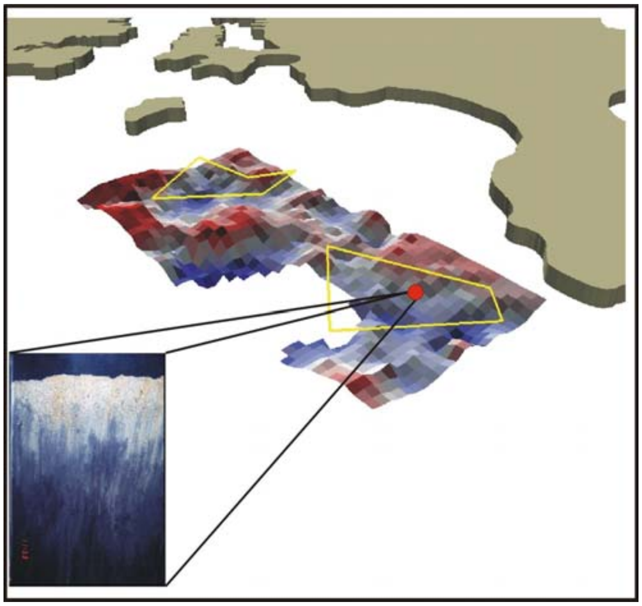
RESULTS OF THE MARCH 2001 SUB-BOTTOM PROFILING AND SEDIMENT PROFILE IMAGING SURVEY OF THE OUTER GLOUCESTER HARBOR

Draft Report



June 2001
SAIC Report No. 541

***Prepared by*:**

Science Applications International Corporation
Suite 1, Admiral’s Gate
221 Third Street
Newport, RI 02840

***In association with*:**

Maguire Group Inc.
One Court Street
New Britain, CT 06051

***Prepared for*:**

Massachusetts Coastal Zone Management Agency
100 Cambridge Street
Boston, MA 02202

TABLE OF CONTENTS

Page

LIST OF TABLES

LIST OF FIGURES

ACKNOWLEDGMENTS

This report presents the results of a combined sub-bottom profile and REMOTS® survey conducted in the outer Gloucester Harbor. Science Applications International Corporation (SAIC) of Newport, RI conducted the fieldwork on March 12-14, 2001 under contract to the Maguire Group, Inc. Terry Whalen was Maguire's manager of technical activities for this contract and Ray Valente was SAIC's project manager.

All field work was conducted aboard the R/V *Cyprinodon* owned and operated by C.R. Environmental of Falmouth, MA.

Jason Infantino, Michael Cole, and Tom Waddington of SAIC were responsible for mobilizing the navigation, sub-bottom profiling, and REMOTS® equipment and conducting the survey operations aboard the R/V *Cyprinodon*.

Jason Infantino and Tom Waddington processed the sub-bottom profile data and created the resulting graphic data products. Greg Tufts of SAIC processed the REMOTS® data. Tom Waddington and Ray Valente authored this report and Brian Andrews, Jason Infantino, and Greg Tufts prepared the supporting figures and tables. Ray Valente provided technical oversight and final review of this report. Tom Fox of SAIC was responsible for report production.

1.0 INTRODUCTION

1.1 Background

This report presents the results of sub-bottom profiling and REMOTS® sediment profile imaging surveys conducted in the Outer Gloucester Harbor in mid-March 2001 (Figure 1-1). The surveys were conducted to support the Dredged Material Management Plan (DMMP) for the Massachusetts Coastal Zone Management Agency (MCZM). The objective of these surveys was to characterize the surface and subsurface geology in the Outer Gloucester Harbor to determine if any areas had sufficient depth-to-bedrock to warrant further consideration as possible confined aquatic disposal (CAD) sites for material dredged from Gloucester projects. The results of the March 2001 surveys serve to augment those obtained in similar REMOTS® and sub-bottom surveys conducted in the inner harbor in late 1998 (SAIC 1999a and 1999b).

Generally speaking, the creation of a CAD site initially requires the excavation of existing sediments to construct a pit or containment area. Dredged material classified as unsuitable for open-water disposal is then placed within this excavated pit and isolated from the surrounding aquatic environment by placing a capping layer of clean material over it. One of the main factors limiting the potential capacity of a CAD site is the presence of a hard bedrock layer near the seafloor. In New England, bedrock generally consists of hard, crystalline rock that is very costly to excavate. Therefore, this bedrock layer becomes the basement for any CAD site excavation and directly impacts the potential capacity of such a site. To maximize potential capacity, CAD sites should be sited over areas of the seafloor with the greatest depth-to-bedrock. The sub-bottom survey discussed in this report was conducted to provide preliminary locations of potential CAD sites and to provide approximate capacity estimates for these sites. This capacity characterization is only one part of an extensive environmental screening process being conducted to evaluate the suitability of each site for dredged material disposal.

To avoid erosion of the surface cap layer and thereby facilitate effective long-term isolation of the underlying material, CAD sites ideally should be located in protected, low-energy seafloor areas. Furthermore, they should be located where they are least likely to disrupt existing water-based activities or have negative long-term environmental impacts. Because fine-grained sediments tend to be carried away by bottom currents in higher-energy environments and accumulate in more quiescent, depositional ones, knowledge of the existing surface sediment types in an area provides insight on the energy regime. The REMOTS® sediment-profile imaging survey performed in conjunction with the sub-bottom survey involved sampling at 40 stations throughout Outer Gloucester Harbor, to provide information on sediment types and benthic habitat quality. Four of these REMOTS® stations were positioned near the presumed location of the former municipal wastewater (i.e., sewer) outfall. Six of the stations were located in the area west and north of Tenpound Island, in the vicinity of four candidate CAD cells. These six "CAD cell" stations were sampled previously in November 1998 to define sediment types and benthic habitat conditions (SAIC 1999a).

1.2 Survey Objectives

The primary objective of the sub-bottom and REMOTS® survey reported here was to collect data on the existing surface and subsurface geology in the outer Gloucester Harbor area. The sub-bottom data were used to determine if any areas had sufficient depth-to-bedrock to warrant further consideration as possible CAD sites for material dredged from Gloucester Harbor projects. The REMOTS® data were used to evaluate the general erosional/depositional characteristics of the seafloor in the outer harbor area, to assess existing benthic habitat quality in the area around the former sewer outfall, and to evaluate any changes in benthic conditions in the vicinity of the four candidate CAD sites west and north of Tenpound Island.

This report presents the results of the March 2001 REMOTS® and sub-bottom surveys in the outer harbor and integrates these results with those obtained previously in the inner harbor to provide an overview of conditions throughout Gloucester Harbor.

2.0 METHODS

SAIC conducted all of the field operations aboard the *R/V Cyprinodon*, operated by C.R. Environmental out of Falmouth, MA. The *R/V Cyprinodon* was trailered to Gloucester on March 12, 2001, then launched and moored at a marina on the north side of the outer Gloucester Harbor. SAIC scientists traveled to Gloucester on March 13, 2001 to install the Hypack® data acquisition system, the Trimble DGPS navigation system, the Datasonics® Chirp II sub-bottom profiling system, and the Datasonics® Bubble Pulser sub-bottom profiling system. The sub-bottom profiling survey was started on the evening of March 13 and was completed the following afternoon on March 14, 2001. Following the completion of the sub-bottom profiling survey, the sub-bottom gear was removed from the *R/V Cyprinodon*, and the REMOTS® gear was installed. The REMOTS® survey was completed on March 15, 2001. Following the successful completion of the field operations, all sub-bottom and REMOTS® data were transferred to SAIC's Newport, RI office for processing. All equipment was removed from the boat on March 16, 2001, and the boat was recovered and trailered back to Falmouth.

