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Impact of Water Based Drilling Fluid and Cuttings Discharge Offshore Nigeria Using Sediment Profile Imaging Technology

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Abstract

Sediment profile imaging (SPI) technology is an effective tool for offshore oil and gas environmental assessment and monitoring. This paper demonstrates how SPI was used to evaluate the impact on the sea floor of water-based drilling fluid and cuttings discharged during drilling operations at five wellhead platforms offshore Nigeria in 2010. Pre-drill and post-drill SPI surveys were performed according to an orthogonal array of 20 nearfield stations, configured at 100 m, 200 m, 500 m, 800 m and 1,200 m distance along the cardinal directions from each platform. Three far-field reference stations were located at distances of up to 10 km from each platform. In the post-drill survey, the station array was supplemented by the addition of stations at 200 m and 500 m distance from each platform in the northwest, northeast, southeast and southwest directions.

The results of the surveys indicated that physical processes dominated the sea bottom environment in the study area which consisted of either muddy sediments with relatively well-developed and mature infaunal communities or fine sand where no traces of infauna were observed. Examination of over 2,000 pre-drill and post-drill SPI images indicated an absence of widespread nearfield accumulation of drilling solids on the sea floor. Out of the 100 stations where co-located before and after images were available for direct side-by-side comparison, only two stations located 100 m and 200 m distant from one platform yielded evidence of an episodic deposition event potentially linked with discharges from the 2010 drilling operations. No other indications of contemporaneous mud and cuttings discharges were found during the SPI surveys. Comparisons are made of the use of SPI technology with the results of physical, chemical and biological sampling and testing, and predictions using dispersion modeling.

Introduction

Mobil Producing Nigeria (MPN) first began oil exploration and production operations offshore Nigeria in 1970. Up until 2002 waste materials from drilling were discharged into the sea locally at each drill site. Since 2002, only water-based mud and cuttings from the drilling operations have been discharged, all other drilling wastes (i.e., oil-based and synthetic mud and cuttings) have been transported for treatment onshore.

In 2010 MPN commissioned a study to evaluate the potential environmental impacts of the water-based fluid (WBF) and cuttings discharges associated with the conduct of a drilling program at oil production platforms in MPN’s offshore operational area. This was required as a result of the Nigeria Department of Petroleum Resources *Environmental Guidelines and Standards for the Petroleum Industry In Nigeria* (EGASPIN) 2002 Edition, which prohibits offshore discharge except in permitted discharge zones more than 12 nmi from shoreline in more than 200 feet water depth. In order to pursue a science-based approach for EGASPIN requirements, SPI surveys were conducted to evaluate seabed conditions before drilling began (pre-drill survey) and after drilling was completed (post-drill survey). Comparison of the before and after drilling SPI survey results were used in evaluating the impact of drilling operations discharges on the seabed.

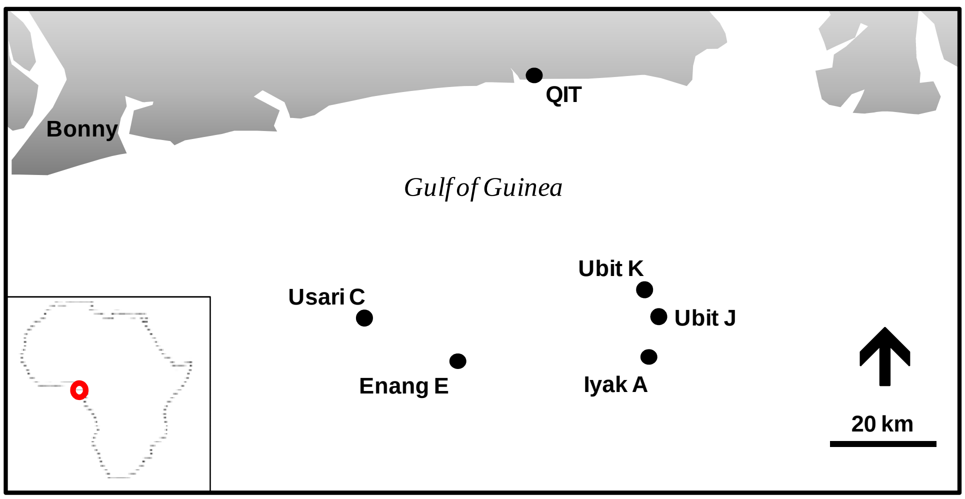
Study Area

The locations of the five platforms where SPI surveys were conducted before and after drilling discharges took place, are listed in Table 1 and shown graphically in Figure 1.

