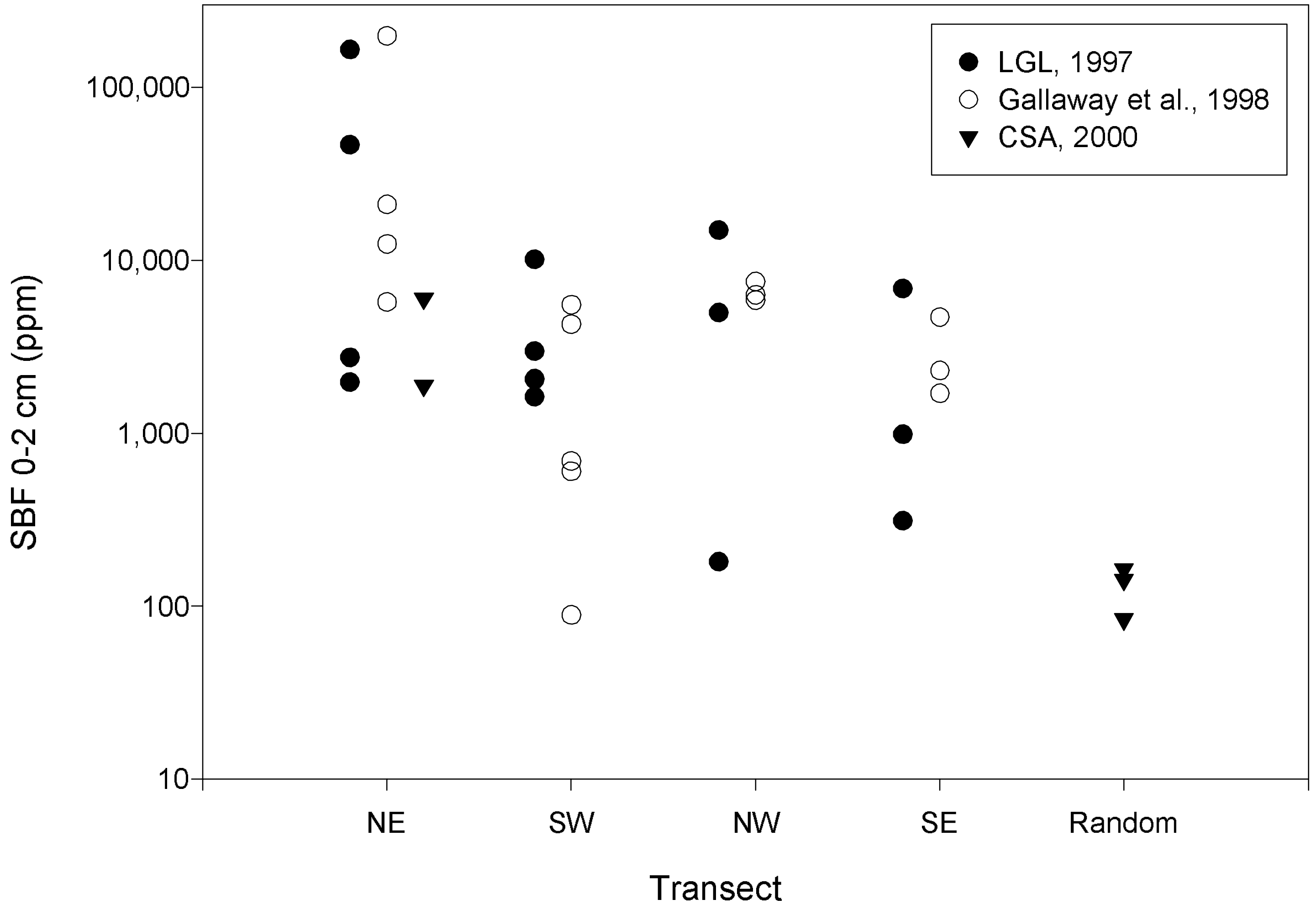


Figure 4-8. Synthetic based fluid (SBF) concentrations in surficial sediments from Mississippi Canyon 28, grouped by transect. Concentrations in samples collected from randomly selected locations during the 2000 survey are grouped separately. Data from: LGL Ecological Research Associates, Inc. (LGL) (1997), Gallaway et al. (1998), and Continental Shelf Associates, Inc. (CSA) (2000).

concentrations in surficial sediments were lower (except for the one high value), ranging from 89 to 49,000 mg/kg. In 2000, LAO concentrations in five near-field sediment samples collected by CSA ranged from 78 to 5,567 mg/kg. An additional 17 to 195 mg/kg of ester was present in these sediment samples.

The mean concentration of LAO in surficial sediments (all sampling stations combined) was 17,652 mg/kg in 1997, 17,727 mg/kg in 1998 (mean for 1997 and 1998 combined, 17,690 mg/kg), and 1,536 mg/kg in 2000 (if the ester is included, the mean concentration of total SBM base chemical in near-field sediments at MC 28 in 2000 is 1,616 mg/kg). If all near-field samples from the three surveys are considered, and if the set of 1997/98 data from all four transects is considered as a surrogate for random sampling in the near-field zone, there was a highly statistically significant ($\rho<0.002$) decrease in concentrations of LAO in near-field sediments at MC 28 between 1997/98 and 2000.

4.3.6 Summary of Temporal Trends in Drill Cuttings Solids in Sediments Near Discharge Sites

Concentrations of all monitored components of SBM cuttings, except nannofossils and glass spheres, in sediments near drillsites on the continental shelf and slope of the Gulf of Mexico tended to decrease or return to background values with time after the last cuttings discharge. Cuttings particles were observed less frequently in near-field sediment samples at the time of Sampling Cruise 2 than at the time of Sampling Cruise 1, 1 year earlier. This change was even greater in mid-field sediments (100 to 250 m from the discharge sites) and far-field sediments (3,000 to 6,000 m from the discharge sites).

Concentrations of Fe and Al tended to increase at near-field and mid-field locations at most discharge sites between Sampling Cruises 1 and 2. The concentrations approached those in far-field stations, indicating that cuttings particles in sediments were being diluted by deposition of fine natural clay particles, probably from terrigenous sources.

Barium (as barite) is a good indicator of the inorganic fine particulate fraction of drill cuttings. Concentrations in sediments decreased with distance from the discharge at all drillsites monitored, in most cases approaching background at the far-field stations. In the year between Sampling Cruises 1 and 2, there was a small decrease in the concentration of Ba in near-field and mid-field sediments at most discharge sites. The decrease in Ba concentration probably was caused by dispersion by bed transport and dilution by burial by settling particles or downward settling of the dense barite particles in sediments. A small amount of the barite may have dissolved, particularly if surface layers of sediments were anoxic.

There was a decrease in the concentration of SBM base chemical in near-field and mid-field sediments in the year between Sampling Cruises 1 and 2 at most discharge sites. Because of the heterogeneous distribution of SBM cuttings on the seafloor near the discharge sites, it was difficult to detect statistically significant temporal trends in sediment SBM base chemical concentrations. However, a trend of decreasing concentration was clearly evident from the sediment SBM base chemical relative to Ba concentration and bulk concentration data. At the one site where ester-based SBM was used, ester concentrations in sediments were low and decreased between Sampling Cruises 1 and 2. SBM base chemical was detected in only a few far-field samples, indicating that this component of drill cuttings is deposited primarily very close to the discharge site. Radial dispersal of the SBM base chemical was not evident in the year between Sampling Cruises 1 and 2. The main mechanisms of loss of SBM base chemical from surficial sediments appear to be biodegradation and burial by natural sediment deposition or bioturbation.

4.4 ALTERATION OF SEDIMENT PHYSICAL/CHEMICAL PROPERTIES NEAR OFFSHORE DISCHARGE SITES

SBM cuttings usually are coarser than continental shelf and slope sediments and contain high concentrations of fine, dense particles of barite. They also contain high concentrations of biodegradable organic matter (Neff et al., 2000). Both sediment grain size and TOC concentration affect benthic community structure and function.

4.4.1 Sediment Grain Size

As a general rule, near-field surficial sediments contained more sand than mid-field and far-field sediments at seven discharge sites; some far-field sediment samples from MP 288 contained high concentrations of sand (Tables 4-3 and 4-10). Far-field sediments contained the lowest percent sand and the highest percent silt and clay at all sites. The differences were not large but suggest that drill cuttings solids are collecting on the bottom in the near-field and, to a lesser extent, mid-field zones around the discharge sites.

Table 4-10. Percent sand, silt, and clay in near-field (NF), mid-field (MF), and far-field (FF) sediments at six primary drillsites in the Gulf of Mexico. Data from: Continental Shelf Associates, Inc., 2002.

Site	Zone	Sand (%)	Silt (%)	Clay (%)
Eugene Island 346	NF	11.9 – 35.9	26.6 – 44.3	20.3 – 58.3
	MF	3.4 – 25.4	25.8 – 57.9	30.1 – 70.5
	FF	0.9 – 3.2	37.8 – 53.6	43.2 – 60.9
Main Pass 299	NF	2.6 – 12.5	20.8 – 34.6	52.8 – 76.5
	MF	3.0 – 27.6	18.3 – 39.9	54.8 – 65.2
	FF	1.8 – 6.7	27.6 – 36.7	54.4 – 70.6
Main Pass 288	NF	6.8 – 31.9	15.0 – 41.7	45.3 – 63.4
	MF	5.9 – 13.3	13.9 – 37.4	50.6 – 64.5
	FF	5.2 – 98.6	0 – 50.7	0 – 62.1
Ewing Bank 963	NF	1.2 – 15.5	15.2 – 56.3	35.8 – 69.2
	MF	4.0 – 12.8	15.3 – 61.6	31.6 – 71.8
	FF	1.2 – 3.6	13.1 – 28.7	66.4 – 75.0
Green Canyon 112	NF	1.8 – 24.1	23.1 – 65.4	10.5 – 69.2
	MF	1.4 – 4.4	18.9 – 46.2	51.8 – 77.6
	FF	0.7 – 2.4	26.3 – 46.0	51.5 – 73.0
Mississippi Canyon 496	NF	0.9 – 11.7	19.3 – 35.2	58.3 – 79.2
	MF	2.0 – 6.9	28.7 – 38.2	58.8 – 69.3
	FF	0.4 – 1.6	17.3 – 29.1	58.3 – 82.3

In general, sediment grain size distributions were more variable at the continental shelf sites than at the slope sites. A few surficial sediment samples in all zones at continental shelf sites contained more than 5% sand, with one exception, the far-field zone at EI 346. One far-field station at MP 288 contained nearly 99% sand. At most other locations, the dominant sediment grain size was clay.

4.4.2 Biodegradable Organic Matter

Biodegradable organic matter usually has a greater effect on benthic communities than coarse sediment grain size and presence of dense particles. Bacteria and fungi indigenous to offshore sediments degrade the organic matter associated with cuttings and, in the process, may deplete the oxygen in surface layers of the sediments and generate toxic ammonia and sulfide (Wang and Chapman, 1999; Wu, 2002; Hartley et al., 2003). Different benthic taxa vary widely in their sensitivity to organic enrichment and associated sediment hypoxia and accumulation of sulfide and ammonia (Lenihan et al., 2003). Thus, organic enrichment often leads to a change in the structure and functional biology of benthic communities.

The most important redox reactions in the pore water of marine sediments, including cuttings accumulations, primarily involve organic carbon and inorganic compounds of nitrogen, oxygen, sulfur, Fe, and manganese (Mn) (Förstner and Wittmann, 1981; Shimmield and Pedersen, 1990). Aerobic bacteria in sediments use sediment organic matter as a source of nutrition, utilizing dissolved oxygen (DO) as an electron acceptor. In fine-grained, low permeability sediments containing high concentrations of biodegradable organic matter, such as some SBM cuttings-contaminated sediments, sediment bacteria consume oxygen more rapidly than it can be replaced by diffusion from the overlying water, and oxygen concentration in surface layers of sediment decreases and the depth of the anoxic zone in the sediment column decreases. A typical oxygen penetration depth (the depth at which O_2 concentration drops below 1 μM) in uncontaminated fine-grained continental shelf sediments is 10 to 12 mm (Van Cappellen and Wang, 1995). The concentration of biodegradable organic matter usually is lower in deep-sea sediments, which often have a high porosity, and O_2 penetration depth may increase to more than 100 mm.

When oxygen is depleted, nitrate reducing bacteria in the sediment begin to use nitrate and dissolved Fe (abundant in most suboxic marine sediments) as electron acceptors for oxidative metabolism of sediment organic matter, producing ammonia and iron sulfide in the process; as oxygen is depleted further, sulfate reducing bacteria continue to degrade the organic matter, producing sulfide (Thode-Andersen and Jørgensen, 1989; Santschi et al., 1990; Luther et al., 1992; Slomp et al., 1997). As concentrations of oxygen, nitrate, reducible Fe, and sulfate decline in sediment pore water, the redox potential (Eh) also drops. The onset of bacterial reduction of nitrate to ammonia occurs at an Eh somewhat below 200 mV. The onset of sulfate reduction to H_2S occurs as Eh values fall below 0 to -100 mV (see Chapter 9). The slope of the vertical Eh gradient in sediment and, therefore, the depth at which Eh reaches 0 mV (the RPD where the sediment becomes reducing) and different redox reactions occur depends on the oxygen concentration in the overlying water, the permeability of the sediment, and the availability of biodegradable organic matter and reducible inorganic substrates. This process is called organic enrichment and results in substantial changes in sediment physical/chemical properties and in benthic community structure (Pearson and Rosenberg, 1978).

Concentrations of TOC in surficial sediments near the six discharge sites ranged from 0.38% to 7.36%. Mean TOC concentrations tended to be higher in sediments at near-field and mid-field stations than at far-field stations, but the differences were not large. Concentrations of TOC did not correlate well with SBM or TPH concentrations in the sediments. Thus, the nature of the TOC is uncertain. If the TOC is largely biodegradable, there probably is sufficient organic matter in some near-field and mid-field sediments to support the reactions characteristic of organic enrichment. This is the case for some near-field and mid-field sediments at continental shelf site EI 346 and continental slope sites GC 112, EW 963, and MC 496.

4.4.3 Sediment Oxygen Concentration and Redox Potential

Sediment profile imaging was performed on the Screening Cruise and Sampling Cruises 1 and 2 to characterize sediments at the eight discharge sites monitored on the Sampling Cruises and three additional discharge sites surveyed during the Screening Cruise: MC 28, GB 128, and VK 780. It is possible to semiquantitatively estimate redox conditions in sediments based on the SPI images. The mean RPD depth was shallower in near-field than in far-field sediments at the six primary monitoring sites (Table 4-11). Below the RPD depth, sediments are reducing. The mean RPD depth at far-field stations was in the range of 0.7 to 6.1 cm and was as great as 24.5 cm, as measured by SPI. Mean RPD depth at near-field stations was in the range of 0.1 to 1.6 cm, indicating that some near-field surficial sediments were suboxic and reducing.

Table 4-11. Summary of selected redox parameters in sediments at drillsites as revealed by sediment profile imagery and visual observation of depth of oxic layer performed during the Screening Cruise and Sampling Cruises 1 and 2 (Data from: Chapter 11).

Site	Location	Mean RPD Depth (cm)	Low Interfacial DO	Bacterial Mat
Main Pass 299	NF	0.6	Yes	No
	MF	0.4	No	No
	FF	1.5	No	No
Main Pass 288	NF	1.3	Yes?	No
	MF	1.4	No	No
	FF	4.8	No	No
Green Canyon 112	NF	1.0	Yes	No
	MF	NA	NA	NA
	FF	4.0	No	No
Mississippi Canyon 496	NF	1.6	No	No
	MF	1.3	No	No
	FF	6.1	No	No
Eugene Island 346	NF	0.1	Yes	Yes
	MF	1.1	No	No
	FF	0.7	No	No
Ewing Bank 963	NF	1.2	No	No
	MF	0.8	Yes	No
	FF	0.7	No	No

FF = Far-field. DO = Dissolved oxygen.
MF = Mid-field. NA = Not analyzed.
NF = Near-field. RPD = Redox potential discontinuity.

The SPI images indicated a sediment column in which RPD depth was at or very close to the sediment surface. The RPD depth of North Sea OBM and SBM cuttings piles often is at or near the surface of the cuttings pile (Hartley et al., 2003). Cuttings piles containing high concentrations of organic matter from OBM or SBM often become anoxic within about 1 to 2 mm of the surface. This steep gradient of decreasing oxygen concentration with depth in the cuttings pile is caused by a combination of rapid biodegradation of labile organic matter and the low permeability of the cuttings material, which slows oxygen diffusion into the pile from the overlying water (Shimmield and Breuer, 2000).

Some near-field sediments at EI 346 had a surface coating of bacterial mat (Table 4-11). This bacterial mat was absent from the sediments in other zones and at other primary discharge sites. However, near-field and mid-field sediments at secondary continental shelf site ST 160 and candidate site GB 128, visited during the Screening Cruise, also had bacterial mats. Similar white mats of the bacterium *Beggiatoa* spp. have been observed on the surface of OBM and SBM cuttings piles in the North Sea (Breuer et al., 1999; Shimmield and Breuer, 2000; Hartley et al., 2003). These bacterial mats overlay anoxic sulfide-rich marine sediments (Gundersen et al., 1992) and are an indication of underlying sulfide-rich reducing sediments (Rosenberg and Diaz, 1993). *Beggiatoa* are chemoautotrophs that oxidize sulfide through elemental sulfur to sulfate.

Trefry et al. (Chapter 9) measured the DO concentration and Eh in intact sediment cores at most of the stations near the six discharge sites and confirmed the observations from SPI (Table 4-12). The depth in the sediment at which oxygen concentration dropped to 0 usually was less than 1 cm in near-field sediments at continental shelf sites. In most cases, the zero O_2 depth (RPD depth) was slightly greater at mid-field and far-field stations. The maximum depth was more than 5 cm at a far-field station at EI 346. Oxygen penetrated continental slope sediments to a greater depth in most cases. The RPD depth in near-field sediments at slope sites ranged from 0.2 to 3.7 cm. The RPD depth in far-field sediments at slope sites ranged from 0.1 to 4.9 cm. At most sites, the depth of zero O_2 concentration was similar at the time of Sampling Cruises 1 and 2.

Table 4-12. Depth of oxygen penetration and redox potential at 1 and 10 cm in sediments from the six drillsites from Sampling Cruise 1 (C1) and Sampling Cruise 2 (C2) (Data from: Chapter 9).

Site	Station	RPD Depth (cm)	$\text{Eh}_{1\text{ cm}}$ Range (mV)		$\text{Eh}_{10\text{ cm}}$ Range (mV)	
Main Pass 299	NF (C1)	0.1 – 0.5	+537	-178	+94	-171
	(C2)	0.1 – 1.2	+519	+82	+136	+60
	MF (C1)	0.3 – 1.5	+405	+102	+108	+74
	(C2)	0.2 – 0.7	+450	+134	+167	+81
	FF (C1)	0.5 – 2.2	+513	+110	+119	+20
	(C2)	0.1 – 0.9	+541	+78	+120	+65
Main Pass 288	NF (C1)	0.2 – 0.8	+580	+134	+120	-81
	(C2)	0.1 – 0.9	+527	+161	+176	+76
	MF (C1)	0.5 – 2.3	+306	+90	+70	-50
	(C2)	0.1 – 1.6	+540	+91	+162	+7
	FF (C1)	0.7 – 1.9	+503	+226	+150	+71
	(C2)	0.1 – >3.1	+570	+42	+204	-91

Table 4-12. (Continued).