2.1 Navigation

During field operations, a Trimble DSM212L Differential Global Positioning System (DGPS) receiver provided precise navigation data. Because of its proximity to the survey area, the U.S. Coast Guard differential beacon broadcasting from Boston, MA was used for generating the real-time differential corrections. During all survey operations, the Trimble DGPS system output real-time navigation data (NAD83 Latitude and Longitude) at a rate of once per second to an accuracy of ±3 m.

Coastal Oceanographic's HYPACK® survey and data acquisition software was used to provide the real-time interface, display, and logging of the DGPS data. Prior to field operations, HYPACK® was used to define a State Plane grid (Massachusetts – Main) around the survey area and to establish the planned sub-bottom survey lines (Figure 2-1). During the survey operations, the incoming navigation data were translated into state plane coordinates, time-tagged, and stored within HYPACK®. Depending on the type of field operation being conducted, the real-time navigation information was displayed in a variety of user-defined modes within HYPACK®.

2.2 Sub-bottom Profiling

2.2.1 Sub-bottom Profiling Data Acquisition

The sub-bottom profiling operations included a series of closely spaced sub-bottom survey lines over the main area of interest south of Tenpound Island and a more widely spaced series of survey lines over the rest of the outer Harbor (Figure 2-1). Over the detailed area south of Tenpound Island, the sub-bottom survey coverage consisted of 13 North/South survey lines spaced 50 m apart and 13 East/West survey lines spaced 100 m apart. The survey over the broader area consisted of 3 North/South survey lines spaced 400 m apart and 10 East/West survey lines (out of a possible 16) spaced 200 m apart (Figure 2-1). During these operations, both the higher frequency ChirpII data and the lower frequency Bubble Pulser data were recorded simultaneously within the ChirpII topside processing unit.

Sub-bottom profiling data were acquired with a Benthos/Datasonics ChirpII® dual-frequency, digital, sub-bottom profiling system, operating at swept frequency ranges of 2-7 kHz and 8-20 kHz. In addition, the ChirpII® system was supplemented with a Benthos/Datasonics Bubble Pulser sub-bottom system operating at a frequency of 0.4 kHz. The ChirpII® towfish, the Bubble Pulser transducer, and the Bubble Pulser hydrophone were towed behind the survey vessel during all sub-bottom operations. By disabling the higher frequency ChirpII signal, the Bubble Pulser analog hydrophone data could be interfaced directly with the ChirpII® topside data acquisition system. The ChirpII® topside data acquisition system recorded and displayed the acoustic data from both the ChirpII® towfish and the Bubble Pulser hydrophone providing a real-time view of all of the sub-bottom data.

Sub-bottom profiling is a standard technique used for distinguishing and measuring various sediment layers that exist below the sediment/water interface. Sub-bottom systems are able to distinguish these sediment layers by measuring differences in acoustic impedance between the layers. Acoustic impedance is a function of both the density of a layer and speed of sound within that layer, and is affected by differences in grain size, roughness, and porosity. Sound energy transmitted to the seafloor is reflected off the boundaries between sediment layers of different acoustic impedance. A sub-bottom system uses the energy reflected from these boundary layers to build the image. The depth of penetration and the degree of resolution of a sub-bottom system depends on the frequency and pulse width of the acoustic signal and the characteristics of the various layers encountered. Because of the shorter wavelengths associated with higher frequency signals, the ChirpII® system will provide higher resolution relative to the lower frequency Bubble Pulser. The lower frequency Bubble Pulser is more likely to provide greater sub-bottom penetration, particularly in areas where the initial seafloor reflector is quite hard.

2.2.2 Sub-bottom Profiling Data Analysis

During data acquisition, each sub-bottom survey line was saved into a separate file to facilitate post-processing. After data acquisition, both the ChirpII® and Bubble Pulser sub-bottom data were analyzed and edited as necessary using the Triton-Elics ISIS® software. The ISIS® Bottom-Picking routine enables automatic or manual detection, tracking, and digitizing of any sub-bottom layers that are present in the data. Both the ChirpII® and Bubble Pulser data from each survey line were reviewed within ISIS® and any detected sub-bottom layers were digitized. For this survey, the two primary layers that were distinguished were the initial seafloor reflector and the bedrock reflector. The output from this operation was a data file that contained time, position, and sub-bottom depth records for each layer along each survey line at a user-defined interval. Because of the higher resolution provided by the ChirpII® system, it was the primary tool used for the initial sub-bottom analysis. The Bubble Pulser data were used to supplement the digitizing process in those areas where the ChirpII® was unable to provide any definitive sub-bottom layers.

After the sub-bottom digitizing process was completed, a single merged xyz data file was created for both the seafloor reflector and the bedrock reflector. In addition, an xyz data file was also created that provided the depth difference between the seafloor and the bedrock layer.

These merged xyz data files were then imported into the ArcView® GIS for further analysis. Because of the grid-type survey pattern used to acquire the sub-bottom data, there were many overlapping data points that could be reviewed to evaluate the consistency of the sub-bottom digitizing process. Because of the subjectivity of the sub-bottom interpretation and the presence of some additional reflectors (besides seafloor and bedrock), this cross-check comparison was used to highlight areas that needed to be re-analyzed.

After any inconsistencies in the digitizing process were resolved, the final depth-to-bedrock data file was used to generate a spatially averaged gridded data model over the detailed survey area. The data model was based on a square grid cell size of 25 m and was used to produce a depth-to-bedrock surface model for the detailed survey area. Based on the depth-to-bedrock data model, some sample boundaries were defined around potential CAD site areas and approximate capacities were generated using three different values for the controlling CAD site basement. These results are presented in Section 3.2. The depth-to-bedrock data model and images of selected sub-bottom transect lines have been incorporated into the DMMP GIS database.

2.3 REMOTS® Sediment-Profile Imaging

2.3.1 REMOTS® Image Acquisition

A total of 40 stations were occupied during the REMOTS® sediment-profile imaging survey conducted on March 15, 2001. This included stations 1 through 30 located throughout the outer harbor area, stations OF-1 through OF-4 around the suspected location of the former sewer outfall, and stations 73 through 78 in the vicinity of the four candidate CAD cells labeled G-cell-1 through G-cell-4 (Figure 2-2). Immediately following the REMOTS® sampling operations, the 35-mm slide film was processed by SAIC's field technician to ensure that images suitable for analysis were obtained at all 40 stations.