Table 1: Platform Locations

Platform Name	Location	Latitude (WGS 1984)	Longitude (WGS 1984)	Distance from Shoreline (km)	Water Depth (m)
Enang E	OML 70	7° 54' 39.661" E	4° 11' 08.776" N	38.1	28
Iyak A	OML 67	8° 09' 06.354" E	4° 11' 24.743" N	39.0	33
Ubit J	OML 67	8° 09' 57.613" E	4° 14' 37.599" N	33.2	30
Ubit K	OML 67	8° 8' 54.049" E	4° 16' 27.362" N	29.8	28
Usari C	OML 70	7° 47' 29.983" E	4° 14' 25.609" N	30.7	24

Figure 1: Study Area



Drilling Operations

The pre-drill SPI survey fieldwork was performed aboard the M/V *Wilbert Tide* from 2–10 March 2010. Following the SPI survey, MPN's drilling program commenced and water-based fluid and cuttings were discharged at the five platforms between March and October 2010 (Table 2). A post-drill survey was then conducted aboard the same vessel from 9 – 14 December 2010.

Table 2: Water Based Fluid Discharge Periods

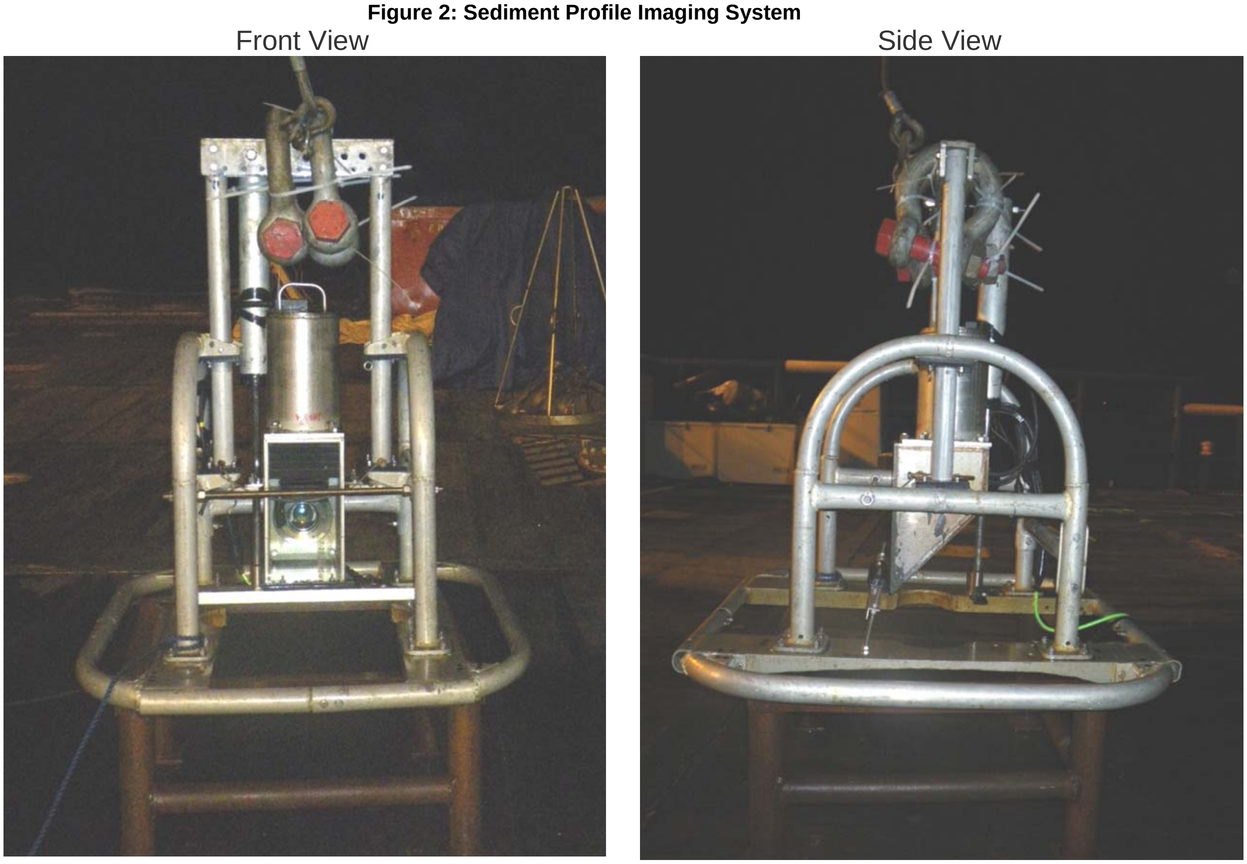
Platform	Well Name	Wellhead Location		WBF Discharge Period	
		Longitude	Latitude	Start Date	End Date
Enang E	Enang 67E (West-AA1)	7° 54' 39.486" E	4° 11' 08.859" N	29-Apr-2010	5-May-2010
	Enang 68E (E-South)	7° 54' 39.670" E	4° 11' 08.757" N	12-Jun-2010	15-Jun-2010
Iyak A	Iyak 20A (A4 UB)	8° 09' 06.267" E	4° 11' 24.739" N	22-Mar-2010	27-Mar-2010
Ubit J	Ubit 159J (J-5)	8° 09' 58.020" E	4° 14' 36.970" N	29-Sep-2010	01-Oct-2010
	Ubit 160J (J-4)	8° 09' 57.885" E	4° 14' 36.628" N	04-Oct-2010	06-Oct-2010
	Ubit 161J (J-6)	8° 09' 58.020" E	4° 14' 36.970" N	09-Oct-2010	11-Oct-2010
	Ubit 162J (J-AGL)	8° 09' 57.920" E	4° 14' 37.000" N	14-Oct-2010	15-Oct-2010
Ubit K	Ubit 153K (K-4)	8° 08' 53.852" E	4° 16' 27.227" N	10-Mar-2010	14-Mar-2010
	Ubit 154K (K-5)	8° 08' 53.852" E	4° 16' 27.218" N	08-Apr-2010	13-Apr-2010
	Ubit 155K (K-6)	8° 08' 53.839" E	4° 16' 27.223" N	15-Apr-2010	20-Apr-2010
Usari C	Usari 46C HZ (BB1)	7° 47' 29.872" E	4° 14' 25.538" N	09-Jul-2010	13-Jul-2010
	Usari 47C HZ (AA1)	7° 47' 29.708" E	4° 14' 25.380" N	15-Jul-2010	19-Jul-2010