Site	Station	RPD Depth (cm)	Eh$_{1\text{ cm}}$ Range (mV)		Eh$_{10\text{ cm}}$ Range (mV)	
Eugene Island 346	NF (C1)	0.0 – 0.6	+112	-215	-6	-272
	(C2)	0 – 0.8	+130	-174	+68	-183
	MF (C1)	0.1 – 1.5	+105	-164	+53	-164
	(C2)	0.2 – 1.1	+481	-123	+85	-154
	FF (C1)	1.7 – 5.3	+521	+470	+101	+54
	(C2)	0.3 – 2.9	+535	+103	+117	+55
Green Canyon 112	NF (C1)	0.3 – 2.5	+350	-280	+76	-198
	(C2)	0.5 – 1.7	+516	-91	+162	-108
	MF (C1)	0.3 – 4.4	+501	+126	+425	+82
	(C2)	0.2 – 1.9	+521	+259	+272	+89
	FF (C1)	2.6 – 4.9	+498	+155	+294	+81
	(C2)	2.2 – 3.1	+542	+472	+333	+128
Ewing Bank 963	NF (C1)	0.2 – 3.6	+319	-144	+165	-157
	(C2)	0 – 1.8	+529	-137	+286	+74
	MF (C1)	0.6 – 3.7	+541	-63	+360	-69
	(C2)	1.9 – 2.4	+535	+282	+345	+108
	FF (C1)	2.8 – 3.6	+382	+240	+280	+114
	(C2)	2.1 – 3.3	+537	+339	+315	+103
Mississippi Canyon 496	NF (C1)	0.4 – 3.7	+490	+320	+177	+44
	(C2)	0.3 – 2.3	+546	+180	+130	+74
	MF (C1)	0.5 – 3.7	+485	+105	+66	+38
	(C2)	0.2 – 2.4	+564	+490	+123	+96
	FF (C1)	1.2 – 2.3	+223	+204	+90	+71
	(C2)	0.1 – 2.8	+541	+106	+423	+86

FF = Far-field. NF = Near-field.
MF = Mid-field. RPD = Redox potential discontinuity.

Redox potential (Eh) at 1 cm ranged from +580 to -280 mV in sediments from the six primary sites (Table 4-12). At most sites, the Eh range was lower at 10 cm than at 1 cm. Sediments with Eh below 0 at 1 cm (reducing sediments) were present at one or more near-field stations at four discharge sites and at one or more mid-field stations at two discharge sites. Eugene Island 346, the most heavily contaminated continental shelf site, had the lowest Eh values in near-field and mid-field sediments. None of the far-field stations at any discharge site had Eh below 0 mV at 1 cm depth; however, at the time of Sampling Cruise 2, a far-field sediment at MP 288 had an Eh of -91 mV.

The RPD depth in near-field and mid-field sediments at the primary discharge sites was in the range of 0 to 4.4 cm at the time of Sampling Cruises 1 and 2; the RPD depth in far-field sediments was in the range of 0.1 to 5.3 cm (Table 4-12). Mean RPD depths were less in continental shelf sediments than in continental slope sediments. All near-field sediments collected during Sampling Cruises 1 and 2 at EI 346 and MP 288 had RPD depths between

0 and 0.8 cm and were essentially anoxic. Thus, sediments near some of the drillsites were hypoxic/anoxic and reducing. This probably is an organic enrichment effect caused by accumulation of organic chemicals from SBM cuttings in the sediments.

At sites containing high concentrations of SBM solids, there was a steep gradient with depth in sediments of decreasing DO concentration and redox potential (see Chapter 9). The low redox potential and oxygen concentrations in many near-field and some mid-field sediments probably was caused primarily by organic enrichment from rapid deposition of drill cuttings rich in biodegradable organic matter.

Because most benthic fauna live in the upper few centimeters of offshore, fine-grained sediments, a useful way to express the potential for harm to benthic communities from low sediment oxygen concentrations is to express sediment oxygen concentration as the integrated amount of oxygen per unit area of sediment surface (see Chapter 9). The integrated oxygen amount is defined as the nannomoles (nM) of O_2 between the sediment surface and the RPD depth per cm^2 of sediment.

As expected from the sediment DO and Eh data discussed above, there was a sharp gradient of increasing integrated amounts of oxygen in sediments with distance from outer continental shelf (Figure 4-9) and continental slope (Figure 4-10) drill cuttings discharge sites. The integrated oxygen gradient was most pronounced at continental shelf site EI 346 and continental slope sites GC 112 and EW 963. Except at EI 346, the gradients were more pronounced at the time of Sampling Cruise 1 than at the time of Sampling Cruise 2. This result suggests that biodegradable organic matter in the contaminated sediments is disappearing to an extent sufficient to allow oxygenation of surface sediments and an increase in the depth of the RPD, changes important for ecosystem recovery (Olsgard and Gray, 1995).

4.4.4 Ammonia, Sulfide, and Phosphate

A secondary effect of organic enrichment in offshore sediments is an increase in concentrations of ammonia and free and bound sulfide and sometimes a decrease in nitrate and phosphate. As sediment microbiota deplete sediment oxygen during biodegradation of organic matter, they switch first to nitrate and reducible Fe and then to sulfate for reducible substrates to support oxidation of organic matter, producing ammonia and sulfide. Phosphate is more soluble and mobile in hypoxic sediments and may be released to the water from reduced sediment layers.

Pore water in selected sediment cores collected from four of the discharge sites during the Screening Cruise was analyzed for depth profiles of phosphate, sulfide, and ammonia (Table 4-13). Concentrations of sulfide and ammonia were elevated (compared to concentrations in sediments from far-field sites) in near-field sediments at the three sites sampled (MP 299, GC 112, and MC 496). Sulfide reached 12,800 µM 1.5 cm below the sediment surface near continental shelf site MP 299. Concentrations of phosphate were similar at far-field and near-field sites.

Phosphate, sulfide, and ammonia also were measured in selected near-field sediment core samples collected during Sampling Cruise 1 (Continental Shelf Associates, Inc., 2002). Phosphate concentrations in most cores were similar to those in cores from the Screening Cruise. However, at a near-field station at MP 299, phosphate concentration was 63.5 µM at 0.5 cm and reached a high of 113 µM at 3.5 cm. Sulfide concentrations in the same core reached a maximum of 44.2 µM at 1.5 cm and declined to about 2 µM below 6 cm. Ammonia was not measured in sections near the top of the core but exceeded 375 µM at a depth of 29.5 cm.

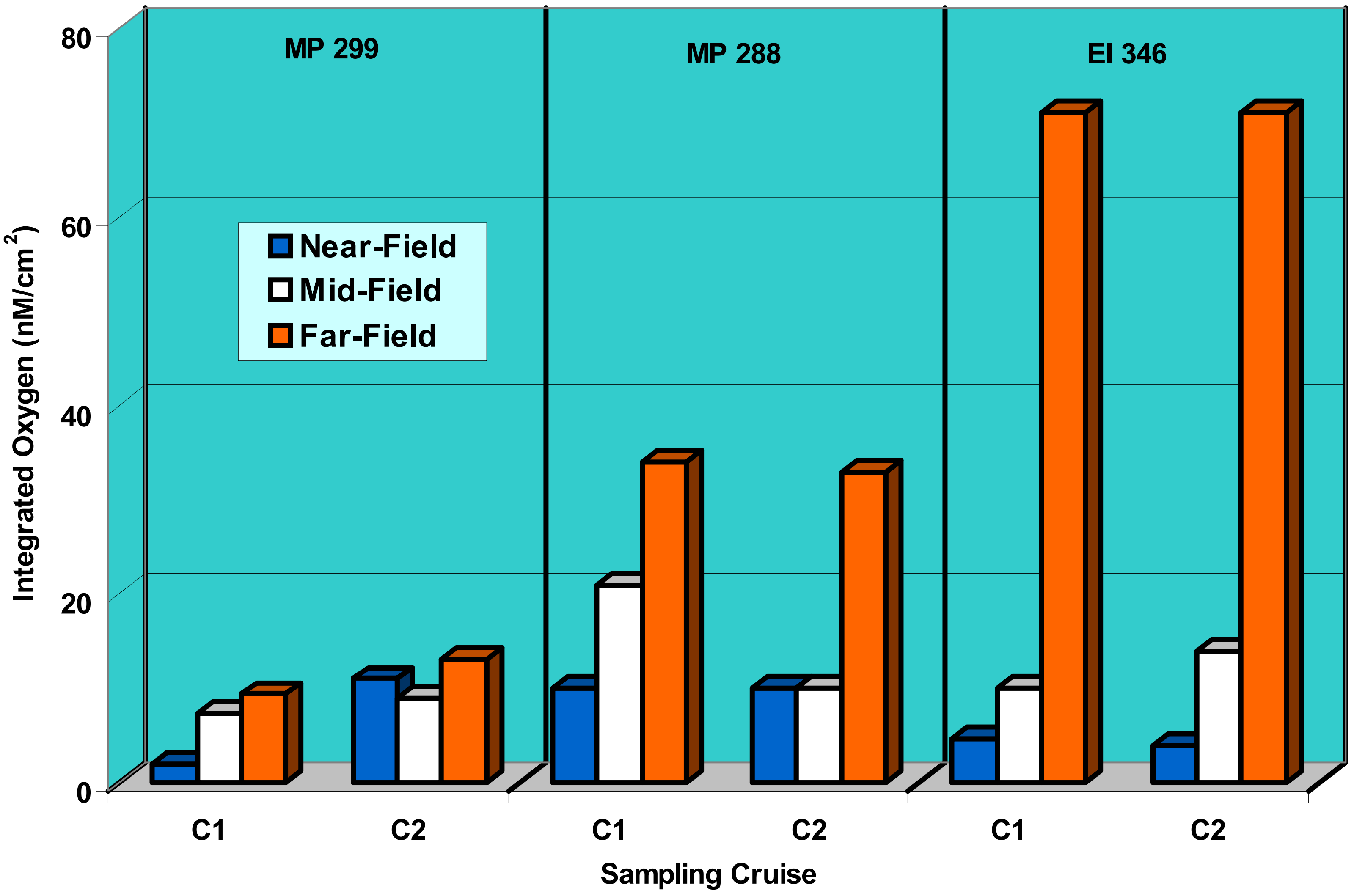


Figure 4-9. Integrated amounts of oxygen (defined as the nM of O_2 between the sediment surface and the redox potential discontinuity depth underlying 1 cm^2 of sediment) in the sediment column at near-field, mid-field, and far-field stations at three continental shelf sites at the time of Sampling Cruise 1 (May 2001) and Sampling Cruise 2 (May 2002). Data from: Chapter 9.

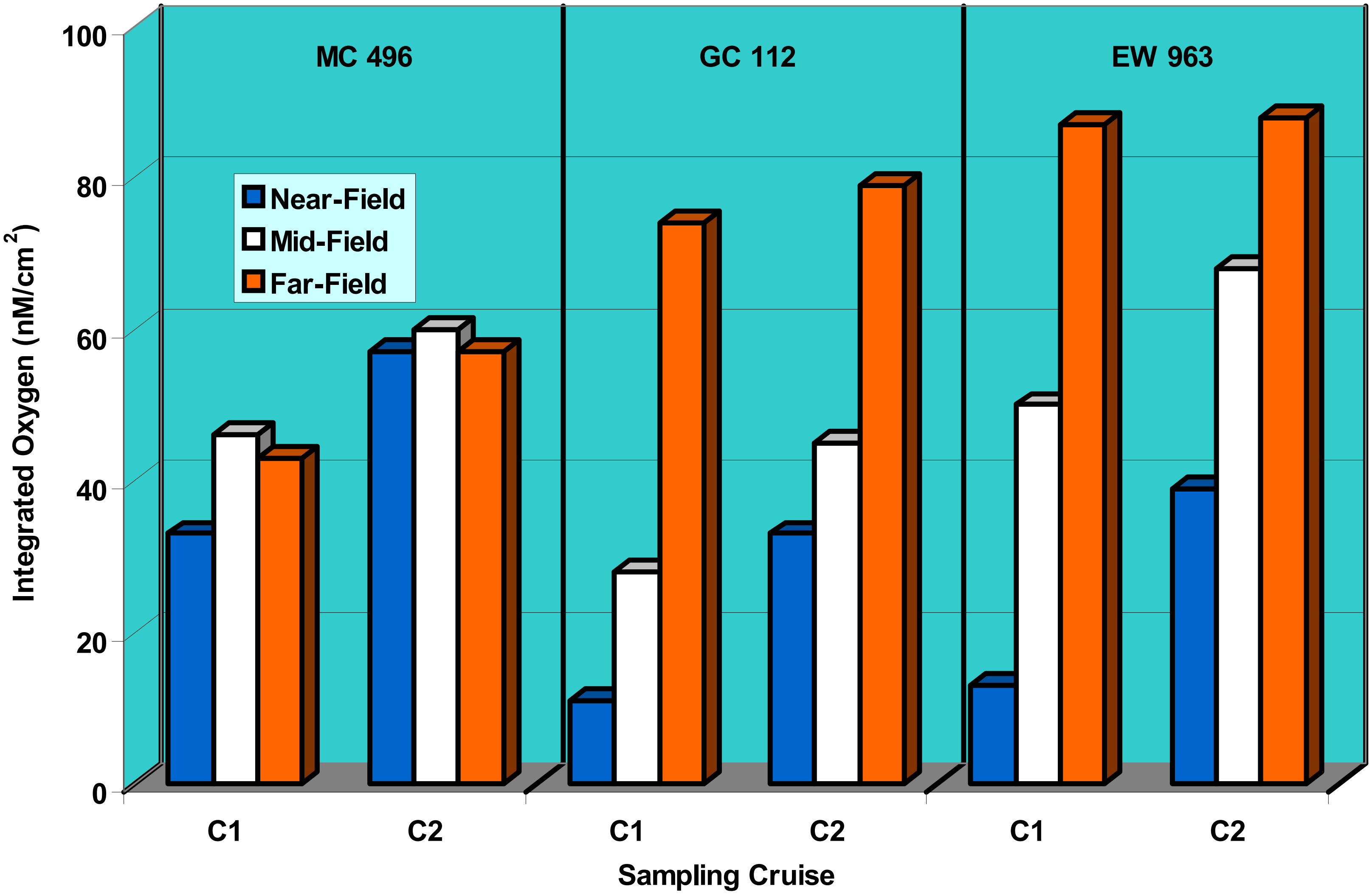


Figure 4-10. Integrated amounts of oxygen (defined as the nM of O_2 between the sediment surface and the redox potential discontinuity depth underlying 1 cm^2 of sediment) in the sediment column at near-field, mid-field, and far-field stations at three continental slope sites at the time of Sampling Cruise 1 (May 2001) and Sampling Cruise 2 (May 2002). Data from: Chapter 9.

Table 4-13. Concentrations of phosphate, sulfide, and ammonia in surficial sediment pore water collected from two continental shelf and two continental slope drillsites during the Screening Cruise. Data from: Continental Shelf Associates, Inc. (2000).

Site	Depth (cm)	Phosphate (µM)	Sulfide (µM)	Ammonia (µM)
Main Pass 288 FF	0	11.5	2.17	18.9
	1.5	13.2	0.92	39.4
Main Pass 299 DISC	0.5	11.3	246	NA
	1.5	22.6	12,800	NA
Green Canyon 112 DISC	0.5	9.61	67.8	20.0
	1.5	7.88	113	32.4
Green Canyon 112 FF	0.5	5.0	NA	1.69
	1.5	6.46	NA	12.5
Mississippi Canyon 496 DISC	0.5	14.7	14.3	84.5
	1.5	9.56	136	66.8
Mississippi Canyon 496 FF	0.5	10.6	3.53	13.7
	1.5	13.2	NA	39.3

DISC = Discretionary sample from near-field.
FF = Far-field.

At sites with the most organic enrichment, sulfide concentrations increased sharply with depth in the near-field sediment cores, reaching a maximum at between 2 and 12 cm below the surface and then declining at greater depths (Figure 4-11). The decreasing sulfide concentration with depth below the sulfide maximum in the cores is due primarily to precipitation of metal sulfides, particularly iron sulfides, including pyrite.

Sulfide and ammonia are toxic to marine organisms (Wang and Chapman, 1999; Randall and Tsui, 2002; Constable et al., 2003) and, when coupled with sediment hypoxia (Wu, 2002), play a major role in toxicity and ecological degradation of sediments that are heavily contaminated with OBM or SBM cuttings (Kingston, 1992; Olsgard and Gray, 1995; Neff et al., 2000; Hartley et al., 2003).

4.4.5 Manganese

Manganese, like Fe, is a redox-sensitive metal in marine sediments. Under oxidizing conditions, it is present primarily as insoluble Mn oxyhydroxides. As redox potential declines, the Fe and Mn oxyhydroxides are reduced and gradually dissolve. Iron and Mn reduction often is coupled to oxidation of organic matter, including SBM base chemicals, particularly esters, in the sediment (Brannon et al., 1984; Shimmield et al., 2000; van der Zee et al., 2003) and usually is microbially mediated (Cranfield, 1989). Soluble Mn may leach into the overlying water column (Thamdrup et al., 1994; Tankére et al., 2000). Thus, under reducing (low oxygen) conditions in surficial sediments caused by the organic enrichment effects of SBM cuttings accumulation, dissolved Mn concentration usually increases in sediment pore water and solid Mn concentration in bulk sediment may decrease as oxygen concentration and Eh decrease. Thus, differences in the distribution and concentrations of Mn in sediments near drillsites compared to reference site sediments can be used as an indication of physical/chemical alteration and recovery of surficial sediments by SBM cuttings accumulation.