REMOTS® is a formal and standardized technique for sediment-profile imaging and analysis (Rhoads and Germano 1982; 1986). A Benthos Model 3731 Sediment Profile Camera (Benthos, Inc., North Falmouth, MA) was used in this study (Figure 2-3). The camera is designed to obtain *in situ* profile images of the top 20 cm of sediment. Functioning like an inverted periscope, the camera consists of a wedge-shaped prism with a front faceplate and a back mirror mounted at a 45-degree angle to reflect the profile of the sediment-water interface facing the camera. The prism is filled with distilled water, the assembly contains an internal strobe used to illuminate the images, and a 35-mm camera is mounted horizontally on top of the prism. The prism assembly is moved up and down into the sediments by producing tension or slack on the winch wire. Tension on the wire keeps the prism in the up position, out of the sediments.

The camera frame is lowered to the seafloor at a rate of about 1 m/sec (Figure 2-3). When the frame settles onto the bottom, slack on the winch wire allows the prism to penetrate the seafloor vertically. A passive hydraulic piston ensures that the prism enters the bottom slowly (approximately 6 cm/sec) and does not disturb the sediment-water interface. As the prism starts to penetrate the seafloor, a trigger activates a 13-second time delay on the shutter release to allow maximum penetration before a photo is taken. A Benthos Model 2216 Deep Sea Pinger is attached to the camera and outputs a constant 12 kHz signal of one ping per second; upon discharge of the camera strobe, the ping rate doubles for 10 seconds. Monitoring the signal output on deck provides confirmation that a successful image was obtained. Because the sediment photographed is directly against the faceplate, turbidity of the ambient seawater does not affect image quality. When the camera is raised, a wiper blade cleans off the faceplate, the film is advanced by a motor drive, the strobe is recharged, and the camera can be lowered for another image.

2.3.2 REMOTS® Image Analysis

The REMOTS® images were analyzed with SAIC's full-color digital image analysis system. This is a PC-based system integrated with a Javelin CCTV video camera and frame grabber. Color slides are digitally recorded as color images on computer disk. The image analysis software is a menu-driven program that incorporates user commands via keyboard and mouse. The system displays each color slide on the CRT while measurements of physical and biological parameters are obtained. Proprietary SAIC software allows the measurement and storage of data on up to 21 different variables for each REMOTS® image obtained. Automatic disk storage of all measured parameters allows data from any variables of interest to be compiled, sorted, displayed graphically, contoured, or compared statistically. All measurements were printed out on data sheets for a quality assurance check by an SAIC Senior Scientist before being approved for final data synthesis, statistical analyses, and interpretation. A summary of the major categories of REMOTS® data is presented below.

2.3.3 Sediment Type Determination

The sediment grain size major mode and range are estimated visually from the photographs by overlaying a grain size comparator which is at the same scale. This comparator was prepared by photographing a series of Udden-Wentworth size classes (equal to or less than coarse silt up to granule and larger sizes) through the REMOTS® camera. Seven grain size classes are on this comparator: >4 phi, 4-3 phi, 3-2 phi, 2-1 phi, 1-0 phi, 0-(-1 phi), and <-1 phi. The lower limit of optical resolution of the photographic system is about 62 microns (4 phi), allowing recognition of grain sizes equal to or greater than coarse silt. The accuracy of this method has been documented by comparing REMOTS® estimates with grain size statistics determined from laboratory sieve analyses. Table 2-1 is provided to show the relationship between phi units and other commonly used grain size scales.

The major modal grain size that is assigned to an image is the dominant grain size as estimated by area within the imaged sediment column. In those images that show layering of sand and mud, the dominant major mode assigned to a replicate therefore depends on how much area of the photograph is represented by sand versus mud. These textural assignments may or may not correspond to traditional sieve analyses depending on how closely the vertical sampling intervals are matched between the grab or core sample and the depth of the imaged sediment.

2.3.4 Optical Prism Penetration Depth

The optical prism penetrates the bottom under a static driving force imparted by the weight of the descending optical prism, camera housing, supporting mechanism, and weight packs. The penetration depth into the bottom depends on the force exerted by the optical prism and the bearing strength of the sediment. If the weight of the camera prism is held constant, the change in penetration depth over a surveyed site will reflect changes in geotechnical properties of the bottom. In this sense, the camera prism acts as a static-load penetrometer. The depth of penetration of the optical prism into the bottom can be a useful parameter, because dredged and capped materials often will have different shear strengths and bearing capacities.

2.3.5 Apparent Redox Potential Discontinuity (RPD) Depth

Aerobic near-surface marine sediments typically have higher reflectance values relative to underlying anoxic sediments. Sand also has higher optical reflectance than mud. These differences in optical reflectance are readily apparent in REMOTS® images; the oxidized surface sediment contains particles coated with ferric hydroxide (an olive color when associated with particles) or iron oxide, producing a rust color, while reduced and muddy sediments below this oxygenated layer are darker, generally grey to black. The boundary between the colored ferric hydroxide surface sediment and underlying grey to black sediment is called the apparent redox potential discontinuity, or RPD.

Table 2-1

Grain Size Scales for Sediments

ASTM (Unified) Classification[1]	U.S. Std. Sieve[2]	Size in mm	Phi (Φ) Size	Wentworth Classification[3]
Boulder		4096.	-12.0	
		1024.	-10.0	Boulder
	12 in (300 mm)	256.	-8.0	
		128.	-7.0	Large Cobble
		107.64	-6.75	
Cobble		90.51	-6.5	Small Cobble
	3 in (75mm)	76.11	-6.25	
		64.00	-6.0	
		53.82	-5.75	
		45.26	-5.5	
		38.05	-5.25	Very Large Pebble
Coarse Gravel		32.00	-5.0	
		26.91	-4.75	
		22.63	-4.5	
	3/4 in (19 mm)	19.03	-4.25	Large Pebble
		16.00	-4.0	
		13.45	-3.75	
		11.31	-3.5	
		9.51	-3.25	Medium Pebble
Fine Gravel	2.5	8.00	-3.0	
	3	6.73	-2.75	
	3.5	5.66	-2.5	
	4 (4.75 mm)	4.76	-2.25	Small Pebble
	5	4.00	-2.0	
	6	3.36	-1.75	
Coarse Sand	7	2.83	-1.5	
	8	2.38	-1.25	
	10 (2.0 mm)	2.00	-1.0	Granule
	12	1.68	-0.75	
	14	1.41	-0.5	
	16	1.19	-0.25	
	18	1.00	0.0	Very Coarse Sand
Medium Sand	20	0.84	0.25	
	25	0.71	0.5	
	30	0.59	0.75	
	35	0.50	1.0	Coarse Sand
	40 (0.425 mm)	0.420	1.25	
	45	0.354	1.5	
	50	0.297	1.75	
	60	0.250	2.0	Medium Sand
	70	0.210	2.25	
	80	0.177	2.5	
	100	0.149	2.75	
Fine Sand	120	0.125	3.0	
	140	0.105	3.25	Fine Sand
	170	0.088	3.5	
	200 (0.075 mm)	0.074	3.75	
	230	0.0625	4.0	
	270	0.0526	4.25	Very Fine Sand
	325	0.0442	4.5	
Fine-grained Soil: Clay if PI ³ 4 and plot of PI vs. LL is on or above "A" line* Silt if PI < 4 and plot of PI vs. LL is below "A" line* * and the presence of organic matter does not influence LL.	400	0.0372	4.75	
		0.0312	5.0	
		0.0156	6.0	Coarse Silt
		0.0078	7.0	
		0.0039	8.0	
		0.00195	9.0	Medium Silt
		0.00098	10.0	
		0.00049	11.0	Fine Silt
		0.00024	12.0	Very Fine Silt
		0.00012	13.0	Coarse Clay
		0.000061	14.0	Medium Clay
				Fine Clay

---

1. ASTM Standard D 2487-92. This is the ASTM version of the Unified Soil Classification System. Both systems are similar (from ASTM (1993)).
2. Note that British Standard, French, and German DIN mesh sizes and classifications are different.
3. Wentworth sizes (in inches) cited in Krumbein and Sloss (1963).