SPI Equipment

SPI technology is an effective reconnaissance tool for evaluating and characterizing seabed conditions; the technology involves the use of a submersible digital camera to penetrate and acquire vertical cross-sectional photographic images of the seabed surface and underlying substrate that can be visually analyzed for a range of physical, chemical, and biological properties.

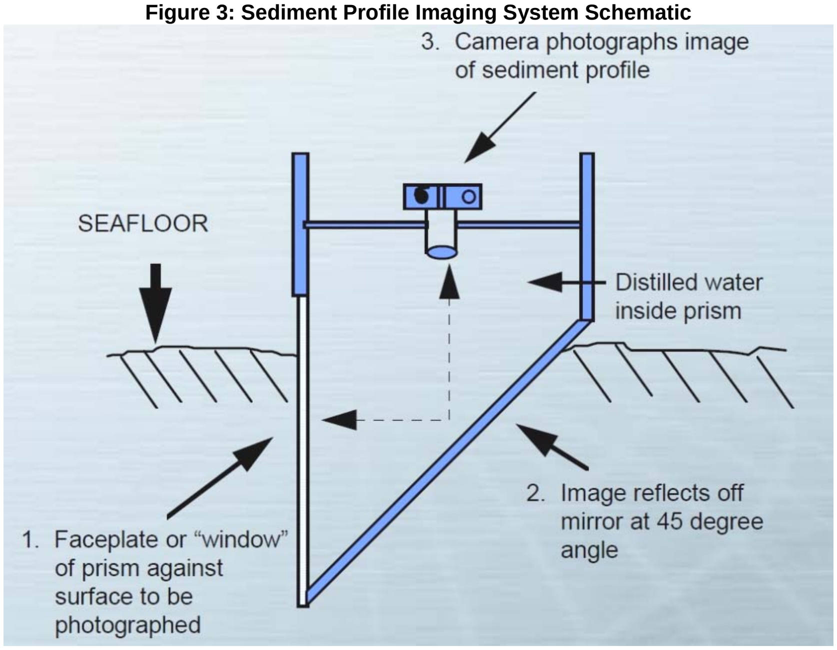
The sediment profile camera equipment (Figure 2) was developed to investigate the nature and structure of the sediment-water interface, and as a means of obtaining *in situ* data on benthic habitat conditions (Rhoads and Cande 1971). SPI technology has allowed for the development of an improved understanding of the complexity of sediment dynamics from physical, chemical, and biological points of view (Rhoads and Germano 1986, Nisson and Rosenberg 1997, Rosenberg et al. 2001).

Figure 2: Sediment Profile Imaging System



The SPI system works like an inverted periscope, wherein a digital SLR camera enclosed in a water-tight, pressure-resistant housing is mounted on top of a wedge-shaped optical prism (Figure 3). The prism has an anterior transparent faceplate (1) with a mirror placed at a 45º angle to the rear (2). The camera lens (3) looks down at the mirror and reflects the image from the faceplate. The prism has a light-emitting diode (LED) and strobe mounted next to the camera lens to provide sub-seabed illumination. The interior prism chamber is filled with fresh or distilled water which is exchanged periodically to ensure the camera/prism assembly always has a clear optical path; on some models the chamber is air-filled.

Figure 3: Sediment Profile Imaging System Schematic



The camera/prism assembly is mounted on a carriage attached to a frame which enables the prism to move up and down relative to the frame and penetrate the sediment when lowered to the seabed. After attaching to a winch wire and hoisting overboard, the frame is lowered at a steady rate to the seafloor with the prism in its 'up' position. When the frame encounters the sediment, the winch wire goes slack and the camera/prism assembly descends orthogonally into the seabed at a slow rate controlled by the dampening action of a hydraulic piston so as to minimize disturbance of the sediment. The leading-edge of the prism transects the sediment-seawater interface as it penetrates the seafloor.

