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Final Report

Boston Harbor Deep Draft Navigation Improvement Project Biological Resource Surveys,

Sediment Profile Imaging (SPI) Survey

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Biological Resource Surveys,

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To:

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1.0 INTRODUCTION

1.1 Background

There are many harbors, channels and navigation dependant facilities in Boston Harbor, Massachusetts that must undergo periodic maintenance dredging to ensure safe navigation. Some harbors occasionally must be deepened beyond historical depths to meet changing economic and safety needs. The U.S. Army Corps of Engineers, New England District (NAE), and the Massachusetts Port Authority (Massport) are preparing a joint Supplemental Environmental Impact Statement (SEIS) and Notice of Project Change (NPC) for the Boston Harbor Deep Draft Navigation Improvement Project. The purpose of the joint SEIS/NPC is to evaluate the feasibility of deep draft navigation improvements to the Boston Harbor, Massachusetts Federal Navigation Project. The project will explore alternatives for accommodating increased deep draft vessel traffic in Boston Harbor including a no action alternative. Alternatives will include incremental deepening schemes for the Broad Sound North Entrance Channel, President Roads Ship Channel and Anchorage area, Reserved Channel and the Main Ship Channel (below the Ted Williams Tunnel) from –40 feet up to –50 feet mean lower low water (MLLW), a portion of the Mystic River channel from –35 feet to –40 feet MLLW and the Chelsea River channel from –38 feet to –40 feet MLLW, all with deepening of associated berthing areas. Although the quantity of dredged material that could be generated varies depending on the alternative, it is estimated that the typical plan would generate approximately six million cubic yards of dredged material. While the full range of disposal alternatives will be investigated, it is expected that the majority of the material will be suitable for disposal at the Massachusetts Bay Disposal Site. The remaining unsuitable material may be disposed in one of the previously permitted confined aquatic disposal (CAD) cells identified as part of the previous Boston Harbor navigation improvement project. One additional disposal alternative that may be considered as part of the deepening project is the creation of hard bottom habitat using the rock and cobble dredged from the channel. A series of field surveys to collect data describing Boston Harbor at five areas are being performed to provide data for evaluation of hard bottom habitat creation.

1.2 Objectives

This report summarizes the results of the Sediment Profile Image (SPI) survey (Task 11B-1). SPI data were collected from five areas proposed for hard bottom habitat creation within Boston Harbor and Massachusetts Bay (Figure 1). Results will be used to (a) determine from sediment profile images (SPI) the typical range of values for Redox Potential Discontinuity (RPD), surface roughness whether biologically or physically induced, grain size (composite of grain size throughout entire photograph), presence of any layering in the sediment, presence of methane or other evidence of low dissolved oxygen, and comparison of benthic organisms observed by those collected from the grab samples, (b) determine whether there are differences in benthic community and habitat parameters between sites, (c) determine whether there are differences in benthic community or habitat parameters associated with differences in grain size of the substrate, and (d) determine which sites are appropriate to support rock rubble by determining the surface and underlying sediment type. Ultimately this data will be used to rank sites for suitability for rock enhancement.

This survey was conducted at five areas of interest identified by the Corps of Engineers (Figure 1) and was intended as a general characterization of soft bottom substrates within the complex topography of Massachusetts Bay and Boston Harbor. Station locations were chosen based on preliminary review of sidescan data collected just prior to this survey (Battelle 2004). Sites were chosen that represented soft bottom that could easily be penetrated by the SPI camera and that represented the range of soft bottom habitat types within each area. Areas that could not be sampled using SPI methodology (e.g. hard bottom areas) must be characterized by other means such as sidescan, video, etc.

2.0 METHODS

To characterize the benthic habitats at proposed disposal sites a sediment profile image (SPI) survey was conducted on September 11, 2004. The sediment profile camera was developed by Rhoads and Cande (1971) to investigate processes structuring the sediment-water interface and as a means of obtaining *in situ* data on benthic habitat conditions. The technology of remote ecological monitoring of the sea floor (REMOTS) or sediment profile imaging (SPI) has allowed for the development of a better understanding of the complexity of sediment dynamics, from both a biological and physical point of view (for recent examples see: Bonsdorff et al. (1996), Nilsson and Rosenberg (2000), and Rosenberg et al. (2001)). This approach to evaluating the environment, and potential impacts, can be easily combined with classical approaches to habitat and impact assessment providing scientists and managers with a more holistic ecosystem view. The best example of this is the regional long-term monitoring conducted by the Massachusetts Water Resources Authority (MWRA), recently summarized by Werme and Hunt (2001, 2002, 2003).

At each station, a digital Hulcher sediment profile camera (Figure 2) was deployed twice. The digital profile camera captured a 5.2 megapixel image that produced a 14.1-megabyte Red/Green/Blue (RGB) image. Images were stored in the camera on a 1-gigabyte IBM microdrive. A video feed from the digital camera to the surface vessel allowed monitoring of camera operation and image capture in real time. The combination of video and digital images ensured a more reliable collection of SPI data. If the video indicated the camera frame did not deploy properly, additional replicates were taken. The camera was triggered from the surface about 1-sec after bottom contact and after the prism stopped penetrating the sediment. Each touch down of the camera was marked as an event on the NavSam©. In addition, the station and time of each camera penetration was recorded by hand in a Battelle field log. To improve penetration, 75 lbs of lead was added to the camera frame. While still in the field, images were transferred from the microdrive to a computer and then to a CD for more permanent storage. More detail on sediment profile camera operation can be found in Rhoads and Cande (1971).

Within each area, seven stations were located based on side-scan sonar maps. Emphasis was given to areas of low side-scan reflectance to avoid coarser sediments of pebble, cobble, or bolder which show up as darker areas on the side-scan sonar maps (Figures 3 to 7).

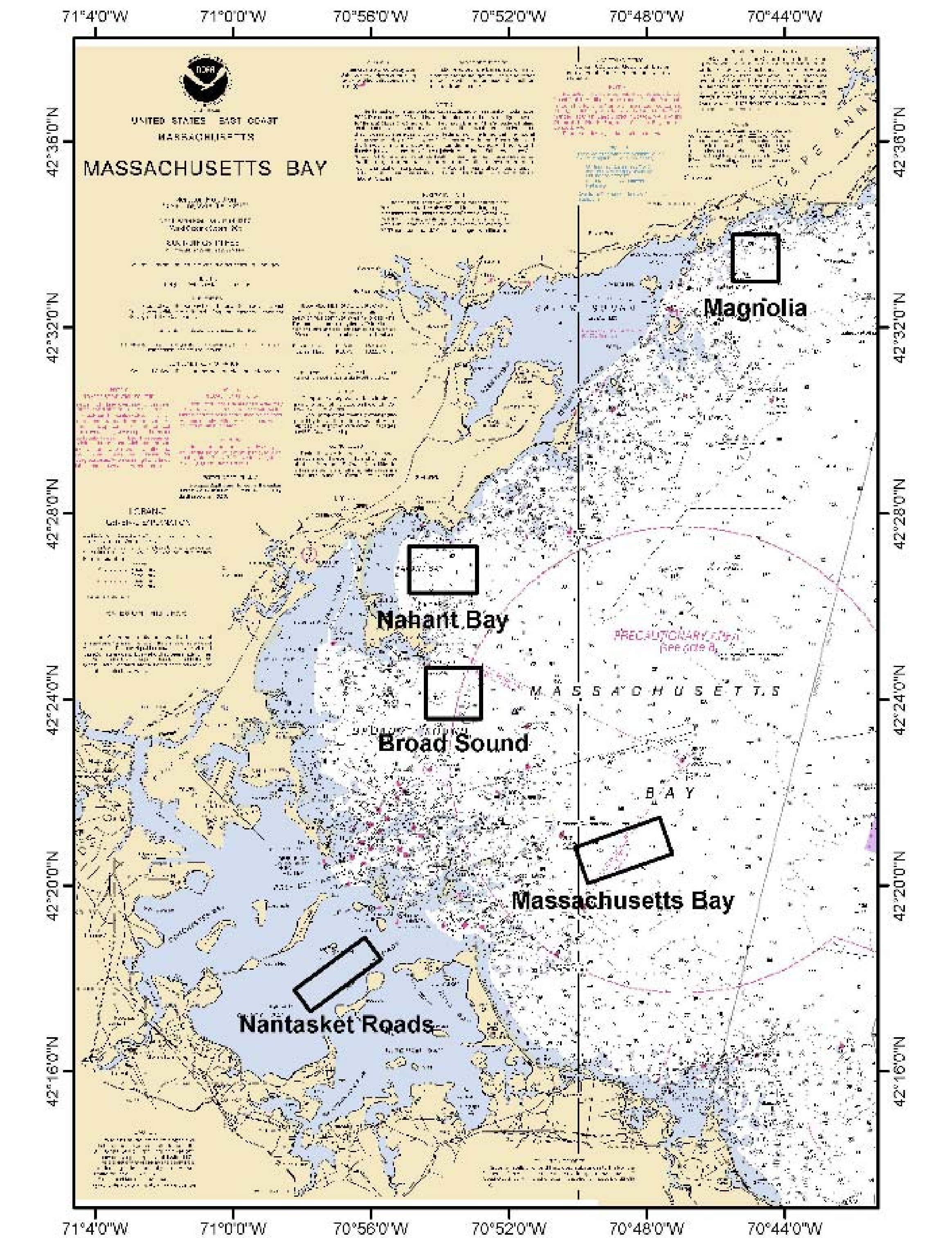

Figure 1. Sampling Locations for the SPI Survey.

Figure 2. Sediment Profile Camera, Width of Prism is 15.5 cm.