The depth of the apparent RPD in the sediment column is an important time-integrator of dissolved oxygen conditions within sediment pore waters. In the absence of bioturbating organisms, this high reflectance layer (in muds) will typically reach a thickness of 2 mm (Rhoads 1974). This depth is related to the supply rate of molecular oxygen by diffusion into the bottom and the consumption of that oxygen by the sediment and associated microflora. In sediments that have very high sediment-oxygen demand, the sediment may lack a high reflectance layer even when the overlying water column is aerobic.

In the presence of bioturbating macrofauna, the thickness of the high reflectance layer may be several centimeters. The relationship between the thickness of this high reflectance layer and the presence or absence of free molecular oxygen in the associated pore waters must be made with caution. The boundary (or horizon) which separates the positive Eh region (oxidized) from the underlying negative Eh region (reduced) can only be determined accurately with microelectrodes. For this reason, we describe the optical reflectance boundary, as imaged, as the "apparent" RPD, and it is mapped as a mean value.

The depression of the apparent RPD within the sediment is relatively slow in organic-rich muds (on the order of 200 to 300 micrometers per day); therefore, this parameter has a long time constant (Germano and Rhoads 1984). The rebound in the apparent RPD is also slow (Germano 1983). Measurable changes in the apparent RPD depth using the REMOTS® optical technique can be detected over periods of one or two months. This parameter is used effectively to document changes (or gradients) which develop over a seasonal or yearly cycle related to water temperature effects on bioturbation rates, seasonal hypoxia, sediment oxygen demand, and infaunal recruitment.

In sediment-profile surveys of ocean disposal sites sampled seasonally or on an annual basis throughout the New England region performed under the DAMOS (Disposal Area Monitoring System) Program for the New England Army Corps of Engineers, SAIC repeatedly has documented a drastic reduction in apparent RPD depths at disposal sites immediately after dredged material placement, followed by a progressive postdisposal apparent RPD deepening (barring further physical disturbance). Consequently, time-series RPD measurements can be a critical diagnostic element in monitoring the degree of recolonization in an area by the ambient benthos.

The depth of the mean apparent RPD also can be affected by local erosion. The peaks of dredged material disposal mounds commonly are scoured by flow over the mound. This can result in washing away of fines, development of shell or gravel lag deposits, and very thin apparent RPD depths. During storm periods, erosion may completely remove any evidence of the apparent RPD (Fredette et al. 1988).

Another important characteristic of the apparent RPD is the contrast in reflectance values at this boundary. This contrast is related to the interactions among the degree of organic-loading, bioturbational activity in the sediment, and the levels of bottom-water dissolved oxygen in an area. High inputs of labile organic material increase sediment oxygen demand and, subsequently, sulfate reduction rates (and the abundance of sulfide end-products). This results in more highly reduced (lower reflectance) sediments at depth and higher RPD contrasts. In a region of generally low RPD contrasts, images with high RPD contrasts indicate localized sites of relatively high past inputs of organic-rich material (e.g., organic or phytoplankton detritus, dredged material, sewage effluent, etc.).

2.3.6 Infaunal Successional Stage Designation

The mapping of successional stages, as employed in this project, is based on the theory that organism-sediment interactions in fine-grained sediments follow a predictable sequence after a major seafloor perturbation (e.g., passage of a storm, disturbance by bottom trawlers, dredged material deposition, hypoxia). This theory states that primary succession results in "the predictable appearance of macrobenthic invertebrates belonging to specific functional types following a benthic disturbance. These invertebrates interact with sediment in specific ways. Because functional types are the biological units of interest, our definition does not demand a sequential appearance of particular invertebrate species or genera" (Rhoads and Boyer 1982). This theory is formally developed in Rhoads and Germano (1982; 1986) and Rhoads and Boyer (1982).

The term disturbance is used here to define natural processes, such as seafloor erosion, changes in seafloor chemistry, and foraging disturbances which cause major reorganization of the resident benthos; disturbance also includes anthropogenic impacts, such as dredged material or sewage sludge placement, thermal effluent from power plants, bottom trawling, pollution impacts from industrial discharge, etc. An important aspect of using this successional approach to interpret benthic monitoring results is relating organism-sediment relationships to the dynamical aspects of end-member successional stages (i.e., Stage I, II, or III communities as defined in the following paragraphs). This involves deducing dynamics from structure, a technique pioneered by Johnson (1972) for marine soft-bottom habitats. The application of this approach to benthic monitoring requires *in situ* measurements of salient structural features of organism-sediment relationships as imaged through REMOTS® technology.

Pioneering assemblages (Stage I assemblages) usually consist of dense aggregations of near-surface living, tube-dwelling polychaetes; alternately, opportunistic bivalves may colonize in dense aggregations after a disturbance (Rhoads and Germano 1982, Santos and Simon 1980a). These functional types are usually associated with a shallow redox boundary; bioturbation depths are shallow, particularly in the earliest stages of colonization. In the absence of further disturbance, these early successional assemblages are eventually replaced by infaunal deposit feeders; the start of this "infaunalization" process is designated arbitrarily as Stage II. Typical Stage II species are shallow dwelling bivalves or, as is common in New England waters, tubicolous amphipods. In studies of hypoxia-induced benthic defaunation events in Tampa Bay, Florida, ampeliscid amphipods appeared as the second temporal dominant in two of the four recolonization cycles (Santos and Simon 1980a, 1980b).

Stage III taxa, in turn, represent high-order successional stages typically found in low-disturbance regimes. These invertebrates are infaunal, and many feed at depth in a head-down orientation. The localized feeding activity results in distinctive excavations called feeding voids. Diagnostic features of these feeding structures include a generally semicircular shape with a flat bottom and arched roof, and a distinct granulometric change in the sediment particles overlying the floor of the structure. This granulometric change is caused by the accumulation of coarse particles that are rejected by the animals feeding selectively on fine-grained material. Other subsurface structures, such as burrows or methane gas bubbles, do not exhibit these characteristics and therefore are quite distinguishable from these distinctive feeding structures. The bioturbational activities of these deposit-feeders are responsible for aerating the sediment and causing the redox horizon to be located several centimeters below the sediment-water interface. In the retrograde transition of Stage III to Stage I, it is sometimes possible to recognize the presence of relic (i.e., collapsed and inactive) feeding voids.

The end-member stages (Stages I and III) are easily recognized in REMOTS® images by the presence of dense assemblages of near-surface polychaetes and the presence of subsurface feeding voids, respectively; both types of assemblages may be present in the same image. Additional information on REMOTS® image interpretation can be found in Rhoads and Germano (1982, 1986).