The camera operator, while remotely viewing the prism as it penetrates the seabed, chooses when to record the sediment profile images. The camera is triggered at the desired moment and the strobe is discharged to obtain a cross-sectional photograph of the sediment profile. The resulting image gives the viewer a perspective analogous to looking through the side of an aquarium. The system is then raised up about 2-3 meters off the bottom; the strobe recharges within several seconds, and the system is ready to be lowered again for replicate images.

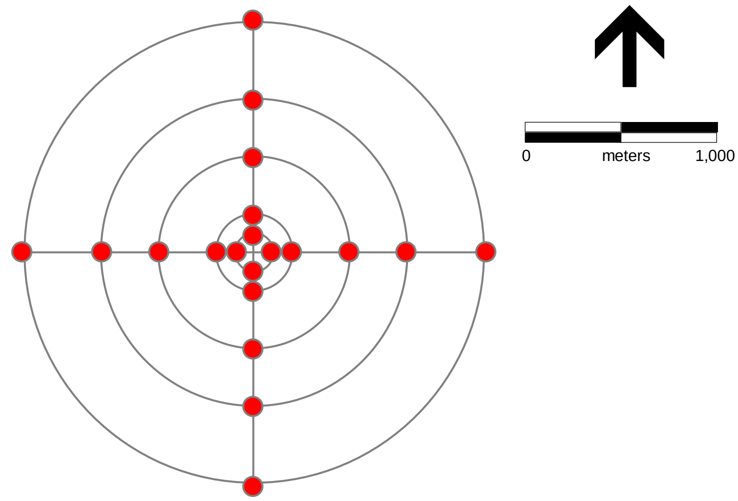
At each station, up to three or more replicate drops were performed using the SPI system. Each time the camera touched the sea bottom, a series of two to four photographs was taken, generally within the first 15 seconds after bottom contact. Each red/green/blue (RGB) exposure was stored to a flash memory card. This level of redundancy helped ensure that at least one composite photograph of the full depth of the sediment profile up to about 20 cm depth could be produced at each station, and so that local sea bottom variability could be assessed.

After the desired number of replicates was performed, the system was retrieved to the vessel, and the date, time, location, station, water depth, image number, and estimated penetration depth recorded. Vessel navigation to each station was performed by the vessel crew; on-station location was independently verified and recorded using a Garmin GPSMAP® 76CSx high-sensitivity global positioning system (GPS) receiver.

Survey Design

The pre-drill seabed conditions at each of the six platforms were surveyed using an array of 20 nearfield stations, configured at 100 m, 200 m, 500 m, 800 m and 1,200 m distance along of the cardinal directions from each platform (Figure 4). A set of three farfield reference stations was also located up to as much as 10 km or more from each platform for a total of 138 stations that were conducted during the March 2010 pre-drill survey.

Figure 4: Pre-Drill Nearfield SPI Station Array



During the December 2010 post-drill survey, the images obtained were evaluated as they were captured in real-time to allow in-field adjustment of the survey plan and station locations. Based on the initial post-drill survey results indicating an absence of widespread nearfield cuttings accumulation detected on the sea floor, the orthogonal array of 20 pre-drill station locations was supplemented by the addition of stations at 200 m and 500 m distance from the platform in the northwest, northeast, southeast and southwest directions at the five platforms where discharges took place (Figure 5).

Figure 5: Post-Drill Nearfield SPI Station Array

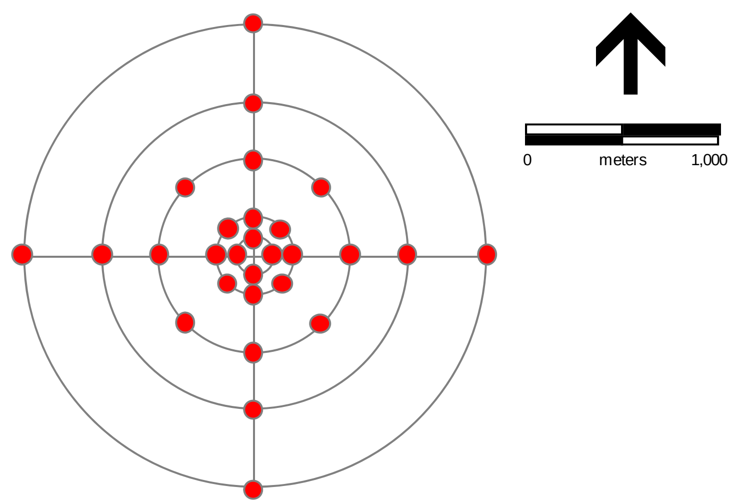


Image Analysis

The sediment profile images obtained from the pre-drill and post-drill surveys were analyzed visually and the data recorded in a preformatted spreadsheet file. The best image, usually one of the last in each series, was analyzed digitally with Adobe® PhotoShop® and ImageJ, a public domain, Java-based image processing program developed at the National Institutes of Health (Collins 2007). Data from each image were saved sequentially to a spreadsheet file for later analysis according to the methods of Diaz and Schaffner (1988) and Rhoads and Germano (1982). A listing of parameters recorded is provided in Table 3; a description of each parameter measured and evaluated follows.