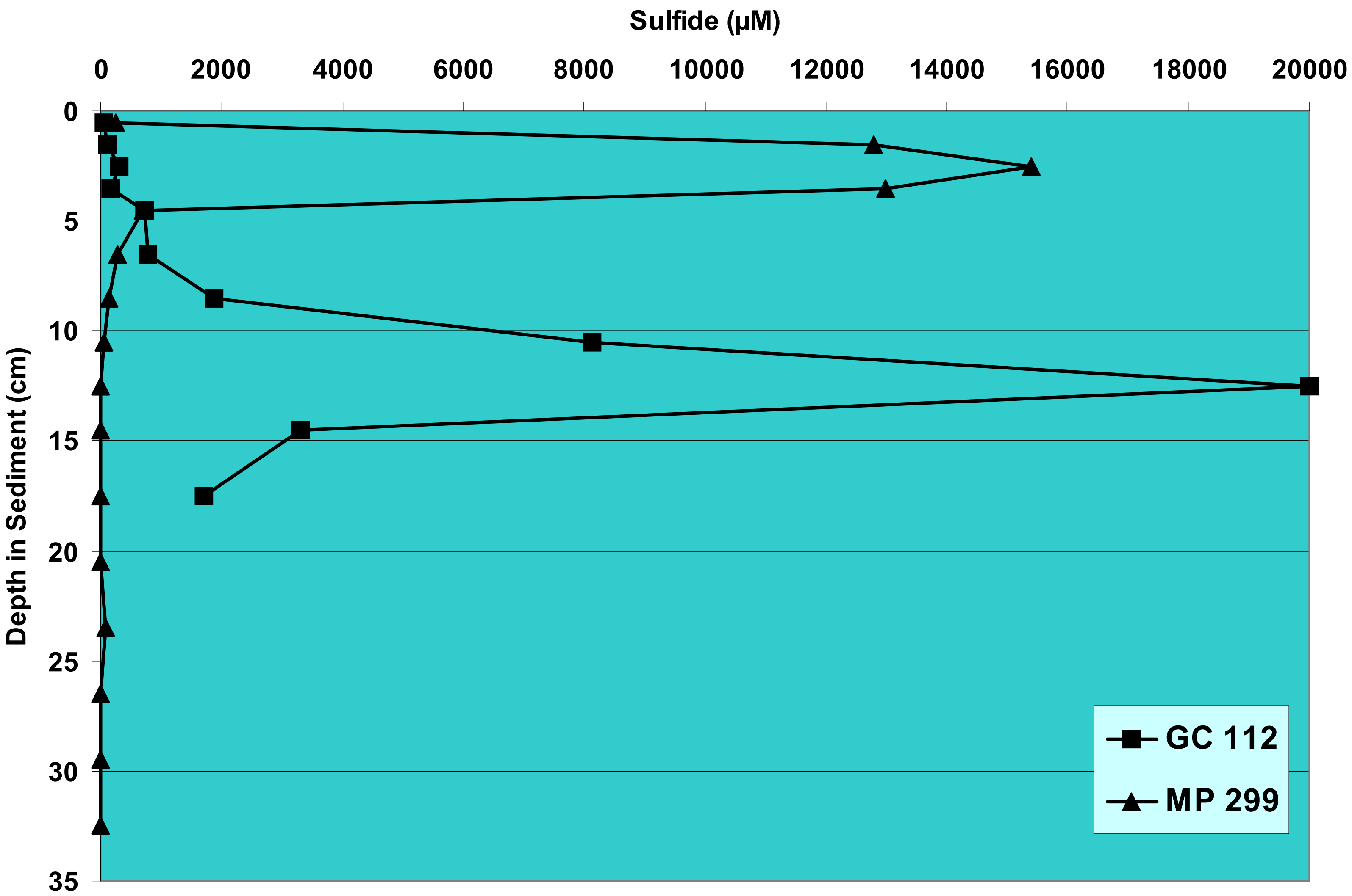


Figure 4-11. Vertical profiles of sulfide concentration in near-field sediments at a continental shelf (Main Pass [MP] 299) and continental slope (Green Canyon [GC] 112) synthetic based mud cuttings discharge site. Data from: Continental Shelf Associates, Inc., 2000.

There was a gradient of increasing Mn concentration in sediments with distance from all platforms; the gradient was steepest at the slope sites (Figures 4-12 and 4-13). There was a statistically significant relationship between zone (distance from the discharge site) and Mn concentration in surficial sediments at all six primary discharge sites. In most cases, either mid-field or far-field sediments contained higher concentrations of Mn than did near-field sediments. This probably is indicative of a shallower RPD depth (sediment hypoxia) in near-field sediments than in far-field sediments, likely caused by organic enrichment of sediments with SBM cuttings organics.

At MP 299, MP 288, EW 963, and MC 496, mean Mn concentrations in near-field sediments increased between Sampling Cruises 1 and 2, possibly indicating a reduction in organic enrichment. At the most heavily contaminated sites, EI 346 and GC 112, mean Mn concentrations in near-field and mid-field sediments did not change much in the year between Sampling Cruises 1 and 2, suggesting slower recovery. Dilution of sediment Mn with drill mud/cuttings solids also could contribute to the gradient.

4.5 SUMMARY OF PHYSICAL/CHEMICAL DISTURBANCE TO THE BENTHOS NEAR DRILL CUTTINGS DISCHARGE SITES

The first three objectives of this monitoring program focused on characterization of the magnitude and spatial and temporal trends of physical/chemical alteration (disturbance) of the benthic environment near discharge sites on the continental shelf and slope of the Gulf of Mexico attributable to previous discharges of SBM cuttings. The fourth objective focused on characterizing the biological disturbance to the benthic ecosystem near discharge sites and assessing possible relationships between the SBM cuttings mediated physical/chemical disturbance and the biological disturbance. This section summarizes the main findings of Sections 4.2, 4.3, and 4.4 about physical/chemical disturbance.

Deposition of drilling mud/cuttings in sediments may alter several physical/chemical properties of the sediments. Several parameters were used as indices of physical/chemical disturbance of sediments near six drillsites on the continental shelf and slope of the Gulf of Mexico (Tables 4-14 and 4-15). Far-field stations (3,000 to 6,000 m) at each site were minimally affected by the drilling discharges and were used as reference or comparison stations. Differences in the parameter values between near-field, mid-field, and far-field sediment samples were used as evidence of accumulation of drilling solids.

There is a clear indication of physical/chemical disturbance in near-field sediments at all six primary drillsites (Table 4-14). Cuttings were visible in all near-field zones, and nannofossils (or glass spheres) were observed visually in near-field sediments at higher concentrations than in far-field sediments at all but two locations, MP 299 and EW 963. An increase in mean grain size and percent sand were observed in all near-field zones except EW 963, where mean grain size was the same at near-field and far-field stations.

Elevated concentrations (compared to concentrations in far-field sediments) of Ba, SBM base chemical, and TPH were the best indicators of the presence of drilling solids in near-field sediments. These chemicals were detected at elevated concentrations in sediments from the near-field zones of all six primary discharge sites. Several other metals were measured in near-field and far-field sediments from three discharge sites. Concentrations of one or more metals were elevated in near-field sediments compared to far-field sediments at GC 112 and MC 496.

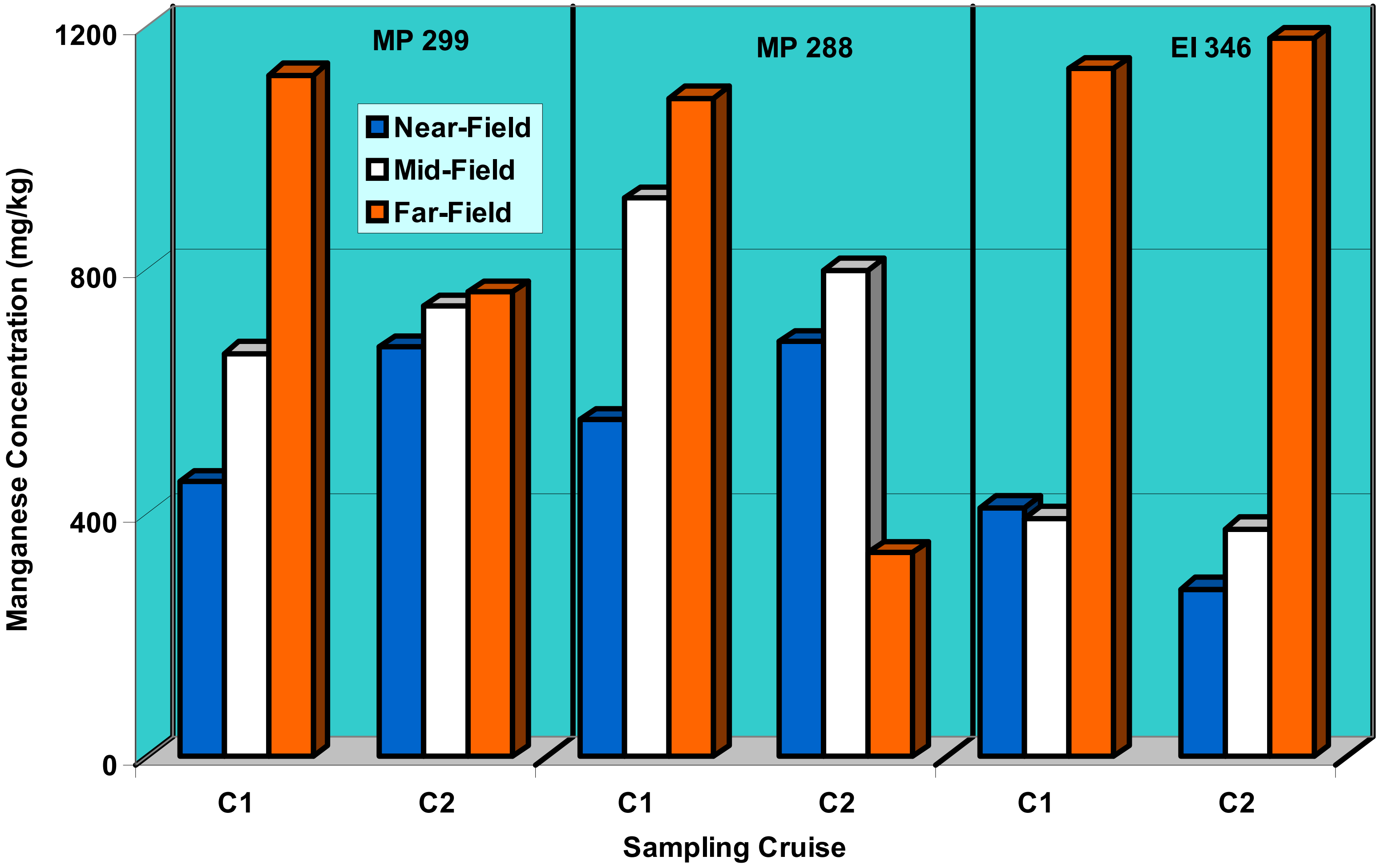


Figure 4-12. Manganese concentrations in surficial sediments from three continental shelf synthetic based mud cuttings discharge sites sampled during Sampling Cruise 1 (May 2001) and Sampling Cruise 2 (May 2002). Data from: Chapter 9.

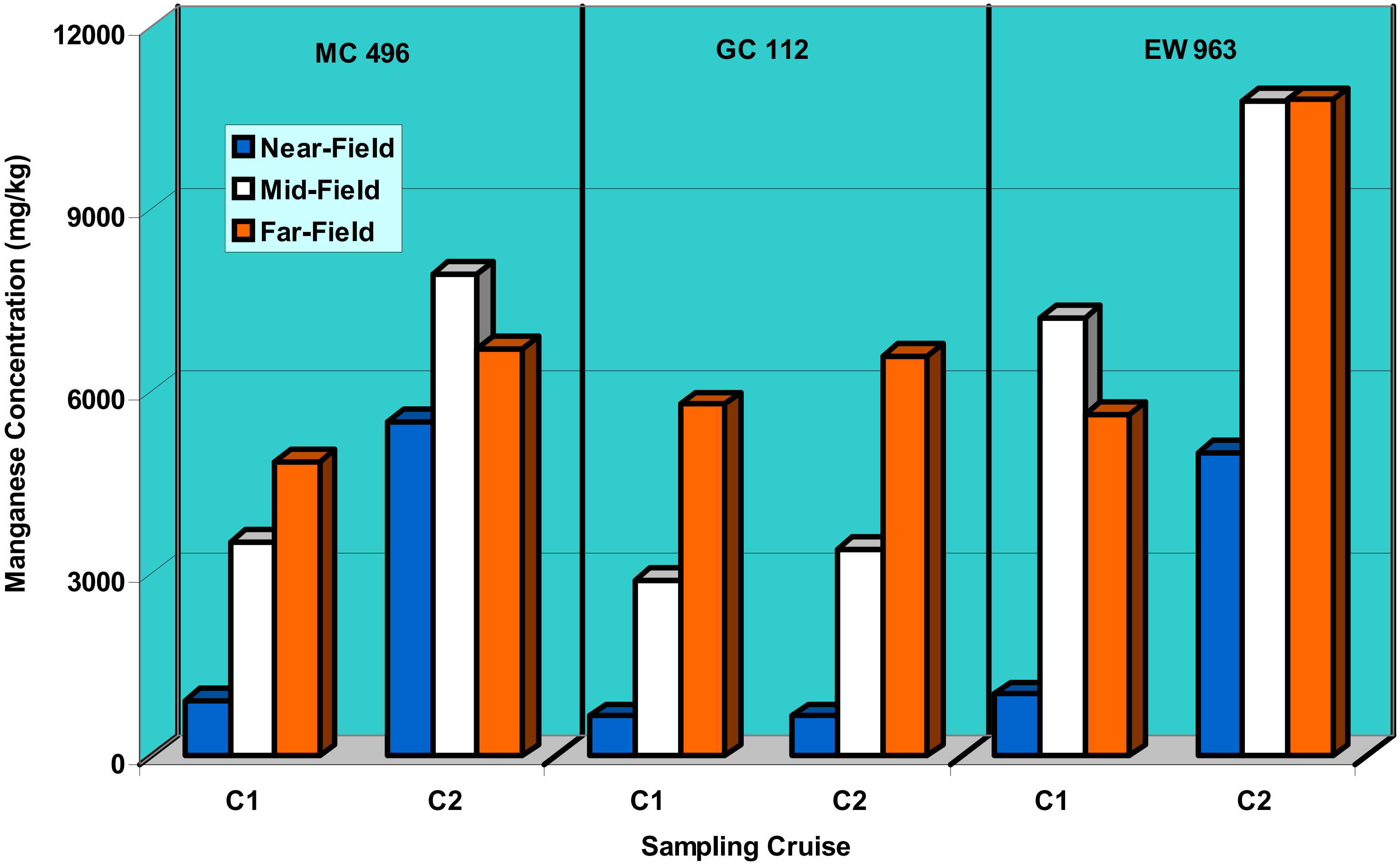


Figure 4-13. Manganese concentrations in surficial sediments from three continental slope synthetic based mud cuttings discharge sites sampled during Sampling Cruise 1 (May 2001) and Sampling Cruise 2 (May 2002). Data from: Chapter 9.

Table 4-14. Summary of physical/chemical differences between near-field (NF) and far-field (FF) sediments near six primary synthetic based mud (SBM) drill cuttings discharge sites on the outer continental shelf and slope of the Gulf of Mexico: (1) difference (either higher or lower) between NF and FF values or difference between Sampling Cruises 1 and 2; (0) little or no difference between NF and FF values; (0.5) small difference or difference at time of only one cruise between NF and FF values.

Parameter	Main Pass 299	Eugene Island 346	Main Pass 288	Green Canyon 112	Ewing Bank 963	Mississippi Canyon 496
Cuttings	0.5	1	1	1	1	1
Nannofossils	0	1	1	0.5	0	1
Grain Size	0.5	1	0.5	0.5	0	0.5
% Sand	1	1	1	1	1	1
Barium	0.5	1	1	1	1	1
Metals	0	NA	NA	1	NA	1
Iron and Aluminum	0.5	1	1	0.5	1	1
Manganese	1	1	1	1	1	1
SBF	1	1	1	1	1	1
TPH	1	1	1	1	1	1
TOC	0	1	0.5	0.5	0.5	1
RPD Depth	1	0.5	1	1	0.5	1
Zero O_2 Depth	1	1	1	1	0.5	0
$Eh_{1\ cm}$ Range	1	1	0	1	1	0
Integrated O_2	0	1	1	1	1	0.5
Sum	9	13	12	13	10.5	12

NA = Not analyzed.
RPD = Redox potential discontinuity.
SBF = Synthetic based fluid.
TOC = Total organic carbon.
TPH = Total petroleum hydrocarbons.

Several parameters were used to estimate decreases in sediment dissolved O_2 concentration and redox potential in near-field sediments, an indication of SBM/TPH-mediated organic enrichment. Total organic carbon concentration was higher in near-field than far-field sediments at all locations except MP 299 (Table 4-14). Manganese concentration was lower in sediments from the near-field zone than in far-field sediments at all locations. Manganese is lost from sediments when the RPD depth approaches the sediment surface. Two or more of RPD depth, $Eh_{1\ cm}$ range, and integrated O_2 concentration were lower in sediments from near-field zones than from far-field zones at all cuttings discharge locations where these parameters were measured. These results indicate that there was varying degrees of organic enrichment in the near-field zone at all six SBM cuttings discharge sites. These changes in oxidation/reduction chemistry of the sediments are the best predictors of the potential effects of drilling solids accumulation on benthic communities (Olsgard and Gray, 1995; Hartley et al., 2003).

Evidence of physical/chemical disturbance and altered redox conditions was weaker in mid-field sediments (Table 4-15). Altered sediment redox conditions were most pronounced at mid-field stations where highest SBM base chemical concentrations were observed. Redox profiles were normal in mid-field sediments where little or no SBM base chemical and TPH had accumulated.

As in near-field sediments, concentrations of Ba were elevated in mid-field stations at all six primary discharge sites, compared to concentrations in far-field sediments. Concentrations were much lower in mid-field sediments than in near-field sediments. These results indicate that there is a steep gradient of decreasing mud/cuttings ingredients and organic enrichment with distance from discharges in continental shelf and continental slope sediments.

Table 4-15. Summary of physical/chemical differences between mid-field (MF) and far-field (FF) sediments near six primary synthetic based mud (SBM) drill cuttings discharge sites on the outer continental shelf and slope of the Gulf of Mexico: (1) difference (either higher or lower) between MF and FF values or difference between Sampling Cruises 1 and 2; (0) little or no difference between MF and FF values; (0.5) small difference or difference at time of only one cruise between MF and FF values.

Parameter	Main Pass 299	Eugene Island 346	Main Pass 288	Green Canyon 112	Ewing Bank 963	Mississippi Canyon 496
Cuttings	0.5	1	0.5	0	1	1
Nannofossils	0.5	0.5	0.5	0.5	0	0.5
Grain Size	1	1	0	0	1	0.5
% Sand	1	1	0	0.5	1	1
Barium	0.5	1	0.5	0.5	1	1
Iron and Aluminum	0	1	1	0.5	0.5	0.5
Manganese	1	1	0.5	1	0	0
SBF	1	1	1	1	1	1
TPH	1	1	1	1	1	1
TOC	0	1	0.5	0.5	1	0.5
RPD Depth	1	0.5	1	NA	0	1
Zero O_2 Depth	0	1	0	0.5	0.5	0
$Eh_{1\ cm}$	0	1	1	0	0.5	0
Integrated O_2	0	1	1	1	1	0
Sum	7.5	13	8.5	7	9.5	8

NA = Not analyzed.
RPD = Redox potential discontinuity.
SBF = Synthetic based fluid.
TOC = Total organic carbon.
TPH = Total petroleum hydrocarbons.

Based on the sum of disturbance indices in Table 4-14, physical/chemical disturbance of sediments at near-field sites can be ranked as follows, from most to least disturbed: EI 346 = GC 112 > MP 288 = MC 496 > EW 963 > MP 299. The relative magnitude of disturbance of mid-field sediments has a different pattern based on the sum of disturbance indices in Table 4-15: EI 346 > EW 963 > MP 288 > MC 496 > MP 299 > GC 112. The ranking of near-field disturbance seems to be related loosely to volume of SBM discharged. The extent of mid-field disturbance does not seem to be related to the magnitude of drilling discharges or to water depth.

These results show that much of the SBM drilling mud cuttings solids discharged from offshore platforms settle within about 100 m of the discharge site, irrespective of water depth. Small amounts of solids accumulate in sediments 100 to 250 m from the discharge, but little or no discharged solids settle in sediments 3,000 m from the discharge. This is the pattern of deposition of OBM and SBM cuttings observed by others in the Gulf of Mexico and North Sea (Neff et al., 2000; Hartley et al., 2003). Discharged WBMs and WBM cuttings tend to disperse more and settle on the seafloor over a larger area but at lower concentrations (National Research Council, 1983; Neff et al., 1987).