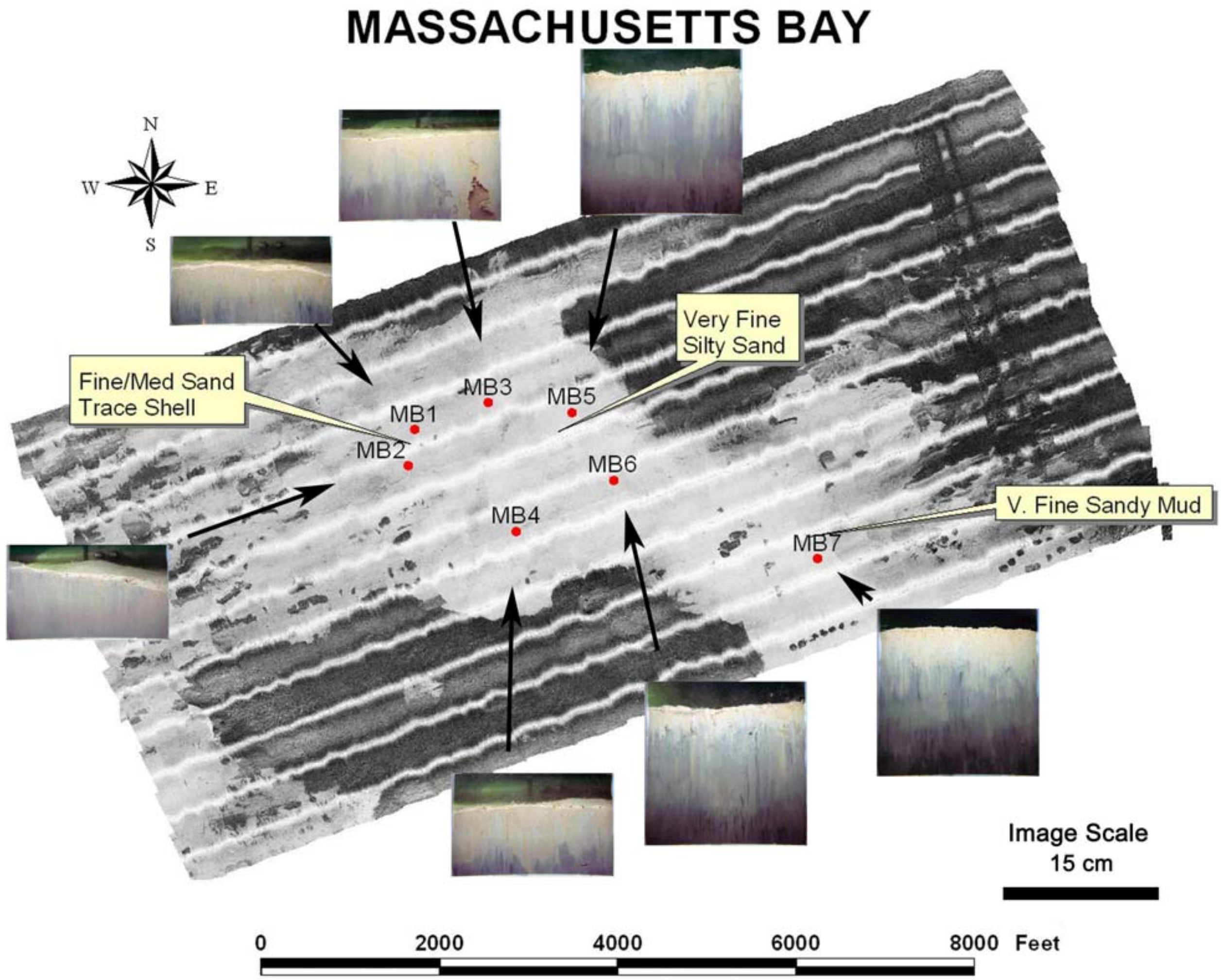

Figure 3. Location of SPI Stations within the Massachusetts Bay Site.

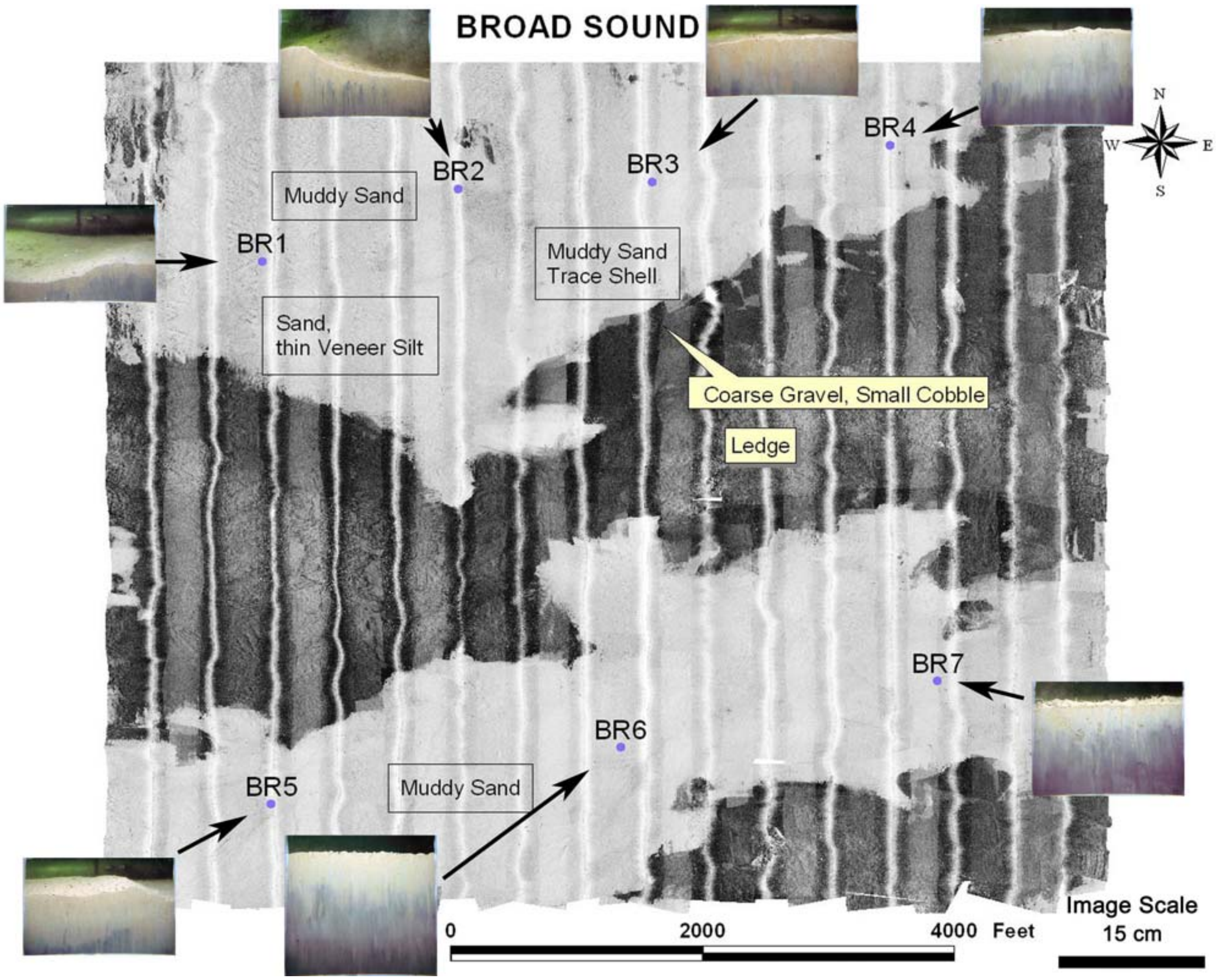

Figure 4. Location of SPI Stations within the Broad Sound Site.

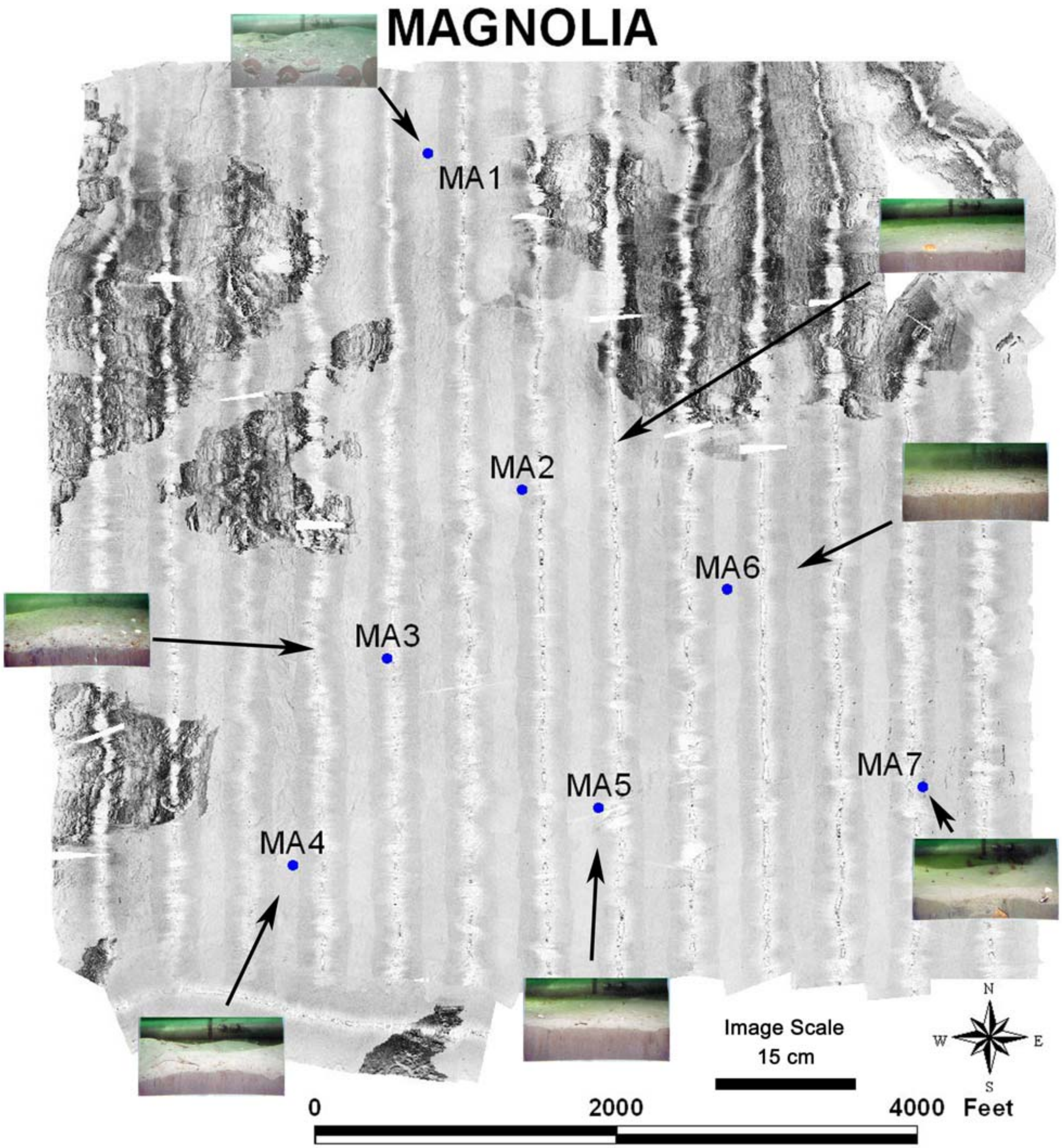

Figure 5. Location of SPI Stations within the Magnolia Site.

