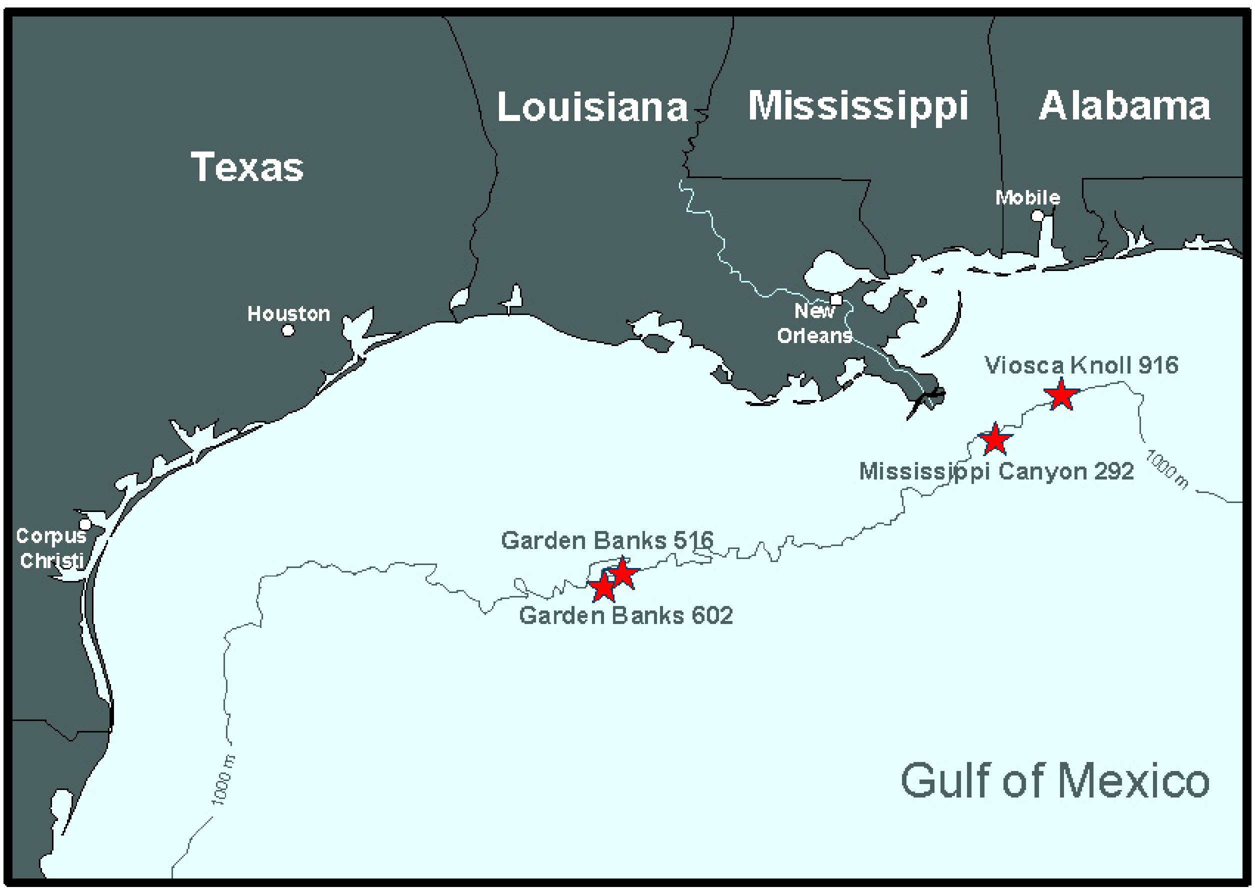
OCS Study
MMS 2006-044

Effects of Oil and Gas Exploration and Development at Selected Continental Slope Sites in the Gulf of Mexico

Volume I: Executive Summary



U.S. Department of the Interior
Minerals Management Service
Gulf of Mexico OCS Region

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MMS 2006-044

Effects of Oil and Gas Exploration and Development at Selected Continental Slope Sites in the Gulf of Mexico

Volume I: Executive Summary

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Prepared under MMS Contract
1435-01-00-CT-31034
by
Continental Shelf Associates, Inc.
759 Parkway Street
Jupiter, Florida 33477-9596

Published by

U.S. Department of the Interior
Minerals Management Service
Gulf of Mexico OCS Region

New Orleans
July 2006

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Citation

Suggested citation:

Continental Shelf Associates, Inc. 2006. Effects of Oil and Gas Exploration and Development at Selected Continental Slope Sites in the Gulf of Mexico. Volume I: Executive Summary. U.S. Department of the Interior, Minerals Management Service, Gulf of Mexico OCS Region, New Orleans, LA. OCS Study MMS 2006-044. 45 pp.

Acknowledgments

The program was conducted by a large, multidisciplinary team under the direction of Continental Shelf Associates, Inc. (CSA). David Gettleson was the program manager and Alan Hart served as deputy program manager and data manager. Neal Phillips was the scientific editor for the final report. Principal investigators are acknowledged at the head of each report chapter in Volume II (Technical Report).

We appreciate the assistance of MMS staff including Greg Boland (Contracting Officer's Technical Representative), Mary Boatman (Technical Performance Evaluation Committee), Debra Bridge (Contracting Officer), and Tom Ahlfeld. Jill Leale with the MMS Mapping & Automation Unit provided historical well data and georeferenced maps of well locations based on the MMS Technical Information Management System.

Drilling discharge data were kindly provided by Vince Cottone (ChevronTexaco) and Kent Satterlee, Ellen Polanski, and Jane Chady (Shell). Joe Smith (ExxonMobil) sent unpublished reports that were helpful in drilling discharge calculations.

The Scientific Review Board consisted of Andy Glickman (ChevronTexaco), Donald Harper (Texas A&M University at Galveston), and Jim Ray (Oceanic Environmental Solutions). Additional input in the study design was provided by Peter Arnold (independent consultant), Maynard Brandsma (Brandsma Engineering), and Woollcott Smith (Temple University).

We wish to recognize the following individuals for their roles in the field surveys:

- Jay Northcutt (C&C Technologies) – Project manager, geophysical cruises
- Tony George (C&C Technologies) – Manager, geophysical interpretation
- Scott Melancon – Party chief, geophysical Cruises 2A and 3A
- Tim MacEwan – Senior operator, geophysical Cruise 2A
- Scott McBay, David Aucoin, and Paige Melancon – Party chiefs, geophysical Cruise 1A
- Roger Fay (TDI-Brooks International, Inc.) – Chief scientist, chemical/biological cruises
- Lynwood Powell (CSA) – Field operations manager, chemical/biological Cruises 1B and 2B; navigation/post-plotting and geographic information system development
- Frank Johnson (CSA) – Field operations manager, chemical/biological Cruise 3B

Other cruise participants including staff from Continental Shelf Associates, Inc., C&C Technologies, TDI-Brooks International, Inc., Florida Institute of Technology, and Louisiana State University are too numerous to list individually, but their contributions are sincerely appreciated. We also wish to acknowledge Wayne Isphording (University of South Alabama) for conducting laboratory sediment grain size analyses.

The CSA document production team included Melody Powell (document production coordinator and technical editor), Heidi Glick (technical editor), Suzanne Short (graphics), and Debbie Raffel, Karen Stokesbury, Lynanne Rockhill, and Debbie Cannon (word processing).

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A field study was conducted between November 2000 and August 2002 to assess benthic impacts of drilling at four sites on the Gulf of Mexico continental slope (**Figure 1**). The study was conducted for the Minerals Management Service (MMS) by a team of scientists under the management of Continental Shelf Associates, Inc.

There have been few field measurements and observations around deepwater drillsites in the Gulf of Mexico (Fechhelm et al. 1999; Continental Shelf Associates, Inc. 2004). Studies on the continental shelf have documented impacts of water-based drilling fluids and cuttings on benthic organisms near wellsites. However, the applicability of this knowledge to the deepwater environment is uncertain (Carney 2001). In addition to environmental differences between continental slope and shelf communities, deepwater drilling more frequently uses synthetic-based drilling muds (SBMs) (Neff et al. 2000).

Specific objectives of this study were to document (1) drilling mud and cuttings accumulations; (2) physical modification/disturbance of the seabed due to anchors and their mooring systems; (3) debris accumulations; (4) physical/chemical modification of sediments; and (5) effects on benthic organisms. The findings from this study will assist the MMS in conducting environmental analyses, as well as in developing mitigative measures and regulations specifically tailored to deepwater operations.

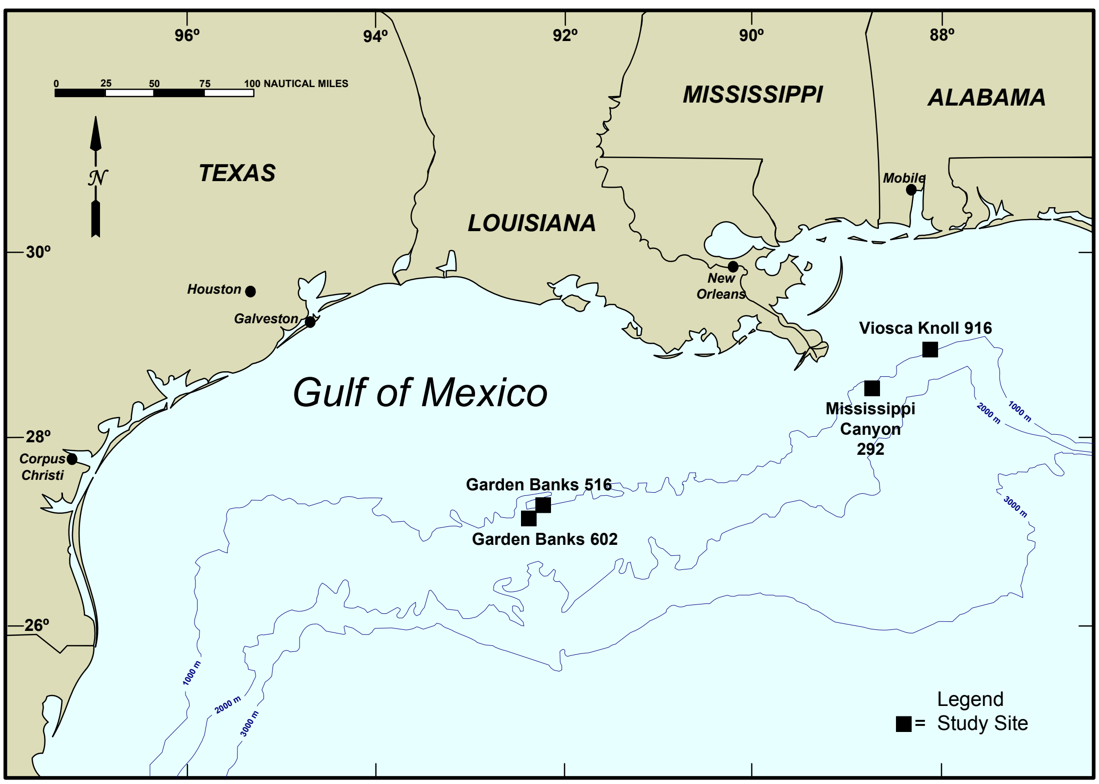

Figure 1. Study sites.

SITE SELECTION

Four study sites were selected within MMS offshore lease blocks on the northern Gulf of Mexico continental slope. These were Viosca Knoll Block 916 (VK 916), Garden Banks Block 516 (GB 516), Garden Banks Block 602 (GB 602), and Mississippi Canyon Block 292 (MC 292). Coordinates and water depths are provided in **Table 1**.

Site selection was based on MMS requirements and operators' drilling schedules. The MMS initially requested that two exploration sites and three post-development sites be selected (the number of post-development sites was ultimately reduced to two). The general requirements were as follows:

- Sites should be located in water depths greater than 1,000 m.
- Sites should be located at a similar water depth and be biologically and geologically similar.
- At least one exploration site and one post-development site must be located as far east as possible in the Central Planning Area (e.g., near DeSoto Canyon). Ideally, the other sites should be selected to represent the central Gulf and western Gulf.
- Sites drilled with an anchored drilling unit were preferred so that physical effects of anchoring could be studied.

For exploration sites, it was preferred that no previous drilling had occurred in the block. For post-development sites, all drilling activities were to have been completed prior to the first cruise.

To select potential exploration sites, the project team worked with the MMS and operators to identify Exploration Plans for wells in water depths of 1,000 to 1,500 m with a projected starting date in the fourth quarter of 2000. This range of water depths was selected because anchoring impacts were of interest and anchored rigs are infrequently used in deeper water. It also was assumed that the geology and biology of sites within this depth range in the Central and Western Planning Areas would be generally similar. This process ultimately resulted in the selection of VK 916, which fulfills the requirement for a site near the eastern edge of the Central Planning Area. No previous wells had been drilled in VK 916.

Table 1. Coordinates and water depths of study sites.

Site	Water Depth (m)	X/Y Coordinates[a]		Latitude/Longitude	
		X (ft)	Y (ft)	Latitude	Longitude
VK 916	1,125	1,356,696.75	10,564,161.84	29°06'24.31"N	87°53'19.48"W
GB 516	1,033	1,839,531.91	9,975,977.93	27°29'23.81"N	92°23'08.26"W
GB 602	1,125	1,815,625.00	9,934,903.00	27°22'38.02"N	92°27'35.79"W
MC 292	1,034	1,129,042.00	10,419,990.00	28°42'13.08"N	88°35'44.19"W

[a] X/Y coordinates are for Universal Transverse Mercator, North American Datum 1927, Zone 15 (Garden Banks Block 516 and Garden Banks Block 602) and Zone 16 (Mississippi Canyon Block 292 and Viosca Knoll Block 916).

Although a second exploration site with no previous drilling was sought, none was available where an operator was planning to drill within the time frame for the pre- and post-drilling cruises. Therefore, GB 516 in the Western Planning Area was selected as the best available site, even though previous exploration wells had been drilled in the block. This was essentially an exploration/development site that was sampled after exploration drilling and again after additional development wells were drilled during this study.

To select potential post-development sites, the project team worked with the MMS and operators to identify development/production sites in water depths greater than 1,000 m where drilling (with an anchored drilling rig) would be completed by September 2000. Five potential sites were identified, and ultimately two were selected. These were GB 602 (in the Western Planning Area) and MC 292 (which fulfills the requirement for a site near the eastern edge of the Central Planning Area).

NEAR-FIELD AND FAR-FIELD SITES

Each of the four study locations consisted of a single near-field site and six far-field ("reference") sites (**Figures 2** and **3**). The near-field sites were centered on well locations, and the far-field sites were 10 to 25 km away in the same water depths. Far-field sites were located using bathymetric maps provided by the MMS showing locations of previous wells in the vicinity of each near-field site. Although previous wellsites were avoided to the extent practicable, most far-field sites had at least one previous well drilled within 10 km.

For chemical and biological sampling, each near-field site was defined as a circle 500 m in radius around the drillsite(s). Each far-field site was a circle 204 m in radius (so that the total area of six far-field sites was equal to that of a single near-field site). For geophysical surveys, a broader radius of 3,000 m was used for the near-field sites (see *Study Methods*).