2.3.7 Organism-Sediment Index (OSI)

The multi-parameter REMOTS® Organism-Sediment Index (OSI) has been constructed to characterize habitat quality. Habitat quality is defined relative to two end-member standards. The lowest value is given to those bottoms which have low or no dissolved oxygen in the overlying bottom water, no apparent macrofaunal life, and methane gas present in the sediment (see Rhoads and Germano 1982, 1986, for REMOTS® criteria for these conditions). The OSI for such a condition is -10. At the other end of the scale, an aerobic bottom with a deeply depressed RPD, evidence of a mature macrofaunal assemblage, and no apparent methane gas bubbles at depth will have an OSI value of +11.

The OSI is a sum of the subset indices shown in Table 2-2. The OSI is calculated automatically by SAIC software after completion of all measurements from each REMOTS® photographic negative. The index has proven to be an excellent parameter for mapping disturbance gradients in an area and documenting ecosystem recovery after disturbance (Germano and Rhoads 1984, Revelas et al. 1987, Valente et al. 1992).

The OSI may be subject to seasonal changes because the mean apparent RPD depths vary as a result of temperature-controlled changes of bioturbation rates and sediment oxygen demand. Furthermore, the successional status of a station may change over the course of a season related to recruitment and mortality patterns or the disturbance history of the bottom. The sub-annual change in successional status is generally limited to Stage I (Polychaete-dominated) and Stage II (amphipod-dominated) seres. Stage III seres tend to be maintained over periods of several years unless they are eliminated by increasing organic loading, extended periods of hypoxia, or burial by thick layers of dredged material. The recovery of Stage III seres following abatement of such events may take several years (Rhoads and Germano 1982). Stations that have low OSI values (+6) are indicative of recently disturbed areas and tend to have greater temporal and spatial variation in benthic habitat quality than stations with higher OSI values (> +8).

2.3.8 Benthic Habitat Classification

Based on extensive past REMOTS® survey experience in coastal New England, five basic benthic habitat types have been found to exist in shallow-water estuarine and open-water nearshore environments: AM = Ampelisca mat, SH = shell bed, SA = hard sand bottom, HR = hard rock/gravel bottom, and UN = unconsolidated soft bottom (Table 2-3). Several sub-habitat types exist within these major categories (Table 2-3). Each of the REMOTS® sediment-profile images obtained in the present study was assigned one of the habitat categories listed in Table 2-3.

Table 2-2

Calculation of the REMOTS® Organism Sediment Index Value

A. CHOOSE ONE VALUE:

Mean RPD Depth	Index Value
0.00 cm	0
>0 - 0.75 cm	1
0.75 - 1.50 cm	2
1.51 - 2.25 cm	3
2.26 - 3.00 cm	4
3.01 - 3.75 cm	5
>3.75 cm	6

B. CHOOSE ONE VALUE:

Successional Stage	Index Value
Azoic	-4
Stage I	1
Stage I to II	2
Stage II	3
Stage II to III	4
Stage III	5
Stage I on III	5
Stage II on III	5

C. CHOOSE ONE OR BOTH IF APPROPRIATE:

Chemical Parameters	Index Value
Methane Present	-2
No/Low Dissolved Oxygen**	-4

REMOTS® ORGANISM-SEDIMENT INDEX = Total of above subset indices (A+B+C)

RANGE: -10 - +11

** **Note:** This is not based on a Winkler or polarigraphic electrode measurement. It is based on the imaged evidence of reduced, low reflectance (i.e., high oxygen demand) sediment at the sediment-water interface.

Table 2-3.

Benthic habitat categories assigned to sediment-profile images obtained in this study.

Habitat AM: *Ampelisca* Mat
Uniformly fine-grained (i.e., silty) sediments having well-formed amphipod (*Ampelisca* spp.) tube mats at the sediment-water interface.

Habitat SH: Shell Bed
A layer of dead shells and shell fragments at the sediment surface overlying sediment ranging from hard sand to silts. Epifauna (e.g., bryozoans, tube-building polychaetes) commonly found attached to or living among the shells. Two distinct shell bed habitats:

- **SH.SI: Shell Bed over silty sediment** - shell layer overlying sediments ranging from fine sands to silts to silt-clay.
- **SH.SA: Shell Bed over sandy sediment** - shell layer overlying sediments ranging from fine to coarse sand.

Habitat SA: Hard Sand Bottom
Homogeneous hard sandy sediments, do not appear to be bioturbated, bedforms common, successional stage mostly indeterminate because of low prism penetration.

- **SA.F: Fine sand** - uniform fine sand sediments (grain size: 4 to 3 phi).
- **SA.M: Medium sand** - uniform medium sand sediments (grain size: 3 to 2 phi).
- **SA.G: Medium sand with gravel** - predominately medium to coarse sand with a minor gravel fraction.

Habitat HR: Hard Rock/Gravel Bottom
Hard bottom consisting of pebbles, cobbles and/or boulders, resulting in no or minimal penetration of the REMOTS® camera prism. Some images showed pebbles overlying silty-sediments. The hard rock surfaces typically were covered with epifauna (e.g., bryozoans, sponges, tunicates).

Habitat UN: Unconsolidated Soft Bottom
Fine-grained sediments ranging from very fine sand to silt-clay, with a complete range of successional stages (I, II and III). Biogenic features were common (e.g., amphipod and polychaete tubes at the sediment surface, small surface pits and mounds, large borrow openings, and feeding voids at depth). Several sub-categories:

- **UN.SS: Fine Sand/Silty** - very fine sand mixed with silt (grain size range from 4 to 2 phi), with little or no shell hash.
- **UN.SI: Silty** - homogeneous soft silty sediments (grain size range from >4 to 3 phi), with little or no shell hash. Generally deep prism penetration.
- **UN.SF: Very Soft Mud** - very soft muddy sediments (>4 phi) of high apparent water content, methane gas bubbles present in some images, deep prism penetration.

3.0 RESULTS

3.1 Sub-bottom Characterization of the Outer Gloucester Harbor.

No major data problems were encountered during processing of the sub-bottom data, and the entire survey area was covered as planned. Figure 3-1 presents a color-coded trackline view of the bedrock depth below the seafloor for each of the sub-bottom survey lines. Because the data coverage for the broader "reconnaissance" survey area was relatively sparse, the primary focus for this section and the subsequent Discussion section will be on the observed results within the detailed survey area south of Tenpound Island.

A review of the initial digitizing of the sub-bottom reflectors showed generally strong agreement between most of the overlapping data points. In those areas where the agreement was not strong, the raw sub-bottom data were re-analyzed to determine the reasons for the inconsistency. In almost all cases, the major inconsistencies were caused by the presence of a third reflector. In some cases this third reflector was incorrectly digitized as the bedrock layer and in other instances this reflector completely masked the bedrock reflector. In these areas, the raw sub-bottom data were re-edited to generate updated digitized sub-bottom layer data files. In those areas where the bedrock layer could not be definitively identified, the bedrock layer was left blank. This area of unknown depth-to-bedrock is outlined and labeled in Figure 3-1.