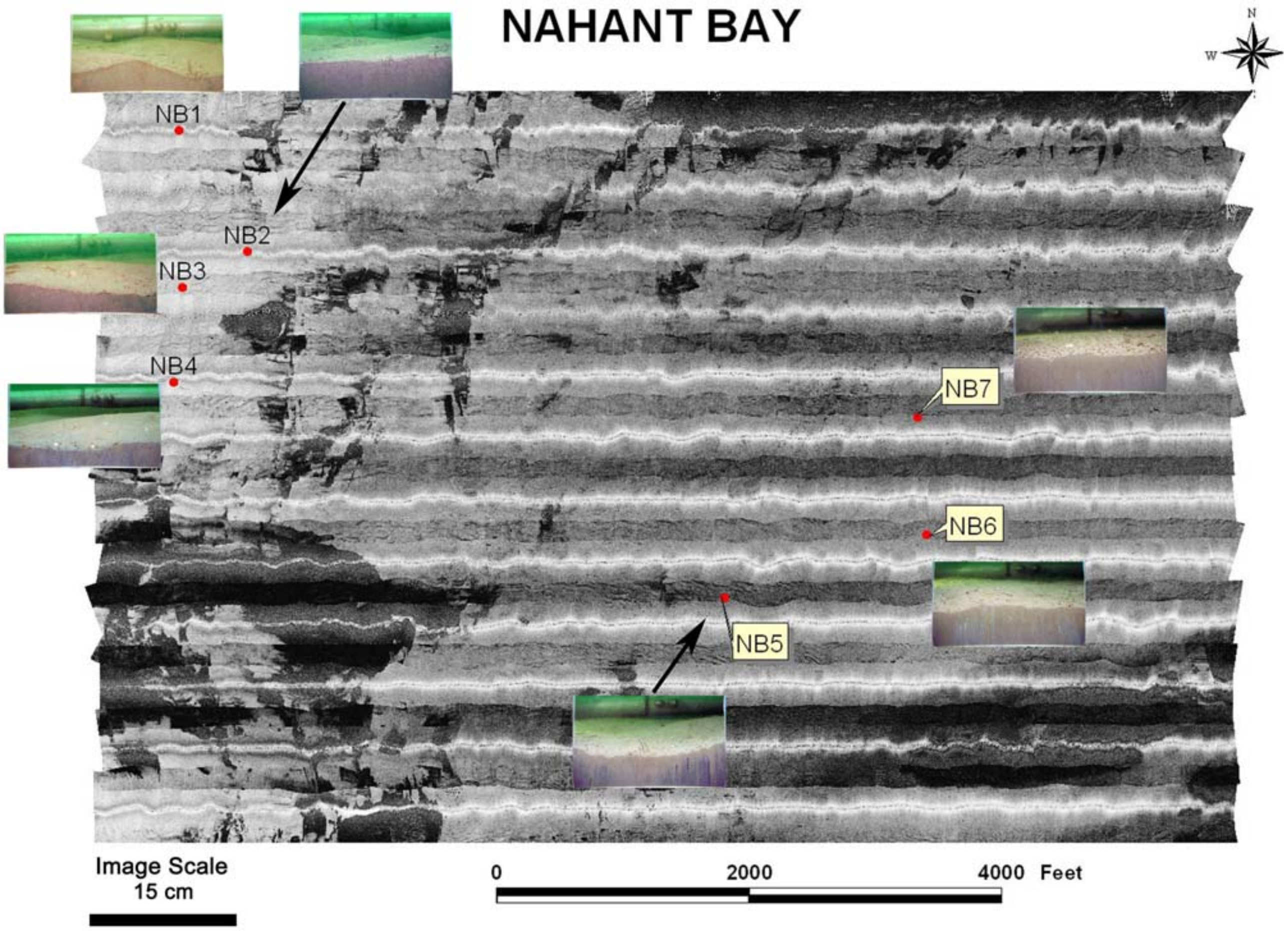

Figure 6. Location of SPI Stations within the Nahant Bay Site.

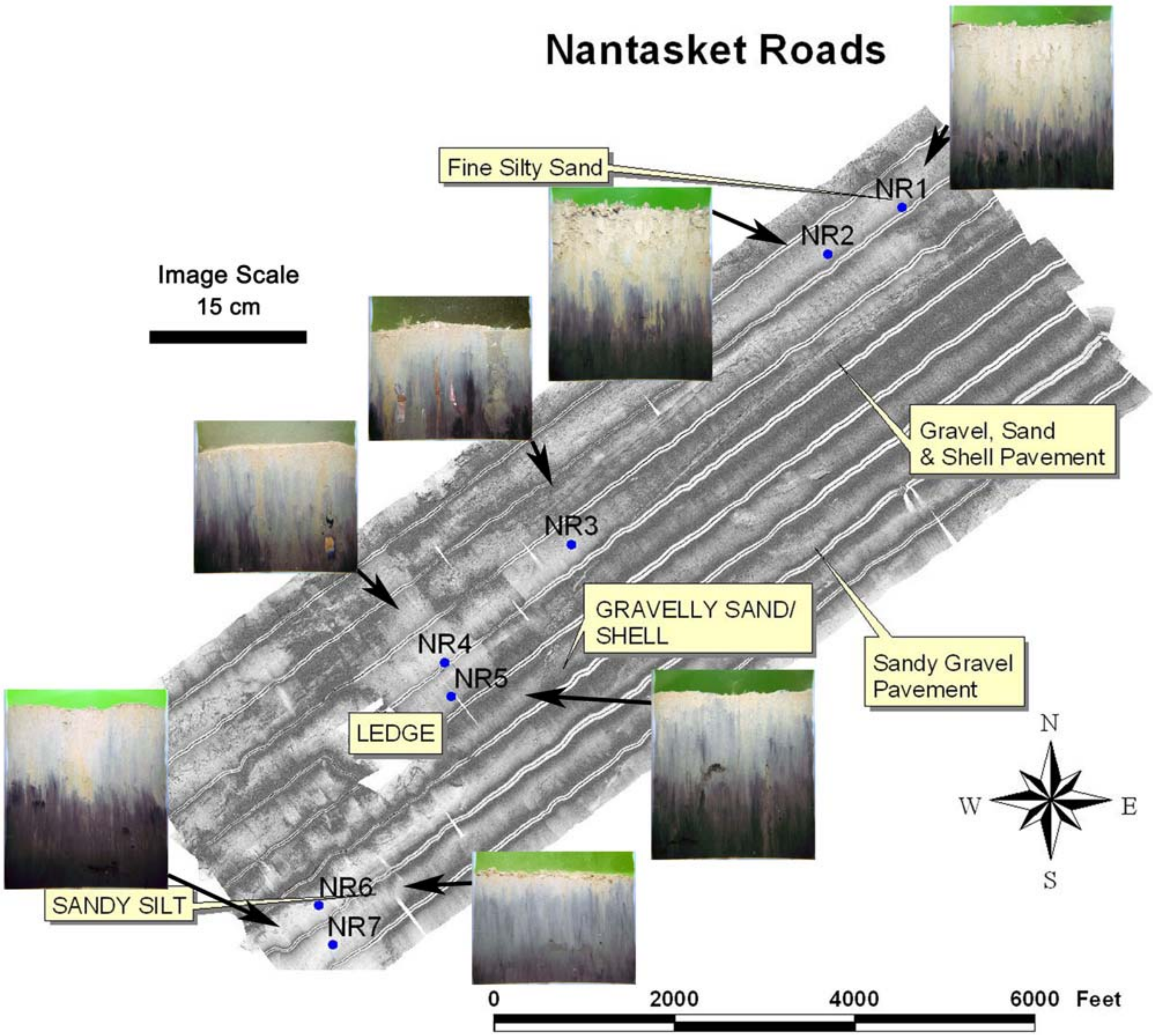

Figure 7. Location of SPI Stations within the Nantasket Roads Site.

2.1 Image Analysis

All sediment profile images were analyzed visually with data on all features seen recorded in a preformatted spreadsheet file. The least disturbed image, usually the last in the series, was analyzed digitally with Adobe PhotoShop and NTIS Image programs. Steps in the computer analysis of each image were standardized and followed the basic procedures in Viles and Diaz (1991). Data from each image were sequentially saved to a spreadsheet file for later analysis. Details of how these data were obtained can be found in Diaz and Schaffner (1988) and Rhoads and Germano (1986). A description of each parameter measured and evaluated follows.

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 sediment, the softer the sediments, and likely the higher the water content. Penetration was measured as the distance the sediment moved up the 23-cm length of the faceplate.

Surface Relief - Surface relief or boundary roughness was measured as the difference between the maximum and minimum distance the prism penetrated. This parameter also estimated small-scale bed roughness, on the order of the prism faceplate width (15.5 cm), which is an important parameter for predicting sediment transport and in determining processes that dominate surface sediments. The origin of bed roughness can be determined from visual analysis of the images. In physically dominated habitats, features such as bedforms and sediment granularity cause bed roughness. In biologically dominated habitats, bed roughness is a result of biogenic activity such as tube structures, defecation mounds, feeding pits, or epifaunal organisms such as hydroids. See Figure 8 for examples.

Apparent Color Redox Potential Discontinuity (RPD) Layer - This parameter is an important estimator of benthic habitat conditions, which relates directly to the quality of the habitat (Rhoads and Germano 1986, Diaz and Schaffner 1988, Nilsson and Rosenberg 2000). RPD provides an estimate of the depth to which sediments appear to be oxidized. The term "apparent" is used in describing this parameter because no actual measurement was made of the redox potential. It is assumed that given the complexities of iron and sulfate reduction-oxidation chemistry the reddish-brown sediment color tones (Diaz and Schaffner 1988, Rosenberg et al. 2001) indicate sediments are in an oxidative geochemical state, or at least are not intensely reducing. This is in accordance with the classical concept of RPD layer depth, which associates it with sediment color (Fenchel 1969, Vismann 1991). The apparent color RPD has been very useful in assessing the quality of a habitat for epifaunal and infaunal organisms from both physical and biological points of view. Rhoads and Germano (1986), Diaz and Schaffner (1988), Valente et al. (1992), Bonsdorff et al. (1996), Nilsson and Rosenberg (2000), and Rosenberg et al. (2001) all found the depth of the RPD layer from sediment profile images to be directly correlated to the quality of the benthic habitat with deeper RPD layers in fine-grained sediments associated with better benthic habitat quality.