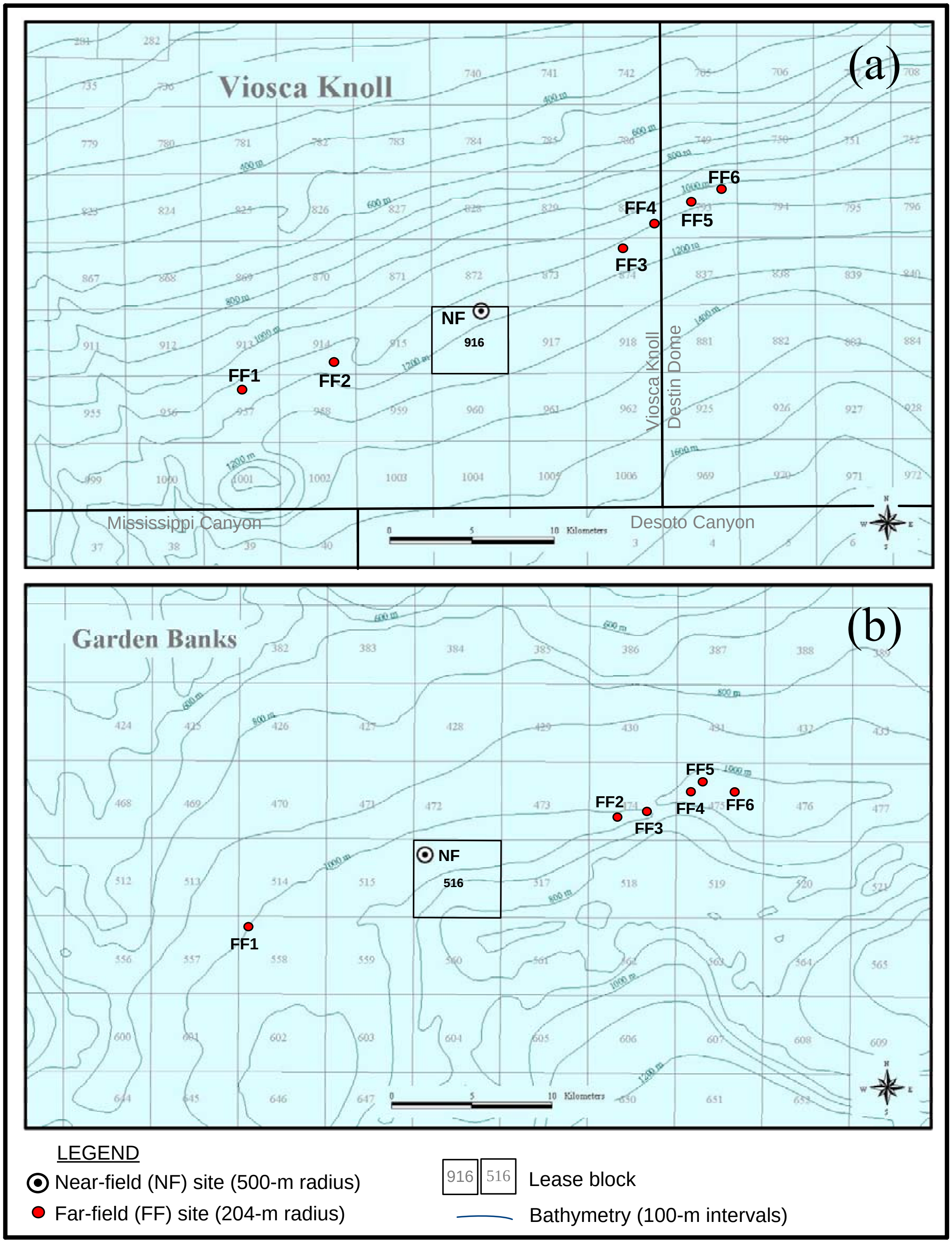

Figure 2. Location of near-field (NF) and far-field (FF) sites for (a) Viosca Knoll Block 916 and (b) Garden Banks Block 516.

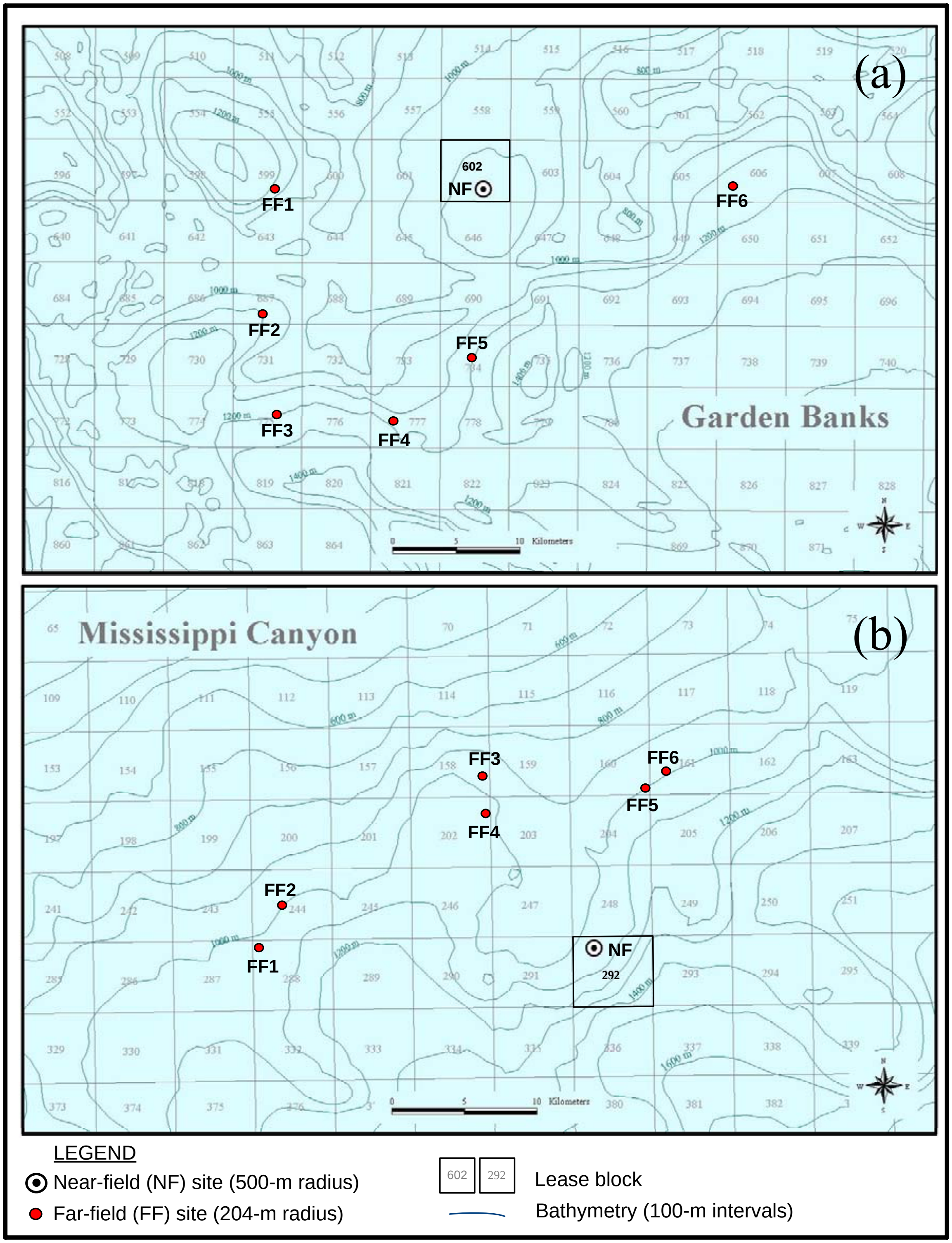

Figure 3. Location of near-field (NF) and far-field (FF) sites for (a) Garden Banks Block 602 and (b) Mississippi Canyon Block 292.

The four sites represent a range of drilling activities:

- VK 916 was an exploration site sampled before and after drilling of a single exploration well.
- GB 516 was an exploration/development site that was sampled once after exploration drilling and again after several development wells were drilled.
- GB 602 and MC 292 were post-development sites sampled once after several exploration and development wells had been drilled.

Anchored semisubmersible drilling rigs were used for all sites, with an anchor radius of about 2,400 to 3,000 m. Anchor locations were plotted, where possible, based on information in the operators' exploration plan or development plan submitted to the MMS. At the three development sites (GB 516, GB 602, and MC 292), subsea wellheads, manifolds, and flowlines had been installed on the seafloor, connecting to remote platforms.

Table 2 summarizes the number of wells and estimated drilling mud and cuttings discharges for each site. Both water-based muds (WBMs) and SBMs were used during drilling at all sites. However, at MC 292, most of the drilling was done with WBMs, and the quantity of SBM cuttings discharged was relatively small.

Table 2. Drilling summary for wells within each near-field site.

Site	Total No. Wells Within 500-m Radius	Estimated Seafloor Discharges (bbl)		Estimated Drilling Rig Discharges (bbl)			SBM Type
		WBM	WBM Cuttings	WBM	WBM Cuttings	SBM Cuttings	
Exploration							
VK 916	1	3,074	419	12,807	1,746	2,510	Syn-Teq (IO)
GB 516	2	6,501	887	14,731	2,009	1,904	Novaplus (IO) or Petrofree LE (LAO)
Development							
GB 516	7[a]	13,002	1,774	29,462	4,018	7,313	Novaplus (IO) and possibly Petrofree LE (LAO)
GB 602	7	23,946	3,266	91,301	12,450	28,339	Novadril (IO) or Petrofree ester (1 well); Novaplus (IO) or Petrofree LE (LAO) (all others)
MC 292	5	10,331	1,409	93,960	12,813	1,490	Novaplus (IO)

IO = internal olefin; LAO = linear-α-olefin; SBM = synthetic-based mud; WBM = water-based mud.
[a] Totals for GB 516 post-development include the two exploration wells listed above.

The general sequence of drilling discharges was similar for most wells. The first part of the well was drilled (jetted) using a water-based spud mud. During this time before the marine riser was set, there were no returns to the drilling rig, and all mud and cuttings were released at the seafloor. Spud muds consisting primarily of water and bentonite clay were used for this jetting process. The wellhead was then connected to a marine riser system that returned muds and cuttings to the drilling rig during the remainder of the drilling process. Subsequently, one or more well intervals were drilled using WBMs, with muds and cuttings discharged from the rig. Finally, in most cases, the mud system was switched to SBM for drilling of remaining well intervals. In some cases, there were bulk discharges of remaining WBMs prior to switching to SBM. During SBM intervals, SBM cuttings were discharged, but muds were retained (except for those adhering to cuttings). In addition, some quantities of SBMs were lost to the formation, lost during casing/cementing operations, or left in the wellbore for future sidetracks. Sidetracks at these sites were drilled primarily using SBMs. At MC 292, SBMs were used *only* during drilling of sidetracks.

VIOSCA KNOLL BLOCK 916 (EXPLORATION SITE)

Viosca Knoll Block 916 is located in the Central Planning Area, about 170 km SSE of Mobile, Alabama. Water depth at this site is approximately 1,125 m. A single exploration well (No. 1) was spudded by Shell on 27 November 2001 and reached total depth on 18 December 2001, when it was plugged and abandoned. Both WBM and SBM were used during drilling. The SBM used was Syn-Teq, an internal olefin isomer.

There were no previous wells in this block. However, several wells had been drilled within 10 km. The nearest were about 2.3 km NNW in VK 872 (**Figure 4**) and were drilled approximately 2 years before the start of this study. Any effects on the near-field site are assumed to be negligible in comparison with the single well drilled in VK 916 during this study.

GARDEN BANKS BLOCK 516 (EXPLORATION/DEVELOPMENT SITE)

Garden Banks Block 516 is located in the Western Planning Area, about 275 km SSE of Cameron, Louisiana. The water depth at this site is about 1,033 m. The prospect is named Serrano.

Three exploration wells had been drilled in GB 516 prior to this study, and five development wells were drilled during the study (**Figure 5**). Two of the previous wells (a straight well and one sidetrack) were at the center of the near-field site and were drilled in July-August 1999. The other was 1,150 m to the southeast and was drilled between September 1995 and July 1996. The five new wells included two additional sidetracks of the 1999 well at the center of the GB 516 near-field site, and one straight well and two sidetracks at a location about 50 m to the northeast of the site center.

Both WBMs and associated cuttings, as well as SBM cuttings, were discharged during drilling. Exploration and development plans included the option of using either of two SBMs, Novaplus (an internal olefin) or Petrofree LE (a linear-α-olefin). Novaplus was the only SBM used for the wells and sidetracks drilled in 2000-2001; it is not known which SBM was used on the 1999 wells.

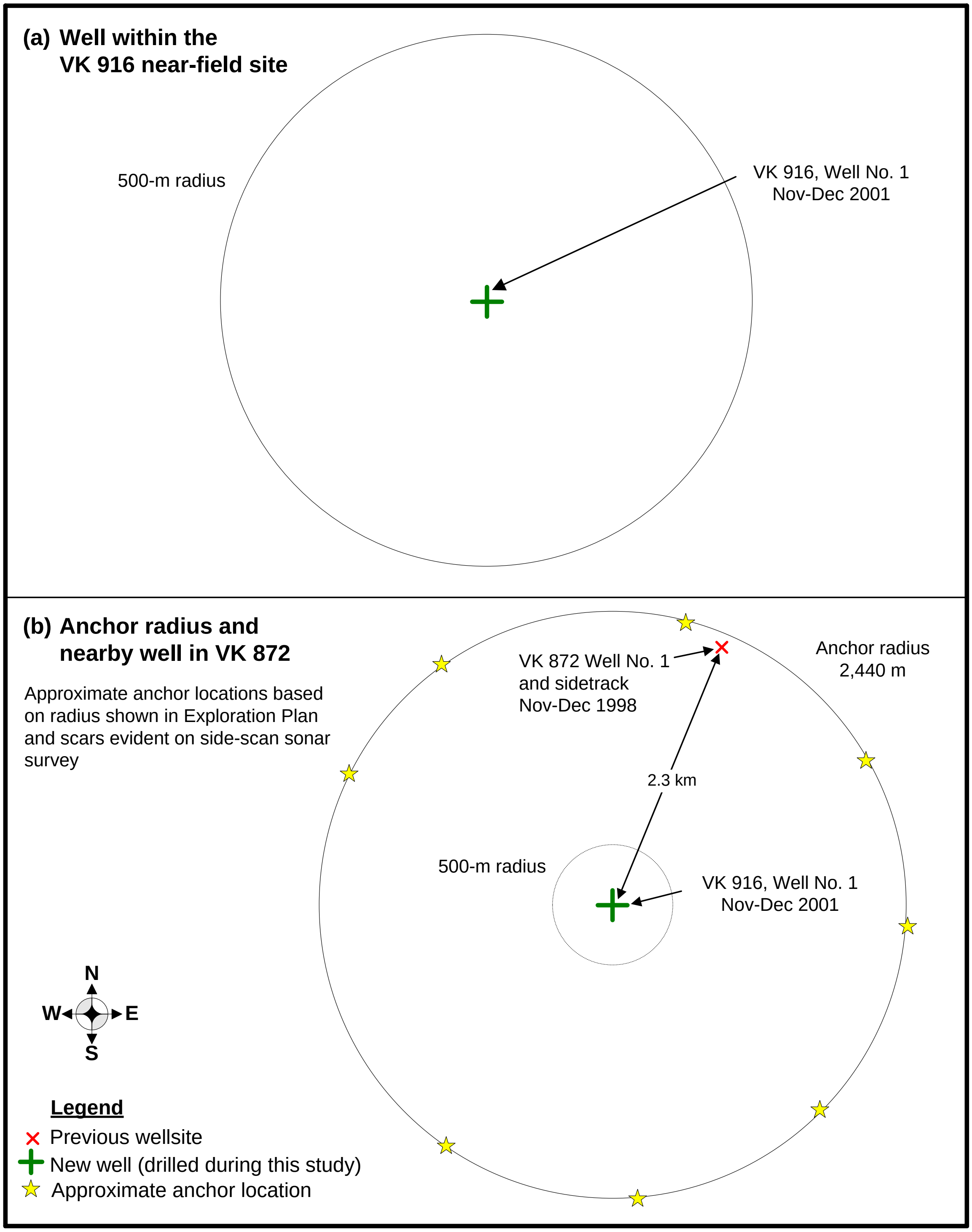

Figure 4. Well locations in and near the Viosca Knoll Block 916 near-field site.