Changes in the values of the indicator parameters also can be used to detect temporal trends in the magnitude of physical/chemical disturbance of sediments near offshore discharge sites. Data from Sampling Cruise 1 (May 2001) and Sampling Cruise 2 (May 2002) were compared for near-field (Table 4-16) and mid-field (Table 4-17) zones at the six primary sites. Parameter values that changed between cruises toward the parameter value for the far-field zone of the same site were identified.

Table 4-16. Summary of physical/chemical differences between Sampling Cruise 1 (May 2001) and Sampling Cruise 2 (May 2002) in near-field sediments near six primary synthetic based mud (SBM) drill cuttings discharge sites on the outer continental shelf and slope of the Gulf of Mexico: (1) large change toward far-field parameter value at the same discharge site; (0.5) small change toward far-field parameter value at the same discharge site; (0) no change or a change away from the far-field parameter value at the same discharge site.

Parameter	Main Pass 299	Eugene Island 346	Main Pass 288	Green Canyon 112	Ewing Bank 963	Mississippi Canyon 496
Cuttings	0.5	0	1	1	1	1
Nannofossils	0	0	0	0.5	0	0
Barium	0.5	1	1	0	1	1
Iron and Aluminum	0.5	0.5	0.5	1	1	0.5
Manganese	1	0	0.5	0	1	1
SBF	0.5	0.5	1	0	0	0.5
TPH	1	1	1	1	1	1
TOC	0	1	1	0	0	0.5
Zero O_2 Depth	0.5	0	0	0	0	0
$Eh_{1\ cm}$ Range	1	0.5	0	0.5	1	0
Integrated O_2	0.5	0	0	1	1	1
Sum	6	4.5	6	5	7	6.5

SBF = Synthetic based fluid. TPH = Total petroleum hydrocarbons.
TOC = Total organic carbon.

Table 4-17. Summary of physical/chemical differences between Sampling Cruise 1 (May 2001) and Sampling Cruise 2 (May 2002) in mid-field sediments near six primary synthetic based mud (SBM) drill cuttings discharge sites on the outer continental shelf and slope of the Gulf of Mexico: (1) large change toward far-field parameter value at the same discharge site; (0.5) small change toward far-field parameter value at the same discharge site; (0) no change or a change away from the far-field parameter value at the same discharge site.

Parameter	Main Pass 299	Eugene Island 346	Main Pass 288	Green Canyon 112	Ewing Bank 963	Mississippi Canyon 496
Cuttings	0.5	0.5	1	0.5	1	1
Nannofossils	0	0	0	0	0	0
Barium	0.5	0	0	0	1	1
Iron and Aluminum	0.5	0.5	0.5	0	0	0
Manganese	0.5	0	0	0.5	1	1
SBF	0.5	0	0	0	0	1
TPH	0.5	1	0.5	0	1	1
TOC	0	1	0.5	0	0.5	0.5
Zero O_2 Depth	0	0	0	0	0	0
$Eh_{1\ cm}$ Range	0	1	0	0	1	0.5
Integrated O_2	0	0.5	0	1	1	1
Sum	3	4.5	2.5	2	6.5	7

SBF = Synthetic based fluid. TPH = Total petroleum hydrocarbons.

TOC = Total organic carbon.

The strongest evidence of a diminution of physical/chemical disturbance (recovery) in the near-field zone was for EW 963 and MC 496 (both slope sites), followed by two less disturbed shelf sites (MP 299 and MP 288). The most highly disturbed near-field sites, EI 346 and GC 112, showed the weakest evidence of near-field recovery in the 1 year between Sampling Cruises 1 and 2. However, there was some evidence of physical/chemical recovery in sediments from all near-field zones. Several field studies in the North Sea and the Gulf of Mexico have shown that the rate of degradation of SBM base chemical in offshore sediments usually is inversely proportional to SBM base chemical concentrations (Neff et al., 2000). High concentrations of SBM base chemical may inhibit microbial degradation, or create more severe sediment hypoxia where degradation is obligatorily anaerobic. Anaerobic degradation of SBM base chemical is much slower than aerobic degradation (Neff et al., 2000).

There is less evidence of physical/chemical recovery in mid-field than in near-field sediments (Table 4-17). This is mainly because the magnitude of the disturbance in most mid-field zones was less than in the near-field zones, so changes toward recovery were more difficult to detect. The strongest evidence of recovery in mid-field sediments was at two continental slope sites, EW 963 and MC 496. The weakest evidence was at the other continental shelf site, GC 112, and at MP 288 and MP 299, both mildly disturbed continental shelf sites. There was good evidence of a drop in sediment organic matter and an improvement in sediment redox conditions in mid-field sediments at the most severely disturbed site, EI 346.

Overall, sediments in all near-field and mid-field zones showed some evidence of recovery or decrease in the severity of disturbance in the year between Sampling Cruises 1 and 2. Various sediment redox condition parameters were the best indicators of sediment disturbance and recovery. One or more of the redox parameters were altered, compared to far-field stations, in near-field and mid-field sediments at all six primary discharge sites (Tables 4-14 and 4-15), and one or more parameters had changed toward far-field reference site values between Sampling Cruises 1 and 2 at most primary sites (Tables 4-16 and 4-17). These redox parameters tended to show the least temporal change at the least disturbed near-field sites and at all mid-field sites.

4.6 BIOLOGICAL EFFECTS OF SBM CUTTINGS IN SEDIMENTS

4.6.1 Toxicity of Sediments Near Offshore Drilling Waste Discharge Sites

The survival of the amphipod *Leptocheirus plumulosus* during exposure to sediments collected near drilling sites was measured to assess the potential for SBM cuttings to contribute to sediment toxicity. USEPA uses toxicity of SBM base chemicals and laboratory-formulated SBM-sediment mixtures as a criterion for the acceptability of SBM cuttings for ocean disposal but does not require toxicity tests with sediments collected adjacent to offshore SBM cuttings discharge sites. In the present investigation, sediment toxicity tests, performed in accordance with protocols recommended by USEPA, were used to evaluate the potential toxicity to benthic communities of sediments containing SBM cuttings solids collected at different distances from offshore drillsites.

Most sediments, even from near-field stations, were not toxic, as indicated by amphipod survival greater than 75%. Mean survival of amphipods in far-field sediments exceeded 80% in all cases. Thus, evaluation of sediment toxicity in near-field and mid-field sediments was based on comparison with percent survival of amphipods in far-field sediments. Near-field sediments showed stronger evidence of toxicity and greater variation in toxicity than sediments from mid-field and far-field stations (Table 4-18). Sediments from only continental shelf sites were evaluated on Sampling Cruise 1. There was little difference in the toxicity of sediments from these continental shelf sites between Sampling Cruises 1 and 2. Toxicity of near-field and mid-field sediments was similar for samples collected on Sampling Cruises 1 and 2 at EI 346, the only continental shelf site where sediment toxicity was detected.

Near-field sediments from three of the six primary sites were statistically significantly more toxic than far-field sediments from the same site (Table 4-18). These sites are continental shelf site EI 346 and continental slope sites GC 112 and EW 963. Mid-field sediments at EI 346 and GC 112 also were significantly more toxic than far-field sediments. Sediments from all zones at sites MP 288, MP 299, and MC 496 exhibited no or low toxicity. There were no significant gradients of sediment toxicity with distance at these sites.

There was a good correlation (Spearman's correlation analysis at $p<0.001$) between SBM base chemical concentration and toxicity at the three sites where there was significant toxicity (Table 4-19). In most cases, near-field and mid-field sediments from EI 346 and GC 112 that contained more than about 700 mg/kg SBM base chemical were toxic to the benthic amphipods. However, some near-field sediments collected at EW 963 on Sampling Cruise 2 were toxic but contained less than 375 mg/kg SBM base chemical; the most toxic sediment samples from the site contained approximately 1,000 mg/kg TPH (probably mainly partially biodegraded SBM base chemical).

Table 4-18. Summary of toxicity test results with amphipod *Leptocheirus plumulosus* and sediments collected during Sampling Cruises 1 and 2 from the vicinity of six drillsites on the continental shelf and slope of the Gulf of Mexico. Near-field (NF) and mid-field (MF) sediments that were statistically significantly ($\alpha = 0.05$) more toxic than the far-field (FF) samples from the same site are highlighted (Data from: Chapter 10).

Site	Zone	Sampling Cruise	Percent Survival		
			Mean	SD	Range
Main Pass 299	NF	1	74	37	1 – 99
		2	92	4	87 – 95
	MF	1	98	2	94 – 100
		2	91	6	81 – 98
	FF	1	97	3	94 – 100
		2	93	2	90 – 96
Eugene Island 346	NF	**1**	**58**	**46**	**0 – 97**
		2	**31**	**28**	**0 – 67**
	MF	**1**	**77**	**30**	**28 – 96**
		2	**56**	**20**	**17 – 73**
	FF	1	97	2	92 – 98
		2	87	7	75 – 95
Main Pass 288	NF	1	79	22	51 – 97
		2	97	1	96 – 99
	MF	1	94	3	90 – 98
		2	97	1	96 – 99
	FF	1	94	4	90 – 98
		2	96	3	92 – 100
Green Canyon 112	NF	**2**	**27**	**30**	**0 – 83**
	MF	**2**	**56**	**35**	**2 – 95**
	FF	**2**	**93**	**2**	**91 – 96**
Ewing Bank 963	NF	**2**	**65**	**21**	**29 – 82**
	MF	2	75	23	30 – 90
	FF	2	89	5	85 – 96
Mississippi Canyon 496	NF	2	85	10	68 – 95
	MF	2	84	12	67 – 97
	FF	2	89	7	79 – 96

SD = Standard deviation.

Table 4-19. Results of Spearman's correlation analysis of the relationship between synthetic based mud (SBM) base chemical concentration in sediments and sediment toxicity (percent survival) at six SBM cuttings discharge sites on the continental shelf and slope of the Gulf of Mexico.

Site	Spearman's Correlation Coefficient	Prob > |r|	Interpretation
Main Pass 299	-0.2	$p > 0.05$	Not Significant
Eugene Island 346	**-0.71**	**$p < 0.001$**	**Significant**
Main Pass 288	-0.28	$p > 0.05$	Not Significant
Green Canyon 112	**-0.92**	**$p < 0.001$**	**Significant**
Ewing Bank 963	**-0.88**	**$p < 0.001$**	**Significant**
Mississippi Canyon 496	-0.22	$p < 0.05$	Not Significant

These results indicate that SBM base chemical or chemical/physical parameters that co-varied with SBM base chemical concentrations contributed to the toxicity of the sediments to amphipods. Several sediment parameters, including Ba and Mn concentration, magnitude of organic enrichment and redox potential alteration, and H_2S concentration also covaried with sediment SBM and TPH concentration at the three sites showing sediment toxicity. Some of the most toxic sediment samples contained high concentrations of sulfide or ammonia at the start or end of the toxicity tests (caused by microbial degradation of organic matter), explaining some of the observed toxicity (Wang and Chapman, 1999; Randall and Tsui, 2002).

The relationships between the sediment physical/chemical parameters and the results of the sediment toxicity tests for the three primary continental shelf sites were evaluated statistically by Spearman's correlation test. Survival was correlated to sediment grain size, merely reflecting the preference of the amphipod test animal for a narrow range of sediment grain size. At EI 346, the only continental shelf site where there was a significantly higher toxicity of near-field and mid-field sediments than far-field sediments (Table 4-18), sediment toxicity was correlated to SBM base chemical, TOC, and Ba concentration. These correlations do not demonstrate causality but merely indicate that the toxicity of continental shelf sediments to benthic amphipods probably is related to accumulation of drilling solids in sediments.

The toxicity of most SBMs is much less (LC_{50} is higher), based on SBM base chemical and TPH concentration, than the most toxic sediments near the three discharge sites where sediment toxicity was detected (Table 4-20). Different species of benthic amphipods vary in their sensitivity to chemical contaminants and organic enrichment effects in sediments; *Leptocheirus* and *Ampelisca* are quite sensitive to both chemicals and organic enrichment, whereas *Corophium* may be quite tolerant to organic enrichment. This suggests that some components of the SBM cuttings solids or the physical/chemical changes they cause in sediments (e.g., elevated NH_3^+ and S^{-2} concentrations and reduced Eh) probably were responsible for most of the sediment toxicity near offshore SBM cuttings discharge sites.

Table 4-20. Mean LC_{50}s of oils and synthetic based mud (SBM) base chemicals in sediments for the marine amphipods *Ampelisca abdida* and *Corophium volutator* in standard 10-day sediment toxicity tests (ASTM E1367-92; ASTM, 1992). LC_{50} and 95% CI concentrations are mg/kg dry wt (From: Candler et al., 1997).

Drilling Mud Base Chemical	Mean LC_{50} (95% Confidence Interval)	
	Ampelisca abdida	*Corophium volutator*
Enhanced mineral oil	557 (493 – 630)	7,146 (5,708 – 8,945)
Diesel fuel	879 (695 – 1,112)	840 (690 – 1,008)
Internal olefin	3,121 (2,503 – 3,893)	>30,000 (ND)
Poly-α-olefin	10,680 (7,665 – 18,599)	>30,000 (ND)

ND = Not determined.

Sediment toxicity was restricted almost exclusively to a radius of 100 m around both continental shelf and slope discharge sites. Toxicity was observed in mid-field sediments at two sites, EI 346 and GC 112, the sites containing the highest concentrations of sediment SBM. Toxicity of mid-field sediments was less than that of near-field sediments at both locations. Thus, to the extent that sediment toxicity is an indicator of hazard to benthic communities, the extent of this potential hazard is limited to a small area of the seafloor near three of the six primary discharge sites.

4.6.2 Benthic Community Structure Near Offshore Drilling Waste Discharge Sites

Benthic infaunal samples were collected at the three continental shelf discharge sites during the Screening Cruise and Sampling Cruises 1 and 2 (see Chapter 12). Data from only the Sampling Cruises will be discussed here. The study sites were MP 299, EI 346, and MP 288. At each site, six cores were collected at different randomly selected near-field, mid-field, and far-field stations; these were the same locations where sediment samples were collected for physical and chemical analysis. Benthic fauna retained by a 0.5-mm mesh screen were identified and counted.

There were substantial differences in benthic community structure among continental shelf sampling sites, but samples collected at different distances within a given site usually were similar. There were no significant differences in mean abundance of benthic infauna at near-field, mid-field, and far-field stations at any of the three continental shelf discharge sites. However, benthic fauna were significantly more abundant at the time of Sampling Cruise 1 than at the time of Sampling Cruise 2 in sediments at all distances from MP 288 (Figure 4-14). The mean number of individuals per 0.1 m^2 was highest at EI 346 and lowest at MP 299 (Figure 4-14, Table 4-21). Mean faunal density varied widely among sampling stations, ranging between 2 and 631 individuals/0.1 m^2.

The number of benthic taxa per station varied between 2 and 93 species (Table 4-21). Infaunal abundance and species numbers were highly variable in far-field sediments at MP 288 at the time of Sampling Cruises 1 and 2. This variance in numbers of individuals and taxa was encountered at the far-field stations at MP 288 and was caused in large part by the wide variation of percent sand in sediments in this zone.

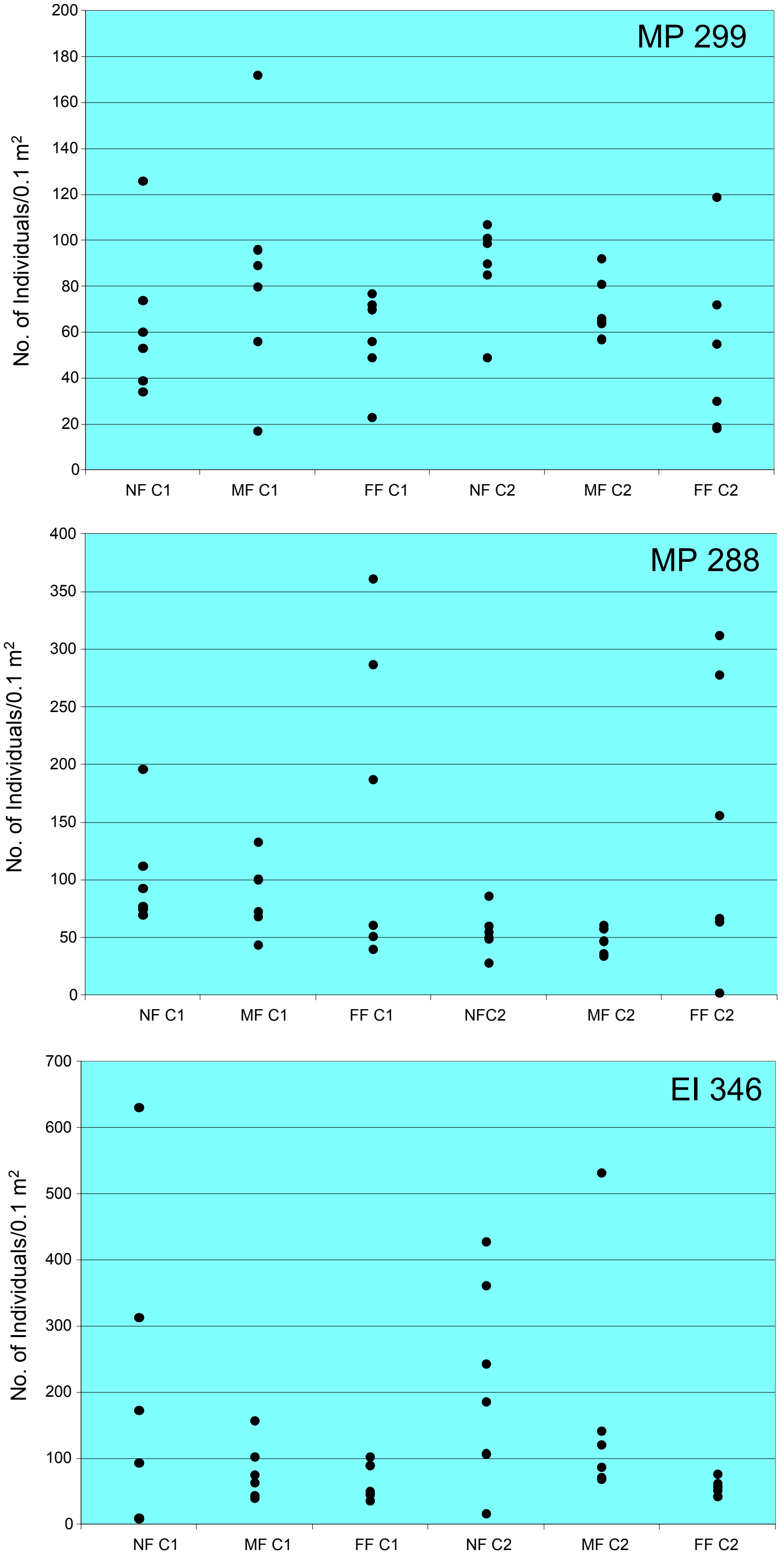


Figure 4-14. Number of individuals of benthic fauna in sediments collected on Sampling Cruise 1 (May 2001) and Sampling Cruise 2 (May 2002) at near-field (NF), mid-field (MF), and far-field (FF) stations at three synthetic based mud cuttings discharge sites on the outer continental shelf of the Gulf of Mexico. Data from: Chapter 12.

Table 4-21. Ranges of benthic community parameters for sediments at different distances from synthetic based mud cuttings discharge sites on the continental shelf of the Gulf of Mexico (From: Chapter 12).