Sediment Grain Size — Grain size is an important parameter for determining the nature of the physical forces acting on a habitat and is a major factor in determining benthic community composition (Rhoads 1974). The sediment type descriptors used for image analysis follow the Unified Soil Classification System (ASTM 1985) and represent the major modal class for each image. Maximum grain size was also estimated. The grain size for silty to gravelly sediments was determined by comparison with a set of standard images for which mean grain size had been previously determined in the laboratory.

Table 3: Sediment Profile Imaging Parameters

Parameter	Units	Method	Description
Sediment Grain Size	Modal phi interval	Visual	An estimate of sediment types present. Determined from comparison of image to images of known grain size
Prism Penetration	cm	Computer Analysis	A geotechnical estimate of sediment compaction. Average of maximum and minimum distance from sediment surface to bottom of prism window
Sediment Surface Relief	cm	Computer Analysis	An estimate of small-scale bed roughness. Maximum depth of penetration minus minimum
Apparent Reduction-oxidation Potential Discontinuity Depth (from color change in sediment)	cm	Computer Analysis	Estimate of depth to which sediments appear to be oxidized. Area of aerobic sediment divided by width of digitized image
Thickness of Sediment Layers	cm	Computer Analysis	Measure thickness above original sediment surface
Methane/Nitrogen Gas Voids	Number	Visual	Count
Epifaunal Occurrence	Number	Visual	Count, identify
Tube Density	Number/sq. cm	Visual	Count
Tube Type			
Burrow Structures	Number	Visual	Identify
Pelletal Layer	Present/Absent	Visual	Determine presence
Bacterial Mats	Present/Absent	Visual	Determine presence and color
Infaunal Occurrence	Number	Visual	Count, identify
Feeding Voids	Number	Visual	Count, measure thickness, area
Apparent Successional Stage	—	Visual, Computer Analysis	Estimated based on all of the above parameters
Organism Sediment Index	—	Computer Analysis	Derived from RPD, successional stage, gas voids

Prism Penetration — This parameter provided a geotechnical estimate of sediment compaction with the profile camera prism acting as a dead weight penetrometer. The further the prism entered into the seabed, the less dense the sediment and likely the higher the water content. Penetration was measured as the distance the 23-cm faceplate entered beneath the seabed surface.

Sediment Surface Relief — Surface relief or boundary roughness was measured as the difference between the minimum and maximum distance the prism penetrated. This parameter also estimated small-scale bed roughness, on the order of the prism faceplate width (15.5 cm). The origin of bed roughness can be determined from visual analysis of the images.

Apparent Redox Potential Discontinuity (aRPD) Layer — This parameter is an important estimator of benthic habitat conditions, which relates directly to the quality of the habitat (Rhoads and Germano 1986, Nilsson and Rosenberg 1997, Diaz and Schaffner 1988). An estimate of the depth to which sediments appear to be oxidized is provided by aRPD. The position of the RPD layer is determined by the depth in the sediment profile where the redox potential changes from positive to negative voltage (i.e. Eh = 0 mV). The term "apparent" is used in describing this parameter because no actual measurement is made of the redox potential during the SPI survey. It is assumed that given the complexities of iron and sulfate reduction-oxidation chemistry the reddish-brown sediment color tones indicate sediments are in an oxidative geochemical state, or at least are not intensely reducing (Diaz and Schaffner 1988, Rosenberg 2001). This is consistent with the classical concept of RPD layer depth, which associates it with sediment color (Fenchel 1969, Vismann 1991). The aRPD has been very useful in assessing the quality of a habitat for epifaunal and infaunal organisms from both physical and biological perspectives. Various researchers have found the depth of the RPD layer from sediment profile images to be directly correlated to the quality of the benthic habitat (Rhoads and Germano 1986, Nisson and Rosenberg 1997, Diaz and Schaffner 1988, Rosenberg 2001, Valente et al. 1992, Bonsdorff et al. 1996). Deeper RPD layers have been associated with higher benthic habitat quality.

Subsurface Features — Subsurface features included a wide variety of characteristics (such as sediment layering, gas voids, epifaunal occurrence, tube density and type, infaunal occurrence or feeding voids) that reveal information about physical and biological processes influencing the sea bottom. For example, habitats with grain-size layers or homogeneous color layers are generally dominated by physical processes, while habitats with burrows, infaunal feeding voids, and/or visible infaunal organisms are generally dominated by biological processes (Rhoads and Germano 1986, Diaz and Schaffner 1988, Valente et al. 1992). Subsurface features were visually evaluated from each image and compiled by type and frequency of occurrence.