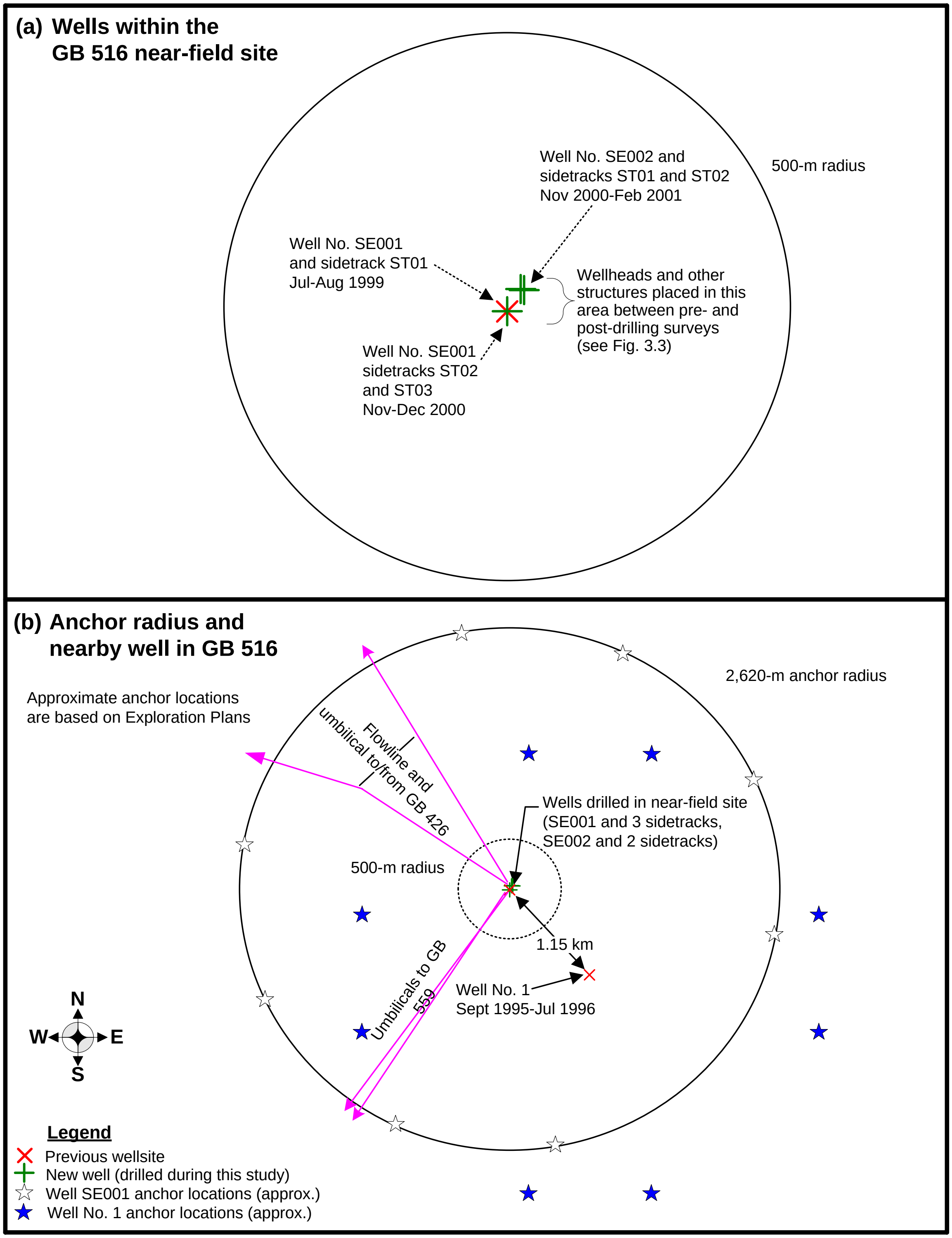

Figure 5. Well locations in and near the Garden Banks Block 516 near-field site.

GARDEN BANKS BLOCK 602 (POST-DEVELOPMENT SITE)

Garden Banks Block 602 is located in the Western Planning Area, about 280 km SSE of Cameron, Louisiana. Water depth at this site is about 1,125 m. The block is leased by Shell, and the prospect has been named Macaroni.

Seven wells were drilled within the GB 602 near-field site between September 1995 and January 2001 (**Figure 6**). All of these were prior to our study. Three other exploration/development wells were drilled in GB 602 approximately 2.3 km NNE of the site center. Also, in February 1996, a geotechnical borehole was drilled about 1.3 km northeast of the near-field site center. Any effects are assumed to be negligible in comparison with the wells drilled within the near-field site.

Exploration Well No. 1, located 247 m west of the site center, was drilled in September 1995 and permanently abandoned ("junked") after it was lost to shallow water flow. Six other wells (three straight wells with corresponding sidetracks) were drilled at three surface locations near the site center between September 1995 and January 2001.

Both WBM and SBM were used during drilling. The Exploration Plan for Well No. 1 included the option of two SBMs, Novadril (an internal olefin) or Petrofree ester. The Development Plan (for Well Nos. 2, 4, and 5) included Novaplus (an internal olefin) and Petrofree LE (a linear-α-olefin). It is not known which SBM was actually used.

MISSISSIPPI CANYON BLOCK 292 (POST-DEVELOPMENT SITE)

Mississippi Canyon Block 292 is located in the Central Planning Area, approximately 200 km southeast of New Orleans. The water depth is approximately 1,034 m. The block is leased by Texaco, and the prospect has been named Gemini.

Figure 7 shows a diagram of wellsite locations at the MC 292 near-field site. Five wells were drilled at three closely-spaced locations near the center of the site between May 1995 and July 1999. From south to north, these are Well Nos. 1, 3 (and sidetrack), and 4 (and sidetrack). These are producing wells with a subsea manifold and flowlines carrying gas to VK 900, about 44 km to the north. All three wells and sidetracks were drilled using a semisubmersible rig. The Exploration Plan indicates an anchor radius of approximately 3,000 m.

Well Nos. 1, 3, and 4 were drilled with WBM, which were discharged along with cuttings. These included initial discharges at the seafloor during jetting, and subsequent discharges from the drilling rig. The two sidetracks were drilled using Novaplus, an internal olefin SBM. Due to the short duration of drilling for the two sidetracks (11 days and 8 days), relatively small quantities of SBM cuttings were discharged from the drilling rig.

The nearest other wells are 2.5 km to the north in MC 248 (three wells, January to March 2000). Several other wells were drilled in the area, but any effects are assumed to be negligible in comparison with the wells drilled within the MC 292 near-field site.

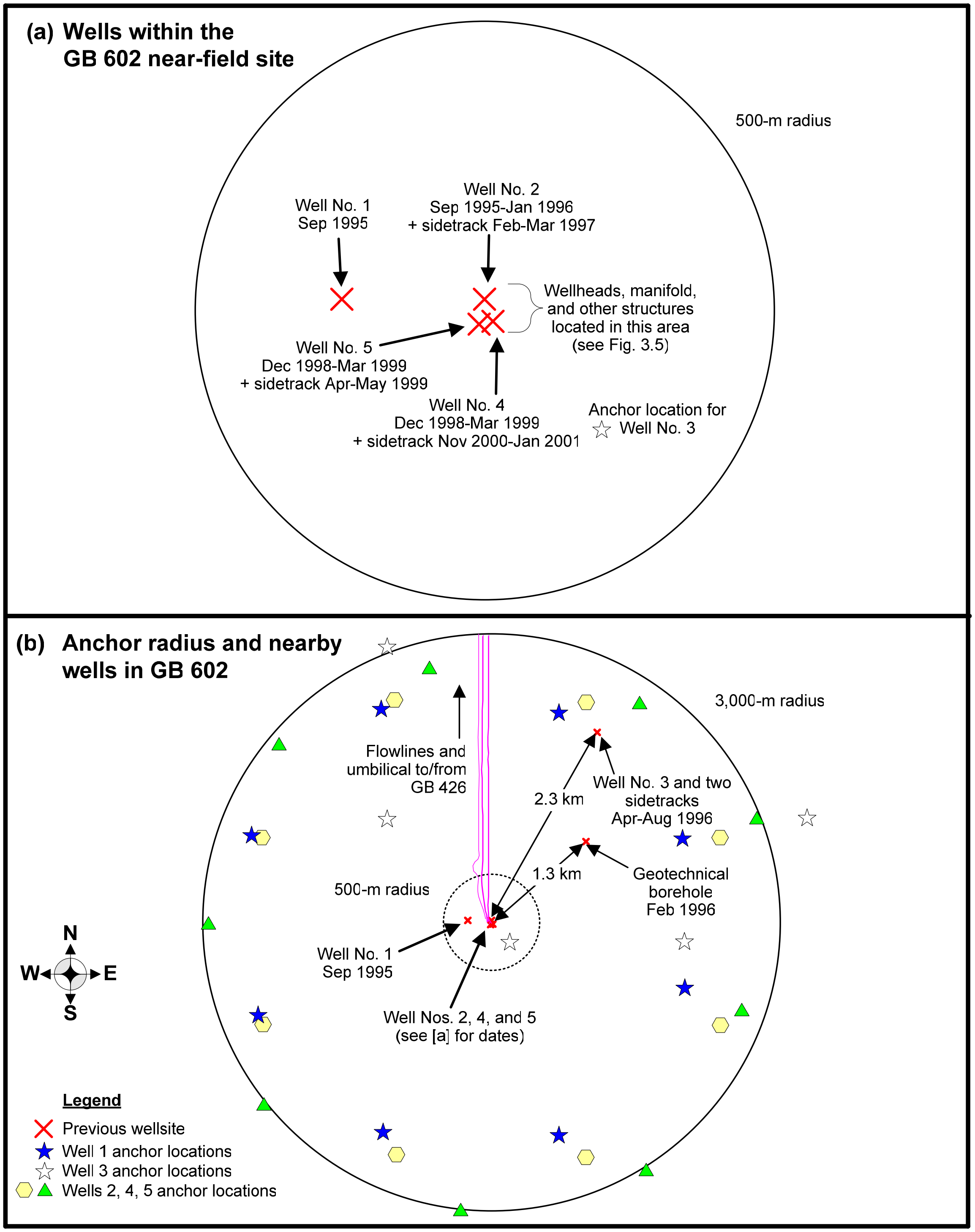

Figure 6. Well locations in and near the Garden Banks Block 602 near-field site.

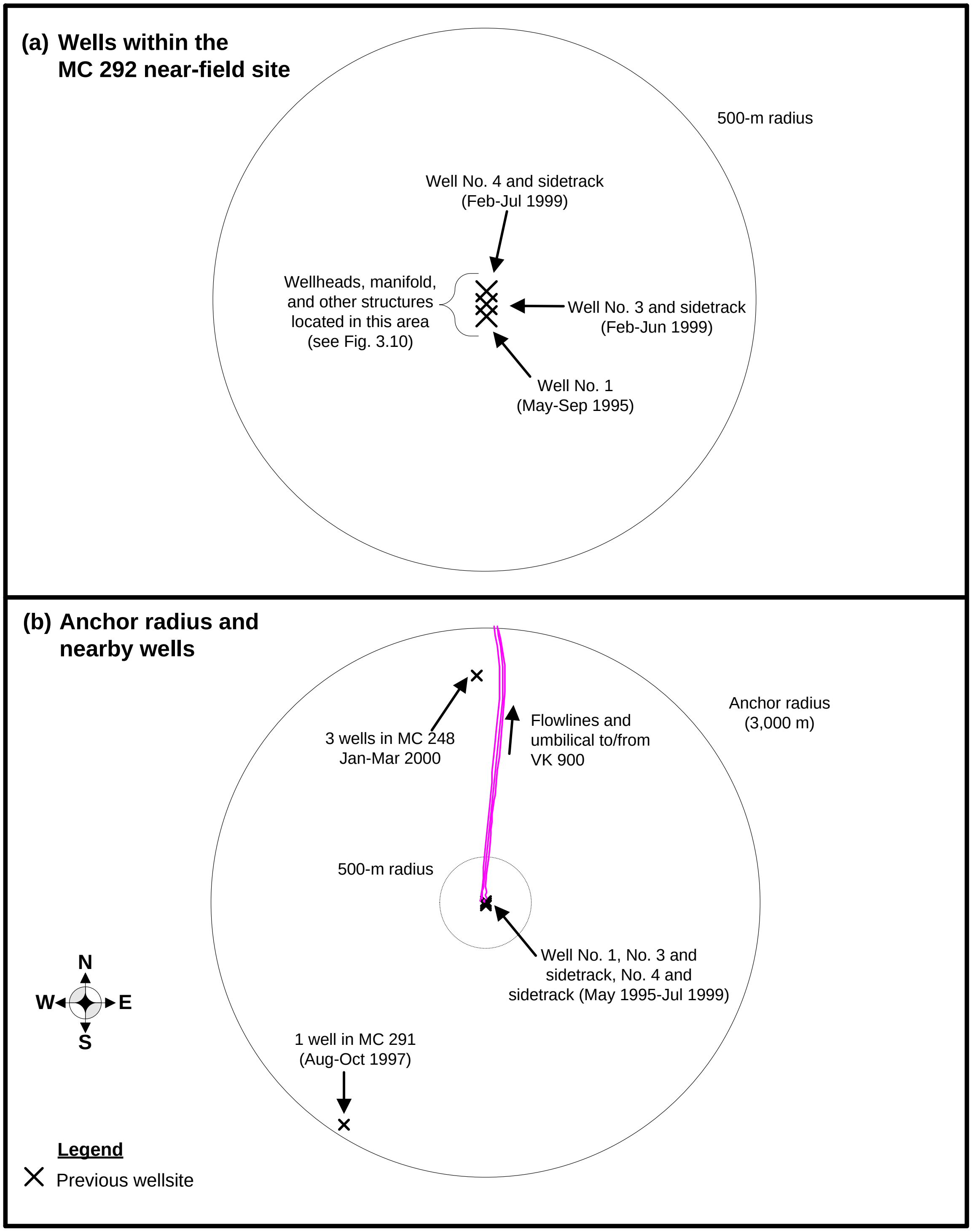

Figure 7. Well locations in and near the Mississippi Canyon Block 292 near-field site.

SAMPLING SCHEDULE

Six cruises were conducted during this study – three geophysical surveys and three chemical/biological sampling cruises (**Table 3**). The geophysical surveys mapped the seafloor within a 3,000-m radius around each near-field site. The chemical/biological cruises collected samples and photographs within a 500-m radius around each near-field site and in smaller circular areas (204-m radius) at each far-field site.

Table 3. Sampling cruises.

Site	Cruise					
	1A	1B	2A	2B	3A	3B
Cruise Type:	*Geophysical*	*Chem/Biol*	*Geophysical*	*Chem/Biol*	*Geophysical*	*Chem/Biol*
Cruise Start:	*11/10/2000*	*10/23/2000*	*6/24/2001*	*7/8/2001*	*8/7/2002*	*8/4/2002*
Cruise End:	*1/1/2001*	*11/17/2000*	*7/7/2001*	*7/25/2001*	*8/12/2002*	*8/14/2002*
VK 916	pre-drilling	pre-drilling	--	--	post-drilling	post-drilling
GB 516	--	post-drilling[a]	post-drilling	post-drilling	--	--
GB 602	--	--	post-drilling	post-drilling	--	--
MC 292	--	--	post-drilling	post-drilling	--	--

[a] Cruise 1B at GB 516 preceded drilling of development wells; however, exploration wells had been drilled previously.

Figure 8 shows the timing of the cruises in relation to drilling at VK 916 and GB 516 during this study. (All previous drilling at GB 602 and MC 292, as well as exploration drilling at GB 516, occurred before this study began, and the dates are not shown.) Cruises 1A (geophysical) and 1B (chemical/biological) were pre-drilling surveys of VK 916 and a pre-development survey of GB 516. Cruises 2A and 2B were post-development surveys of GB 516, GB 602, and MC 292. Cruises 3A and 3B were post-exploration surveys of VK 916.

GEOPHYSICAL SURVEYS

The goal of the geophysical cruises was to determine (1) the areal extent and accumulation of muds and cuttings; (2) the physical modification or disturbance of the sea bed due to impacts from anchors and their mooring systems; and (3) the accumulation of debris.

Bathymetric, side-scan sonar, and subbottom profile data were collected at each site and interpreted to map possible anchor scars and accumulations of cuttings and drilling muds. An area approximately 3,000 m in radius was surveyed at each near-field site, to encompass the anchor patterns for typical moored drilling units in this water depth.

Cruise 1A was the only survey conducted using a deep-tow system, which involved two boats. The data collection systems in the deep-tow fish included a dual frequency side-scan sonar, a chirp subbottom profiler, and a deepwater precision depth sensor. Cruise 1A was originally intended to survey all of the sites. However, due to extended weather delays, as well as equipment, software, and vessel problems, VK 916 was the only site surveyed.