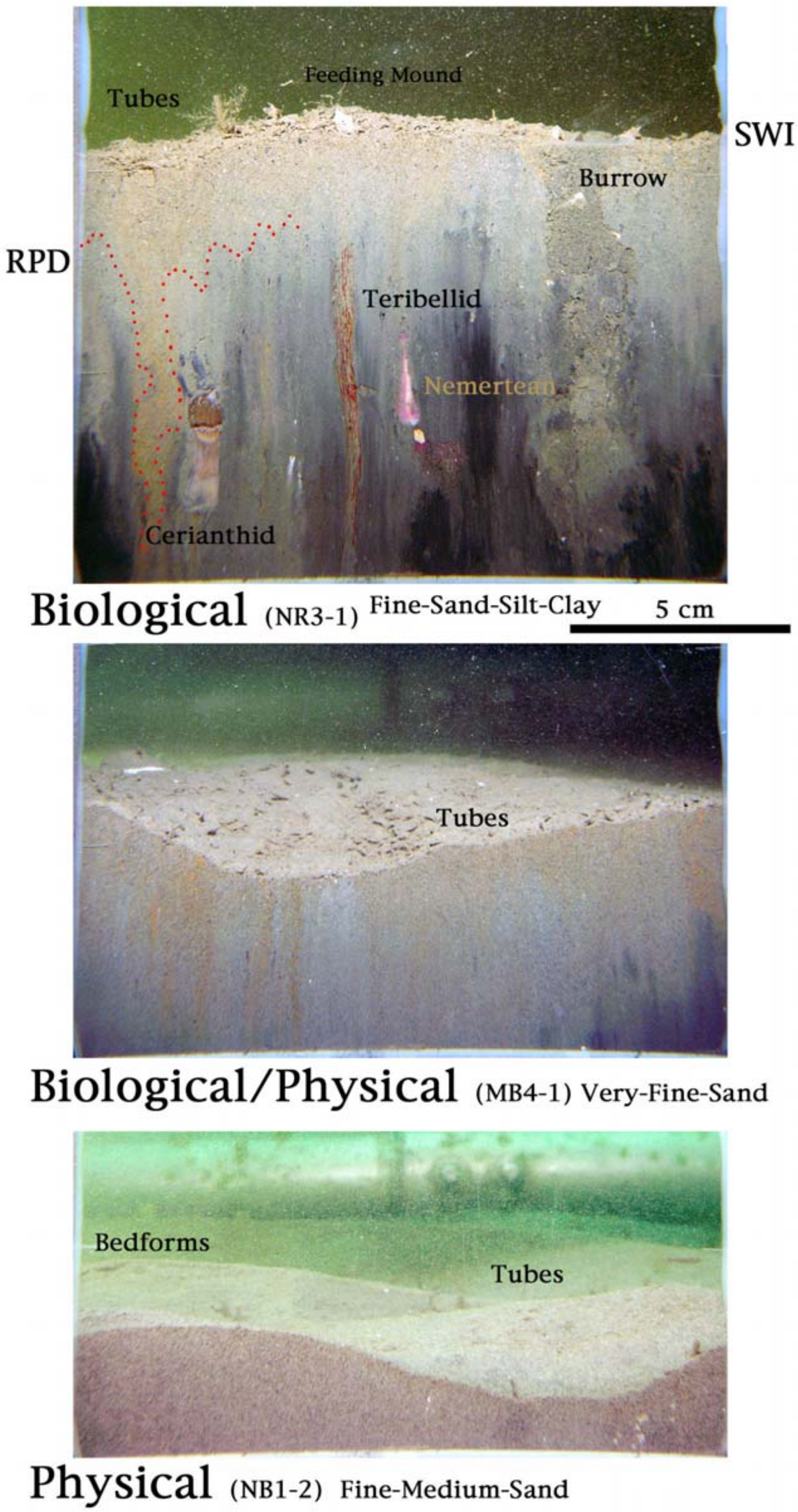

Figure 8. Example Images of Sediment Surfaces Dominated by Physical and Biological Processes and Sediment Types Encountered within the Five Regions of Interest. SWI is sediment-water-interface.

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 Wentworth classification as described in Folk (1974) and represent the major modal class for each image. Maximum grain size was also estimated. For muddy to gravel sediments grain size was determined by comparison of collected images with a set of standard images for which mean grain size had been determined in the laboratory. For sediments larger than gravel, individual grains were measured. Table 1 is provided as a means of comparing Phi scale sizes corresponding to sediment descriptors derived from SPI images. See Figure 8 for examples from the five areas sampled.

Table 1. Comparison of Phi Scale to SPI Sediment Descriptors.

Phi Scale	Upper Limit Size (mm)	Grains per cm of image	SPI Descriptor	Sediment Size Class & Subclass
-6 to -8	256.0	<<1	CB	Cobble
-2 to -6	64.0	<1	PB	Pebble
-1 to -2	4.0	2.5	GR	Gravel
1 to -1	2.0	5	CS	Coarse-sand
2 to 1	0.5	20	MS	Medium-sand
4 to 2	0.25	40	FS	Fine-sand
4 to 3	0.12	80	VFS	Very-fine-sand
5 to 4	0.06	160	FSSI	Fine-sandy-silt
5.5 to 4.5	0.06	160	FSSICL	Fine-sandy-silt-clay
6 to 5	0.0039	>320	SIFS	Silty-fine-sand
8 to 6	<0.0039	>320	SICL	Silty-clay
>8 to 7	<0.0039	>320	CLSI	Clayey-silt
>8	<0.0005	>2560	CL	Clay

Surface Features - These parameters included a wide variety of physical (such as bedforms) and biological features (such as biogenic mounds, shell, or tubes). Each contributes information on the type of habitat and its ability to support benthic organisms. The presence of certain surface features is indicative of the overall nature of a habitat. For example, bedforms are always associated with physically dominated habitats, whereas the presence of worm tubes or feeding pits would be indicative of a more biologically accommodated habitat (Rhoads and Germano 1986, Diaz and Schaffner 1988). Surface features were visually evaluated from each image and compiled by type and frequency of occurrence.

Subsurface Features - Subsurface features included a wide variety of features (such as infaunal organisms, burrows, water filled voids, gas voids, or sediment layering) that reveal a great deal about physical and biological processes influencing the 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, Nilsson and Rosenberg 2000). Subsurface features were visually evaluated from each image and compiled by type and frequency of occurrence.

Successional Stage - Sediment profile data have also been used to estimate successional stage of the fauna (Rhoads and Germano 1986). Characteristics associated with pioneering or colonizing (Stage I) assemblages (in the sense of Odum 1969), such as dense aggregations of small polychaete tubes at the surface and shallow apparent RPD 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 apparent RPD layers and subsurface feeding voids. Stage II is intermediate to 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 2 (- = not associated with, + = associated with, ++ = moderately associated with, +++ = strongly associated with).

Table 2. Relationship of SPI Parameters with Successional Stage.

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

Organism Sediment Index - Rhoads and Germano (1986) developed the multi-parameter organism-sediment index (OSI), from data provided by the sediment profile images, to characterize benthic habitat quality in soft-bottom estuarine and coastal embayments. The OSI defines quality of benthic habitats by evaluating the depth of the apparent RPD, 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 the 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 are used in the calculation of the OSI are in Table 34 (taken from Rhoads and Germano 1986).

Table 3. Parameters Ranges and Scores for Calculation of OSI.

Depth of the apparent color RPD		Estimated successional stage	
0 cm	0	Azoic	-4
>0-0.75	1	I	1
0.76-1.50	2	I-II	2
1.51-2.25	3	II	3
2.26-3.00	4	II-III	4
3.01-3.75	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 to follow ecosystem recovery after disturbance abatement (Rhoads and Germano 1986). 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. For estuarine and coastal bay benthic habitats in the northeastern United States OSI values >6 indicate good habitat conditions and are generally associated with bottoms that are not heavily influenced by stress, either physical or anthropogenic (Rhoads and Germano 1986). However, the level of OSI that defines the breakpoint between stress and non-stressed habitat on dynamic offshore bottoms has not been determined. It could be higher or lower than 6. Diaz et al. (2003) recalibrated the OSI for use in Chesapeake Bay, a temperate coastal embayment, and found that an OSI of 3 was the breakpoint between stressed and non-stressed habitat based on comparison with a benthic index of biotic integrity (Weisberg et al. 1997). Thus for this report, the OSI is used as a relative indicator of habitat conditions with higher OSI values associated with higher benthic habitat quality.

2.2 Data Reduction and Statistics

To summarize the SPI data, quantitative parameters were averaged from the replicate images (prism penetration, surface relief, maximum RPD depth, average RPD depth, OSI, and number of infauna, burrows, and voids per image). For categorical parameters the highest value or presence for all replicate images was assigned to a station. For example, if only one replicate had bedforms then the summary for that station would be bedforms present. When a quantitative parameter for one replicate at a station had a greater than (>) assigned and the other replicate was measured, only the measured value was used in calculation of the average. For example, at station MB1 the RPD was deeper than the prism penetration for replicate 1 and was assigned the value of >3.1 cm based on prism penetration, replicate 2 had a measured RPD of 2.9 cm. Only the 2.9 cm value was used as the summary value for the station.

Analysis of variance was used to test for differences between category levels of the qualitative parameters and between years for the quantitative parameters. Normality was checked with the Shapiro-Wilk test and homogeneity of variance with Bartlett's test (Zar 1999). Data were log (x + 1) transformed when necessary. For statistical analysis, any parameter value that was greater than the prism penetration, indicated by > in the data tables, was not included in the analysis.

At stations where the RPD layer was deeper than prism penetration and penetration was >3.7 cm, which is the lower limit for the highest RPD depth category in the OSI calculation (see OSI methods section and Table 3), the value of 6 was assigned to the RPD contribution and the OSI was not assigned a greater than (>) designation. If the penetration was <3.7 cm, than the > designation was used to indicate that if the RPD depth was actually measured the OSI value could possibly be higher.