Apparent Successional Stage — Sediment profile data have also been used to estimate the successional stage of the benthic infaunal community (Rhoads and Germano 1986). Characteristics associated with pioneering or colonizing (Stage I) assemblages (Odum 1969), such as dense aggregations of small polychaete tubes at the surface and shallow aRPD layers, are easily seen in sediment profile images. Advanced or equilibrium (Stage III) assemblages also have characteristics that are easily seen in profile images, such as deep aRPD layers and subsurface feeding voids. Stage II is intermediate between Stages I and III, and has characteristics of both (Rhoads and Germano 1986). A set of SPI parameters are evaluated to estimate successional stage with the generalized associations described in Table 4.

Table 4: Relationship of SPI Parameters with Successional Stage

Parameter	Successional Stage		
	I	II	III
Average RPD (cm)	<1	1-3	>2
Max depth RPD (cm)	<2	>2	>4
Small Tubes	+++	++	+
Large Tubes	–	++	+++
Burrows	–	++	+++
Feeding Voids	–	+	+++
Small Infauna	+++	++	+
Large Infauna	–	+	++
Epifauna	+	++	++

– = not associated with, + = associated with, ++ = moderately associated with, +++ = strongly associated with

Organism Sediment Index — The multi-parameter organism-sediment index (OSI) was developed to characterize benthic habitat quality from data provided by the sediment profile images (Rhoads and Germano 1986). The OSI defines quality of benthic habitats by evaluating the depth of the aRPD, successional stage of macrofaunal organisms, the presence of gas bubbles in the sediment (an indication of high rates of methanogenesis that are associated with high carbon inputs to sediments), and visual signs of the presence of low dissolved oxygen conditions (sulfide covered tubes, anaerobic sediment at the interface, bacterial mats) at the sediment-water interface. The parameter ranges and scores used in the calculation of the OSI are shown in Table 5 (Rhoads and Germano 1986).

Table 5: Parameter Ranges and Scores for Calculation of OSI

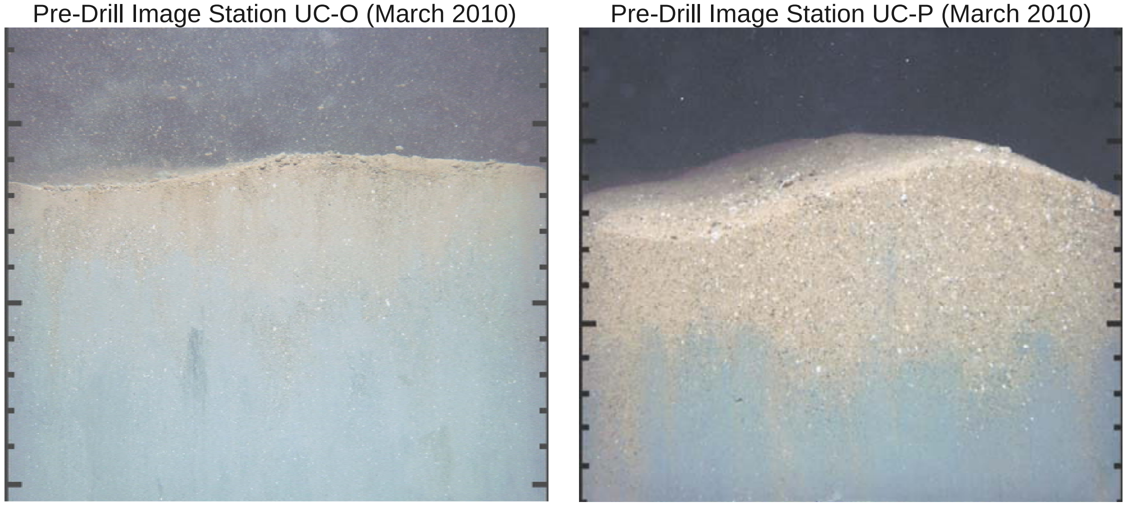
Depth of Apparent Color RPD (cm)		Estimated Successional Stage	
0 =	0	Azoic =	-4
>0-0.75 =	1	I =	1
0.75-1.5 =	2	I-II =	2
1.5-2.25 =	3	II =	3
2.25-3.00 =	4	II-III =	4
3.00-3.75 =	5	III =	5
>3.75 =	6	I on III =	5
		II on III =	5
Other:			
Methane or gas voids present =	-2		
No/Low DO =	-4		

Stage I on III refers to the presence of pioneering Stage I species present on or near the sediment surface, and equilibrium Stage III species present below the sediment surface. Similarly, Stage II on III is the presence of intermediate successional stage species at the surface with equilibrium species at depth in the sediments. The OSI ranges from -10 (poorest quality habitats) to +11 (highest quality habitats). The OSI has been used to map disturbance gradients (Valente et al. 1992) and follow ecosystem recovery after disturbance abatement (Rhoads and Germano 1986). For estuarine and coastal bay benthic habitats in the northeastern United States OSI values >6 indicate good habitat conditions and are generally associated with seabed environments that are not heavily influenced by stress, either physical or anthropogenic. The formulation of the OSI and contribution of each component are scaled to reflect the increasing importance of bioturbation, sediment mixing mediated by organisms, and other biogenic activity such as structure building, in defining good benthic habitat quality.