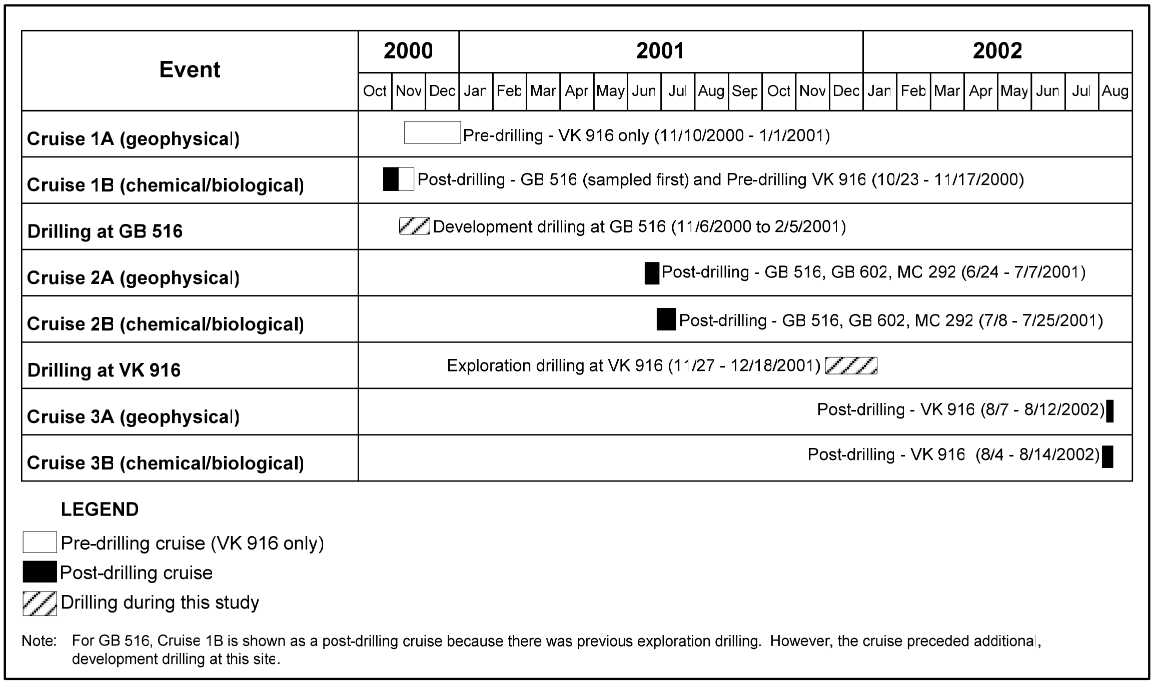

Figure 8. Schedule including sampling cruises and wells drilled during this study. Previous drilling at GB 516, GB 602, and MC 292 occurred at various times before this study, and dates are not shown (see *Chapter 3*).

Cruises 2A and 3A were conducted using the C&C Technologies autonomous underwater vehicle (AUV), the HUGIN 3000 (**Figure 9**). Data collection systems included a dual-frequency side-scan sonar, a chirp subbottom profiler, and a swath bathymetry system. Cruise 2A visited GB 516, GB 602, and MC 292, whereas Cruise 3A revisited VK 916 after exploration drilling.

CHEMICAL/BIOLOGICAL SAMPLING

Chemical/biological sampling was intended to document (1) physical and chemical modification of sediments; and (2) effects on benthic organisms. Samples and data were collected with four types of equipment:

- Box core sampler (to obtain samples of sediment, microbiota, meiofauna, and macroinfauna)
- Sediment profile imaging (SPI) camera (to obtain cross-sectional images of the upper sediment column)
- Still camera on a towed/dragged sled (to obtain photographs of the seafloor and megafauna)
- Baited traps (to obtain animals for tissue analyses)

Near-field samples were collected within a 500-m radius around the drilling location. This area was chosen in order to sample intensively where SBM cuttings are most likely to accumulate at concentrations sufficient to produce biological effects. Each far-field site was a circle 204 m in radius, such that the total area of six far-field sites combined was equal to that of the near-field site, and the number of samples was allocated so that the sampling intensity was the same.

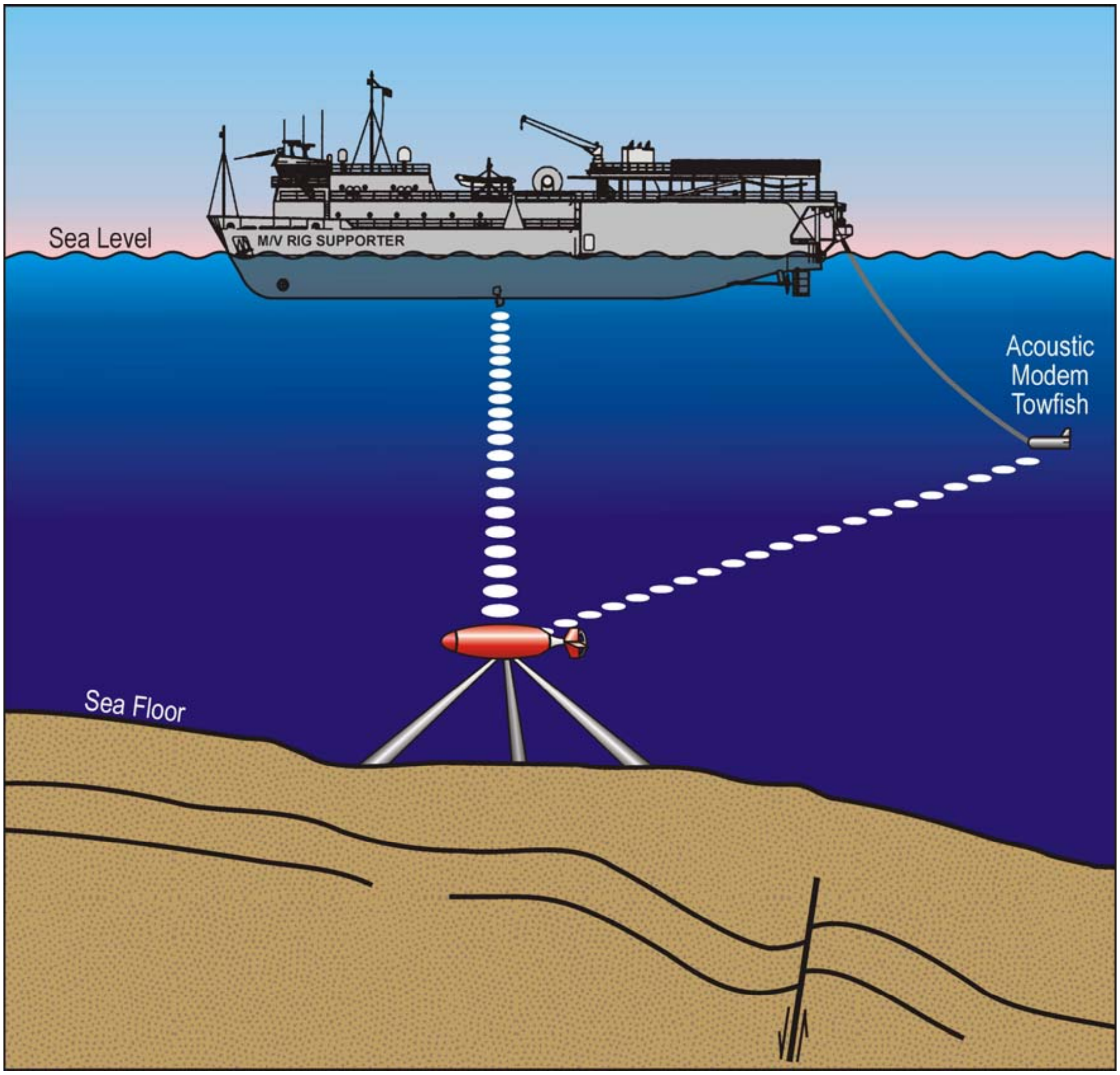

Figure 9. Working configuration of the HUGIN 3000 autonomous underwater vehicle showing the "free-swimming" HUGIN collecting data from a predetermined height above the seafloor. The HUGIN remains in constant communication with the mother ship through acoustic links.

Figure 10 shows the idealized sampling pattern. Box cores were collected at 12 randomly selected locations within the 500-m radius at each site (eight samples within 300 m and four samples between 300 and 500 m radii). Box cores also were collected at 12 far-field locations (two locations selected randomly within each of six far-field sites). Sediment profile photographs were collected along three drift transects in the near-field and along one transect at each of three far-field sites, with approximately 36 images per transect. Still photographs of the seafloor and megafauna were collected along three transects at each near-field site and along one transect at each of three far-field sites (approximately 375 photographs per transect). Baited traps were deployed at the two post-development sites to collect organisms for tissue analyses. For each site, eight traps were deployed in the near-field, and four traps were placed at each of two corresponding far-field sites. Actual numbers of samples and transects differed from the planned number in some cases (**Table 4**).

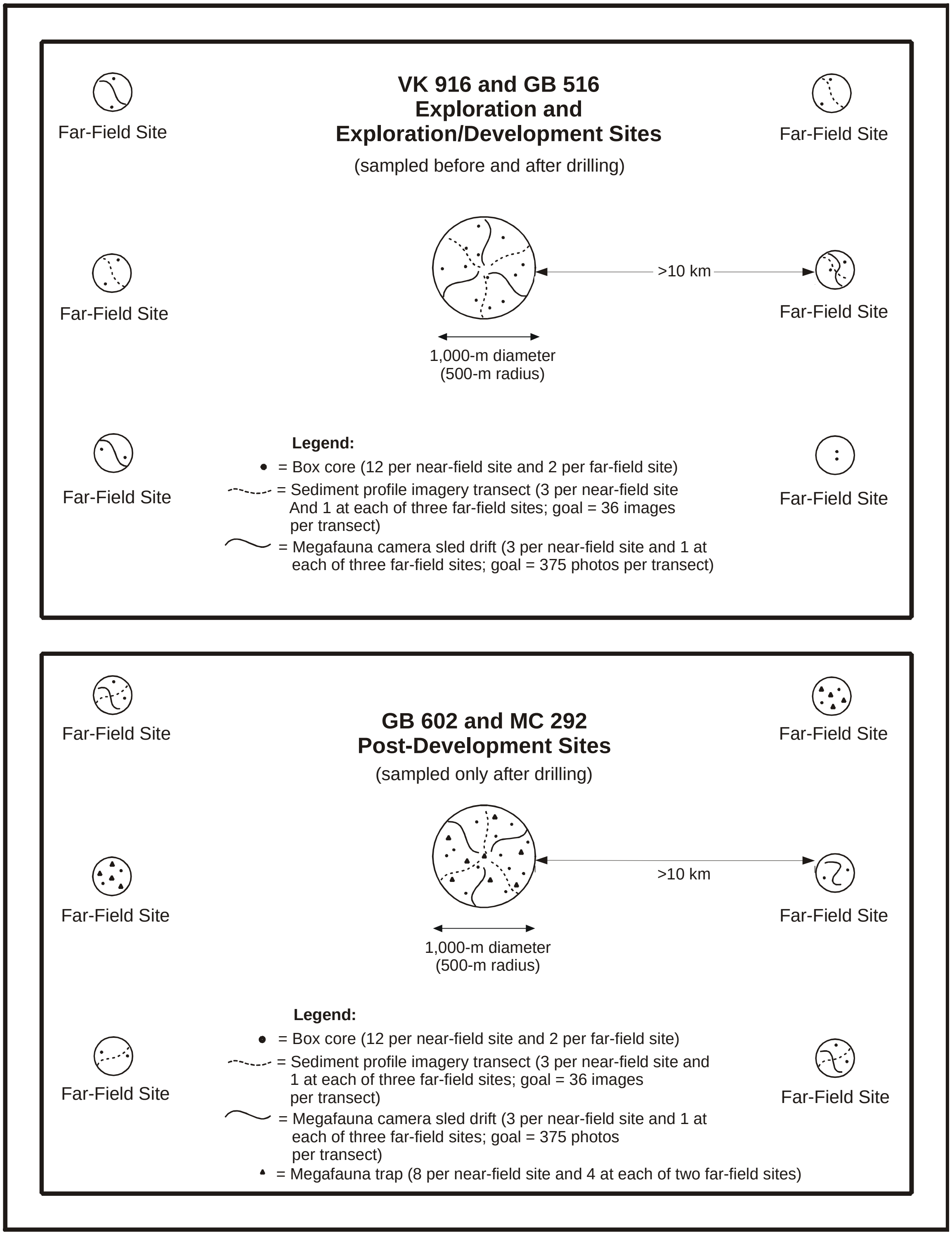

Figure 10. Idealized sampling plans for study sites.

Table 4. Numbers of samples collected and transects completed during chemical/biological cruises.

Cruise and Site	Box Cores		SPI Transects		Sled Transects		Trap Sets[a]	
	NF	FF	NF	FF	NF	FF	NF	FF
Cruise 1B								
VK 916	12	10	2	3	3	4	--	--
GB 516	12	12	3	3	3	5	--	--
Cruise 2B								
GB 516	12+3[b]	12	3	3	3	3	--	--
GB 602	12+3[b]	12	3	3	3	3	2	1
MC 292	12+3[b]	12	2	3	3	3	2	2
Cruise 3B								
VK 916	12+3[b]	12	3	0[c]	3	2	--	--

NF = near-field; FF = far-field; SPI = sediment profile imaging.

[a] Each trap set included four traps.

[b] Three additional "discretionary" box cores samples for subsurface sediment analyses were taken at near-field sites during Cruises 2B and 3B.

[c] During Cruise 3B, far-field transects were attempted at VK 916 FF2 and FF4; however, due to problems with the SPI camera, no usable data were collected.

Box Coring

Sediment samples were collected with a 0.25-m^2 Gray-O'Hara box core. The box was partitioned into subcores for various sample types:

- Sediment grain size and clay mineralogy
- Sediment metals and total organic carbon
- Sediment redox chemistry (direct Eh and pH measurements)
- Sediment hydrocarbons
- Microbiota
- Meiofauna
- Macroinfauna
- Harpacticoid genetic diversity
- Sediment toxicity testing (GB 602 and MC 292 only)

Deployment of box core

In addition, sediment samples for analysis of radionuclides and interstitial water chemistry were removed from selected box cores at each site.

Sediment Profile Imaging

A sediment profile camera was used to take photographs of the sediment column. The profile camera works like an inverted periscope with a deep-sea 35-mm camera mechanism mounted horizontally inside a water-tight housing on top of a wedge-shaped prism. The camera provides images of up to 20 cm of the upper sediment column in profile. At each site, SPI photographs were collected along three drift transects in the near-field and at three of the six far-field sites.

Seafloor Photographs

A deep-sea 35-mm camera on a dragged sled was used to collect still photographs of the seafloor and benthic organisms. These photographs were used for visual analyses of sediment appearance and megafauna. Once deployed on the bottom, the sled was in constant contact with the seafloor. This method produced close-up images of the seafloor looking straight down from a height of 0.6 m. The area of each photograph was about 0.22 m^2.

Baited Traps

Baited traps were used during Cruise 2B to collect animals for tissue analyses at the two post-development sites (GB 602 and MC 292) and corresponding far-field sites. The traps were similar in design to those used in the U.S. Pacific Northwest in the commercial dungeness crab fishery. At each trap station, a set of four baited traps was deployed along a common, weighted line. After deployment, each trap set was allowed to “fish” for a period of 18 to 24 hours, after which the traps were retrieved and any organisms captured were removed.

Two benthic organisms were obtained from the traps in sufficient numbers for tissue analyses. These were the isopod *Bathynomus giganteus* and the red crab *Chaceon quinquedens*.

Isopods – *Bathynomus giganteus*

Red crabs – *Chaceon quinquedens*

FAR-FIELD CONDITIONS

Based on environmental characteristics of the far-field sites (**Table 5**), the four sites are broadly similar. However, water depths at GB 516 and MC 292 were about 120 m shallower than at VK 916 and GB 602. Also, proximity to the Mississippi River mouth is an important influence on ambient conditions, as exemplified by lower sediment oxygen levels at the two easternmost sites (VK 916 and MC 292) and the relatively high sedimentation rate at MC 292.

Table 5. Environmental characteristics of far-field sites. Multiple values for a given site represent data from two different cruises.