3.0 RESULTS

3.1 Overview

On 11 September 2004, sediment profile images were collected at seven stations in each of five areas of interest from Salem Sound to Boston Harbor, MA. (Figures 1, 3 to 7). Sediment profile image (SPI) data are contained in CD-ROM Appendix A. SPI images are contained in Figures 9 to 13 with higher resolution image files in CD-ROM Appendix B. The width of all images on the CD-ROM is 15.5 cm. Tick-marks on the sides of the images are 5.0-cm intervals from the bottom of the prism faceplate. All images have been processed (histogram equalized) to highlight the apparent color RPD layer and other sedimentary features. Replicate data from each station were summarized and presented in Table 4.

Table 4. Sediment Profile Image Data Summarized by Station.

Stat.	Pen Ave cm	Surface Relief cm	RPD Max cm	RPD Ave cm	Bed-forms	Shell	Biogenic Mounds Pits	Modal Grain Size	Bed Rough-ness	Amphipod Tubes	Worm Tubes	Tubes >2mm	Diatom Mat	Infauna #/image	Burrows #/image	Oxic Voids #/image	Oxic Depth cm	Anaerobic Voids #/image	Gas Voids #/image	Succ. Stage	OSI
BR1	2.8	1.9	IND	1.8	+	+	+	VFS	BIO/PHY	0	SOME	+	-	5.5	3.0	0.0		0.0	0.0	I	4.0
BR2	5.0	2.3	6.2	2.5	+	+	+	VFS	BIO/PHY	0	SOME	+	-	3.0	5.5	0.0		0.0	0.0	I-II	6.0
BR3	6.2	0.9	5.6	2.1	-	-	+	VFS	BIO/PHY	0	MANY	+	-	4.0	3.5	0.0		0.0	0.0	I-II	5.0
BR4	9.9	1.4	4.6	2.2	-	-	+	FSSICL	BIO/PHY	0	SOME	+	-	5.5	4.0	2.0	8.5	0.0	0.0	II-III	7.5
BR5	5.6	1.3	4.1	2.8	+	-	+	VFS	BIO/PHY	0	MANY	+	-	5.5	4.0	0.0		0.0	0.0	I-II	6.5
BR6	12.3	0.8	6.2	2.3	-	-	+	FSSICL	BIO/PHY	0	SOME	+	-	7.0	9.5	1.5	9.8	0.0	0.0	II-III	7.5
BR7	11.8	0.7	4.4	2.0	-	-	+	FSSICL	BIO/PHY	0	MANY	+	-	3.5	7.5	3.5	6.7	0.0	0.0	I-III	6.0
MA1	2.0	1.3	IND	>2.0	+	+	-	FSMS	PHY	0	SOME	+	-	0.0	0.0	0.0		0.0	0.0	I-II	>5.0
MA2	2.1	0.7	IND	>2.1	+	+	+	VFS	BIO/PHY	0	SOME	+	-	1.0	0.5	0.0		0.0	0.0	I	>4.5
MA3	1.9	0.4	IND	>1.9	+	+	+	VFS	BIO/PHY	0	MANY	+	-	3.0	1.5	0.0		0.0	0.0	I	>4.0
MA4	2.6	0.9	IND	>2.6	+	-	+	VFS	PHY	FEW	SOME	+	-	0.5	4.0	0.0		0.0	0.0	I-II	>6.0
MA5	3.4	0.7	IND	>3.4	+	+	-	VFS	PHY	0	SOME	+	-	1.0	2.5	0.0		0.0	0.0	I	7.0
MA6	2.7	0.7	IND	2.5	+	+	+	VFS	PHY	0	MANY	+	-	2.0	1.5	0.0		0.0	0.0	I	5.0
MA7	1.5	0.8	IND	>1.5	+	+	+	VFS	PHY	0	SOME	+	-	0.0	0.0	0.0		0.0	0.0	I	>3.5
MB1	4.3	1.3	5.0	2.9	+	-	+	VFS	BIO/PHY	0	SOME	+	-	6.0	4.0	0.0		0.0	0.0	I-III	8.0
MB2	5.8	2.2	3.8	2.0	+	+	+	VFS	BIO/PHY	FEW	SOME	+	-	6.0	4.0	0.5	4.6	0.0	0.0	I-III	6.0
MB3	7.8	0.6	4.1	2.9	+	-	+	VFS	BIO/PHY	FEW	SOME	+	-	4.0	9.0	1.5	7.0	0.0	0.0	II-III	9.0
MB4	6.1	1.2	5.0	3.5	+	+	+	VFS	BIO/PHY	0	MANY	+	-	5.0	7.5	1.0	5.7	0.0	0.0	I-III	8.0
MB5	13.5	2.1	8.8	2.5	-	+	+	FSSICL	BIO/PHY	0	SOME	+	-	5.5	4.5	3.0	6.0	0.0	0.0	II-III	8.0
MB6	13.0	0.8	6.6	3.1	-	+	+	FSSICL	BIO/PHY	0	MANY	-	-	4.5	7.0	3.5	6.3	0.0	0.0	II-III	8.5
MB7	14.9	0.6	5.4	3.5	-	+	+	FSSICL	BIO/PHY	0	MANY	+	-	8.0	5.0	2.5	9.8	0.0	0.0	II-III	9.0
NB1	2.5	1.9	IND	>2.5	+	-	-	FSMS	PHY	0	SOME	+	-	0.0	0.0	0.0		0.0	0.0	I-II	>6.0
NB2	3.1	1.0	IND	>3.1	+	-	-	FSMS	PHY	0	SOME	+	-	0.0	0.0	0.0		0.0	0.0	I-II	8.0
NB3	2.5	1.4	IND	2.2	+	-	-	FSMS	PHY	0	SOME	+	-	0.0	2.0	0.0		0.0	0.0	I-II	5.0
NB4	2.8	0.8	IND	>2.8	+	+	-	FSMS	PHY	0	SOME	+	-	0.0	0.0	0.0		0.0	0.0	I-II	>6.5
NB5	3.0	1.0	IND	1.9	+	+	+	VFS	BIO/PHY	0	MANY	+	-	2.5	5.5	0.0		0.0	0.0	I-II	5.0
NB6	3.7	0.9	IND	3.1	+	+	+	VFS	BIO/PHY	0	SOME	+	-	4.0	1.0	0.0		0.0	0.0	I-II	7.0
NB7	4.3	1.6	4.0	3.0	+	+	+	VFS	BIO/PHY	0	MANY	+	-	5.5	4.0	0.0		0.0	0.0	I-III	7.5
NR1	16.5	0.6	10.3	4.3	-	-	+	FSSICL	BIO	MAT	SOME	+	-	14.0	8.5	6.0	8.4	0.0	0.0	II-III	10.0
NR2	15.6	0.8	8.7	4.2	-	-	+	FSSICL	BIO/PHY	MAT	SOME	+	-	8.5	6.0	7.0	10.3	0.0	0.0	II-III	9.5
NR3	11.9	1.1	8.4	2.9	-	+	+	FSSICL	BIO	0	MANY	+	-	6.0	4.5	1.5	7.5	0.0	0.0	II-III	9.0
NR4	13.4	1.0	7.4	2.8	-	-	+	FSSICL	BIO/PHY	FEW	SOME	+	-	6.0	6.5	2.0	9.1	0.0	0.0	II-III	8.5
NR5	14.7	0.7	3.7	1.8	-	-	+	FSSICL	BIO/PHY	0	SOME	-	+	5.0	4.0	1.0	8.5	1.0	0.0	I-III	6.0
NR6	8.4	2.8	2.9	1.6	-	-	+	FSSICL	BIO/PHY	0	SOME	+	+	2.0	5.5	1.0	7.3	0.0	0.0	I-III	5.5
NR7	18.0	0.9	8.3	3.1	-	-	+	FSSICL	BIO/PHY	0	SOME	+	-	8.0	4.5	2.0	15.9	0.5	0.5	I-III	7.0

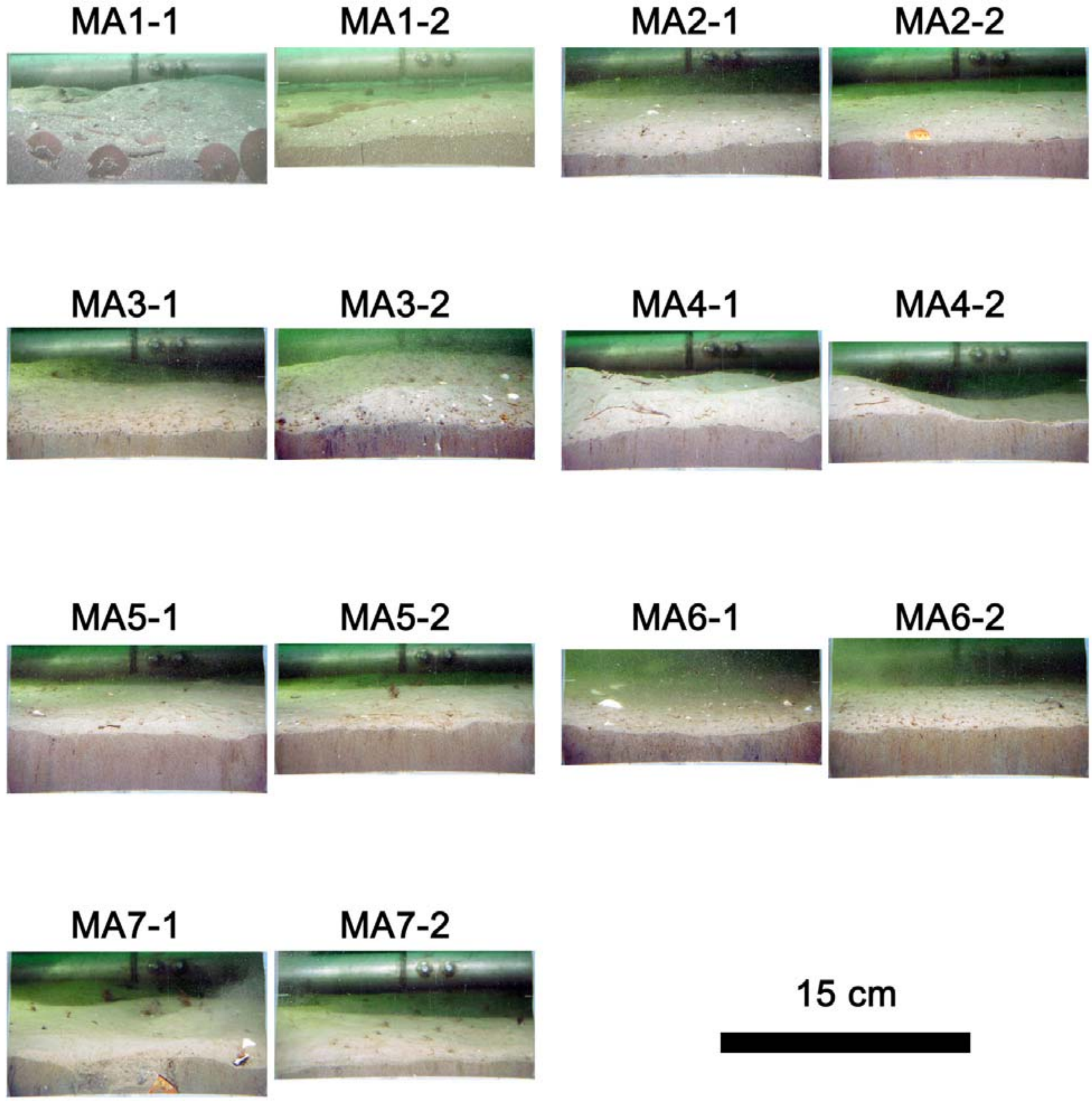

Figure 9. Replicate SPI Images from the Magnolia Site.