Site	Zone/Cruise	Mean No. Individuals	No. Taxa	Diversity (H′)	Evenness (J′)
Main Pass 299	NF (C1)	34 – 126	10 – 40	1.95 – 4.91	0.59 – 0.94
	(C2)	49 – 107	46 – 63	4.61 – 5.37	0.83 – 0.92
	MF (C1)	17 – 172	8 – 37	2.91 – 4.58	0.81 – 0.97
	(C2)	57 – 92	42 – 54	4.70 – 4.98	0.83 – 0.89
	FF (C1)	23 – 77	11 – 31	3.18 – 4.57	0.85 – 0.97
	(C2)	18 – 119	23 – 57	4.27 – 5.09	0.76 – 0.94
Eugene Island 346	NF (C1)	9 – 631	2 – 22	0.99 – 2.14	0.25 – 0.49
	(C2)	17 – 428	3 – 52	0.62 – 4.21	0.17 – 0.97
	MF (C1)	40 – 157	4 – 28	1.19 – 4.31	0.58 – 0.97
	(C2)	69 – 532	27 – 68	0.53 – 5.31	0.11 – 0.91
	FF (C1)	36 – 103	17 – 39	3.46 – 4.86	0.78 – 0.94
	(C2)	43 – 77	46 – 63	4.15 – 5.34	0.72 – 0.93
Main Pass 288	NF (C1)	70 – 196	28 – 39	3.90 – 4.59	0.74 – 0.93
	(C2)	28 – 60	32 – 58	4.59 – 5.14	0.84 – 0.92
	MF (C1)	44 – 133	17 – 39	3.65 – 4.84	0.83 – 0.94
	(C2)	34 – 61	36 – 50	4.48 – 5.16	0.87 – 0.95
	FF (C1)	40 – 361	13 – 70	3.17 – 5.23	0.83 – 0.90
	(C2)	2 – 312	2 – 93	4.84 – 5.26	0.74 – 0.89

FF = Far-field.
MF = Mid-field.
NF = Near-field.

C1 = Sampling Cruise 1.
C2 = Sampling Cruise 2.

Infaunal densities were low and numbers of taxa were relatively high in all zones at MP 299. At the time of the Screening Cruise (August 2000) and Sampling Cruise 1 (May 2001), the opportunist polychaete, *Capitella capitata,* was one of the numerically dominant members of the benthic community at MP 299 near-field stations. It was not a numerical dominant in the near-field benthic community in May 2002. Although this change was not correlated to changes in sediment grain size, TOC, or SBM/TPH, it does indicate that there may have been an improvement of the quality of the benthic environment over the 2 years of monitoring.

The opportunist *Capitella* was not among the dominants in sediments in any zones near MP 288. At EI 346, the most heavily contaminated continental shelf site, *Capitella capitata* represented 1.8% and 1.1% of the benthic fauna in near-field sediments at the time of Sampling Cruises 1 and 2, respectively. *Capitella* represented 8.1% of the benthic fauna at mid-field stations during Sampling Cruise 1 but was not observed in mid-field sediments at the time of Sampling Cruise 2. Thus, abundance of this opportunist provided only a weak indication of adverse effects of drilling discharges on benthic communities.

Several sediment samples collected during Sampling Cruises 1 and 2 at near-field and mid-field zones and during Sampling Cruise 2 in the near-field zone at EI 346 contained large numbers of just a few species of benthic animals (Table 4-21). The numerically dominant benthic fauna at near-field and mid-field stations were bivalve mollusks. Many bivalves are tolerant to low DO concentration, and some, such as *Thyasira trisinuata*, a numerical dominant in the far-field zone at the time of Sampling Cruise 2, are sulfide oxidizers tolerant of organic enrichment (Dando and Southward, 1986). This is a strong indication of sediment disturbance from organic enrichment (Pearson and Rosenberg, 1978; Mirza and Gray, 1981; Hartley et al., 2003).

Shannon-Wiener diversity (H′), evenness (J′), and logarithmic series alpha (LSA) are community diversity parameters frequently used to evaluate effects of disturbance on benthic communities (Figures 4-15, 4-16, and 4-17). Healthy communities often, but not always, have high values of H′, J′, and LSA. In the present investigation, lowest community diversity and evenness were observed in sediments from near-field and mid-field stations at EI 346, reflecting the high abundance of just a few species at these stations (Figure 4-15). In general, diversity and evenness were higher in sediments from MP 288 than in those from MP 299, though the differences were not large (Figures 4-16 and 4-17).

The variability in all benthic community parameters was highest at the near-field stations and usually was much lower at the far-field stations. When community parameters were variable at far-field stations, it usually could be attributed to a heterogeneous distribution of sediment texture. At near-field stations, the variability probably was caused by a combination of variations in sediment texture and a heterogeneous distribution of WBM and SBM cuttings solids in surficial sediments.

Multifactorial correlation analysis was performed to aid in the interpretation of benthic community results. The analysis made use of macrofaunal community parameters and several physical/chemical parameters in the same sediments. These analyses were performed for Sampling Cruises 1 and 2 combined and for each cruise separately (Tables 4-22, 4-23, and 4-24). There were several statistically significant positive or negative correlations between various community parameters and the physical/chemical parameters that included sediment grain size and Ba, Mn, TOC, TPH, and SBM concentrations.

The greatest differences between benthic community parameters at near-field and mid-field stations compared to far-field stations were at EI 346, where near-field and mid-field sediments contained the highest concentrations of SBM base chemical and TPH of the continental shelf sites. Shannon-Wiener diversity (H’) was the only community parameter inversely correlated with SBM concentration, and only at the time of Sampling Cruise 1 (Table 4-22). The correlation was negative ($\rho = -0.61$) for the relationship between SBM base chemical concentration and H’ at the time of Sampling Cruise 1 (diversity declined as SBM base chemical concentration increased) but was positive (not significant) at the time of Sampling Cruise 2. This result implies recovery of benthic communities at this site between the cruises. Barium concentration and mean grain size were inversely correlated with evenness. These results suggest that benthic community structure at EI 346 was modified slightly by the amount of drill cuttings solids in sediment.

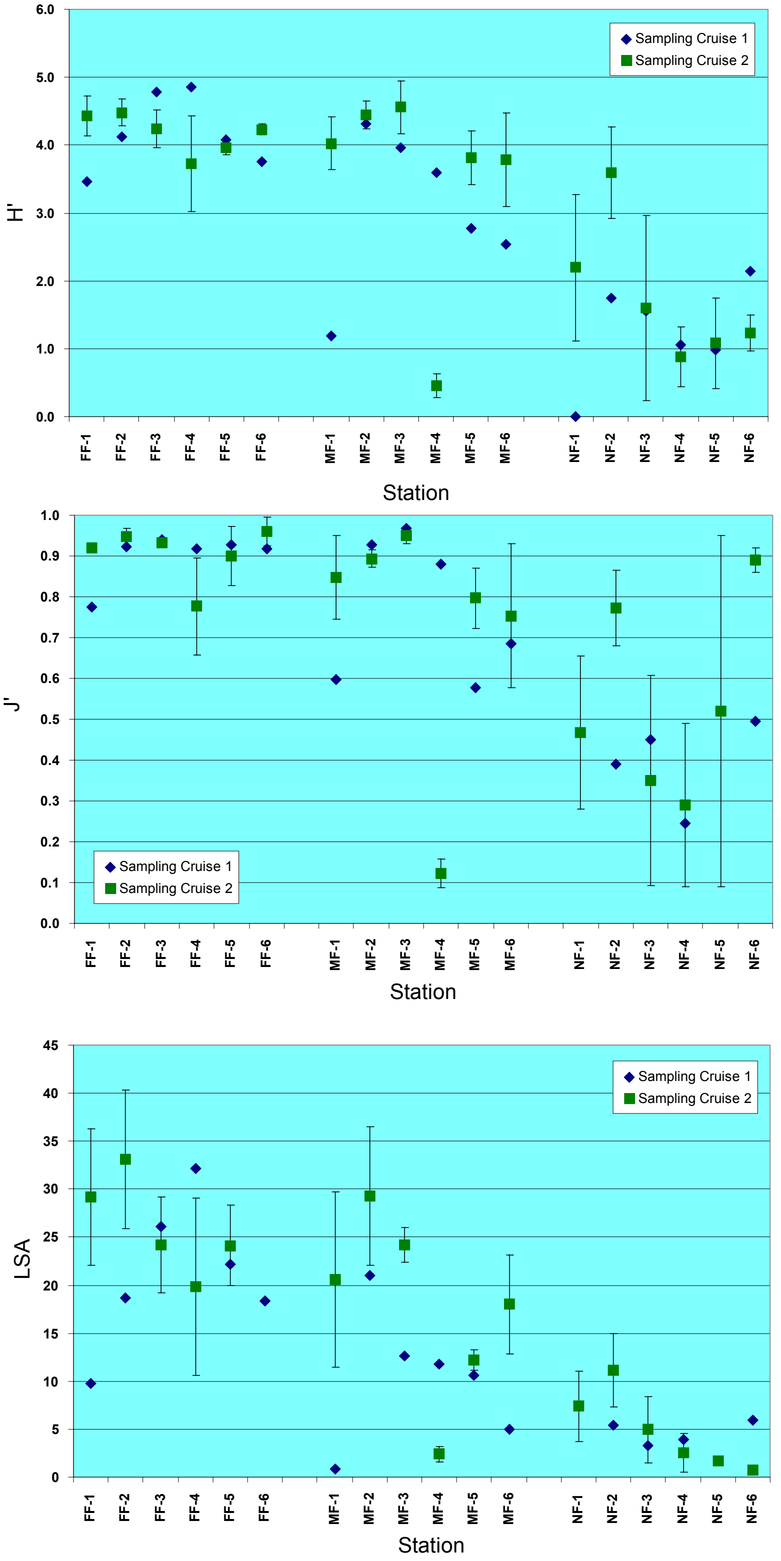


Figure 4-15. Diversity measures for benthic fauna data for Eugune Island 346 from Sampling Cruises 1 and 2. H' is Shannon-Wiener index, J' is evenness, and LSA is Fisher's logarithmic series alpha. Data from: Chapter 12.

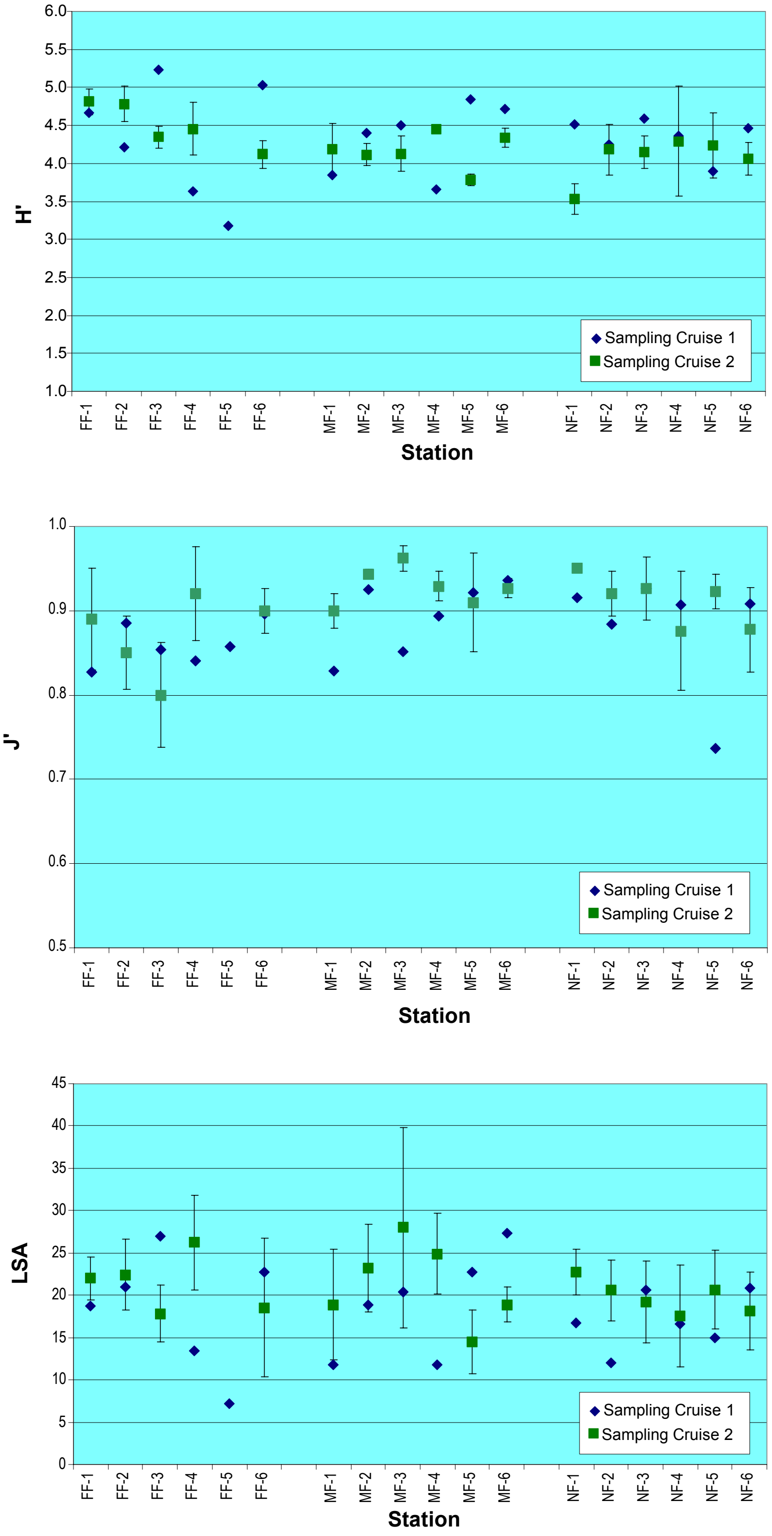


Figure 4-16. Diversity measures for benthic fauna data for Main Pass 288 from Sampling Cruises 1 and 2. H' is Shannon-Wiener index, J' is evenness, and LSA is Fisher's logarithmic series alpha. Data from: Chapter 12.

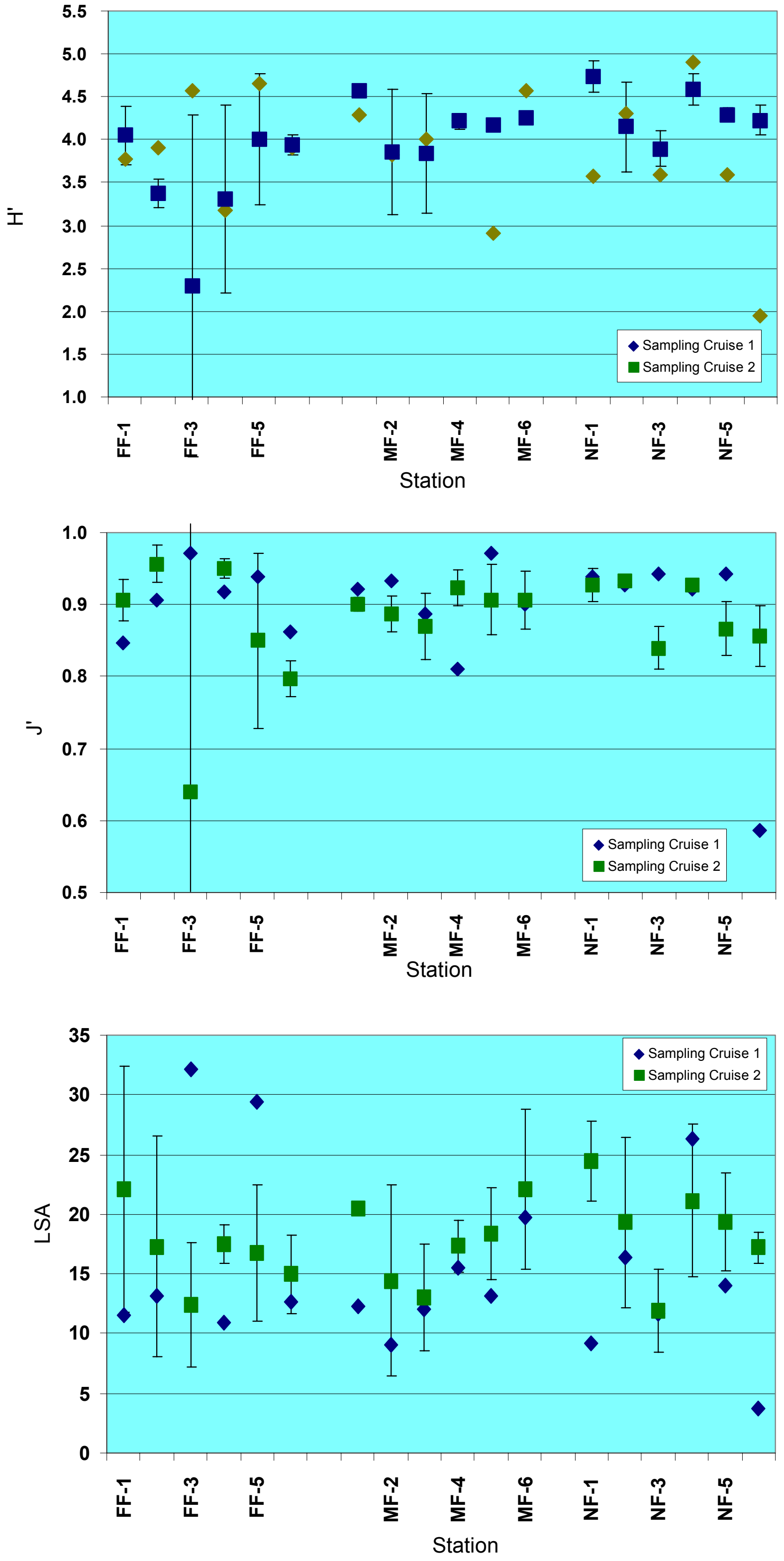


Figure 4-17. Diversity measures for benthic fauna data for Main Pass 299 from Sampling Cruises 1 and 2. H' is Shannon-Wiener index, J' is evenness, and LSA is Fisher's logarithmic series alpha. Data from: Chapter 12.

Table 4-22. Statistical relationships (Spearman's ρ correlation) between sediment physical/chemical parameters (mean grain size, barium [Ba], manganese [Mn], total organic carbon [TOC], total petroleum hydrocarbons [TPH], and synthetic based mud [SBM] base chemical concentration) and benthic community parameters at Eugene Island 346. Significant correlations ($\rho<0.05$) are highlighted.

Physical/Chemical Parameter	Spearman's ρ Correlation, Biological Parameters			
	Abundance	Diversity (H')	No. Taxa	Evenness (J')
Grain Size Comb.	0.01	-0.33	-0.23	**-0.36**
Grain Size C1	0.12	-0.37	0.01	-0.31
Grain Size C2	0.17	-0.31	-0.21	-0.15
Ba Comb.	0.30	-0.17	0.14	-0.25
Ba C1	0.43	-0.16	0.47	-0.11
Ba C2	0.33	-0.37	-0.09	**-0.59**
Mn Comb.	-0.13	-0.23	-0.02	-0.12
Mn C1	-0.13	-0.18	0.28	0.02
Mn C2	0.07	-0.45	-0.24	-0.31
TOC Comb	-0.09	-0.11	-0.21	0.16
TOC C1	-0.11	<0.01	-0.03	0.12
TOC C2	0.05	-0.27	-0.48	0.03
TPH Comb.	0.04	0.02	0.06	<0.01
TPH C1	-0.16	0.32	-0.06	-0.04
TPH C2	0.19	-0.19	-0.01	-0.17
SBM Comb.	-0.18	-0.30	-0.30	-0.22
SBM C1	-0.02	**-0.61**	-0.30	-0.11
SBM C2	-0.22	0.10	-0.03	0.13

C1 = Sampling Cruise 1.
C2 = Sampling Cruise 2.