Site	Water Depth (m)	Approx. Dist. to Miss. R. (km)	Sedimentation Rate (cm/yr)	Sediment Characteristics			
				Mean Grain Size (µm)	Mean Total Organic Carbon (%)	Mean Integrated Oxygen (nmol/cm^2)	Mean Barium (µg/g)
VK 916	1,125	120	0.06	2.44	1.10	90	805
				1.82	1.53	84	866
GB 516	1,033	357	0.07	1.96	0.52	153	1,281
				2.40	1.08	165	1,478
GB 602	1,125	370	0.04	2.03	1.10	227	821
MC 292	1,034	69	0.14	1.64	1.44	65	754

Biological comparisons among sites are complicated by temporal differences. At the VK 916 site, there was an order of magnitude decrease in microbial biomass as well as meiofaunal and macroinfaunal densities between cruises. A similar decrease was evident at GB 516 for microbes and meiofauna but not for macroinfauna. There were also some geographic differences in benthic community composition. Stations from GB 516 and GB 602, which are very close geographically (stations within tens of kilometers), were more similar to each other than to the stations from VK 916 and/or MC 292, which are relatively close to each other but about 400 km away.

NATURE AND EXTENT OF IMPACTS

Table 6 summarizes the physical, chemical, and biological impacts noted during this study. These are discussed briefly in individual subsections.

Table 6. Impact summary.

Parameter	Impact	Extent	Notes
PHYSICAL			
Anchor scars	Presence of anchor scars	Within about 3-km radius from wellsites, 8 radial directions	Individual scars <100 m to >3 km in length
Seafloor equipment and debris	Presence of structures and debris on bottom	Subsea wellheads etc. within few hundred meters; flowlines and umbilicals extend many kilometers to nearby blocks; occasional debris within 3-km radius	VK 916 had the smallest number of side-scan "debris" contacts
Mappable mud and cuttings deposits	Presence of geophysically detectable mud and cuttings zones around wellsites	Well jetting deposits mostly within 100 m of wellsites. Rig discharge deposits extending from several hundred meters to about 1 km	Areal extent greatest at GB 516 and GB 602, smallest at VK 916
Sediment grain size	Increased percentage of (mainly coarse) sand at some stations	Primarily within 300-m radius	Cuttings similar in grain size to surficial sediments
Sediment color/ appearance	Areas of black bottom within near-field	Extent not determined. Most consistent at GB 602; patchy at other sites	Black bottom is presumed due to the presence of cuttings and/or mud
Thickness of drilling deposits	Isopach maps from subbottom profiling at VK 916 indicate thickness ranging from 0 to 45 cm	Extent not determined	Sectioning of a few discretionary cores at VK 916, GB 516, and GB 602 indicates layer of mud/cuttings several centimeters thick. Full range of thicknesses was not sampled by these cores
CHEMICAL			
Sediment Ba	Elevated by orders of magnitude at nearly all near-field stations	Nearly all stations within 500-m radius; highest values within 300-m radius	One discretionary station 1,000 m from GB 602 site center had elevated Ba; far-field data suggest slight effects at 2 to 3 km
Sediment SBF	Elevated by orders of magnitude at most near-field stations	Most stations within 500-m radius; nearly all stations within 300-m radius	One discretionary station 1,000 m from GB 602 site center had elevated SBF; far-field data suggest slight effects at 2 to 3 km
Sediment PAH	Elevated at two GB 516 stations	Within 300-m radius	Not attributable to SBM since these discharges do not contain PAH

Table 6. (continued).

Parameter	Impact	Extent	Notes
Metals other than Ba	Elevated concentrations of As, Cd, Cr, Cu, Hg, Pb, and Zn at some stations; lower concentrations of Al, Fe, Mn, Ni, and V	Few stations	Differences are related to concentrations of these metals in barite, or reductive dissolution in the case of Mn
Sediment TOC	Elevated at some near-field stations	Primarily within 300-m radius	High TOC is associated with high SBF concentrations
Sediment oxygen/Eh	Low oxygen and negative Eh at some near-field sites	Primarily within 300-m radius	Poor redox conditions are associated with high SBF levels; least severe at MC 292
Redox potential discontinuity	Decreased depth of the oxidized layer in the near-field	Patchy within near-field	Poor redox conditions are associated with high SBF levels; least severe at MC 292
Metals in isopods *Bathynomus giganteus*	Elevated Ba, Cr, and Pb in isopods at GB 602 but not at MC 292; lower Cd and Hg in isopods at GB 602, but not at MC 292	Extent not determined	Most consistent finding is elevated Ba (in isopods from GB 602 and in crabs from both GB 602 and MC 292). Possibly due to sediment particles in gut
Metals in red crabs *Chaceon quinquedens*	Elevated Ba and reduced As, Cd, Cu, Hg, Ni, V, and Zn in crabs at GB 602; elevated Ba, Cd, Cr, and V in crabs at MC 292	Extent not determined	
Hydrocarbons in isopods and red crabs	--	--	No impact on tissue PAH concentrations detected
BIOLOGICAL			
Benthic communities (general conditions)	Azoic areas; areas of pioneering communities; poor organism-sediment index	Patchy within near-field	MC 292 appears least affected
Microbiota	Elevated microbial biomass (ATP) at some stations	Patchy within near-field	Generally, stations with high ATP had high SBF levels; order of magnitude decrease in ATP between cruises at VK 916 and GB 516 (both near- and far-field)
Microbial mats	Microbial mats seen in SPI images from several near-field stations	Patchy within near-field	Mats not seen at MC 292 or at GB 516 on Cruise 2B
Meiofauna	Increased meiofaunal densities in near-field including annelids, harpacticoids, and nematodes	Primarily within 300-m radius	Order of magnitude decrease in meiofauna between cruises at VK 916 and GB 516

Table 6. (continued).

Parameter	Impact	Extent	Notes
Meiofauna – harpacticoid genetics	Low genetic diversity in near-field populations of *Bathycletopsyllus* sp.	Extent not determined	*Bathycletopsyllus* sp. absent from far-field sites, but abundant at near-field sites; low genetic diversity is consistent with expansion from a small population
Macroinfauna	Increased polychaete, gastropod, and bivalve densities in near-field; reduced amphipod and ostracod densities	Primarily within 300-m radius	--
Megafauna	Higher fish densities and lower ophiuroid densities within near-field	Extent not determined	Effects evident at VK 916 and GB 516 but not at GB 602 or MC 292

Al = aluminum; ATP = adenosine triphosphate; Ba = barium; Cd = cadmium; Cr = chromium; Cu = copper; Eh = redox potential; Fe = iron; Hg = mercury; Mn = manganese; Ni = nickel; PAH = polycyclic aromatic hydrocarbons; Pb = lead; SBF = synthetic-based fluid; SBM = synthetic-based mud; SPI = sediment profile imaging; TOC = total organic carbon; V = vanadium.

Anchor Scars

Based on the geophysical surveys, anchor scars extended to the limit of the surveyed area (about 3-km radius) around the wellsites. Individual anchor scars, all in soft bottom areas, ranged from less than 100 m to over 3 km in length. VK 916 had only one set of anchor scars associated with exploratory drilling. However, other scars remained from previous drilling in adjacent blocks (VK 872 and VK 873). The other three sites, surveyed post-development, had several sets of anchor scars, reflecting the use of different drilling rigs to drill various wells over time.

Seafloor Equipment and Debris

At the three sites where development drilling had occurred and production was ongoing (GB 516, GB 602, and MC 292), the geophysical survey identified known structures on the seafloor, including pipelines and flowlines, subsea wellheads, umbilical termination modules, etc. The wellheads and associated equipment were mostly within 200 m of the site centers. Pipelines and flowlines extended many kilometers to platforms or other structures in nearby lease blocks.

At all four sites, there were side-scan sonar contacts identified as debris. These could include pieces of pipe, etc. that presumably fell from the drilling rig or other vessels. VK 916 had the smallest number of contacts (four), whereas there were numerous contacts at the other sites. Debris locations were not investigated further in this study.

Mappable Cuttings and Mud Deposits

Side-scan sonar and subbottom profiler records were used to map deposits of drilling mud and cuttings around the wellsites. However, there are no unique geophysical signatures for these deposits. The mapped distribution of mud and cuttings was inferred from a combination of geophysical data and information about discharges. No “ground truth” sampling or analysis was conducted to verify that cuttings or drilling mud particles were present in these zones, or to determine the minimum thickness that could be detected.

Two zones were recognized (**Figure 11**). In the geophysical cruise reports, these were identified as “drilling muds” and “drill cuttings.” However, both zones probably consist of both muds and cuttings, and primarily the latter. The first zone, in the area immediately around wellsites, was recognized by a combination of a smooth seafloor (little backscatter on side-scan sonar records) and a high amplitude response at the seafloor on high resolution subbottom profiles. This zone probably represents an area of cuttings and spud mud deposition from initial jetting of wells. Cuttings probably account for most of the materials deposited during this stage, because spud muds are primarily seawater with low solids concentrations. Typically, these initial deposits, along with excess cement from setting of the well casing, create a shallow, compact mound. Other activities including installation of subsea wellheads, flowlines, and umbilical modules at the three post-development sites (GB 516, GB 602, and MC 292) may also have contributed to the observed reflectance pattern around the wellsites.

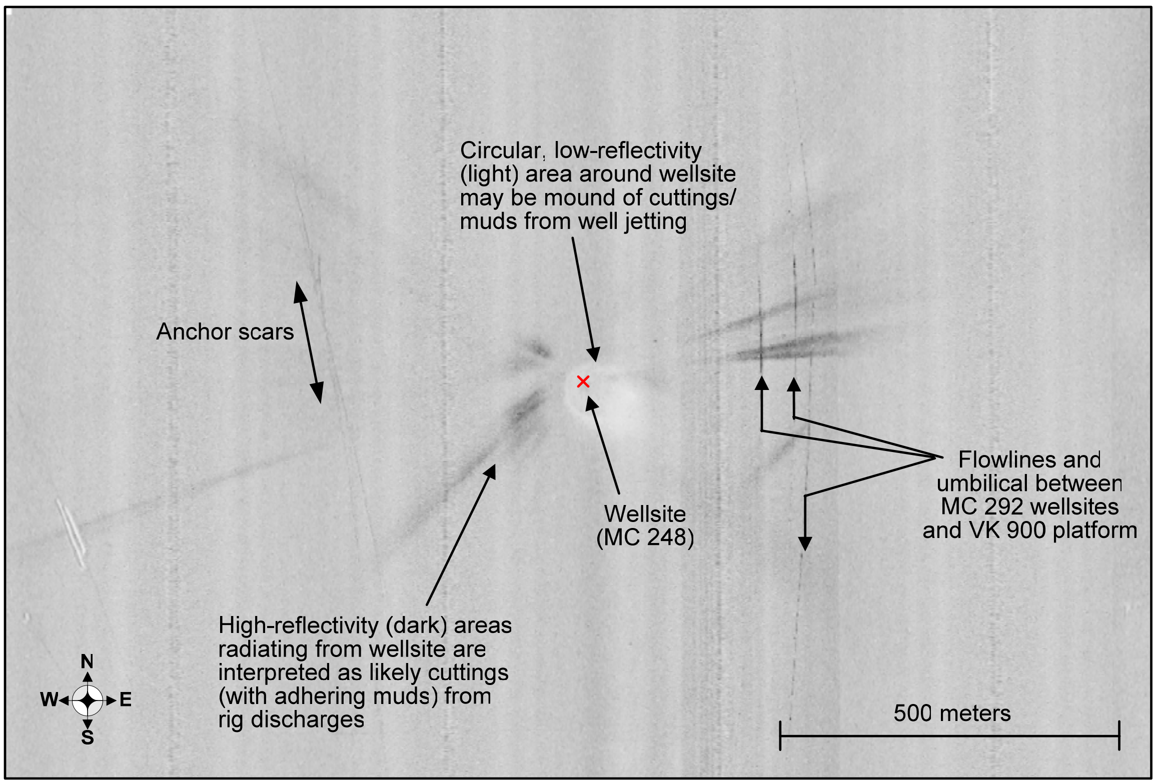

Figure 11. Part of the side-scan sonar mosaic for the MC 292 area showing a wellsite in the adjacent block (MC 248) where three wells were drilled about 1.5 years before Cruise 2A. Though this is not one of the study sites, the image illustrates several of the features commonly noted.

More extensive areas where side-scan sonar showed high reflectivity extending in a radial pattern around the wellsites (**Figure 11**) were interpreted as primarily cuttings (with adhering muds) from rig discharges. Although WBMs were also discharged from the rig at all wellsites, they probably were widely dispersed before reaching the seafloor and would not likely be detected geophysically.

Generally, areas mapped as well jetting deposits were identified within about 100 m of wellsites. Areas mapped as rig discharge deposits typically extended several hundred meters from wellsites, with the greatest extent (about 1 km) observed at GB 602 and GB 516. The estimated area of mud and cuttings accumulation was greatest at GB 516 (Cruise 2B) and smallest at VK 916 (**Table 7**).

Table 7. Geophysically estimated areal extent of drilling mud and cuttings deposits at each near-field site. Both well jetting deposits and rig discharge deposits are assumed to consist of both drilling muds and cuttings (primarily the latter).

Site	Cruise	Stage	Well Jetting Deposits (ha)	Rig Discharge Deposits (ha)
VK 916	3A	Post-exploration	None mapped	13.37
GB 516	2A	Post-development	2.48	108.53
GB 602	2A	Post-development	1.08	43.18
MC 292	2A	Post-development	0.78	25.61

Sediment Grain Size

Sediments at all four sites were predominantly clay and silt. There were no gross changes in grain size around the wellsites. A few near-field samples had slightly elevated percentages of sand-sized particles. Most stations had <10% sand. Higher percentages were evident at several stations at GB 516 on Cruise 2B (up to 18%) and at one MC 292 station (14%). GB 602 had higher sand percentages both near-field and far-field, but one near-field station had the highest value (21%). Near-field, post-drilling elevations in sand percentages were detected statistically at VK 916, GB 516 (Cruise 2B), and MC 292, but not at GB 602 nor at GB 516 on Cruise 1B.

Grain size variations were patchy within near-field sites, and the spatial pattern did not necessarily correspond to the geophysically mapped drilling discharge zones. Also, except for VK 916, there were no strong correlations between percentages of sand, silt, or clay and concentrations of drilling mud indicators. These findings suggest that grain size distribution *per se* is not a very good indicator of drilling discharge impacts.

Sediment Color/Appearance

Color analysis of seafloor photographs showed that areas of “black bottom” (**Figure 12**) were present on post-drilling surveys at all four near-field sites but not at far-field sites (or VK 916 near-field on the pre-drilling survey). Black surface layers also were seen in some sediment profile images. The black bottom was covered in some images by white-to-red mats consistent with the sulfide-using bacteria *Beggiatoa*. These bacterial areas may indicate sites of local bottom anoxia supported by bacterial degradation of SBM. Although impacts were patchy at all sites, most images at GB 602 showed dark bottom, possibly indicating that this site has cuttings more thinly spread over a larger area. The patterns of black bottom coincided with geophysical mapping of cuttings reasonably well where direct comparisons could be made.

Figure 12. Comparison of seafloor photographs from before and after drilling at VK 916. Note the darker color of the sediment surface in the post-drilling photograph.

Thickness of Mud and Cuttings Deposits

During the post-drilling geophysical survey at VK 916, the thickness of mud and cuttings deposits around the wellsite was estimated to range from 0 to 45 cm. Discretionary core samples taken in likely mud/cuttings areas during Cruises 2B and 3B also provide information about the thickness of mud and cuttings at a few stations. These values ranged from 2 to 10 cm. These values do not represent the thickest deposits since the area immediately surrounding the wellsites was not sampled.

Drilling Fluid Tracers (Barium and SBF)

Barium and synthetic-based fluid (SBF[1]) concentrations are sensitive tracers of drilling muds. Barite ($BaSO_4$) is a major ingredient in both WBMs and SBMs. SBF concentrations are related to the amount of SBF adhering to discharged cuttings.

Far-field barium values typically were between 500 and 1,500 µg/g, except at GB 516, where values as high as 2,780 µg/g were observed. Far-field SBF concentrations generally were less than 10 µg/g, except for the Cruise 3B values at VK 916, which were in the 10 to 15 µg/g range. All of the far-field sites had non-zero SBF concentrations (i.e., above the detection limits). However, these values are probably due to small quantities of natural hydrocarbons that eluted in the same range as SBFs in the analytical procedure.