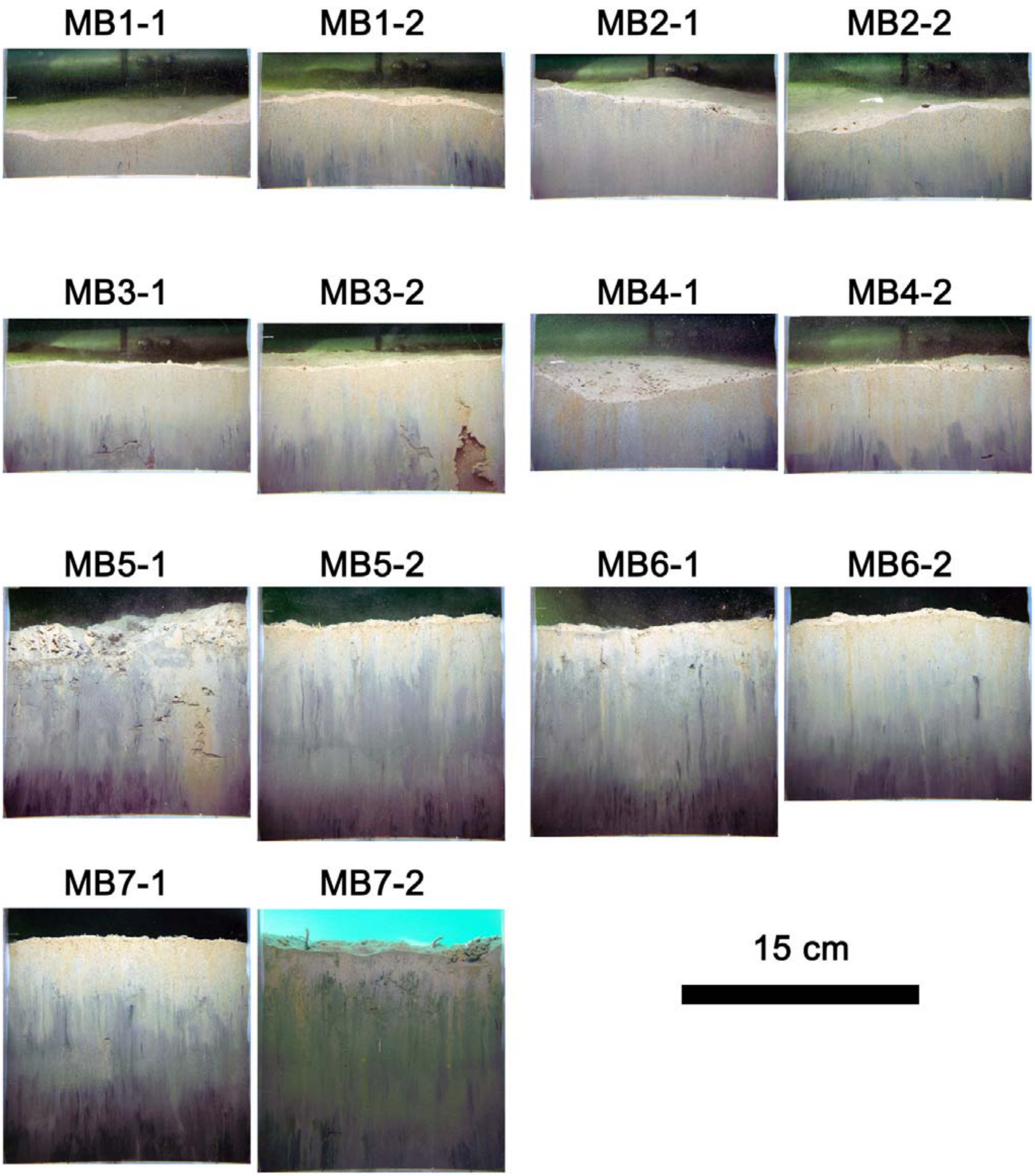

Figure 10. Replicate SPI Images from the Massachusetts Bay Site.

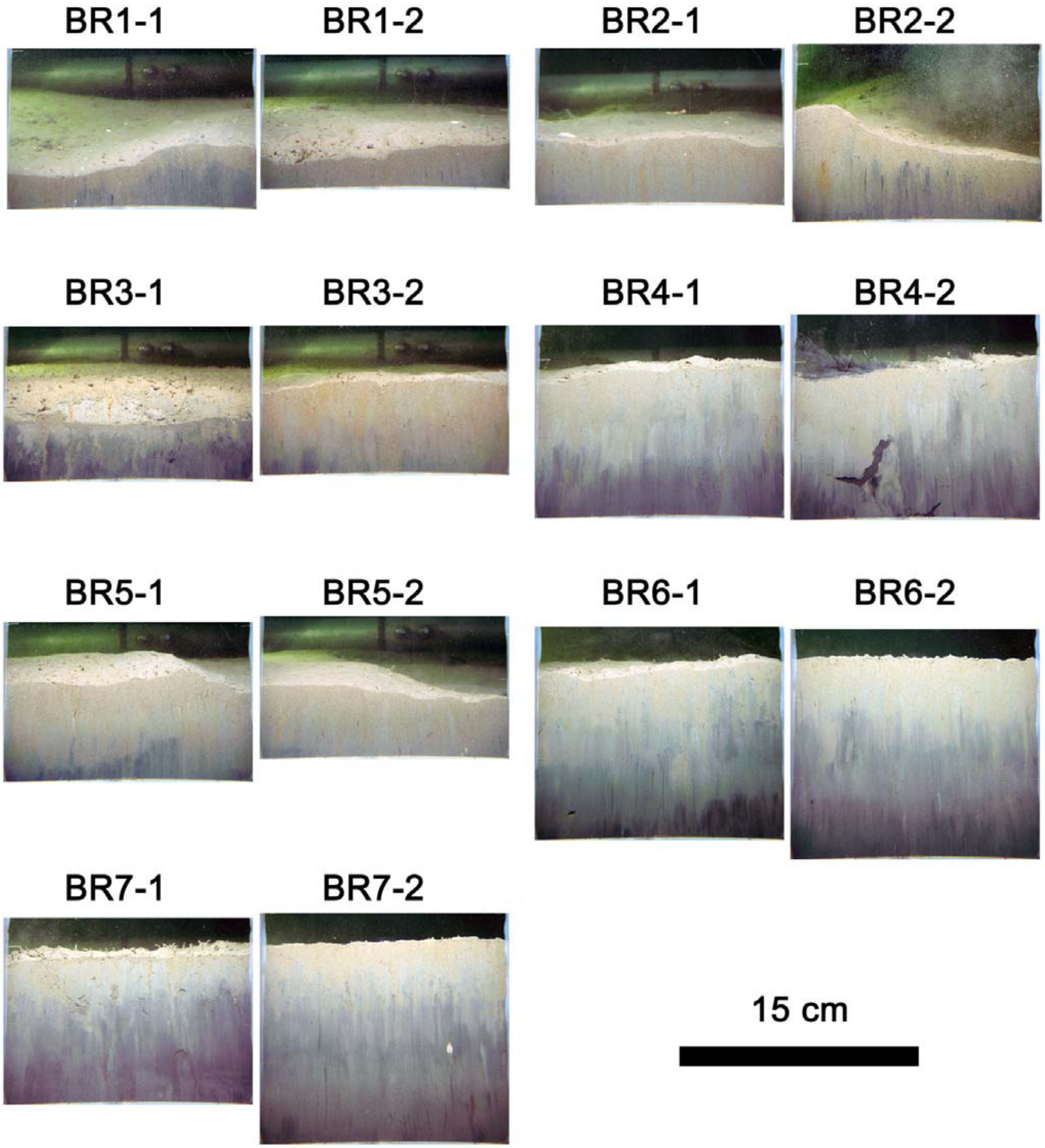

Figure 11. Replicate SPI Images from the Broad Sound Site.