To better illustrate the nature of the sub-bottom data throughout the detailed survey area, some example annotated sub-bottom profiling transects have been provided in Figures 3-2 thru 3-5. The relative location of each of these four transects is highlighted in Figure 3-1. Sub-bottom transect GEN EW 07 (Figure 3-2) runs east to west across the northern portion of the survey area and shows a relatively consistent track of the bedrock layer. This transect shows bedrock outcropping the seafloor in a few places and also shows the sewer outfall area that runs in a southerly direction through the western portion of the survey area. In the central portion of this record, the third reflector can also be identified running approximately 5 m below the seafloor and from 1-7 m above the bedrock layer.

Sub-bottom transect GEN EW 11 (Figure 3-3) runs east to west across the southern portion of the survey area and illustrates a less consistent track of the bedrock layer compared to line GEN EW 07. Although the bedrock layer can be detected in the eastern portions of the record, it is much less distinct to the west. On the western side of the record, where the initial seafloor return is much harder, the Bubble Pulser provides a better depiction of the bedrock layer. As annotated on the figure, the small bedrock data gap area in the central part of the record corresponds with the southern extent of the large blank area depicted in Figure 3-1. This transect also shows the sewer outfall area that runs in a southerly direction through the western portion of the survey area.

Sub-bottom transect DET NS 05 (Figure 3-4) runs north to south across the central portions of the survey area and provides consistent tracking of the bedrock layer only in the northern portions of the area. A relatively long section of the central portion of this transect has been annotated as an area where the bedrock layer cannot be definitively identified through either the ChirpII or the Bubble Pulser data. The large bedrock data gap area identified in this record corresponds with the central extent of the large unknown area depicted in Figure 3-1. In the northern portions of this record, traces of the unknown third reflector can also be identified.

Sub-bottom transect DET NS 07 (Figure 3-5) runs north to south across the central portions of the survey area and provides consistent tracking of the bedrock layer throughout the entire length of the transect. This transect provides the eastern limit for the large unknown area depicted in Figure 3-1. Throughout this record, traces of the unknown third reflector can also be identified.

3.2 Selection of Sample CAD Sites in Outer Gloucester Harbor

Based primarily on the sub-bottom results presented in Section 3.1, two sample CAD sites were selected and have been designated as OG-N and OG-S (Outer Gloucester – North and South). The locations and dimensions of OG-N and OG-S are presented in three different views in Figures 3-6 thru 3-8. Figure 3-6 presents the sample CAD site locations over the depth-to-bedrock sub-bottom trackline data; Figure 3-7 presents the sample CAD site locations over a 25 m gridded data model that was created from the depth-to-bedrock data; and Figure 3-8 presents the sample CAD site locations over a three dimensional surface view of the area that was generated from the gridded data model depicted in Figure 3-7.

These two areas were selected because they are significant in size and possess both reliable sub-bottom coverage and a minimum depth-to-bedrock of 10 m. In general, 10 m was selected as a minimum required depth-to-bedrock for the initial selection of these CAD cells because it provides reasonably sufficient disposal capacity. As discussed in Section 3.1, the “unknown area” on the southwestern edge of the detailed survey area where the bedrock layer could not be detected may provide the largest and most promising location for any eventual CAD site development. However, because any estimate of the true bedrock depth in this area would be speculative, this area was excluded from consideration in this analysis. This area would certainly warrant further consideration during any follow-on coring or other geophysical investigation.

Sample CAD site OG-N comprises an area of 56,626 m^2 and is located about 300 m south of Tenpound Island in a natural bedrock depression that is well-defined by multiple sub-bottom profile transects, including some of the transects presented in Section 3.1. Figures 3-2 and 3-5 have been annotated to indicate the approximate portions of those transects that pass through the area encompassed by OG-N. As both of these figures illustrate, the bedrock layer can be clearly identified and tracked as it outcrops the seafloor around the edges of OG-N and then slopes down to as much as 16 m below the seafloor near the center of OG-N. In addition to the seafloor and bedrock reflectors, these figures also show the presence of an unknown third reflector. This third reflector tracks about 5 m below the seafloor and about 10 m above the bedrock throughout the OG-N area. Within the boundaries of OG-N, the maximum bedrock depth was 16.2 m, the minimum bedrock depth was 6.8 m, and the average bedrock depth was 12.0 m.

Sample CAD site OG-S comprises an area of 88,954 m^2 and is located just to the west of Black Bess Rocks in another bedrock depression that is also well-defined by multiple sub-bottom profile transects, including one of the transects presented in section 3.1. Figure 3-5 has been annotated to indicate the approximate portion of this transect that passes through the area encompassed by OG-S. As this figure shows, the bedrock layer is not quite as clearly defined in this area as it was within OG-N, particularly towards the southern end of the area. As with the OG-N area, the OG-S area also includes the presence of an unknown third reflector. Within OG-S, this third reflector tracks about 10 m below the seafloor and varies between 2-5 m above the underlying bedrock. Within the boundaries of OG-S, the maximum bedrock depth was 20.4 m, the minimum bedrock depth was 8.9 m, and the average bedrock depth was 12.8 m.

Using the gridded data model that was created from the digitized sub-bottom data, approximate capacities have been generated for both OG-N and OG-S. These capacities were generated using a straight surface volume computation and were based solely on the depth-to-bedrock gridded surface model. Detailed CAD cell design characteristics such as side slope requirements and material suitability or any possible design impacts associated with the third reflector were not considered when generating these capacity values. Some of these issues are discussed in more detail below (section 4.0).

The two different capacity values that were generated for each area are presented in Table 3-1. The first capacity column provides the approximate quantity of existing material above the bedrock layer and would provide the maximum capacity theoretically possible within the area. This would entail vertical walls along the perimeter of the area and would require that all in-place material be excavated down to the bedrock layer. Essentially, the variable underlying bedrock layer would be the basement for the entire CAD cell. Because this is an unrealistic design scenario for many reasons, more conservative capacity estimates have also been generated. The second column provides the approximate capacity available by using a fixed CAD cell basement of 10 m below the seafloor. The inclusion of these two values for each of the two sample CAD areas is intended only to provide a first-order capacity estimate based solely on the digitized depth-to-bedrock data derived from the sub-bottom profiling system.

Table 3-1. Approximate capacity estimates for sample CAD sites OG-N and OG-S.

Sample CAD Site	Capacity to Bedrock	Capacity with 10 m Basement
OG-N	681K m^3	566K m^3
OG-S	1,028K m^3	889K m^3

3.3 REMOTS® Characterization of the Outer Gloucester Harbor, Sewage Outfall and CAD Cell Stations.

At 37 of the 40 REMOTS® stations occupied during the March 2001 survey, two replicate sediment-profile images were obtained and analyzed. At stations 5, 21 and OF-1, only one image of suitable quality for analysis was obtained. Therefore, a total of 77 images were obtained and analyzed in the March 2001 REMOTS® survey. A complete set of image analysis results is provided in Appendix A. In the November 1998 REMOTS® survey of the candidate CAD cells west and north of Tenpound Island (SAIC 1999a), two replicate images were obtained and analyzed at each of the six stations (i.e., 12 total images). The results for all 40 of the stations sampled in March 2001 are presented below. A comparison of the November 1998 and March 2001 survey results at the CAD cell stations is provided in the Discussion (Section 4.4).