Barium and SBF concentrations were significantly higher at sites near drilling (near-field, post-drilling) than at sites far from drilling (i.e., far-field sites or the near-field, pre-drilling site at VK 916). Post-drilling, near-field concentrations were as high as 351,000 µg/g for barium and 117,280 µg/g for SBF. While nearly all near-field stations had elevated barium, SBF increases were not as consistently elevated at VK 916 and MC 292 as compared with the other two sites.

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[1] The terms synthetic-based mud (SBM) and synthetic-based fluid (SBF) are often used interchangeably. However, in this report, SBF refers to chemical measurements of the base fluid in sediment, whereas SBM refers to the drilling muds and cuttings *per se*.

Figure 13 shows concentrations of barium and SBF for all sites combined, with stations grouped into three categories (far-field, near-field 300 to 500 m, and near-field <300 m). Most near-field stations had elevated barium and SBF concentrations, with the highest values within 300 m. However, some near-field stations had concentrations similar to those at far-field stations.

There are some data indicating effects beyond the 500-m near-field radius. One discretionary station at GB 602 on Cruise 2B was about 1,000 m southwest of the site center and had a barium concentration of 14,800 µg/g, compared with far-field values typically less than 2,000 µg/g. The SBF concentration was 930 µg/g, compared with far-field values typically less than 15 µg/g. Also, one of the VK 916 far-field sites had slightly elevated barium and SBF concentrations on both cruises, possibly due to drilling discharges in nearby blocks.

Polycyclic Aromatic Hydrocarbons (PAH)

With two exceptions, sediment PAH concentrations ranged from 43 to 748 ng/g dry wt. Two samples at GB 516 had considerably higher concentrations (**Figure 13**). On Cruise 1B, one of the random stations had 3,470 ng/g PAH, and on Cruise 2B, one of the discretionary stations had 23,840 ng/g in the top 2 cm. Both of these stations were within the 300-m radius. The source of the PAH is suggested to be from some other contaminant from the drilling or production activity, as SBMs do not contain PAH.

Sediment Metals Other Than Barium

Near-field concentrations of arsenic, cadmium, chromium, copper, lead, mercury, and zinc were elevated in some near-field sediment samples as compared with far-field samples. Generally, elevated concentrations of these metals were associated with high barium concentrations (i.e., drilling fluid). However, these elevated concentrations are within the expected range of background concentrations for uncontaminated marine sediments (Neff 1987).

Relatively low concentrations of aluminum, iron, nickel, and vanadium were measured in some near-field samples and were attributed to dilution of ambient sediments with barite, which contains no significant amounts of these metals. Also, concentrations of manganese were lower and more variable at near-field sites, a result attributed to reductive dissolution of this metal at stations where the presence of drilling discharges created reducing conditions.

Considerable interest has been generated regarding concentrations of mercury in sediments adjacent to drilling sites because concentrations of total mercury near drilling sites are often 2 to 10 times higher than in nearby background sediments (Neff 2002). This mercury is known to be a natural impurity in barite (Trefry and Smith 2003). Calculations indicate that the mercury concentrations in barite deposited at these sites are in line with U.S. Environmental Protection Agency (USEPA) regulations, which allow a maximum level of 1 mg/kg in barite (USEPA 1993).

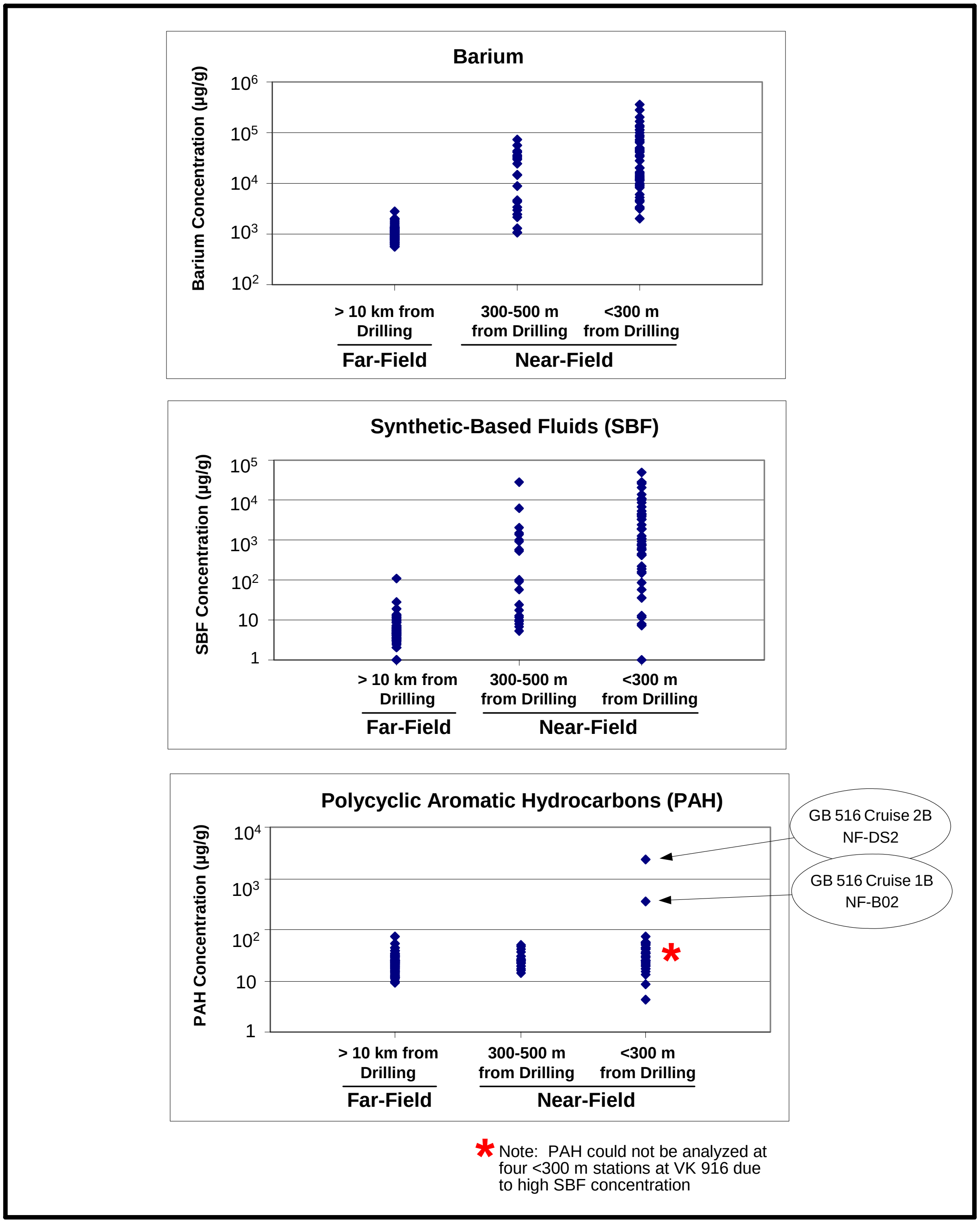


Figure 13. Sediment concentrations of barium, synthetic-based fluids (SBF), and polycyclic aromatic hydrocarbons (PAH) in relation to proximity to drilling. Points are individual stations, including non-random "discretionary"stations. "Far-field" includes near-field, pre-drilling stations at VK916.

Metals and Hydrocarbons in Biota

Concentrations of 11 metals (arsenic, barium, cadmium, chromium, copper, iron, lead, mercury, nickel, vanadium, and zinc) were determined in samples of the giant isopod *Bathynomus giganteus* and the red crab *Chaceon quinquedens* from near-field and far-field stations at sites GB 602 and MC 292.

In isopods from GB 602, levels of barium, chromium, and lead were greater at near-field stations, whereas concentrations of cadmium and mercury were greater at far-field stations. No significant differences were detected for isopods at MC 292. For red crabs from GB 602, barium concentrations were higher in the near-field, whereas concentrations of arsenic, cadmium, copper, mercury, nickel, vanadium, and zinc were higher in the far-field. For MC 292, concentrations of barium, cadmium, chromium, and vanadium were greater at near-field stations.

The most consistent finding in the metals data is elevated barium (in isopods from GB 602 and in crabs from both GB 602 and MC 292). The elevated barium concentrations detected in isopods and crabs may reflect small amounts of sediment particles retained in the gut.

Both species also were analyzed for tissue PAH concentrations. PAH concentrations ranged from 38.6 to 416 ng/g dry. No significant difference was found between the total PAH body burden concentrations in the two deepwater organisms. No significant difference also was found between the total PAH body burden concentrations at near-field and far-field stations.

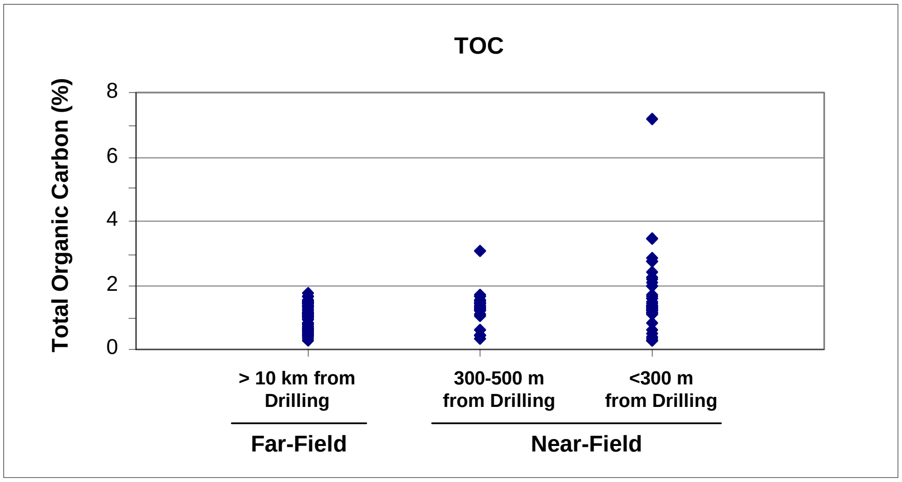
Total Organic Carbon

Sediment TOC concentrations at far-field and pre-drilling near-field stations ranged from 0.28% to 1.73%. In contrast, near-field concentrations ranged from 0.26% to 7.16%. Elevated TOC was noted at a relatively few near-field stations. With one exception, elevated TOC (greater than 2%) was observed only within 300 m of the site center.

All stations with elevated TOC had high SBF and barium concentrations. TOC was strongly correlated with SBF concentration within near-field sites (**Figure 14**), supporting the conclusion that the organic-rich areas were due to deposition of SBM cuttings. Most of the TOC concentrations exceeding 2% occurred at either VK 916 or GB 516 (Cruise 2B). There was little or no elevated TOC at MC 292 or at GB 516 post-exploration (Cruise 1B).

Sediment Redox Conditions

Several study components provided information about sediment redox conditions. These included direct measurements of sediment oxygen concentrations and Eh profiles, as well as visual observations through SPI. As a useful summary measure, **Figure 15** compares integrated oxygen levels in the sediment column at each site. With a couple of exceptions, oxygen levels were markedly reduced at near-field, post-drilling sites. This effect was most pronounced at GB 602 and at GB 516 on Cruise 2B, where all near-field and discretionary stations had much lower oxygen than the far-field.



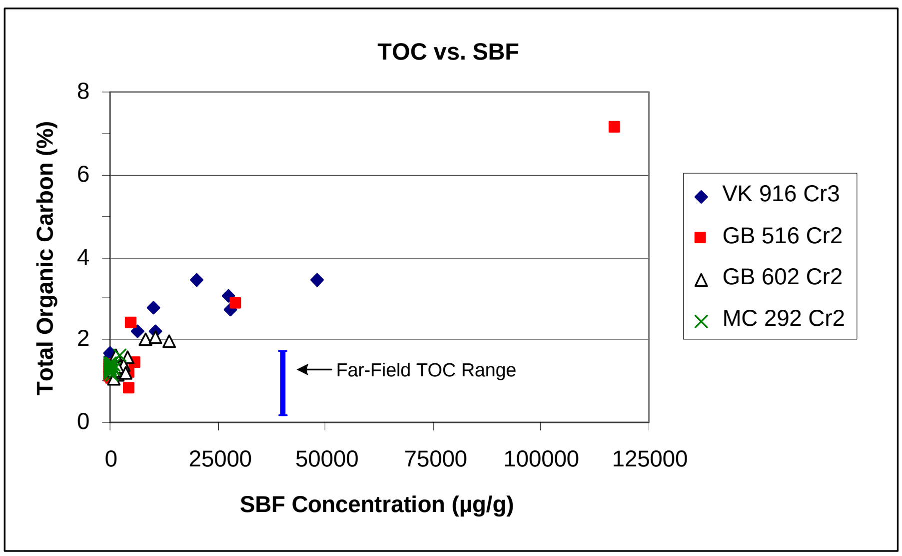


Figure 14. Relationship between total organic carbon (TOC) and synthetic-based fluid (SBF) concentrations in near-field sediments at the four sites.

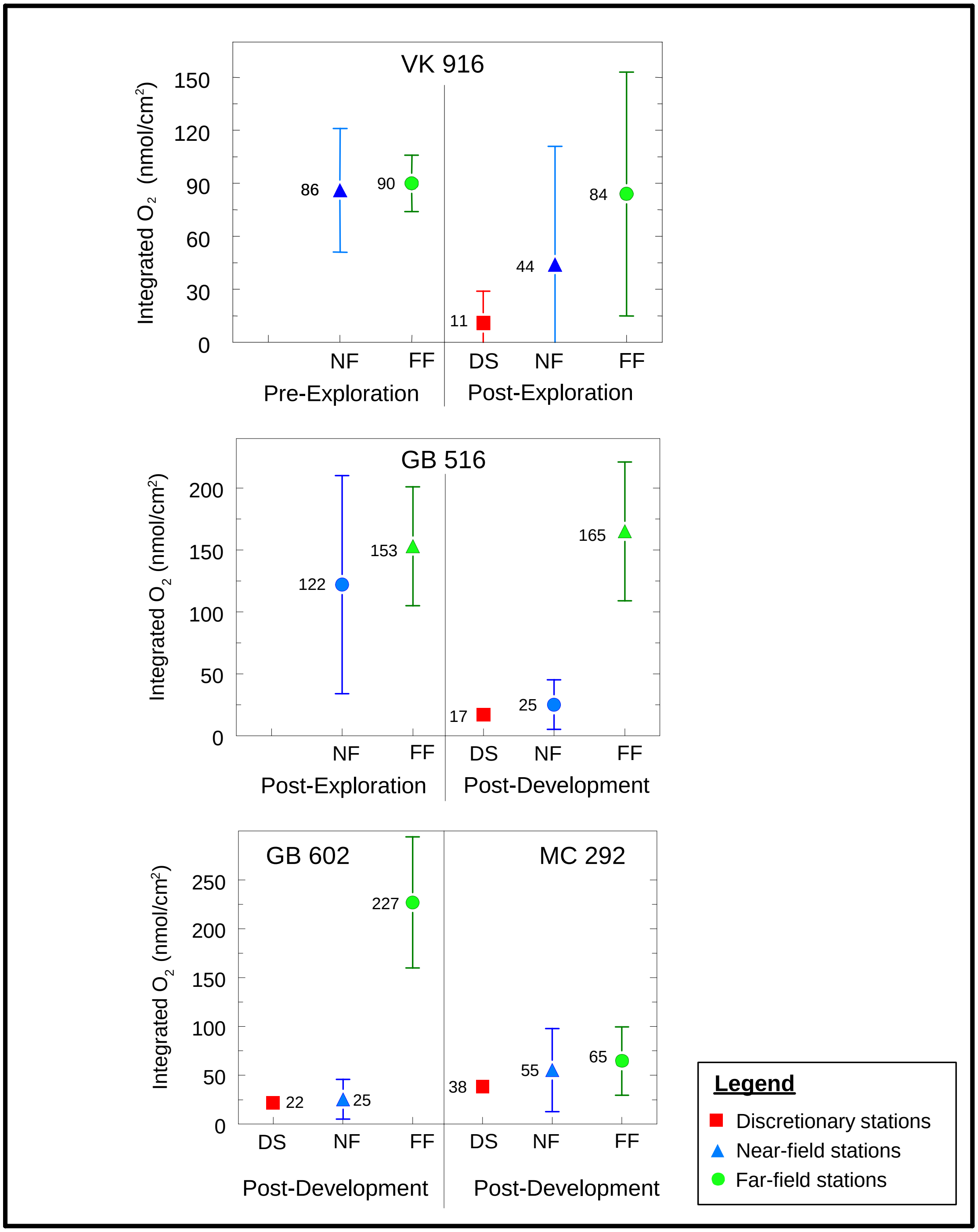


Figure 15. Integrated amounts of oxygen in the sediment column at near-field (NF), far-field (FF), and discretionary (DS) stations at all four sites. Markers and numbers show means and lines show standard deviations. The standard deviation for some DS samples is smaller than the marker.