There were no significant correlations between community parameters and TOC, TPH, or SBF concentrations in sediments at MP 288, the least heavily contaminated of the primary continental shelf discharge sites (Table 4-23). There was a relationship between community parameters and sediment grain size and concentrations of Ba and Mn in sediments. This relationship probably is attributable to the high concentration of coarse sandy sediments at some far-field stations. This analysis indicates that there was minimal detectable effect of drilling discharges on the benthic community at MP 288.

Table 4-23. Statistical relationships (Spearman's ρ correlation) between sediment physical/chemical parameters (mean grain size, barium [Ba], manganese [Mn], total organic carbon [TOC], total petroleum hydrocarbons [TPH], and synthetic based mud [SBM] base chemical concentration) and benthic community parameters at Main Pass 288. Significant correlations (ρ<0.05) are highlighted.

Physical/Chemical Parameter	Spearman's ρ Correlation, Biological Parameters			
	Abundance	Diversity (H')	No. Taxa	Evenness (J')
Grain Size Comb.	**0.47**	**0.45**	**0.51**	-0.20
Grain Size C1	0.18	0.11	0.12	-0.04
Grain Size C2	**0.80**	**0.75**	**0.84**	-0.38
Ba Comb.	**0.40**	**0.38**	**0.40**	-0.12
Ba C1	0.25	0.03	-0.01	0.04
Ba C2	0.19	0.50	0.38	0.06
Mn Comb.	**-0.37**	-0.21	-0.27	0.09
Mn C1	-0.44	-0.39	-0.44	-0.03
Mn C2	0.16	0.16	0.33	-0.02
TOC Comb	0.25	0.03	0.09	-0.21
TOC C1	0.04	<0.01	-0.08	0.08
TOC C2	-0.21	-0.24	-0.45	-0.06
TPH Comb.	-0.19	-0.31	-0.33	0.03
TPH C1	-0.22	-0.25	-0.38	0.16
TPH C2	-0.06	-0.40	-0.07	-0.30
SBM Comb.	-0.30	-0.11	-0.14	0.24
SBM C1	-0.20	0.04	0.19	-0.04
SBM C2	-0.15	0.27	-0.21	0.39

C1 = Sampling Cruise 1.
C2 = Sampling Cruise 2.

There were even fewer significant correlations between sediment physical/chemical parameters and benthic community structure at MP 299 than at MP 288 (Table 4-24). Concentrations of Mn were positively correlated with the number of benthic taxa. The apparent lack of correlation between sediment physical/chemical parameters and benthic community parameters at MP 299 may be due in part to insufficient accumulation of drilling discharged solids to cause disturbance or to area-wide disturbance of sediments caused by the long history of drilling at the site. However, benthic community parameters were similar in sediments at MP 299 and MP 288 where many fewer wells were drilled, suggesting that if area-wide disturbance has occurred, it probably was caused more by influence of the Mississippi River outflow than by drilling discharges.

Table 4-24. Statistical relationships (Spearman's ρ correlation) between sediment physical/chemical parameters (mean grain size, barium [Ba], manganese [Mn], total organic carbon [TOC], total petroleum hydrocarbons [TPH], and synthetic based mud [SBM] base chemical concentration) and benthic community parameters at Main Pass 299. Significant correlations ($\rho<0.05$) are highlighted.

Physical/Chemical Parameter	Spearman's ρ Correlation, Biological Parameters			
	Abundance	Diversity (H')	No. Taxa	Evenness (J')
Grain Size Comb.	0.21	0.11	0.18	-0.12
Grain Size C1	-0.18	-0.13	-0.08	0.07
Grain Size C2	0.16	0.26	0.16	-0.07
Ba Comb.	0.01	0.15	0.12	0.07
Ba C1	0.21	0.17	0.22	0.01
Ba C2	-0.18	-0.22	-0.20	0.14
Mn Comb.	0.34	0.34	**0.40**	0.09
Mn C1	0.35	0.02	0.20	-0.37
Mn C2	0.41	0.46	0.57	0.02
TOC Comb	-0.20	-0.28	-0.32	-0.12
TOC C1	-0.19	-0.27	-0.29	0.08
TOC C2	-0.42	-0.33	-0.48	0.19
TPH Comb.	0.05	0.14	0.17	0.15
TPH C1	-0.28	-0.31	-0.27	0.18
TPH C2	-0.24	0.04	<0.01	0.22
SBM Comb.	0.17	-0.10	-0.02	-0.16
SBM C1	0.33	0.13	0.18	-0.40
SBM C2	0.20	0.11	0.15	-0.10

C1 = Sampling Cruise 1.
C2 = Sampling Cruise 2.

There was a general trend for abundance of benthic fauna at near-field and mid-field locations to increase between the first and second Sampling Cruises. Because sampling sites were randomly selected for each survey, some of this change may have been caused by the different locations within the near-field and mid-field zones where sediment samples were collected. The trend toward increasing abundance of benthic fauna also could indicate recovery of benthic communities from earlier disturbance by deposition of drilling solids.

These results are consistent with the results of other studies of benthic ecological impacts of SBM cuttings discharges (Neff et al., 2000). The most comprehensive field survey published to date on the biological impacts of SBM cuttings discharges was undertaken for a well drilled with an ester based mud in the Dutch sector of the North Sea (Daan et al., 1996; Limia, 1996). Water depth at the drilling location was approximately 30 m. The drilling program for the well produced a discharge of 248.7 metric tons of WBM and 477.2 tons of ester SBM (containing 180.5 tons of esters). If it is assumed that the SBM and WBM had a density of about 1.25 (51% of the mass of the SBM was barite), the volume of SBM discharged was approximately 2,400 bbl. The WBM was heavier than the SBM (85% of the mass of the WBM was barite), so the volume discharged probably was slightly more than 1,000 bbl.

Four months after completion of drilling, sediments within 75 m of the rig site were anaerobic and smelled of hydrogen sulfide. The total abundance of benthic fauna was low at stations within 200 m of the rig site and increased with distance farther away. Abundance of the opportunistic polychaete worm *Capitella capitata* was high at stations 75 and 125 m from the drillsite; *Capitella* was absent from stations more than 200 m away. No effects on species richness were observed at stations between 500 and 3,000 m from the rig. Eleven months after drilling, surficial sediments out to 200 m from the rig site still were more or less anaerobic. Abundance of individuals and species still was low at the 75-m stations but had risen to levels higher than in the pre-drilling survey at greater distances from the discharges. Although effects still were evident 1 year after drilling, there was definite evidence of ecosystem recovery, particularly at stations more than 75 m from the discharge.

Borja et al. (2003) used a biotic index (BI) to evaluate benthic habitat quality near the discharge site monitored by Daan et al. (1996). The BI is based on the relative proportions of different benthic faunal groups, with different sensitivities to physical and chemical disturbance, in sediment samples; it ranges from 0 (normal community structure) to 7 (essentially azoic) (Borja et al., 2000). The value of BI increased at stations within 200 m of the discharges after drilling. This was caused by a decrease in numbers and species of sensitive animals and an increase in numbers of a few opportunistic species. In the year after drill cuttings discharges, BI decreased at most stations toward baseline (undisturbed) values.

Similar results were obtained in a monitoring study in Brunei (Sayle et al., 2002). Ester based mud cuttings were less harmful to the benthos than OBM cuttings but more harmful than WBM cuttings discharges. The effects of ester based SBM cuttings and WBM cuttings were attributed to smothering and organic enrichment effects. The OBM cuttings were toxic. Effects of ester cuttings discharges were restricted to a small area of benthic environment near the discharge, whereas effects of WBM cuttings discharges were more widespread but less persistent. Ecosystem recovery time ranged from about 3 years for WBM cuttings-contaminated sediments to more than 13 years for OBM cuttings-contaminated sediments.

The physical and biological effects of SBM cuttings discharges were studied at a drillsite in 39 m of water in the northwestern Gulf of Mexico (Candler et al., 1995). Water based mud was used to drill the first 3,400 ft of the well. A PAO SBM was used to drill from 3,400 to 8,050 ft. A total of 441 bbl of cuttings (approximately 200 metric tons) and 354 bbl of associated SBM, containing about 45 metric tons of PAO drilling mud, was discharged.

A total of 106 taxa of benthic invertebrates was identified in sediments near the drillsite 2 years after completion of drilling. The benthic community structure, though not necessarily species composition, was typical of those in shallow waters of the western Gulf of Mexico and included 42.5% polychaetes, 24.5% crustaceans, 19.8% mollusks, and 5% echinoderms. The benthic community apparently was unaffected by the drilling discharges (2 years after drilling) at all stations east and north of the drillsite and at stations more than 50 m south and west of the drillsite (Table 4-25). At three of the four stations 25 and 50 m south and west of the drillsite, sediments contained 3,620 to 19,110 mg/kg TPH and 8,415 to 32,634 mg/kg Ba and had reduced numbers or taxa and individuals of benthic fauna. Sediments containing more than about 3,000 mg/kg TPH had depauperate benthic communities. Species diversity was lower in sediments at these stations than at the other stations. Community evenness was about the same at all stations, indicating that effects on benthic fauna were evenly distributed among species of benthic fauna.

Table 4-25. Poly alpha olefin (PAO) concentrations, barium concentrations, and benthic infaunal parameters in sediments near a drillsite in 39 m of water 2 years after discharge of 354 bbl of PAO synthetic based fluid (From: Candler et al., 1995).

Parameter	3 Affected Stations	13 Remaining Stations	4 Reference Stations
PAO (mg/kg TPH)	3,620 – 19,110	ND – 1,080	ND – 46
Barium (mg/kg)	8,415 – 32,634	990 – 4,024	822 – 901
Number of taxa/0.2 m^2	8 – 22	26 – 38	27 – 32
Number of individuals/0.2 m^2	17 – 141	162 – 280	152 – 219
Shannon-Weiner diversity	1.69 – 2.25	2.32 – 3.15	2.49 – 2.86
Evenness	0.73 – 0.92	0.65 – 0.87	0.73 – 0.82

ND = Not detected.

Impacts of SBF cuttings discharges on deeper-water continental slope benthic ecosystems are less well known. The only study to date that included some observations of bottom fauna near a deepwater discharge site was at the Pompano II platform in 565 m of water (Fechhelm et al., 1999). As discussed above, discharges from the rig included 7,700 bbl of WBM cuttings, 5,150 bbl of SBM cuttings, and an estimated 7,695 bbl of a mixed 90% LAO/10% ester SBM. Concentrations of SBF reached a maximum of 198,000 mg/kg in surficial sediments (0 to 2 cm) 75 m northeast of the drilling template. In most areas, drill cuttings accumulated as a thin layer on bottom sediments.

A total of 2,100 macrofaunal animals was collected; polychaetes were most abundant, followed by gastropod mollusks. The abundance of benthic fauna was significantly higher in sediments along the northeastern transect (highest SBF concentrations in sediment) than in sediments along the southwestern transect (Table 4-26). There were larger numbers of individuals but a smaller number of taxa of benthic fauna in the more heavily contaminated sediments northeast of the template than in cleaner sediments southwest of the template, suggesting an organic enrichment effect. Much of the difference in abundance of benthic fauna in sediments along the northeast transect than along the southwest transect was due to polychaetes, which were present in sediments from the northeast transect at a density of more than 85,000/m^2, compared to a density of 16,600/m^2 in sediments from the southwest transect. These polychaete abundances were higher than any observed in the present investigation and probably represent the effects of organic enrichment of sediments, favoring colonization by large numbers of opportunist polychaetes. However, copepods, nematodes, polychaetes, and gastropods all were more abundant in sediments along the northeast transect than in sediments along the southwest transect. Although concentrations of SBF in some sediments were high, effects on benthic fauna were minor.

Table 4-26. Concentrations of linear alpha olefin/ester synthetic based fluid (SBF), benthic macrofauna, and demersal megafauna (mostly fish) along four transects extending to 90 m from a drilling template in 565 m of water in the Gulf of Mexico (From: Fechhelm et al., 1999).

Parameter	Transect Direction from Template			
	NE	SE	SW	NW
Mean SBF, 0–2 cm (mg/kg)	49,000	3,000	2,000	6,000
Mean SBF, 2–5 cm (mg/kg)	30,000	3,000	1,000	6,000
No. megafauna observed	18	15	7	22
No. macrofauna	1,761	---	339	---
No. macrofaunal taxa	8	---	12	---
Macrofauna density (no/cm^2)	15.7	---	2.3	---

Results of these studies suggest that benthic biological effects of SBM cuttings discharges are caused in large part by sediment organic enrichment resulting from accumulation of biodegradable SBM organic chemicals in or on the sediments. Schaanning et al. (1996) performed simulated seabed studies and showed that a thin layer of SBM base chemical or mineral oil (the continuous phase of OBM) usually caused small decreases in species abundance and diversity in the underlying sediments (Table 4-27). Benthic community changes observed in near-field and mid-field sediments in the present investigations were less than those observed by Schaanning et al. (1996) in benthic mesocosms, indicating that insufficient organic matter from SBM cuttings discharges had accumulated on the bottom near discharge sites to cause detectable area-wide changes in benthic community structure.

Table 4-27. Effects of synthetic based mud (SBM) cuttings layered (1.4 to 1.8 mm) on natural sediments in NIVA simulated seabed chambers on characteristics of benthic communities after 187 days (From: Schaanning et al., 1996).

SBM Cuttings	No. Species	No. Individuals	Diversity (H')	Diversity (ES_{100})
Control	36 – 39	281 – 856	2.97 – 3.65	17.74 – 22.94
Ester I	14 – 35	283 – 809	2.20 – 2.31	11.12 – 13.66
Ester II	4 – 6	32 – 83	0.87 – 1.90	---
IO	30 – 36	588 – 647	2.70 – 3.33	13.89 – 19.71
LAO	22 – 26	308 – 338	2.88 – 3.16	14.33 – 16.44
Mineral oil	18 – 20	226 – 309	2.51	13.18 – 13.65

The harmful effects of the SBF cuttings on benthic fauna in the mesocosms, as measured by diversity indices, were correlated to sediment Eh, an indication of the redox state of the sediments (Schaanning et al., 1996) (Figure 4-18). Sediments with an Eh approaching 0 mV are reducing and hypoxic. The lowest Eh values were produced by the esters that are highly biodegradable. The other SBM base chemicals and mineral oil biodegrade slowly and did not markedly decrease sediment Eh. Thus, it is likely that, in these mesocosm tests, microbial degradation of the highly biodegradable esters consumed sediment oxygen more rapidly than it could be replenished by diffusion from the overlying water, causing sediment hypoxia.

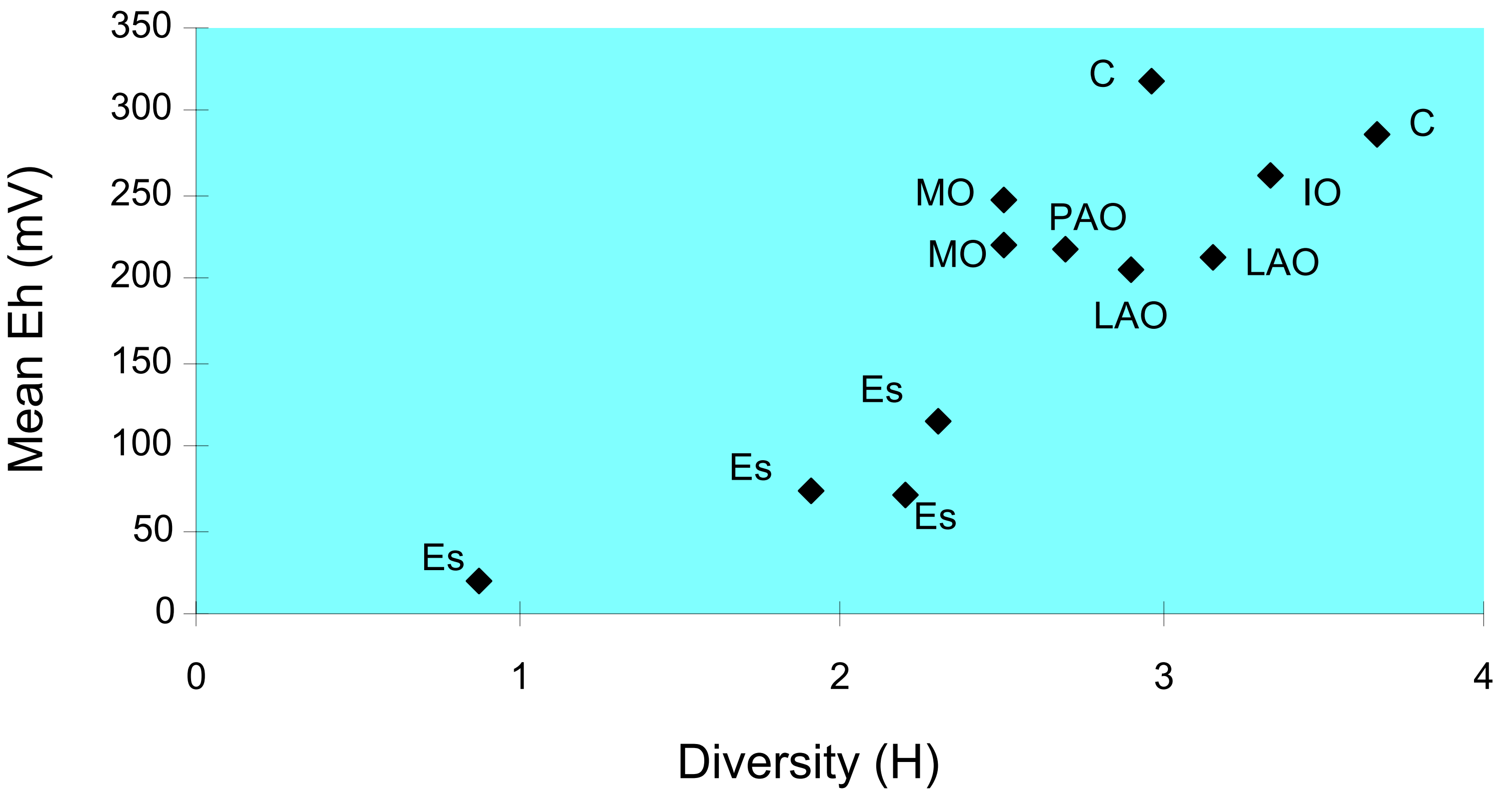


Figure 4-18. Relationship between redox potential and diversity for NIVA seabed simulation studies (C=contro; MO=mineral oil; Es=ester; PAO, IO, LAO = olefins) (From: Schaanning et al., 1996).

Sediment bacteria degraded the less biodegradable olefins and mineral oil more slowly, preventing depletion of sediment oxygen. In the present investigation, RPD depth was at or near the sediment surface at some near-field and mid-field sampling sites; however, distribution of sediment hypoxia was very patchy, probably due to the patchy distribution of clumps of SBM cuttings solids, allowing habitation of less contaminated patches by normal low-DO-intolerant benthic fauna.