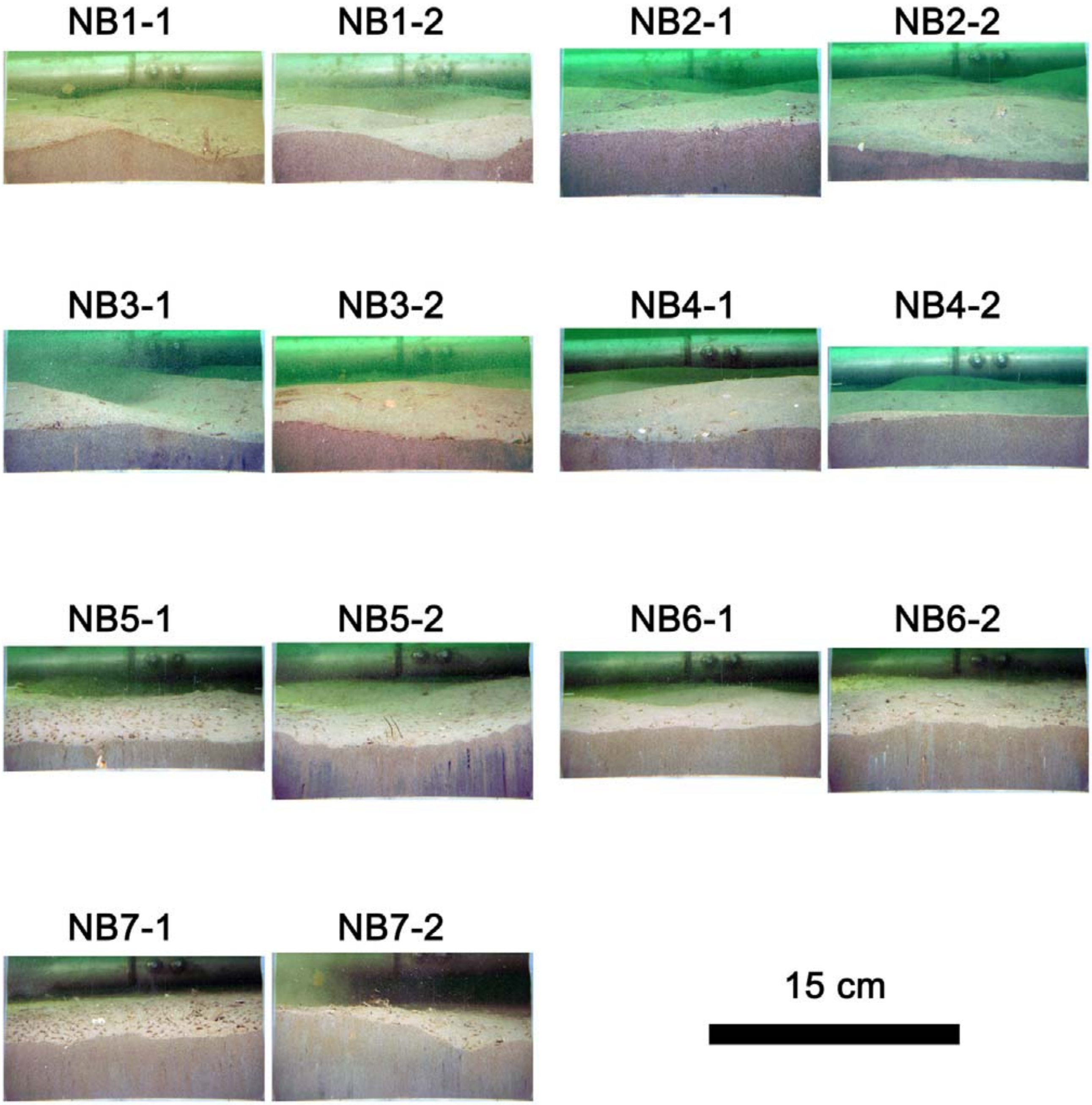

Figure 12. Replicate SPI Images from the Nahant Bay Site.

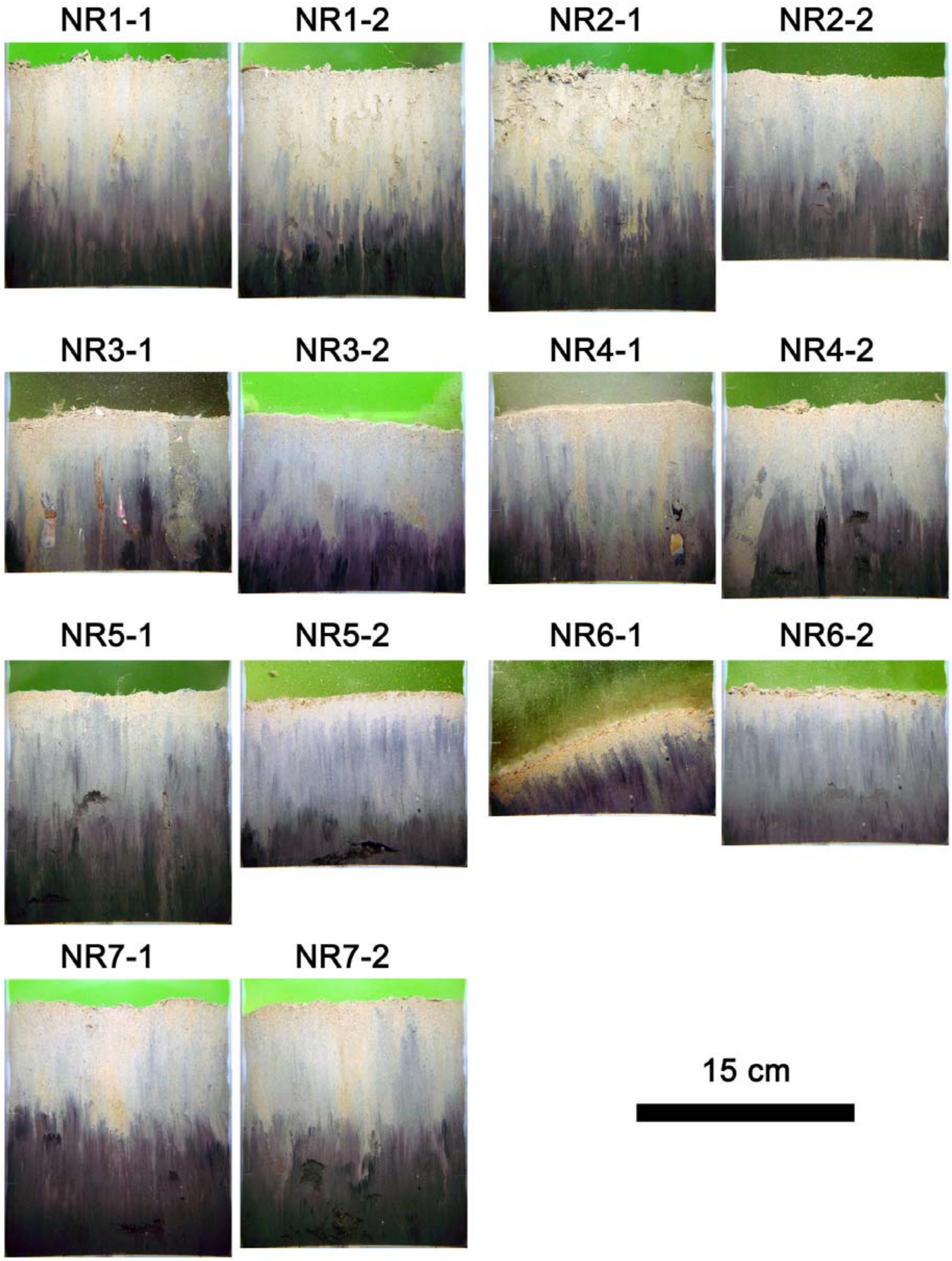

Figure 13. Replicate SPI Images from the Nantasket Roads Site.

3.2 Physical Processes and Sediments

A combination of biological and physical processes appeared to dominate sediment surfaces at 68% of the sampled stations (24 of 35). At 26% of the stations (9 of 35), physical processes dominated and at two stations (6%) biological processes dominated (Table 4, Figure 8). Within a site, the sediment surfaces at all five stations in both Broad Sound and Massachusetts Bay were dominated by a combination of biological and physical processes. Stations that were physically dominated occurred within sites Magnolia and Nahant Bay. The two biologically dominated stations were within site Nantasket Roads.

While the variation in sediment grain-size was not great, physically dominated surfaces were associated with sandy sediments. Biological processes predominated in very-fine-sand and in fine-sand-silt-clay sediments (Table 5).

Table 5. Cross-classification of Sediment Type with Dominant Surface Process.

Sediment Class	Dominant Process			
	Biological	Bio./Phy.	Physical	Total
Fine-Medium-Sand	0	0	5	5
Very-Fine-Sand	0	13	4	17
Fine-Sand-Silt-Clay	2	11	0	13
Total	2	24	9	35

Fine and medium sand sediments, indicative of higher kinetic energy bottoms, were seen at 63% of the stations. Bedforms, also an indicator of higher-energy bottoms, occurred at all but one sandy station (Table 4). All stations in Magnolia and Nahant Bay were sands (Figures 9 and 11). Silts and clays were seen at 37% of the stations with all stations at Nantasket Roads being silty (Figure 13). Stations at Broad Sound and Massachusetts Bay were both sandy and silty (Figures 10 and 12).

3.3 Compaction and Bed Roughness

Prism penetration, a proxy for sediment compaction, was related to sediment grain-size with lowest penetration and therefore higher compaction at sandy stations (Table 6). The range of penetration was 1.5 cm in very-fine-sand to 18.0 cm in fine-sand-silt-clay.

Table 6. Range and Mean Prism Penetration by Sediment Class.

	Prism Penetration (cm)				
Sediment Class	N	Min	Max	Mean	SD
Fine-Medium-Sand	5	2.0	3.1	2.6	0.4
Very-Fine-Sand	17	1.5	7.8	4.0	1.8
Fine-Sand-Silt-Clay	13	8.4	18.0	13.4	2.6

Bed roughness, estimated from surface relief, was not significantly different when either biological or physical processes dominated surface sediments (ANOVA, df = 2, F = 0.41, p = 0.666, Table 7).

Table 7. Range and Mean Surface Roughness by Dominant Process Structuring Surface Sediments.

Dominant Process	Surface Roughness (cm)				
	N	Min	Max	Mean	SD
Biological	2	0.6	1.1	0.9	0.3
Bio./Physical	24	0.4	2.8	1.2	0.6
Physical	9	0.7	1.9	1.1	0.4

In physically dominated sandy habitats, bed roughness consisted of small sand ripples or bedforms. Biogenic activity of benthic organisms dominated bed roughness at many stations and appeared to be related to feeding activities of surface and subsurface fauna, which formed pits and mounds at the sediment surface.