On Cruise 1B at VK 916, where there was no previous drilling, most near-field stations had oxygen levels similar to those seen in the far-field. Similarly, at GB 516, although there was previous drilling prior to Cruise 1B (two exploration wells), oxygen levels at many near-field stations initially were similar to those in the far-field. However, after subsequent drilling of five development wells, the near-field oxygen levels were greatly reduced on Cruise 2B.

At MC 292, differences between near-field and far-field stations were less striking. Oxygen levels were already low in MC 292 area sediments due to the proximity of the Mississippi River delta and the associated higher sedimentation rate. MC 292 and VK 916 had lower far-field oxygen levels than the two western sites (GB 516 and GB 602). In addition, MC 292 had the smallest quantities of SBM discharges and the longest time since drilling.

Benthic Communities

This study included several biological components. SPI provided an overview of benthic community health and successional status. Box core samples were analyzed for microbial adenosine triphosphate (ATP), and meiofauna and macroinfauna. Additional studies of harpacticoid copepod genetics were conducted at GB 602 and MC 292. Photographs taken with the camera sled were examined for the presence of megafauna.

Sediment Profile Imaging

SPI was used to characterize benthic communities at each site. Images were analyzed to determine successional stage using a paradigm based on recolonization of disturbed shallow-water habitats (Rhoads and Germano 1982). Application of this method to our study sites is an extrapolation, as detailed knowledge about infaunal successional stages is not available for these sites.

Post-drilling surveys indicated that the near-field zone at three of the four sites (VK 916, GB 516, and GB 602) consisted of a mosaic of poor benthic conditions (patchy areas of low or negative organism-sediment index [OSI] and azoic or retrograde benthic communities) alternating with areas of moderately high benthic habitat quality. The degraded near-field habitats stand in marked contrast to those seen at far-field sites.

At VK 916, observations suggested that recent surface disturbance (deposition, resuspension, and/or erosion) may have selectively compromised near surface-dwelling species relative to deeper-living infauna. A similar phenomenon has been noted in studies of the ecological effects of bottom trawling (Rosenberg et al. 2003).

At MC 292, only a small number of stations appeared to have been visibly affected by drilling muds and cuttings. Only a few stations along one transect had signs of anoxic conditions. There was evidence of infaunal activity at most stations, and no microbial mats were observed at this site. The relative lack of impacts is consistent with box core redox measurements and may be related to the low volume of SBM cuttings discharged at this site.

Microbiota

Microbial data provided mixed results. ATP concentrations measured on Cruise 1B were about an order of magnitude higher than those measured on Cruises 2B or 3B. The difference is statistically significant for both VK 916 and GB 516. Since the change is noted at both near-field and far-field sites, it is not attributable to drilling discharges. However, the temporal difference complicates interpretation.

There is ample evidence that microbial biomass, though patchy, was higher in areas where drilling discharges accumulated. For example, sediment profile camera images commonly showed microbial mats at near-field sites but not far-field sites (**Figure 16**).

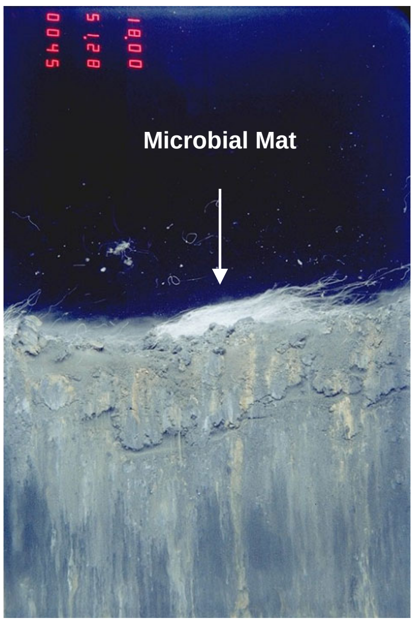


Figure 16. Sediment profile image from the near-field site at Garden Banks 516 during Cruise 1B showing a microbial mat and with the sediment column below completely gray to black. Image width is 15 cm.

Within the VK 916 and GB 516 sites, the stations with the highest microbial biomass corresponded to those with the highest SBF concentrations. This effect was evident at SBF concentrations greater than 1,000 µg/g. A similar effect was not evident at GB 602 or MC 292.

The increased microbial abundance at some near-field stations is consistent with an organic enrichment effect due to the addition of SBM cuttings. The possibility that some inhibition of microbial activity also occurs where SBM cuttings accumulate cannot be ruled out.

Meiofauna

Meiofaunal densities tended to be higher near drilling (**Figure 17**). Although there was considerable overlap in near-field vs. far-field densities, the highest densities of nematodes, harpacticoid copepods, and especially annelids occurred in the near-field. This effect was seen mainly within 300 m of the wellsite(s), although a few stations in the 300- to 500-m range also had elevated numbers. Meiofaunal densities in the near-field were not consistently correlated with drilling indicators (barium, SBF) or other sediment variables (TOC, grain size fractions).

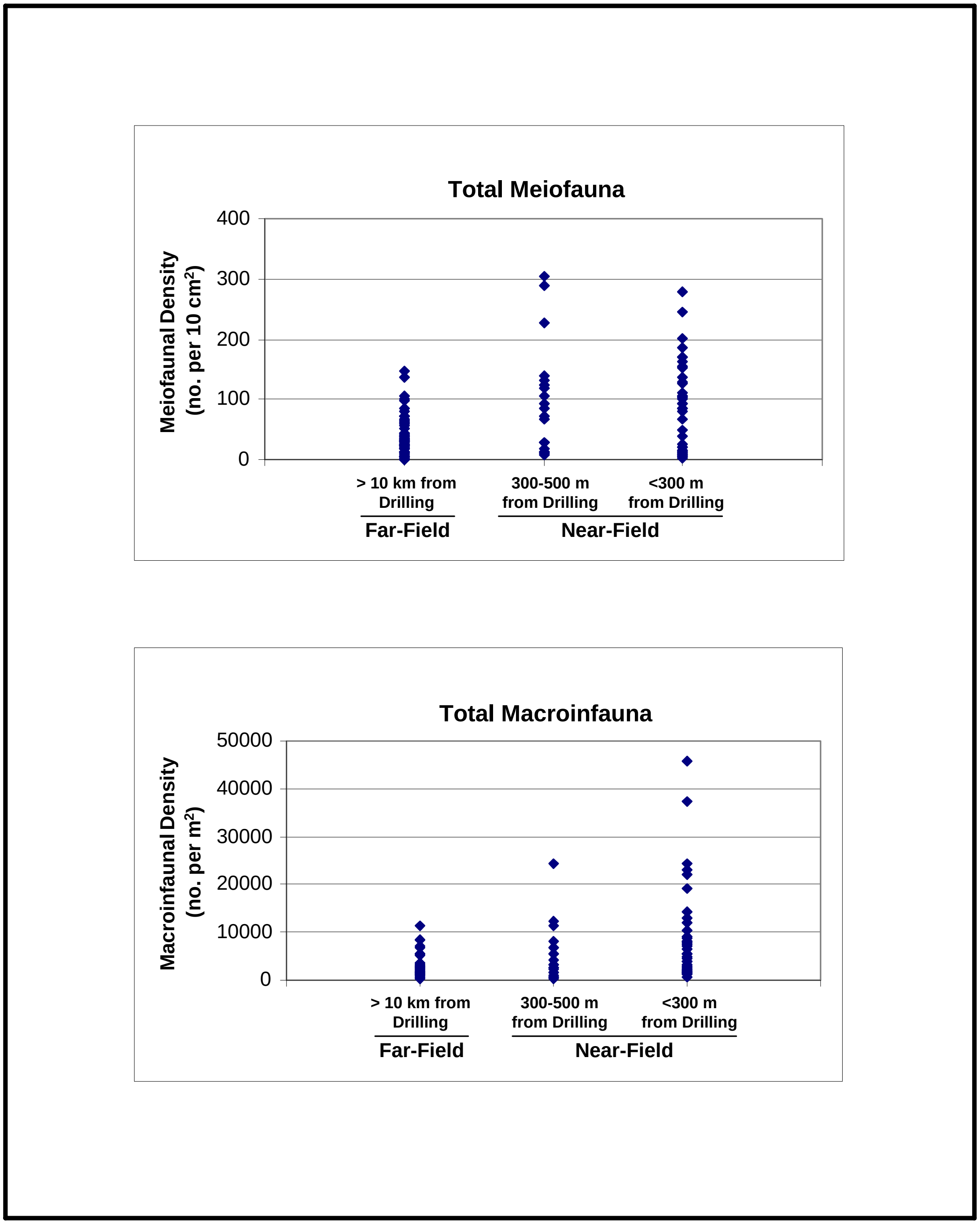


Figure 17. Meiofaunal and macroinfaunal densities in relation to proximity to drilling. Points are individual stations including non-random "discretionary" stations. The pre-drilling survey at Viosca Knoll 916 has been excluded from these plots (higher densities both near- and far-field would obscure other patterns).

A separate study of harpacticoid genetic diversity was conducted at GB 602 and MC 292. The study focused on *Bathycletopsyllus* sp., which was absent from far-field sites, but abundant at near-field sites. Results showed low genetic diversity in near-field populations of *Bathycletopsyllus* sp., which is consistent with expansion from a small, pre-drilling population.

Macroinfauna

Macroinfaunal densities tended to be higher near drilling (**Figure 17**). Although there was considerable overlap in near-field vs. far-field densities, the highest densities occurred in the near-field. This effect was seen almost entirely within 300 m of the wellsite(s).

The highest densities of annelids (predominantly polychaetes), gastropods, and bivalves tended to occur in the near-field. The opposite was true for amphipods and ostracods, with the highest densities generally occurring at one or more far-field stations.

Annelid and gastropod densities in the near-field were positively correlated with drilling indicators (barium, SBF). Some near-field stations with barium concentrations higher than about 10,000 µg/g and/or SBF concentrations greater than about 1,000 µg/g had elevated annelid and/or gastropod densities. Conversely, amphipod densities were negatively correlated with drilling indicators, with reduced densities associated with barium concentrations greater than about 10,000 µg/g and/or SBF concentrations greater than about 1,000 µg/g.

A detailed taxonomic analysis of 24 stations showed that species composition reflects both geographic location and drilling impacts. Some stations "near drilling" had lower diversity, lower evenness, and lower richness indices compared with stations "away from drilling" (**Figure 18**). Station/cruise groups most likely affected by drilling (as indicated by high barium and SBF concentrations) were dominated by high abundances of one or a few deposit-feeding species. For example, at VK 916, Station NF-B07 was numerically dominated by the polychaete *Capitella capitata*, a classic indicator of organic enrichment, and at GB 516, Station NF-B02 was numerically dominated by the gastropod *Solariella* sp. A.

Megafauna

Overall, small megafauna identified in photographs showed little or no impact. However, localized significant shifts were found for two groups. Fishes were more abundant in the near-field, consistent with attraction to disturbance and structure (and possibly, increased food supplies in the form of elevated macroinfaunal densities). Ophiuroids were less abundant in the near-field, perhaps because these flat organisms were buried by cuttings, or perhaps there was a behavior shift, which resulted in fewer animals being seen in the near-field. Near-field vs. far-field differences for fishes and ophiuroids were seen mainly at VK 916 and GB 516. There was little or no difference between near- and far-field at GB 602 or MC 292.

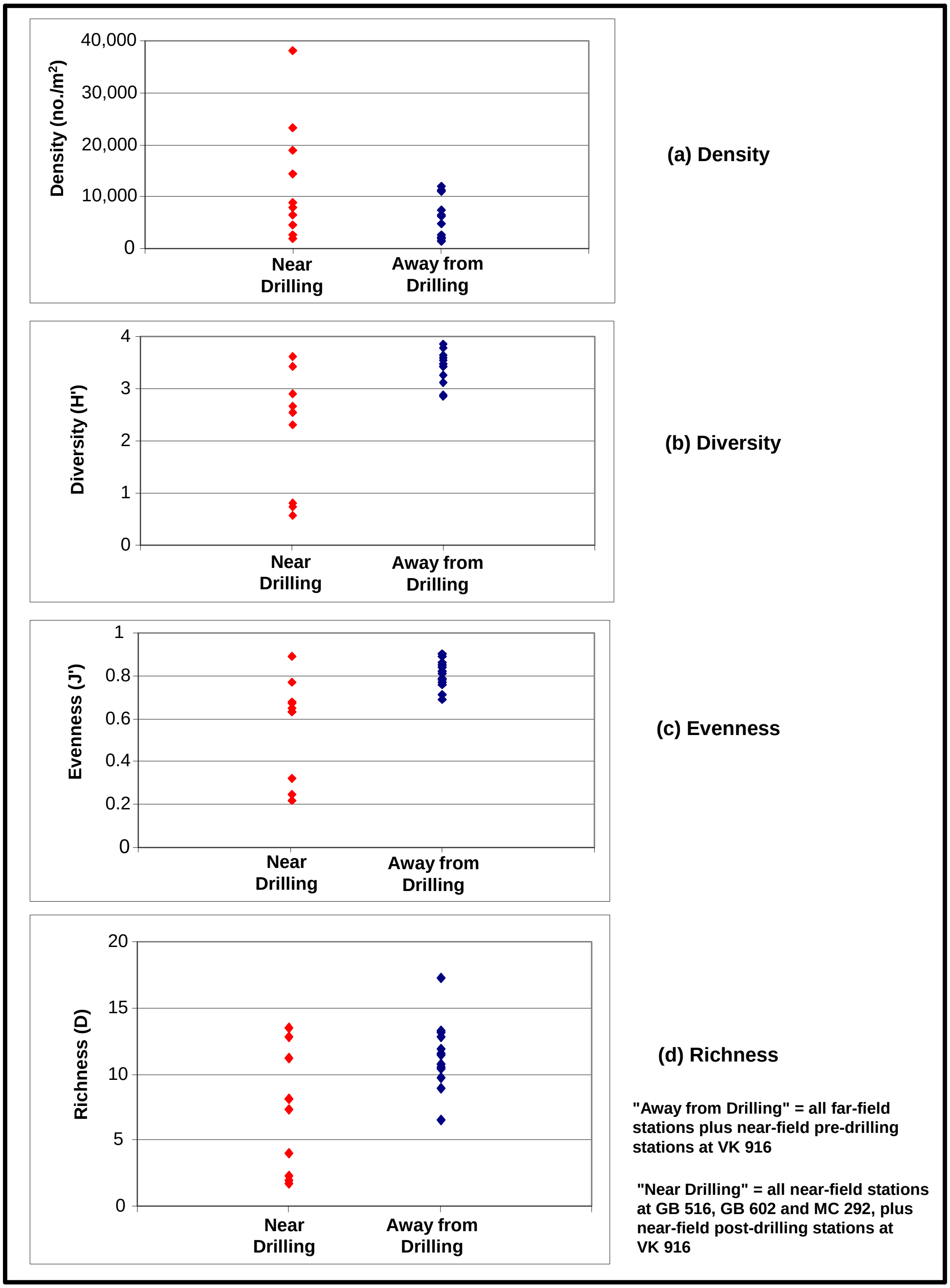


Figure 18. Macroinfaunal community characteristics for the detailed, 24-station analysis.

Discussion of Biological Impacts

Biological observations consistent with burial and/or stressed conditions include

- azoic areas (lacking visible benthic macroinfauna) observed in near-field sediment profile images from VK 916, GB 516, and GB 602;
- absence or rarity of surface-dwelling macroinfauna in near-field sediment profile images from VK 916;
- reduced densities of macroinfaunal amphipods and ostracods in the near-field box cores; and
- reduced densities of ophiuroids in near-field photographs.