3.3.1 Sediment Grain Size

Surface sediments in outer Gloucester Harbor consisted of either silt-clay (>4 phi) or very fine sand (4 to 3 phi; Table 3-2 and Figure 3-9). The very fine sand was found primarily at stations on the western side of the outer Harbor (stations 4 through 7), as well as at stations 29 and 30 inside the breakwater on the eastern side of the harbor (Figures 3-9 and 3-10A). The sand did not appear to be rippled, suggesting that it occurs in a relatively low to medium energy environment where it is not subject to frequent bedload transport. The remainder of the stations, particularly in the area south of Tenpound Island, had primarily soft, muddy (i.e., silt-clay) sediments (Figures 3-9 and 3-10B). At Station 8, the sediment grain size could not be determined due to low camera prism penetration (see Section 3.3.2).

Very fine sand (4 to 3 phi) was found at three of the sewer outfall stations (OF-1, OF-3 and OF-4), while silt-clay (>4 phi) was observed at station OF-2 (Table 3-2; Figure 3-9). The sediment grain size at each of the six candidate CAD cell stations likewise was >4 phi (Table 3-2; Figure 3-9).

3.3.2 Camera Prism Penetration Depth

The depth of penetration of the REMOTS® camera prism can be used to map gradients in the bearing strength (hardness) of seafloor sediments. Older, highly bioturbated and/or sediments comprised primarily of silts and clay tend to be soft and allow deeper penetration than sediments with a higher sand content, which tend to create resistance to camera penetration (e.g., Figure 3-10).

The mean camera penetration for the thirty stations in the outer harbor ranged from 0 cm at station 8 to greater than 20 cm at stations 17 and 18 (Table 3-2; Figure 3-11). The overall mean camera penetration for outer harbor stations was10.9 cm. Most of the stations in the broad area south of Tenpound Island had relatively deep (>10 cm) penetrations depths, reflecting the higher water content and softer nature of the silt-clay sediments in this area. Stations with fine sand on the western side of the outer harbor had shallower penetration depths (<10 cm). There was no camera penetration at station 8 at the entrance to the outer Harbor, presumably due to the presence of hard, rocky bottom at this location.

Table 3-2. Summary of REMOTS$^{®}$ Sediment-Profile Imaging Results for Outer Harbor and Sewer Outfall Stations.

STATION	GRAIN SIZE MAJOR MODE (phi)	MEAN CAMERA PENETRATION (cm)	MEAN BOUNDARY ROUGHNESS (cm)	MEAN APPARENT RPD THICKNESS (cm)	SUCCESSIONAL STAGES PRESENT (# of Replicates)	MEAN OSI	BENTHIC HABITATS PRESENT (# of Replicates)
1	>4	13.5	1.7	11.8	ST_I_TO_II (2)	8	UN.SI (2)
2	>4	11.5	1.5	9.0	ST_I (1) ,ST_I_TO_II (1)	7	UN.SI (2)
3	>4	12.6	0.7	9.6	ST_I_TO_II (l), ST_I_ON_III (1)	9.5	UN.SI (2)
4	4 to 3	7.2	1.2	3.9	ST_I_TO_II (l), ST_I_ON_III (l)	8.5	UN.SS (2)
5	4 to 3	5.4	0.8	4.7	ST_I (1)	7	SA.F (1)
6	4 to 3	3.5	1.9	3.3	ST_I (2)	5.5	SA.F (2)
7	4 to 3	3.6	1.2	3.5	ST_I (2)	6	SA.F (2)
8	NA	0.0	0.0	NA	INDET (2)	99	N/A
9	>4	9.7	1.0	2.5	ST_I (2)	5	UN.SS (2)
10	>4	10.9	1.1	2.9	ST_I_TO_II (1), ST_I_ON_III (1)	8	UN.SI (2)
11	>4	12.0	3.0	4.3	ST_I (1), ST_I_TO_II (1)	7.5	UN.SI (2)
12	>4	9.6	1.4	3.0	ST_I (1), ST_I_TO_II (1)	5	UN.SI (1), UN.SS (1)
13	>4	7.0	0.6	4.5	ST_I_ON_III (2)	9.5	UN.SS (2)
14	>4	12.3	3.4	3.5	ST_I_TO_II (2)	7	UN.SI (2)
15	>4	16.3	2.0	10.4	ST_I_TO_II (2)	8	UN.SI (2)
16	>4	17.7	1.1	13.2	ST_I_ON_III (2)	11	UN.SI (2)
17	>4	20.6	0.0	NA	ST_III (2)	99	UN.SF (2)
18	>4	20.3	0.5	10.4	INDET (2)	99	UN.SF (2)
19	>4	15.6	1.3	13.4	ST_I_TO_II (2)	8	UN.SI (2)
20	>4	13.1	1.2	4.4	ST_I_TO_II (1), ST_I_ON_III (1)	9	UN.SI (2)
21	>4	13.0	3.7	11.8	ST_I_TO_II (1)	8	UN.SI (1)
22	>4	14.1	1.2	11.7	ST_I_TO_II (2)	8	UN.SI (2)
23	>4	13.2	1.4	5.2	ST_I_TO_II (2)	8	UN.SI (2)
24	>4	10.2	1.8	5.7	ST_I_TO_II (2)	8	UN.SI (1), UN.SS (1)
25	>4	15.0	0.7	4.5	ST_I_TO_II (1), ST_I_ON_III (1)	9	UN.SI (2)
26	>4	10.1	0.4	7.4	ST_I_TO_II (2)	8	UN.SI (2)
27	>4	10.2	0.9	1.4	ST_I (2)	3.5	UN.SI (2)
28	>4	10.4	0.5	6.7	ST_I (1), ST_I_TO_II (1)	7.5	UN.SI (2)
29	4 to 3	5.7	1.0	5.7	ST_I (1), ST_I_TO_II (1)	7.5	UN.SS (2)
30	4 to 3	4.2	0.8	1.7	ST_I (2)	4	SA.F (1), UN.SS (1)
OF1	4 to 3	5.6	1.3	1.5	ST_I (1)	3	SA.F (1)
OF2	>4	7.5	0.8	1.8	ST_I (1), ST_I_TO_II (1)	4.5	SA.F (1), UN.SS (1)
OF3	4 to 3	9.7	0.7	1.8	ST_I (1), ST_I_TO_II (1)	4.5	UN.SS (2)
OF4	4 to 3	5.5	0.7	3.5	ST_I_TO_II (2)	7	SA.F (1), UN.SS (1)
73	>4	17.6	3.5	11.5	ST_I_TO_II (1), ST_I_ON_III (1)	9.5	UN.SI (2)
74	>4	14.6	2.5	8.7	ST_I_TO_II (1), ST_I_ON_III (1)	9.5	UN.SI (2)
75	>4	17.8	2.1	16.2	ST_I_TO_II (1), ST_I_ON_III (1)	9.5	UN.SI (2)
76	>4	16.5	2.3	11.3	ST_I_ON_III (2)	11	UN.SI (2)
77	>4	11.0	1.7	6.0	ST_I_TO_II (1), ST_I_ON_III (1)	9.5	UN.SS (2)
78	>4	13.0	3.4	10.4	ST_I_ON_III (2)	11	UN.SI (1), UN.SF (1)

Camera penetration depths at the four outfall stations were in the range 5 to 10 cm (Table 3-2; Figure 3-11). As with the thirty outfall stations, these results correlated well with the results of the sediment grain size analyses described in Section 3.3.1. The sediment at these stations was predominately very fine sand, which tended to resist deeper camera prism penetration. The mean camera penetration for the six CAD cell stations ranged between 11.0 and 17.8 cm (Table 3-2; Figure 3-11). These are relatively deep prism penetration values which reflect the soft, fine-grained nature of the sediment found at these stations.