Survey Results

As revealed by analysis of the images obtained before drilling, blue-gray clay appears to underlie the whole study area (Figure 6). In some areas, brown sand constitutes a relatively thin (generally up to about 5 cm or more in thickness) transient surficial 'veneer' on the seabed surface, the extent and thickness of which may vary in both space and time according to natural hydrodynamic processes at work. At some stations, replicate drops illustrated this variability whereby sand visible in the image from one drop is relatively thin or absent in another drop only a few meters distance away.

Figure 6: Typical Sediment Profile Image (Platform UC)



Physical processes appear to dominate the seabed surface at the stations in the study area. Biogenic activity of benthic organisms is limited to a few burrows and voids that appear to be related to feeding activities of subsurface fauna. Prism penetration, a proxy for sediment compaction, correlates to sediment grain-size with lowest penetration, and therefore higher compaction, at fine sand stations and highest penetration (lowest compaction) in fine sand-silt-clay and silt-clay sediments.

Based on the generally light color of sediments observed in the SPI images at most stations, the Eh values are likely positive over the entire depth of prism penetration. The light color of sediments in the SPI photographs indicates low organic content and oxidized geochemical conditions at many stations. Reduced sediments, which are darker in color, occur at some stations at platforms UC, UJ and UK. The measurements of aRPD within the study area are thought to be more related to the depth to which oxygen penetrates into the sediments compared to organic content. For low organic content in deep-sea sediments, aRPD measurements have been found to correlate with the depth of oxygen penetration and not the actual RPD layer depth (Diaz and Trefry 2006). In higher organic content sediments, aRPD measurements are highly correlated with Eh profiles and the RPD layer depth (Rosenberg et al. 2001).

Based on the pre-drill SPI data, it appears that much of the eastern study area where muddy seafloor sediments are exposed (predominantly in vicinity of IA, UJ and UK) has relatively well-developed and mature infaunal communities. The estimated successional stage ranges from Stage I-II to Stage I-III: Stage I being pioneering or early development and Stage III being mature or equilibrium, with Stage II being intermediate between I and III. Signs of equilibrium species are the subsurface feeding voids. Benthic habitat conditions for infauna were assessed using the SPI-derived OSI (Rhoads and Germano 1986). The OSI ranged from 3 to 11 indicating a range of benthic habitat conditions from stressful to very good. Most stations in the western study area where a fine sandy layer overlies the blue-gray mud (predominantly in vicinity of EE, IA and UC), successional stage could not be determined as few traces of fauna were observed. The source of stressors is considered to be natural physical processes related to lateral sediment movement in sandy areas, and resuspension/deposition in muddy areas.

Comparison of Pre-Drill and Post-Drill Images

Including replicate drops at each station, a total of over 860 pre-drill and over 1,210 post-drill sediment profile images were obtained during the March and December 2010 surveys. Each post-drill image was individually evaluated for evidence of recent depositional characteristics that might be attributable to the discharge of drilling fluid and cuttings based on factors such as color, grain size, textural gradation, aRPD, biota and other criteria.

Sediment profile images obtained in March and December 2010 at the same stations were compared side-by-side. Examination of over 2,000 pre-drill and post-drill images obtained during the SPI surveys indicates an absence of widespread near-field accumulation of drilling solids on the sea floor due to the 2010 discharge of water-based drilling fluid and cuttings. Overall, pre- and post-drill images obtained at each station are remarkably similar. Of the 100 stations where co-located, pre- and post-drill images are available for direct side-by-side comparison, only two stations at one platform (EE-A and EE-B) yielded some evidence of episodic deposition potentially linked with discharges from the 2010 drilling operations. No other indications of contemporaneous discharges were found during the SPI surveys.

Before and after images for Station EE-A 100 m east of the wellsite (Figure 7) are reproduced in Figure 8 below. Compared with the pre-drill image, it can be seen in the post-drill image how a loose, light gray heterogeneous material up to about 2 cm or more in thickness is superimposed with a sharp lateral discontinuity over the underlying darker blue-gray gradationally layered naturally-occurring sediment, with burial of foraminfera evident at the pre-drill seabed surface.