Organic enrichment of sediments often produces a reduction in the number of species and an increase in the abundance of a few stress-tolerant species (Pearson and Rosenberg, 1978). This was observed in the NIVA simulated seabed chambers dosed with ester SBM cuttings (Schaanning et al., 1996). In the Petrofree chambers, most species of benthic fauna were eliminated or their numbers were greatly reduced compared to controls. The abundance of a pollution-tolerant polychaete increased; it represented more than half the individuals in the Petrofree chambers. Several of the species that disappeared from the sediments are known to be intolerant of low oxygen concentrations in sediment pore water.

Similar observations were made in the present investigation. *Capitella capitata*, an opportunistic polychaete, was not found in far-field samples on either Sampling Cruise. Abundance of *Capitella* in near-field sediments decreased between Sampling Cruises 1 and 2 at MP 299 and EI 346. It represented 8.1% of the benthic fauna at mid-field stations at the most heavily contaminated site, EI 346, at the time of Sampling Cruise 1 but was not present at the time of Sampling Cruise 2. It was never abundant at near-field and mid-field sediments at MP 288. These results indicate that there was patchy organic enrichment of some near-field and mid-field sediments, with some benthic recovery in the year between Sampling Cruises.

There were changes in the activity of oxidative enzymes (glutathione reductase and catalase) in the tissues of another polychaete worm, *Hediste (Nereis) diversicolor,* following exposure to SBM cuttings (Schaanning et al., 1996). The enzyme activity responses indicated that the worms exposed to Anco Green (ester), LAO, and IO cuttings were experiencing oxidative stress, probably resulting from a decrease in oxygen concentration in the sediments. The worms did not survive exposure to Petrofree (ester). Benthic invertebrates in the NIVA chambers were adversely affected by a reduction in sediment oxygen concentration caused by organic loading of the sediments with SBF base chemicals, not by the toxicity of the chemicals. *Capitella* is an opportunistic species complex that is tolerant to sediment organic enrichment and hypoxia, explaining its abundance at some near-field and mid-field locations.

4.6.3 The Sediment Quality Triad for SBM-Contaminated Sediments

4.6.3.1 Definition of the Sediment Quality Triad. Environmental assessments of effects of human activities on the offshore benthic environment often focus on collection of chemical and physical data to characterize sediment disturbance and the magnitude of sediment contamination. These data are very valuable for characterizing sediment disturbance but are inadequate for characterizing impacts of human activities on marine organisms and ecosystems (Long and Chapman, 1985). Assessments also are needed on the toxicity of the sediments and on benthic community structure and function. The sediment quality triad was proposed as an effective way to integrate chemistry, toxicology, and benthic ecology data to draw technically sound conclusions about the effects of a particular human activity on a local demersal/benthic ecosystem (Chapman and Long, 1983; Chapman et al., 1997). In the sediment quality triad, measures of sediment chemistry (contaminant concentrations), sediment toxicity, and benthic faunal community structure are integrated and compared to evaluate impacts of human activities on sediment quality.

Chapman et al. (1991) used the sediment quality triad approach to evaluate the impacts of discharges from a platform off the Texas coast on the local benthic environment. Six wells were drilled with saltwater/gel spud WBM and chrome lignosulfonate WBM. Nearly 20,000 metric tons of drilling mud ingredients, including nearly 17,000 tons of barite, were used to drill the six wells.

Sediments from stations within a radius of 25 m of the central platform and a station adjacent to a remote wellhead platform contained elevated concentrations of several chemical contaminants and were toxic to marine organisms in laboratory sediment toxicity tests. Sediments at greater distances from the platform had lower levels of contamination and were not toxic. Benthic community structure was altered at the stations where sediments were toxic and most heavily contaminated.

The sediment quality triad analysis revealed that the four stations within 25 m of the central platform and the single station nearest a remote platform were different from the stations located farther from the platforms. Effects of the platform itself and waste discharges, including drilling muds, cuttings, produced water, and other wastes, were restricted to a small area of sediments immediately adjacent to the platform and were manifested as elevated contaminant concentrations and sediment toxicity but not marked alteration in the benthic faunal community. Thus, to the extent that water based drilling mud and cuttings discharges contributed to adverse environmental effects in sediments, the effects were very localized and minor.

4.6.3.2 Sediment Quality Triad for Sediments at Three Continental Shelf SBM Cuttings Discharge Sites. The data summarized and reviewed in Sections 4.2 through 4.5 were used as the basis for a screening sediment quality triad analysis. Benthic ecology data are available for only the three continental shelf sites, so the analysis was restricted to these locations. Two types of chemical/physical parameters were used: chemical indicators of the presence and concentration of SBM cuttings solids in sediments, and indicators of redox status of sediments. SBM concentrations were below the method detection limit at all far-field stations for the three continental shelf sites; therefore, ratio-to-reference (RTR) values for SBM could not be calculated. Total petroleum hydrocarbons concentration, which was correlated with SBM concentration, was used instead as an indication of SBM cuttings accumulations. As discussed earlier, integrated O_2 amount was the best indicator of apparent organic enrichment of sediments. Therefore, this parameter was used as a physical/chemical indicator of sediment hypoxia. Toxicity test results were expressed as mean fraction of amphipods that died during the test (% mortality). Benthic ecology data used for the triad included Shannon-Wiener diversity (H′) and Pielou's evenness (J′). The reciprocal mean values were used for parameters that were expected to decrease in value with increasing sediment disturbance.

Triad values for each parameter were expressed as the RTR value. In this exercise, RTR is defined as the ratio of the mean parameter value for the near-field or mid-field samples for each cruise treated separately to the mean parameter value for the far-field samples from the same site and cruise. Thus, RTR is the factorial difference between mean near-field or mid-field parameter values and far-field parameter values. Total scores were obtained by adding all RTR values for a zone, cruise, and site.

Because changes in different physical, chemical, and biological parameters do not have equal effects on sediment quality, the RTR for a particular parameter merely gives a semiquantitative indication of how the parameter differs from the parameter value at "high quality" reference locations. A large RTR value indicates a large deviation from the reference value but not necessarily a large adverse effect on sediment quality. Thus, RTR values should be used as qualitative indices of factors contributing to reduced sediment quality or for comparison of sediment quality at several locations.

Total RTR values were highest for near-field sediments at EI 346 for both Sampling Cruises 1 and 2 (Table 4-28). Highest RTR values for all parameters were for near-field stations at EI 346, followed by mid-field stations at EI 346 for both Sampling Cruises 1 and 2. Total RTR scores ranged from 9.4 in mid-field sediments at the time of Sampling Cruise 2 to 907 in near-field sediments at the time of Sampling Cruise 1. The near-field and, to a lesser extent, mid-field sediments at EI 346 were disturbed by discharges from the platform at that site.

Table 4-28. Sediment quality triad input values for near-field and mid-field sediments at three synthetic based mud cuttings discharge sites on the continental shelf of the Gulf of Mexico. All values are ratio-to-reference (RTR) values based on the ratio of mean parameter values for near-field and mid-field stations to far-field (reference) stations (Chapman et al., 1991) for Sampling Cruises 1 and 2. Reciprocal values were used where parameter value is expected to decrease with increasing level of disturbance.

Parameter	Sampling Cruise 1		Sampling Cruise 2	
	Near-Field	Mid-Field	Near-Field	Mid-Field
	Eugene Island 346			
% Sand	13.3	7.5	6.7	4.6
Barium	35.8	24.9	90.6	36.1
Total Petroleum Hydrocarbons	816	85	216	12.2
1/Integrated O_2	22	10	25	7
Toxicity (% Mortality)	14	7.7	5.3	3.4
Ecology (1/Diversity)	3.4	1.4	2.4	1.2
Ecology (1/Evenness)	2.9	1.2	1.8	1.2
Total Score	907	138	348	65.7
	Main Pass 288			
% Sand	0.44	0.23	0.23	0.25
Barium	21.0	4.9	3.0	4.1
Total Petroleum Hydrocarbons	27.3	4.2	3.6	7.6
1/Integrated O_2	3.3	1.7	3.3	3.3
Toxicity (% Mortality)	3.5	1.0	0.75	0.75
Ecology (1/Diversity)	1.0	1.0	1.1	1.1
Ecology (1/Evenness)	0.98	0.97	0.95	0.94
Total Score	57.5	14.0	12.9	18.0
	Main Pass 299			
% Sand	2.2	2.2	1.8	1.6
Barium	3.4	2.2	2.7	2.4
Total Petroleum Hydrocarbons	55.3	10.8	0.96	1.4
1/Integrated O_2	4.5	1.3	1.1	1.4
Toxicity (% Mortality)	8.7	0.67	1.1	1.3
Ecology (1/Diversity)	1.1	1.0	0.79	0.83
Ecology (1/Evenness)	1.0	1.0	0.95	0.94
Total Score	76.2	19.2	9.4	9.9

Highest RTR values were for TPH (and by correlation, for SBM) in near-field sediments at EI 346. Barium RTR values also were high for near-field and mid-field sediments at EI 346. Ratio-to-reference values were above 10 for TPH in near-field sediments at MP 288 and MP 299, mid-field sediments at MP 299, and Ba in near-field sediments at MP 288 at the time of Sampling Cruise 1. No other parameter RTR values were above 10 at the time of either Sampling Cruise. These results indicate that near-field and mid-field sediments at EI 346 and near-field sediments at MP 288 and MP 299 were contaminated with drill cuttings solids at the time of Sampling Cruise 1 and, to a lesser extent, at the time of Sampling Cruise 2.

Integrated O_2 RTR values were highest in the near-field and mid-field zones of EI 346 at the time of both Sampling Cruises. Integrated O_2 RTR values were slightly elevated in near-field sediments at MP 288 and MP 299 at the time of Sampling Cruise 1 but had returned to normal values (RTR ~ 1) at MP 299 at the time of Sampling Cruise 2. The integrated O_2 RTR value also was elevated in mid-field sediments at MP 288 at the time of Sampling Cruise 2. These results indicate the presence of sediment hypoxia in near-field sediments and, to a lesser extent, in mid-field sediments, probably caused by accumulation of biodegradable organic matter from drilling discharges.

Toxicity RTR values were elevated at near-field and mid-field stations at EI 346 at the time of both Sampling Cruises. However, RTR values for the two ecological parameters, diversity and evenness, were elevated only at near-field stations at the time of both Sampling Cruises. These values were only slightly elevated at mid-field stations. Thus, benthic communities in near-field sediments showed evidence of adverse effects of cuttings accumulations at the time of both Sampling Cruises. Mid-field sediments were less severely affected. Effects were less severe at the time of Sampling Cruise 2 than at the time of Sampling Cruise 1.

Near-field sediments MP 299 and MP 288 had slightly elevated toxicity RTR values (3.5 and 4.5) at the time of Sampling Cruise 1, but all other toxicity RTR values for these sites were near normal. Ratio-to-reference values for the two ecological parameters were near 1 (no effect) at both sites at the time of both Sampling Cruises, indicating that benthic communities were similar in all zones around both discharge sites. Thus, habitat quality at these two sites was not seriously degraded by a long history of discharges at these sites.

Ratio-to-reference values for all physical/chemical and toxicological/ecological parameters except Ba concentration were lower in mid-field than in near-field sediments and declined between Sampling Cruises 1 and 2 in near-and mid-field sediments at EI 346 (Figure 4-19). There was a nearly 10-fold decline in the near-field TPH RTR value between Sampling Cruises 1 and 2. There was a slight increase in the Ba RTR value between Sampling Cruises 1 and 2 in both near-field and mid-field sediments. Ratio-to-reference values for integrated O_2 and % sand declined between cruises.

The sediment toxicity RTR was lower in near-field than in mid-field sediments and declined between Sampling Cruises 1 and 2 at EI 346 (Figure 4-19). There also was a decline in the two ecological RTR values in the year between Sampling Cruises 1 and 2. These results indicate that sediment disturbance was greater in near-field sediments than in mid-field sediments and declined between Sampling Cruises. There was strong evidence of improvement of habitat quality (recovery) in both near-field and mid-field sediments at EI 346 in the year between Sampling Cruises, in terms of both physical/chemical parameters and toxicological/ecological parameters.

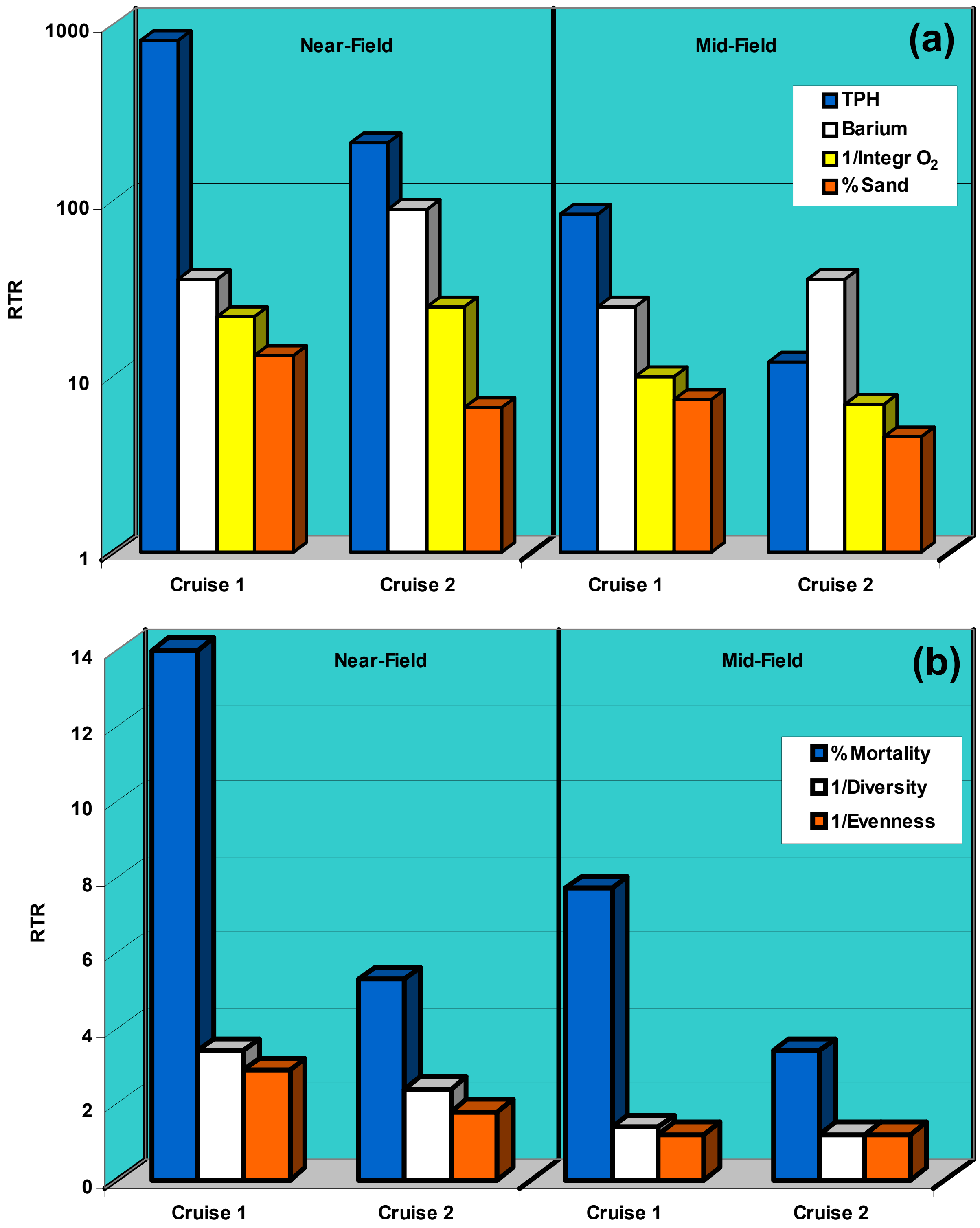


Figure 4-19. Ratio to reference (RTR) values for four physical/chemical parameters (a) and toxicological/ecological parameters (b) in near-field and mid-field sediments collected at Eugene Island 346 during Sampling Cruise 1 (May 2001) and Sampling Cruise 2 (May 2002). RTR is the ratio of the mean parameter value at the near-field or mid-field stations to the mean value at the far-field stations.

Ratio-to-reference values for TPH, Ba, and sediment toxicity were elevated in near-field sediments at MP 288 at the time of Sampling Cruise 1 (Figure 4-20). Other physical/chemical RTR values, except % sand, were slightly elevated in near-field and mid-field sediments at both sampling times. However, the toxicity RTR was normal (~1) at other times and zones, and the ecological RTR values were normal in near-field and mid-field sediments at the time of both Sampling Cruises. Thus, although some near-field sediments near the discharge site at MP 288 contained elevated concentrations of drilling solids ingredients and were slightly toxic, there was no evidence of disturbance to the local benthic communities.

The same pattern was evident at MP 299 (Figure 4-21). Although TPH and toxicity RTRs were elevated in near-field sediments at the time of Sampling Cruise 1, there was no evidence of disturbed benthic communities in near-field and mid-field sediments at the time of either Sampling Cruises 1 or 2.

The sediment quality triad clearly shows the difference in benthic habitat quality at near-field and mid-field stations at the three drilling waste discharge sites. However, caution is required in evaluating the individual RTR values for chemical/physical parameters for clues to the causes of lower sediment quality at EI 346 than at MP 299 and MP 288. Chemical/physical parameters were not weighted for their relative influence on sediment quality. Large RTR values for some parameters may have little effect on sediment toxicity or benthic ecology (e.g., Ba). Other parameters may cause serious biological disturbance, even at low RTR values (e.g., integrated O_2 amount).

Much of the differences in chemical/physical RTR values among near-field stations at EI 346, MP 299, and MP 288 are due to TPH concentration. If this parameter is removed, most of the remaining difference is due to Ba concentration. However, both of these parameters tend to co-vary with the parameter describing sediment redox conditions (integrated O_2 amount). Thus, it is unclear if the elevated “toxicity” and depressed benthic community structure in sediments at EI 346, compared to MP 299 and MP 288, is caused by direct toxicity of SBM base chemical and Ba (or to other organic chemicals included in TPH that co-vary with them), or to secondary effects of SBM cuttings-induced organic enrichment of the sediments.

Barite has a very low acute and chronic toxicity to marine organisms in laboratory toxicity tests and adversely affects benthic communities only when it is present in sediments at very high concentrations (several percent) (Neff, 1987; Neff and Sauer, 1995). As discussed above, SBM base chemicals and whole SBM have a relatively low toxicity to benthic marine animals (Neff et al., 2000). However, high barite and SBM concentrations may combine with sediment hypoxia and associated increases in sulfide and ammonia concentrations to degrade sediment quality, leading to alterations in benthic community structure and function. Near platforms where large amounts of SBM cuttings solids accumulate in sediments, the distribution of contaminants is extremely heterogeneous and most of the contaminants accumulate close to the discharge site. Their concentrations tend to decrease with time, through burial, bed transport, and biodegradation. Thus, where adverse effects in benthic communities are observed, they are of limited areal and temporal extent.