Because SBM cuttings were discharged, toxicity, organic enrichment, and anoxia (including potentially toxic concentrations of sulfide and ammonia) are possible contributing factors (Neff et al. 2000). Acute toxicity tests with near-field and far-field sediments from MC 292 and GB 602 showed that mean amphipod survival was significantly lower in sediments from near-field stations than in sediments from far-field stations. Amphipod survival was negatively correlated with drilling mud and cuttings indicators (barium and SBF) for both sites. However, the bioassays were conducted with estuarine amphipods (rather than indigenous deep-sea fauna) and do not simulate actual field conditions.

On the other hand, there is evidence of elevated biological activity associated with a disturbed, organically enriched habitat. This includes

- microbial mats observed in sediment profile images;
- elevated microbial biomass associated with high SBF concentrations;
- elevated near-field densities of meiofauna, including annelids, harpacticoid copepods, and nematodes;
- elevated near-field densities of macroinfauna, including annelids, bivalves, and gastropods;
- predominance of pioneering stage macroinfaunal assemblages at some near-field stations; and
- elevated near-field densities of fishes at VK 916 and GB 516.

SITE COMPARISONS

Areal Extent of Impacts

Overall, the areal extent of impacts was greatest at two post-development sites (GB 516 and GB 602). These two sites had relatively large mapped mud and cuttings zones, and most stations had high barium and SBF concentrations. Impact extent was smallest at the VK 916 exploration site, where only a single well was drilled. Among the post-development sites, MC 292 had the smallest extent of impacts based on both the mapped extent of mud and cuttings deposits and the relatively few stations having very high barium and SBF concentrations. The latter result may reflect the limited use of SBM at this site and the longer elapsed time since drilling ended there.

Severity of Impacts

Generally, the two Garden Banks post-development sites were the most severely affected, having high mean barium and SBF concentrations and the greatest reduction in sediment integrated oxygen levels. By all measures, MC 292 was least severely affected, having low maximum and mean barium and SBF concentrations and the smallest decrease in sediment integrated oxygen levels. Mean barium and SBF concentrations in near-field sediments were positively correlated with estimated SBM cuttings volume (**Figure 19**). Decreases in mean sediment oxygen levels also were strongly negatively correlated with both mean sediment SBF concentrations and the estimated SBM cuttings discharges (**Figure 20**).

Duration of Impacts

The timing of drilling activities vs. sampling cruises differed among sites. The interval between cessation of drilling and the date when the surveys began ranged from 5 months to nearly 2 years depending on the site. Over time, SBF residues are decomposed by microbes, resulting in significant decreases in SBF concentration (Candler et al. 1995). Our observations indicate that sediment SBF concentrations tended to increase with increasing SBM discharge volume and decrease with longer elapsed time since drilling.

Observations from the study sites and adjacent blocks suggest that geophysically detectable mud/cuttings deposits persist for 5 years or more and anchor scars may persist for 14 years or more. Because no chemical or biological sampling was done in adjacent blocks, it is not known if the mapped mud/cuttings deposits from older wells are associated with persistent elevations in barium and SBF, anoxic conditions, or altered benthic communities.

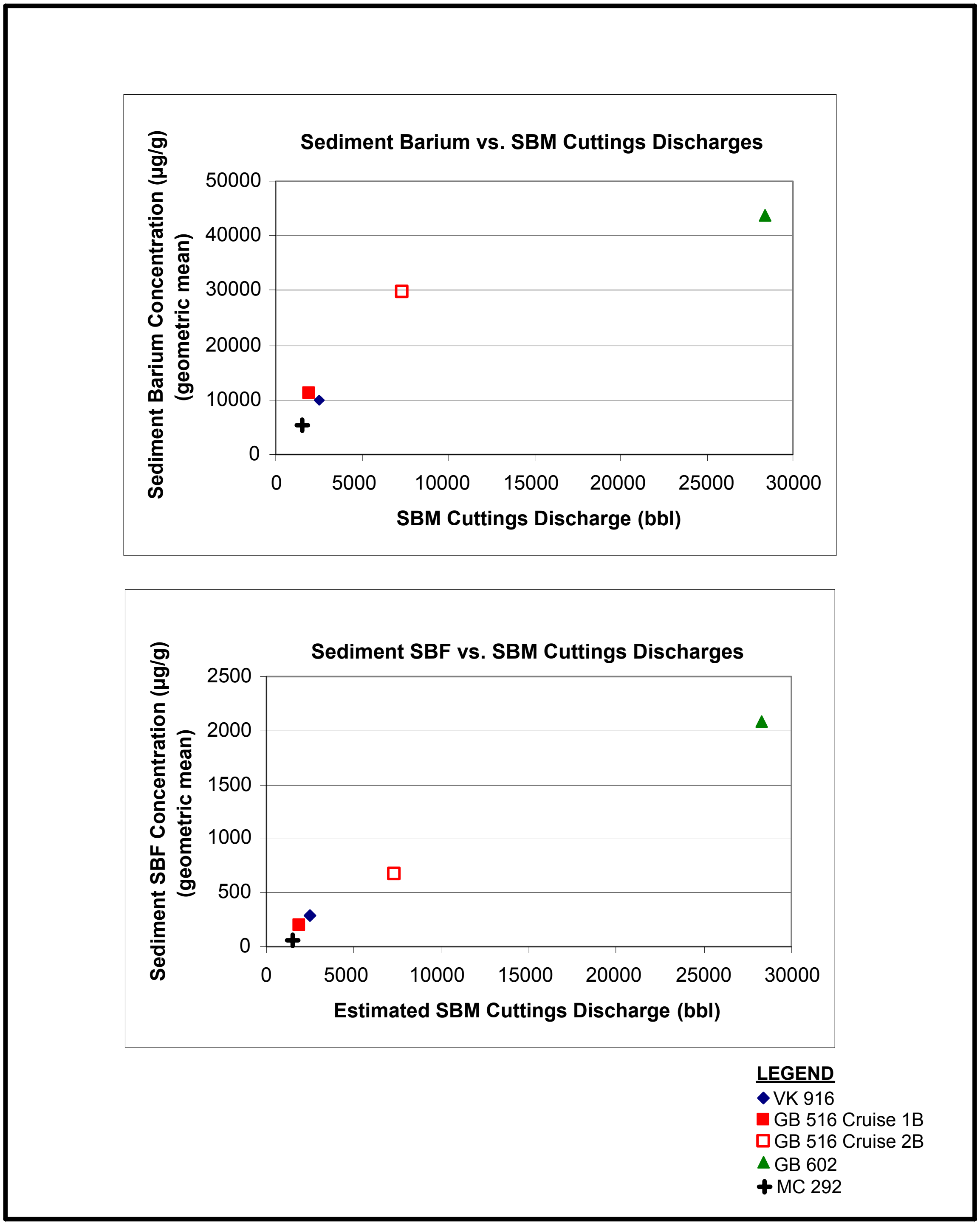


Figure 19. Relationship between post-drilling sediment barium and synthetic-based fluid (SBF) concentrations within near-field sites and estimated volumes of synthetic-based mud (SBM) cuttings discharges.

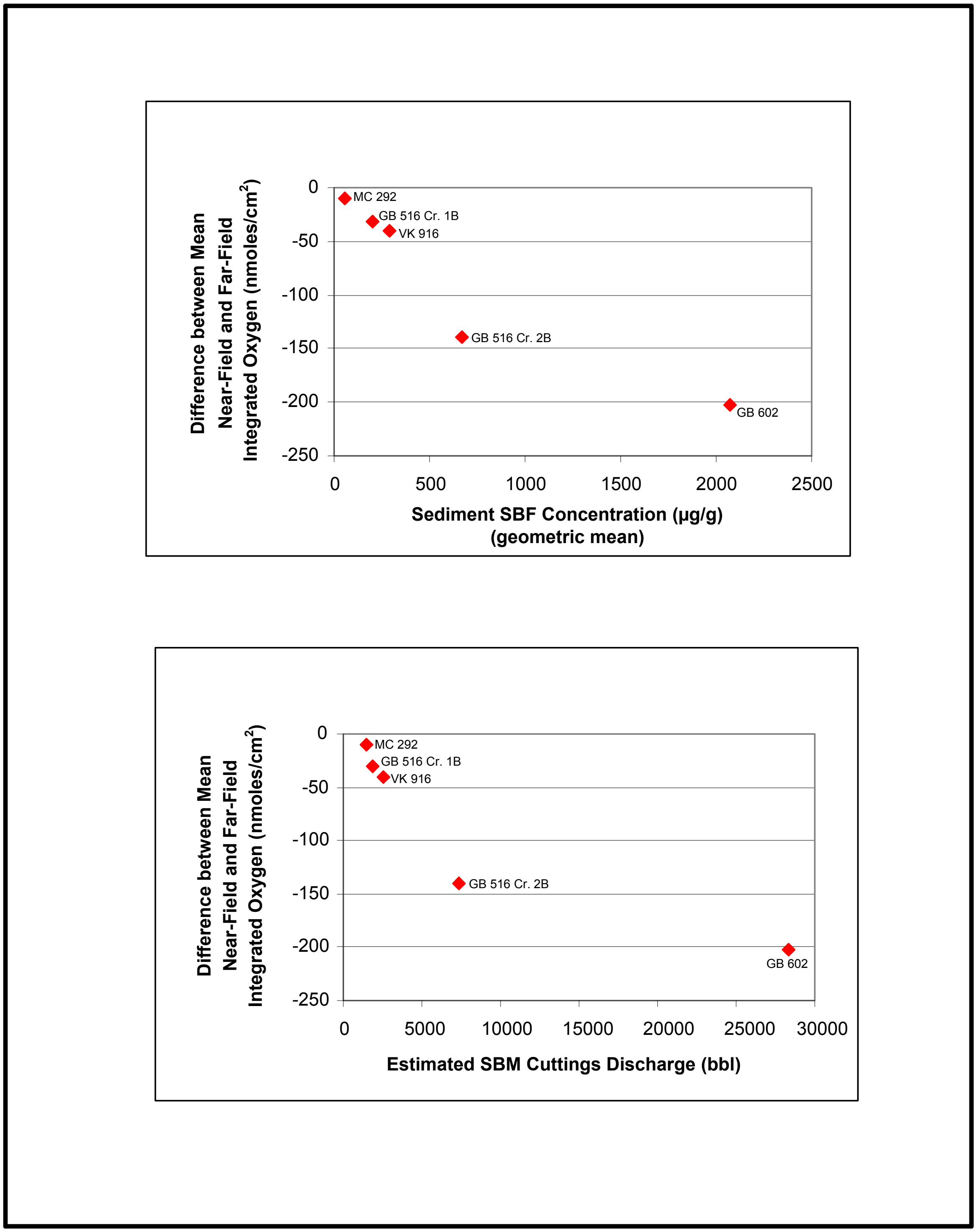


Figure 20. Difference between mean near-field and far-field sediment oxygen levels in relation to sediment synthetic-based fluid (SBF) concentrations and estimated synthetic-based mud (SBM) cuttings discharges.

The following are the main conclusions of the study:

- Geophysical and chemical measurements indicated that a layer of SBM cuttings and muds was deposited within the near-field radius. Geophysically mapped mud and cuttings zones ranged from 13 to 109 ha in area, with larger zones observed at post-development sites. These zones typically extended several hundred meters from wellsites, with the greatest extent (about 1 km) observed at GB 602 and GB 516. Cuttings deposits were estimated to be up to 45 cm thick at one site (VK 916).
- Concentrations of drilling fluid tracers (barium and SBF) were elevated by several orders of magnitude within near-field sites. Mean sediment concentrations of barium and SBF were positively correlated with estimated discharge volumes of SBM cuttings.
- Areas of SBM cuttings deposition were associated with elevated TOC and anoxic conditions, including low dissolved oxygen, negative Eh, and shallow depth of the oxidized layer. Sites with larger volumes of SBM cuttings discharges and higher mean sediment SBF concentrations had the greatest reduction in mean sediment oxygen levels.
- SPI indicated that the near-field sites had patchy zones of disturbed benthic communities, including microbial mats, areas lacking visible benthic macroinfauna, zones dominated by pioneering stage assemblages, and areas where surface-dwelling species were selectively lost.
- Macroinfaunal and meiofaunal densities generally were higher near drilling, although some faunal groups were less abundant in the near-field (amphipods, ostracods). Among megafauna, increased fish densities and reduced ophiuroid densities were noted in the near-field of two sites (VK 916 and GB 516).
- Microbial biomass (ATP) was elevated in some samples near drilling and positively correlated with SBF concentrations above about 1,000 µg/g at VK 916 and GB 516, but not at GB 602 or MC 292. The ATP data were problematic, however, with major temporal changes and apparent far-field "outliers" complicating the interpretation.
- Meiofaunal densities in the near-field were not consistently correlated with drilling indicators (barium, SBF) or other sediment variables (TOC, grain size fractions).
- Annelid (predominantly polychaete) and gastropod densities in the near-field were positively correlated with drilling indicators (barium, SBF). Some near-field stations with barium concentrations higher than about 10,000 µg/g and/or SBF concentrations greater than about 1,000 µg/g had elevated polychaete densities. A few near-field stations at GB 516 and GB 602 had very high gastropod densities, which were associated with barium concentrations of 55,000 µg/g or higher and SBF concentrations of 4,500 µg/g or higher.
- Amphipod densities in the near-field were negatively correlated with drilling indicators (barium and SBF). Generally, near-field stations with barium concentrations higher than about 10,000 µg/g and/or SBF concentrations greater than about 1,000 µg/g had low amphipod densities. Separately, acute toxicity tests with near-field and far-field sediments from MC 292 and GB 602 showed that mean amphipod survival was significantly lower in sediments from near-field stations than in sediments from far-field stations. Amphipod survival in the toxicity tests was negatively correlated with drilling indicators.
- Detailed taxonomic analysis of a subset of the macroinfaunal samples showed some stations near drilling had lower diversity, lower evenness, and lower richness indices compared with

stations away from drilling. Species composition varied in relation to both geographic location and drilling impacts. Station/cruise groups most likely affected by drilling were dominated by high abundances of one or a few deposit-feeding species, including known pollution indicators.

- At all four near-field sites, impacts were patchy, with some stations showing conditions similar to those at the far-field sites. Impacts generally were less extensive and less severe at post-exploration sites than at post-development sites.
- Impacts attributable to SBM cuttings such as elevated TOC, poor redox conditions, and associated biological changes were least severe at MC 292, where the smallest quantities of SBM cuttings were discharged. However, the time elapsed since drilling also was longer at this site (about 2 years) than at the other three sites (5 to 14 months), and the less severe impacts may reflect recovery of this site over time.
- Observations from the study sites and adjacent lease blocks suggest that geophysically detectable mud/cuttings deposits may persist for 5 years or more and anchor scars may persist for 14 years or more. Because no chemical or biological sampling was done in adjacent blocks, it is not known if the mapped mud/cuttings from older wells are associated with persistent elevations in barium, anoxic conditions, or altered benthic communities.

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The Department of the Interior Mission

As the Nation's principal conservation agency, the Department of the Interior has responsibility for most of our nationally owned public lands and natural resources. This includes fostering sound use of our land and water resources; protecting our fish, wildlife, and biological diversity; preserving the environmental and cultural values of our national parks and historical places; and providing for the enjoyment of life through outdoor recreation. The Department assesses our energy and mineral resources and works to ensure that their development is in the best interests of all our people by encouraging stewardship and citizen participation in their care. The Department also has a major responsibility for American Indian reservation communities and for people who live in island territories under U.S. administration.

The Minerals Management Service Mission

As a bureau of the Department of the Interior, the Minerals Management Service's (MMS) primary responsibilities are to manage the mineral resources located on the Nation's Outer Continental Shelf (OCS), collect revenue from the Federal OCS and onshore Federal and Indian lands, and distribute those revenues.

Moreover, in working to meet its responsibilities, the **Offshore Minerals Management Program** administers the OCS competitive leasing program and oversees the safe and environmentally sound exploration and production of our Nation's offshore natural gas, oil and other mineral resources. The MMS **Minerals Revenue Management** meets its responsibilities by ensuring the efficient, timely and accurate collection and disbursement of revenue from mineral leasing and production due to Indian tribes and allottees, States and the U.S. Treasury.

The MMS strives to fulfill its responsibilities through the general guiding principles of: (1) being responsive to the public's concerns and interests by maintaining a dialogue with all potentially affected parties and (2) carrying out its programs with an emphasis on working to enhance the quality of life for all Americans by lending MMS assistance and expertise to economic development and environmental protection.