Figure 7: Platform Enang Station EE-A

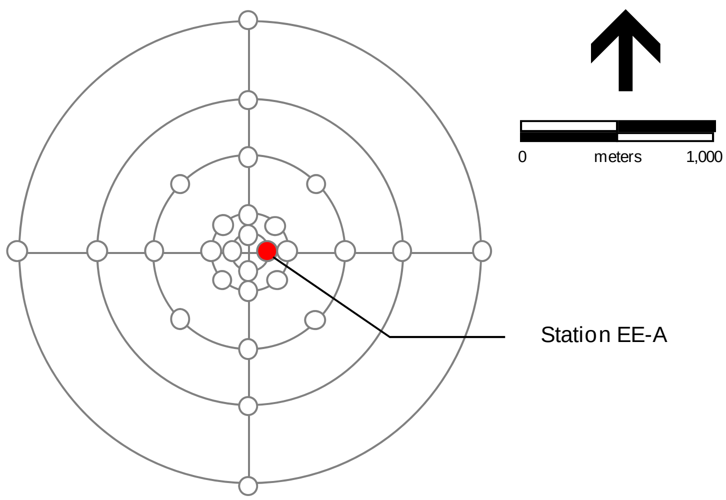
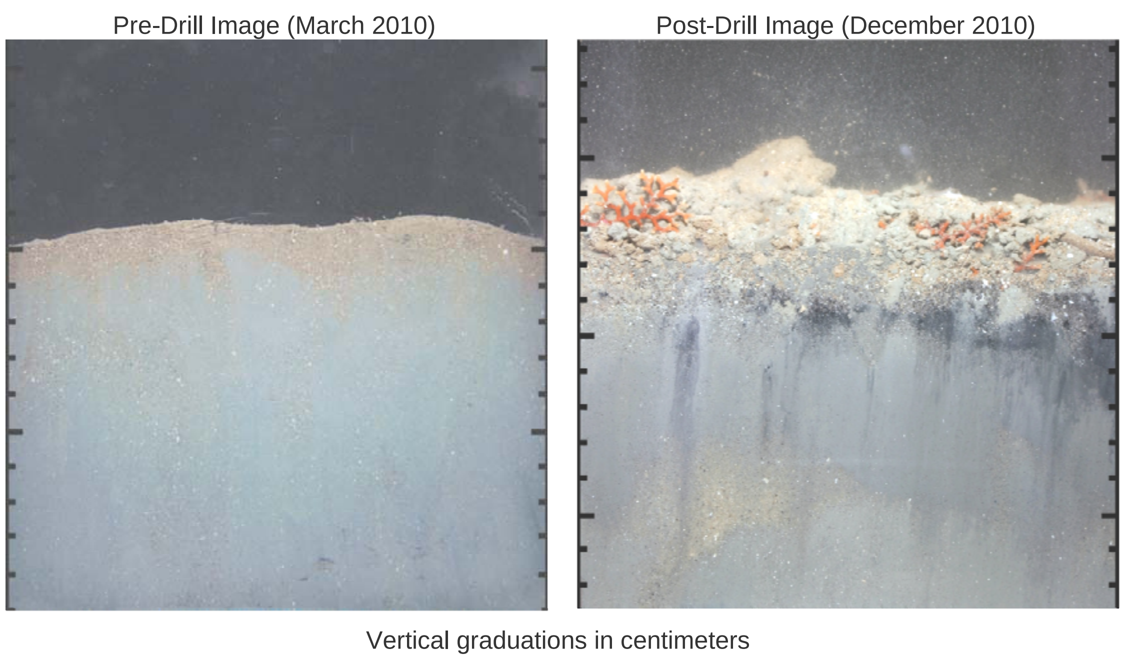


Figure 8: Comparison of Pre-Drill and Post-Drill Images at Station EE-A



Complementary Lines of Investigation

The results of the SPI survey were compared with numerical simulations using the Offshore Operators Committee (OOC) mud and produced water discharge model. The OOC model simulations predicted the material discharged would form a deposit on the seabed elongated in the north-south direction, in line with the prevailing tidal currents. Discharged drilling fluids and cuttings were predicted to travel maximum distances of approximately 2,500 meters to the north and south, 1,300 meters to the east and 500 meters to the west. The maximum predicted loading, occurring immediately adjacent to the wells (within approximately 50 meters distance), ranged from 200 – 448 kg/m^2. However, based on the lack of SPI supporting evidence it was concluded that the model over-estimated the accumulation of mud and cuttings at locations outside this area.

The results of the SPI survey combined with the findings from other contemporaneous lines of physical, chemical and biological multimedia investigations commissioned by MPN showed there was no observable long-term impact on the marine environment, as follows:

- Drilling fluids and cuttings tested were chemically similar to typical marine sediments and did not contain elevated concentrations of heavy metals.
- Drilling fluids and cuttings submitted to standard toxicity testing rated from ‘almost nontoxic’ to ‘nontoxic’ to aquatic organisms (GESAMP 2002).
- Impacts on water quality (TSS) diminished rapidly with distance from point of discharge.
- Impacts on the water and seabed biological communities were transient; impacted communities demonstrated considerable resiliency.
- Statistical analysis of the distribution patterns of chemical constituents and concentrations in benthic samples collected did not reveal the presence of a defined sedimentary plume on the sea floor as a result of the 2010 drilling program.

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