3.4 Apparent Color RPD Layer Depth

RPD layer depth is a measure of the depth to which sediment geochemical processes are primarily oxidative. The thickness of the RPD layer has long been associated with benthic habitat quality, in particular with regards to organic enrichment gradients (Pearson and Rosenberg 1978) with habitat quality positively correlated with RPD layer depth (Rhoads and Germano 1986, Nilsson and Rosenberg 2000). Below the RPD layer, geochemical processes are primarily anaerobic or reducing (Fenchel and Riedl 1970). In sandy porous sediments, deep RPD layers are primarily a function of pore water circulation driven by current or wave action that pumps oxygenated water in the sediments. For example, very-fine-sand sediments at MA-5 had an RPD that was beyond the 3.4 cm depth of prism penetration. In finer sediments, those with a significant silt and clay component, physical diffusion limits oxygen penetration to <1 cm (Jørgensen and Revsbech 1985). There were no examples of diffusion-limited RPD layers at any of the 35 stations sampled. Even at station NR-6 where the average RPD was 1.6 cm, infaunal and burrow structures projected small cylinders of oxidized sediments to a maximum depth of 2.9 cm. The halo of oxidized sediment around these types of biogenic structure increases the total volume of oxidized sediment and surface area of the RPD layer (Aller and Aller 1998). When the RPD layers in fine sediments are >1 cm, it is bioturbation by infauna (Rhoads 1974) or major resuspension/deposition events (Don Rhoads, personal communication) that are responsible for oxygenating sediments. Burrows convoluted the plane of the RPD layer and produced oxidized sediments >5 cm below the sediment-water-interface at 13 of 21 stations (62%) with measured RPD layer depths (Table 4). At station NR-1 the maximum extent of oxidized sediments was 10.3 cm below the sediment-water-interface (Figure 13).

Average station RPD layer depths ranged from 1.6 cm (NR-6) to 4.3 cm (NR-1) with the deeper RPD layers associated with either finer sediments and high levels of biogenic activity, or pure sand sediments. Anaerobic sediments below the RPD layer did not appear to be intensely reducing or sulfitic (dark gray-blue in color) at any station (Figures 9 to 13). This indicated that organic carbon loading to the sediments was not an important factor in determining benthic habitat conditions. The darker color of reduced sediments underlying the oxidized lighter colored sediments is a function of organic carbon content and geochemistry (Vismann 1991). Darkest sediments occurred in Nantasket Roads within Boston Harbor (Figure 13).

The most important factors regulating RPDs in sites Magnolia and Nahant Bay appeared to be grain-size and porewater flow, both functions of the intensity of physical processes. Bioturbation, a function of biological processes, was most important in sites Nantasket Roads, Nahant Bay, and Broad Sound. These and other factors, such as season and water quality, are all known to regulate the RPD layer depth (Rhoads and Boyer 1982, Jones and Jago 1993, Diaz and Rosenberg 1995, Aller and Aller 1998).

3.5 Successional Stage and Biogenic Activity

The successional stage estimated for 17% of the stations was Stage I, indicating that benthic communities were composed mainly of pioneering species, such as small tube-building spionid polychaetes, associated with early stages of community development (for example MA-2). Most of the stations (54%) had evidence of well-developed communities but surface sediments were still dominated by pioneering Stage I characteristics (for example NB-2 and NR-6). Intermediate successional Stage II communities were present at 59% of the stations (for example MA-4), which were characterized by surface tube-building species such as the amphipod *Ampelisca* spp. (present at six stations, Table 4). *Ampelisca* spp. occurred at high densities at stations NR-1 and NR-2. Evidence of successional Stage III equilibrium communities was observed at 51% of the stations. Stage III was characterized by head-down deposit feeding polychaetes that formed subsurface feeding voids (NR-3 or NR-4). Intermediate successional Stage II and equilibrium Stage III communities were associated with finer sediment stations, those with significant silt components, which could support the construction of biogenic structures of advanced successional stage species.

Surface biogenic structures associated with successional Stage II and III fauna were large tubes (>2 mm in diameter, for example NR2), and feeding mounds and pits (MB6). Subsurface biogenic structures associated with infaunal organisms, mostly polychaetes, included active burrows (NR7), water filled oxic voids that were areas of active feeding by head-down deposit feeders such as maldanid polychaetes (MB3), and large infaunal organisms (NR3). Subsurface biogenic activity was the most important factor in deepening the RPD layers. Oxic feeding voids occurred as deep as 15.9 cm (NR7) and oxic burrows and extended the RPD to >10 cm at station NR1 (Table 5). As many as 14.0 infauna/image (NR1), 9.5 burrow/image (BR6), and 7.0 oxic voids/image (NR7) were observed.

The most abundant biogenic surface features were tubes that occurred at all 35 stations (Table 4). It was likely that most of the small tubes, <2 mm diameter, were made by spionid polychaetes such as *Prionospio steenstrupi* and *Dipolydora socialis*, which were the numerically dominant species at the nearby MWRA outfall monitoring stations (Kropp et al. 2002) and HubLine stations (Normandeau Associates and TRC Environmental 2002). Larger tubes, >2 mm diameter, of what appeared to belong to the amphipod *Ampelisca* spp., occurred at six stations (NR1). Other larger tubes appeared to be a polychaete tubes and were present at almost all stations (MA4). Mobile organisms observed on the sediment surface included the sand dollar *Echinarachnius parma* (MA1), caprellid amphipods (MB6), a cancer crab (NB2), and a small flounder (NB2).

3.6 Organism Sediment Index

The Organism Sediment Index (OSI) ranged from 4 to 10 indicating a broad range of benthic habitat conditions at the five regions of interest. Higher OSI values (8 and greater) were typically associated with intermediate Stage II or equilibrium Stage III fauna. Overall, OSI values were significantly higher at biologically dominated stations than at physically dominated stations, but not different from biologically/physically dominated stations, which were also not different from stations that were physically dominated (ANOVA, only measured OSI values, > values were excluded, 2 df, F = 3.40, p = 0.049, Table 8).

Table 8. Range and Mean OSI by Dominant Process Structuring Surface Sediments.

	OSI only measured values				
Dominant Process	**N**	**Min**	**Max**	**Mean**	**SD**
Biological	2	9.0	10.0	9.5	0.50
Biological/Physical	22	4.0	9.5	7.0	0.32
Physical	4	5.0	8.0	6.2	0.75

The distribution of OSI between sites (Figure 14) was related primarily to the distribution of sediment types and level of bioturbation, which were the same factors that determined the distribution of OSI at the MWRA nearfield stations (Werme and Hunt 2001, 2002, 2003).

4.0 SUMMARY

The limited range of sediment types in the SPI images, from fine-sand-silt to fine-medium sand, resulted, in part, from restricting station locations to avoid hard bottom areas where the camera could not penetrate (Figures 3 to 7). Sampling sites were chosen using preliminary sidescan mosaics to represent soft bottom areas where good SPI camera penetration was most likely and to represent the range of soft bottom habitat types within an area.

Most sediment surfaces were dominated by a combination of physical and biological processes. Even at fine-medium-sand stations that were physically dominated with bedforms there was some level of biogenic activity in the form of small tubes (Figure 8). Biogenic activity was higher at stations within Nantasket Roads, Massachusetts Bay, and Broad Sound sites, and lower at stations within the Nahant Bay and Magnolia sites.

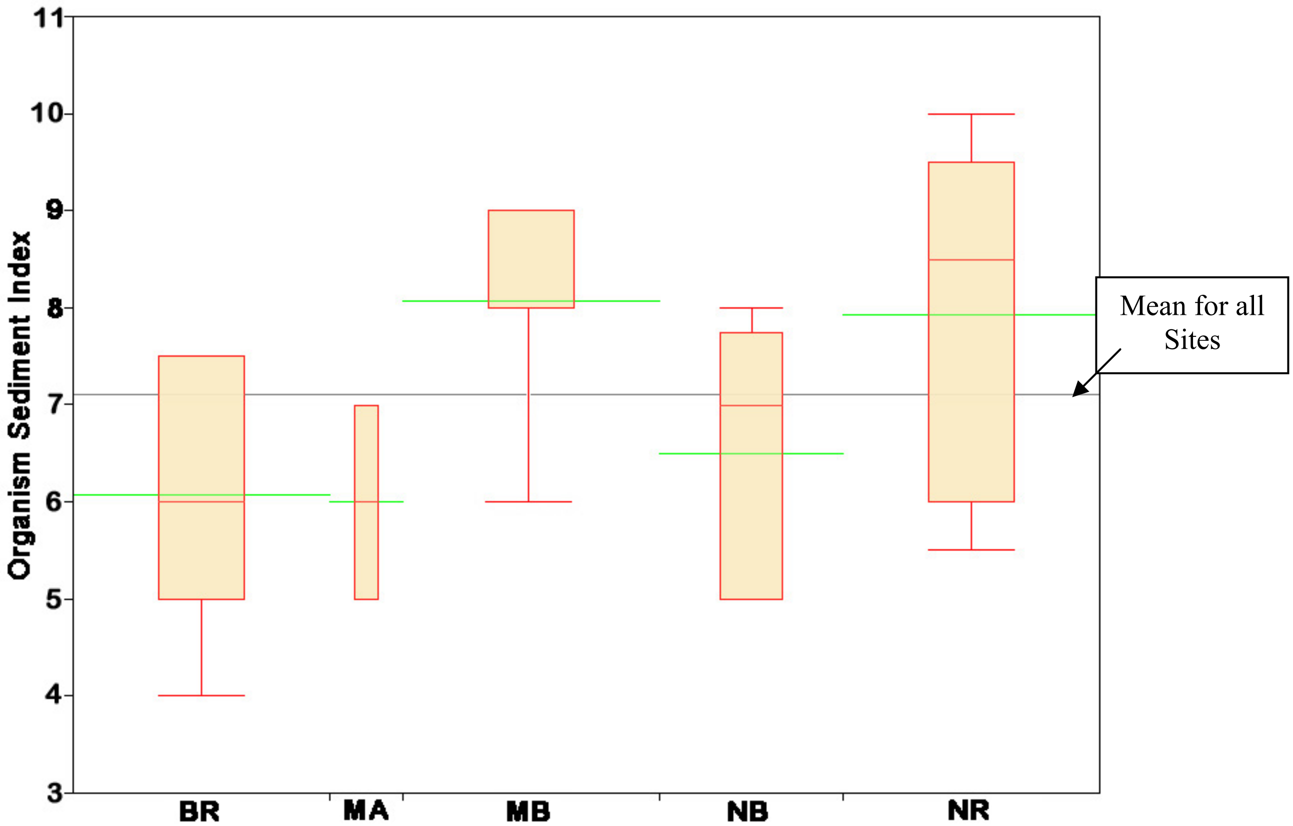

Figure 14. Organism Sediment Index (OSI) Summarized by Site (> values excluded). Box is interquartile range (top of box is 75th percentile and bottom is 25th percentile), bar in box is median (50th percentile), wide bar (green) is mean, and whiskers are data range. Horizontal line is grand mean for all five sites. Width of box is proportional to the number of images with measured OSI values.

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