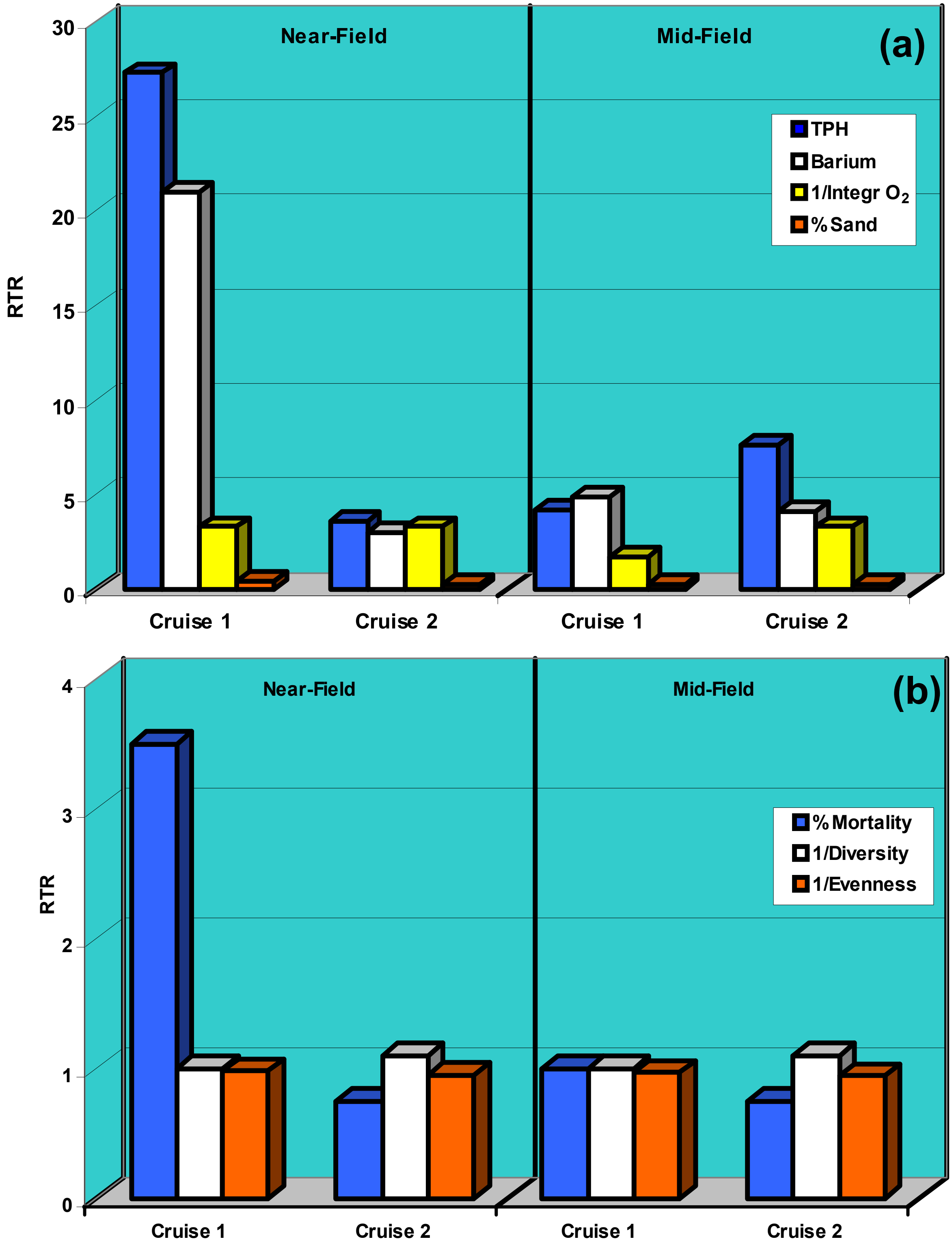


Figure 4-20. Ratio to reference (RTR) values for four physical/chemical parameters (a) and toxicological/ecological parameters (b) in near-field and mid-field sediments collected at Main Pass 288 during Sampling Cruise 1 (May 2001) and Sampling Cruise 2 (May 2002). RTR is the ratio of the mean parameter value at the near-field or mid-field stations to the mean value at the far-field stations.

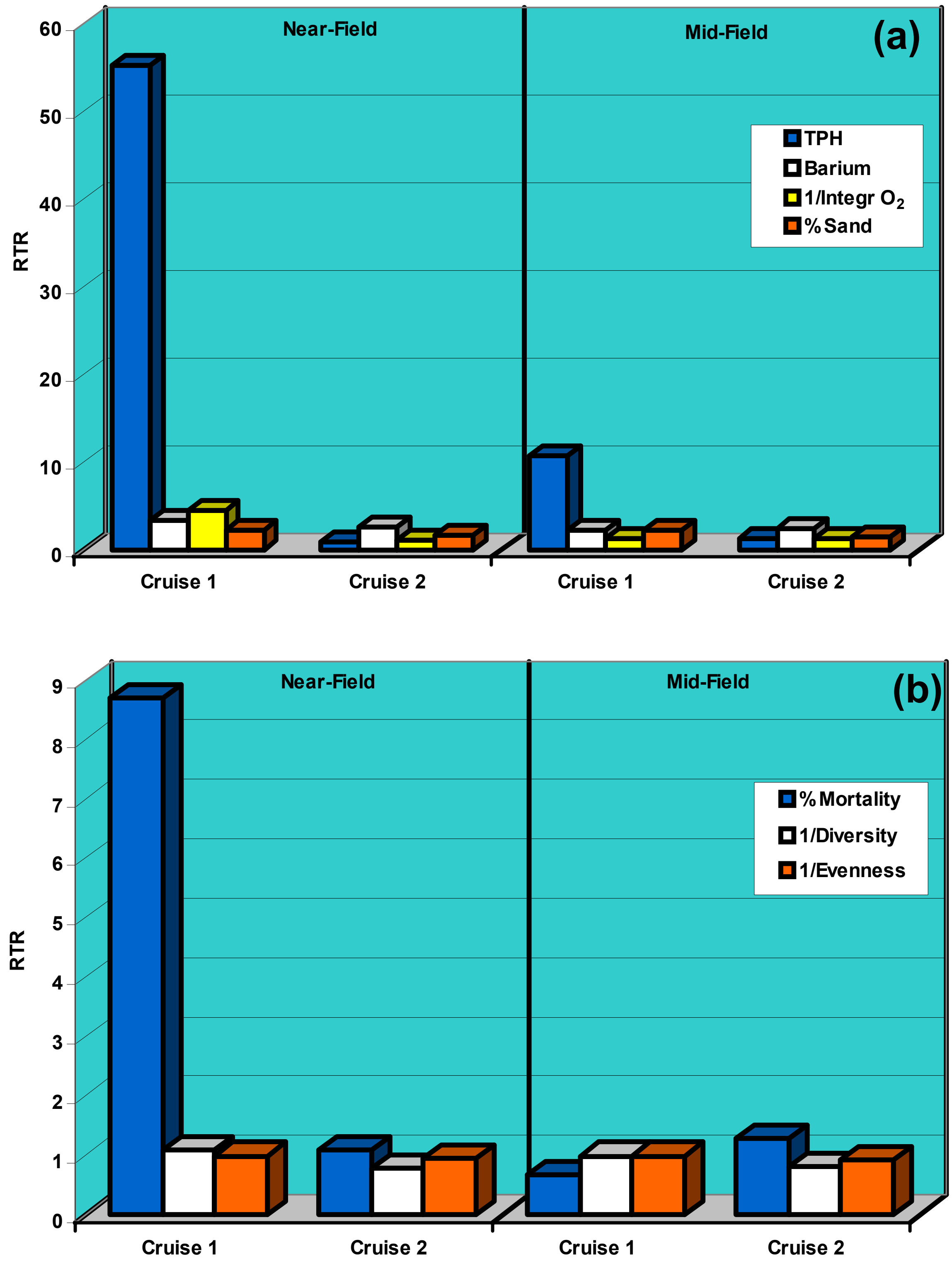


Figure 4-21. Ratio to reference (RTR) values for four physical/chemical parameters (a) and toxicological/ecological parameters (b) in near-field and mid-field sediments collected at Main Pass 299 during Sampling Cruise 1 (May 2001) and Sampling Cruise 2 (May 2002). RTR is the ratio of the mean parameter value at the near-field or mid-field stations to the mean value at the far-field stations.

4.6.4 Summary of Biological Effects of SBM Cuttings in Sediments

The main environmental concern resulting from discharge of SBM cuttings to shelf and slope waters of the Gulf of Mexico is that the cuttings solids may accumulate on the seafloor and adversely affect the benthic communities living there. As discussed above, adverse effects on benthic communities may occur as a result of the toxicity of SBM cuttings ingredients, organic enrichment of sediments from biodegradation of organic matter in the SBM cuttings, direct smothering of benthic fauna by the accumulation of cuttings solids on the seafloor, and alteration of sediment texture and physical/chemical properties, rendering the sediments less suitable for some species and more suitable for others.

All far-field sediment samples and most mid-field and near-field sediment samples were not toxic in laboratory tests with benthic amphipods. Mean toxicity of near-field sediments was significantly greater than mean toxicity of far-field sediments at EI 346, GC 112, and EW 963. Some mid-field sediments at EI 346 and GC112 also were toxic. Most sediments from the other three discharge sites were not toxic. Thus, sediment toxicity was nearly completely restricted to a zone within a 100-m radius of the discharge site. At the sites where sediment toxicity was observed, toxicity varied widely among replicate sediment samples from near-field and mid-field zones and from the two Sampling Cruises. These results indicate that the disturbance-causing agent(s) had a patchy distribution, even in near-field sediments at the most severely disturbed site (EI 346). This is a strong indication that the drilling discharge solids did not form a discrete "cuttings pile," as has been observed in the North Sea (Hartley et al., 2003).

Sediments containing more than about 700 to 1,000 mg/kg SBM base chemical and more than about 10,000 mg/kg Ba often, but not always, were toxic to amphipods. Thus, sediment toxicity probably was a direct or indirect effect of accumulation of drilling waste solids in the sediments.

When SBM base chemical concentrations in sediments exceed about 1,000 mg/kg, SBM toxicity may contribute to effects of SBM cuttings deposition on benthic communities (Neff et al., 2000). Concentrations of linear paraffin SBM above about 500 mg/kg in sediments near drillsites in the UK Sector of the North Sea were associated with decreases in abundance and diversity of benthic fauna (Neff et al., 2000). Sediments containing more than about 3,000 mg/kg of PAO (measured as TPH) near a drillsite in the Gulf of Mexico supported only a depauperate benthic community (Candler et al., 1995). Esters are less toxic than IO, LAO, and PAO to benthic fauna (Neff et al., 2000) and probably do not cause direct toxicity even when they accumulate to high concentrations in sediments.

SBM base chemicals in sediments seem to exert their adverse effects on benthic communities indirectly by organic enrichment and to a lesser extent by direct chemical toxicity. Organic enrichment appears to be the main mechanism of adverse impact of OBM and SBM cuttings deposition on benthic communities near offshore platforms in the North Sea (Hartley et al., 2003). Field studies of OBM cuttings discharges have indicated that sediments may become anaerobic if they contain 1,000 mg/kg or more of mineral oil (Vik et al., 1996a). Biodegradability of most SBM is greater than that of diesel fuel or mineral oils (Table 4-29). The mean half-life of the organic phase of OBM and SBM cuttings in NIVA simulated seabed studies ranged from 24 days for ester SBM cuttings to 311 days for mineral oil OBM cuttings; mean half-lives of LAO and IO cuttings were 54 and 104 days, respectively (Vik et al., 1996a,b). Esters (the most biodegradable SBM base chemical) may cause sediment anoxia at concentrations well below 1,000 mg/kg (Daan et al., 1996). Internal olefin and LAO SBM did not cause sediment anoxia in NIVA simulated seabed tests (Schaanning et al., 1996) but may in the field if concentrations in sediments exceed about 1,000 mg/kg. There was a good correlation in NIVA seabed simulation biodegradation studies with SBM between benthic faunal diversity and sediment redox potential (Schaanning et al., 1996) (Figure 4-18), suggesting that oxygen depletion by SBM biodegradation in sediments contributes to effects of SBM cuttings on benthic communities.

Table 4-29. Summary of results of five NIVA simulated seabed synthetic based mud (SBM) biodegradation studies. Test substances were SBM or mineral oil cuttings from offshore platforms. Biodegradation is expressed as percent disappearance from test chambers after 28 and 160 days. Regression analysis of loss-rate data were used to estimate the half-lives (days) of SBM in marine sediments (From: Vik et al., 1996a,b).

Mud/Cuttings Tested	Biodegradation (Disappearance) %		Mean Half-Life $t_{½}$ (Days)
	After 28 Days	After 160 Days	
Ester	46	97	24
Linear alpha olefin	38	38	54
Internal olefin	17	66	104
Acetal	12	39	200
Poly alpha olefin	11	43	207
Mineral oil	23	44	311

Effects of burial with SBM cuttings solids on continental shelf and slope benthic fauna are not known. Natural sedimentation rates in shelf and slope sediments at the discharge sites monitored in this study are quite uniform at 0.2 to 0.3 cm/year, with a decrease in deposition rate with distance from the Mississippi River outflow. Cuttings accumulations on the continental shelf and slope of the Gulf of Mexico usually are not higher than a few tens of centimeters and rarely reach 1 m or more, as sometimes occurs on the continental shelf of the North Sea (Hartley et al., 2003). Drill cuttings piles, primarily from discharge of OBM cuttings, near multiwell production platforms on the Norwegian continental shelf range in height from 0.3 to 16 m, in volume from 500 to 25,000 m^3, and in area from 1,500 to 16,000 m^2 (Kjeilen et al., 2001). By comparison, following drilling with SBM and discharge of SBM cuttings from a rig in 565 m of water in the northern Gulf of Mexico, there was a thin veneer of cuttings dispersed over much of the bottom in a patchy distribution near the drilling template (Gallaway et al., 1998; Fechhelm et al., 1999). Maximum cuttings accumulation appeared to be 0.2 to 0.25 m thick in some locations. The reason for the differences in cuttings pile heights and volumes in the North Sea and Gulf of Mexico is not fully understood but probably relates to the historic OBM, SBM, and WBM usage and discharge practices in the two geographic areas. The relatively shallow cuttings accumulations on Gulf of Mexico sediments probably have minimal burial effects on benthic communities.

Shallow water benthic animals are able to migrate upward through several centimeters of sediment following burial (Maurer et al., 1986). Small benthic fauna typical of deepwater sediments cannot migrate as far as larger macrofauna. Deep-sea benthic fauna, acclimated to sediments with a very low net deposition rate, probably cannot migrate vertically for more than a few centimeters. Because of the patchy distribution of SBM cuttings on the bottom, particularly in deeper waters, it is likely that burial effects will be highly localized and of short duration. Where cuttings accumulations are sufficient to bury and kill benthic fauna in continental shelf and slope habitats, the piles probably are recolonized rapidly by benthic fauna that are tolerant of organic enrichment of the sediments (Hartley et al., 2003).

In the present monitoring study, concentrations of drilling solids, as indicated by Ba and SBM base chemical concentrations, were elevated in most near-field and many mid-field sediments near six primary platforms where SBM drilling discharges had occurred from 1 to about 6 years before Sampling Cruise 1. However, benthic community structure was moderately affected, at the level of analysis used in this investigation, even at locations where large amounts of cuttings solids accumulated. The greatest alterations of community structure occurred in near-field and mid-field sediments at the most heavily contaminated site, EI 346.

The benthic community near the three continental shelf sites monitored was highly variable, indicating a patchy distribution of many taxa, particularly within about 250 m of the discharge sites. Benthic communities in near-field and mid-field sediments at EI 346, the most heavily contaminated continental shelf site, contained fewer individuals and had a low species diversity. Opportunistic species were among the numerical dominants at these stations. Sediments at the other two continental shelf discharge sites had only slightly disturbed benthic community structure that probably was affected mainly by sediment texture and proximity to the suspended sediment load from the Mississippi River. The benthic fauna at EI 346 included species with known tolerance to organic enrichment and low DO concentration. The altered benthic community structure in near-field and mid-field sediments at this site probably was caused in large part by organic enrichment, leading to sediment hypoxia, resulting from accumulation of biodegradable organic chemicals from SBM cuttings. There was substantial evidence of recovery of the benthic communities in near-field and mid-field sediments in the year between the two Sampling Cruises.

An important factor in the potential effects of SBM cuttings on benthic communities is the rate of ecosystem recovery following cessation of cuttings discharge. The rate of ecosystem recovery depends on the persistence of impact-causing biodegradable SBM cuttings ingredients in sediments, and the rate of recruitment to or recolonization of benthic habitats. SBM base chemical and TPH concentrations in near-field and mid-field sediments at EI 346 declined and average RPD depth and Eh increased in the year between Sampling Cruises 1 and 2. The sediment quality triad analysis indicated that there was an improvement in both the physical/chemical and toxicological/ecological habitat quality of sediments near EI 346 in the year between Sampling Cruises. Benthic ecosystem recovery probably began when concentrations of biodegradable organic chemicals in surficial sediments were reduced by dilution with clean sediments or biodegradation to levels low enough that oxygen could diffuse back into and increase in surficial sediment layers, allowing recolonization by low-DO-sensitive species.

No benthic ecological observations were made at the four continental slope sites and at the secondary continental shelf site. However, the range of concentrations of SBM base chemical and its change between the two Sampling Cruises were similar to those of the three primary continental shelf sites. Three patterns were observed. Little or no SBM base chemical was detected in sediments near VK 783, and there was no change over time. Sediments at MC 496 and EW 963 contained moderate concentrations of SBM base chemical (means of 2,000 to 4,000 mg/kg), and concentrations dropped sharply in the year between the Sampling Cruises. Sediments at GC 112 and ST 160 contained higher SBM base chemical concentrations at the time of Sampling Cruise 1 (means of about 5,000 and 12,000 mg/kg), and concentrations had dropped sharply by the time of Sampling Cruise 2. Only some near-field and mid-field sediments at GC 112 were toxic in laboratory toxicity tests and contained sufficient SBM base chemical during Sampling Cruise 2 to represent a risk of adverse effects on benthic communities. Sediments at all other sites showed strong evidence of a decrease in physical/chemical disturbance in the year between Sampling Cruises.

4.6.5 Conclusions

- Large accumulations of cuttings in North Sea-type cuttings piles were not observed near the eight multiwell discharge sites monitored in this investigation. However, there was evidence of accumulation of drill cuttings solids in sediments in all near-field (≤100 m) and some mid-field (100 to 250 m) zones around platforms. The distribution of cuttings solids in sediments was extremely patchy, but amounts tended to decrease sharply with distance from the discharge sites.
- Physical/chemical and toxicological/ecological alteration of the benthic environment was found, using several lines of evidence, primarily within 100 m of the center of the study site (near-field) at the six sites where significant "disturbance" (here practically defined as a SBM base chemical concentration ≥1,000 mg/kg) was observed for Sampling Cruise 1. Only a few mid-field (100 to 250 m) sediments showed evidence of such disturbance, and two sites showed little or no evidence of disturbance due to drilling discharges.
- The changes to benthic communities were not severe, even at the sites that were the most heavily contaminated with drill cuttings solids (SBM, TPH, and Ba) and probably were caused primarily by organic enrichment of sediments by deposition of biodegradable SBM cuttings ingredients and, to a lesser extent, by direct chemical toxicity of cuttings ingredients.
- The degree of physical/chemical and toxicological/ecological alteration observed in near-field and mid-field sediments (wherever it was observed) decreased in the year between Sampling Cruises.
- Loss of drill cuttings solids from sediments and improvement in oxygen status of sediments was slightly greater over time in continental shelf than in continental slope sediments, indicating that ecological recovery of deepwater sediments may be slower than that for shallow-water sediments.

Chapter 5
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