3.3.3 Boundary Roughness

Boundary roughness is a measure of small-scale surface relief and represents the difference between the minimum and maximum camera prism penetration depth. This small-scale relief can be attributed to either physical (e.g., currents) or biological (e.g., burrows or fecal mounds) processes that may affect seafloor topography.

The mean boundary roughness of the majority of the outer harbor stations ranged between 0 and 3 cm (Table 3-2; Figure 3-12). Values in this range reflect a moderate amount of small-scale surface relief, due primarily to biological reworking of the surface sediments. Stations 14 and 21 had slightly higher boundary roughness values, ranging from 3 to 5 cm. These values are attributed to physical processes affecting the sediments at station 14 and biological activity (dissection of a burrow) at station 21. The boundary roughness at station 8 was indeterminate because the camera prism did not penetrate at this hard-bottom station.

Mean boundary roughness values at the four outfall stations were also quite low, ranging from 0 to 2 cm (Table 3-2; Figure 3-12). Three of the stations had small-scale relief of only 0 to 1 cm. The remaining station (OF-1) had a mean boundary roughness of 1.3 cm, suggesting minimal influence of biological or physical processes on surface topography at these stations.

The boundary roughness for the six CAD stations ranged from a low of 1.7 cm at station 77 to a high of 3.5 cm at station 73 (Table 3-2; Figure 3-12). This range of values reflects a moderate amount of small-scale surface relief, attributed mainly to reworking of the sediment surface by benthic organisms at the CAD cell stations.

3.3.4 Apparent RPD Depth

The majority (23 of 30) of the outer harbor stations had well-developed mean apparent RPD depths of greater than 3 cm, indicative of normal or healthy oxygen penetration into the surface sediments (Table 3-2 and Figure 3-13). At 14 of the 30 stations, the RPD was exceptionally well-developed (>5 cm), indicating deep sediment aeration attributed to extensive bioturbation by deep-dwelling infauna (Figure 3-14A). At a significant number of stations (11 of 30), the reduced sediment below the oxidized surface RPD layer was extremely black in appearance (Figure 3-14A and B), suggesting a high inventory of organic matter and elevated levels of sulfides. The blackness of the underlying sediment suggests that there is a significant input of organic matter to the bottom in outer Gloucester Harbor, but the well-developed RPD depths indicate that the benthic community is able to process this input and maintain a well-oxygenated environment in the upper sediment column.

A group of stations located behind the breakwater in the southeast corner of outer Harbor (stations 9, 10, 27 and 30) had shallower mean apparent RPD depths ranging from 1 to 3 cm. It is possible that tidal circulation in the outer Harbor produces an eddy or still area behind the breakwater that results in higher rates of organic matter deposition to the bottom in this location (i.e., a focusing site). This elevated organic matter input apparently is not readily processed by the resident benthic community, resulting in the observed shallower RPD depths.

The mean apparent RPD depths for outfall stations OF-1, OF-2 and OF-3 were in the range of 1 to 2 cm, and station OF-1 had very black, reduced sediments at depth (Table 3-2; Figures 3-13 and 3-14B). The relatively shallow RPD depths at 3 of the 4 outfall stations, and the reduced sediment at station OF-1, may indicate continued elevated levels of organic matter in the sediment in this location related to the former outfall. In contrast, outfall station OF-4 had a mean RPD of 3.5 cm.

All of the CAD stations had mean apparent RPD depths greater than 5 cm in the March 2001 survey, with values ranging between 6.0 cm at station 77 to 16.2 cm at station 75 (Table 3-2; Figure 3-13). These very deep apparent RPD depths are indicative of a relatively high degree of biological re-working of the surface sediment (i.e., bioturbation activity), which results in extensive sediment aeration.

3.3.5 Infaunal Successional Stage

At the majority of the outer harbor stations (20 of 30), the successional stage designation was Stage I and/or Stage I progressing to Stage II (i.e., “Stage I going to II”; Table 3-2 and Figure 3-15). The Stage I going to II designation indicates the presence of both small, opportunistic polychaetes at the sediment surface together with evidence of extensive burrowing just below the sediment surface (Figure 3-16A). This near-surface burrowing is attributed to amphipods and other shallow-dwelling, “Stage II” organisms that become abundant as benthic succession beyond Stage I results in a community living increasingly deeper with the sediment.

Stage I by itself was observed mainly at the stations having fine sand on the western side of the harbor, as well as at several of the stations immediately behind the breakwater in the southeast corner (Figure 3-15). Stage III, alone or in combination with Stage I, occurred at 8 of the 30 stations, mainly those having muddy sediment in the central part of the surveyed area (Figure 3-16B). The successional stage designation at stations 8 and 18 was indeterminate due to either under- or over-penetrations of the camera prism.

Two of the outfall stations (OF-2 and OF-3) had both Stage I and Stage I to II successional stages present (Table 3-2; Figure 3-15). Station OF-1 was characterized as having only Stage I organisms present, and station OF-4 had a successional stage of I to II. The apparent dominance of opportunistic Stage I taxa at these stations may reflect the former higher rates of organic loading associated with the relative proximity of the stations to the sewage outfall.

At least one replicate image at each of the CAD cell stations in 2001 had a Stage I on III successional designation, indicative of an apparent diverse and reasonably well-established benthic community (Table 3-2 and Figure 3-15).

3.3.6 Organism-Sediment Index

The majority of the outer harbor stations (21 of 30) had OSI values greater than +6.01, considered indicative of relatively healthy or undisturbed benthic habitat quality (Table 3-2; Figure 3-17). These relatively high values mainly reflect the extremely well-developed apparent RPD depths at these stations, together with an apparent diverse benthic community consisting of a combination of Stage I, II and III taxa. Six stations (Stations 6, 7, 9, 12, 27, and 30) had average OSI values ranging from +3.01 to +6.0, considered indicative of only moderately degraded benthic habitat quality. These values reflect both the dominance of lower-order successional stages at these stations (I or I to II) in combination with relatively shallow (< 3 cm) apparent RPD depths. The OSI for the three remaining stations (stations 8, 17 and 18) was indeterminate, due to either the over-penetration (stations 17 and 18) or under-penetration (station 8) of the camera prism

One of the stations at the sewer outfall (OF-4) had an OSI value of +7.0, which fell in the “non-degraded” range of +6.01 to +11 (Table 3-2; Figure 3-17). Two stations (OF-2 and OF-3) had OSI values in the moderately degraded range of +3.01 to +6.0. The remaining station (OF-1) had an OSI of +3.0 (considered indicative of disturbed benthic habitat quality) due to the station’s shallow RPD and presence of only an early, opportunistic successional stage (Stage I organisms).

The mean organism sediment index (OSI) values at the six CAD cells were all greater than +6.01, indicative of non-degraded or healthy benthic habitat quality (Table 3-2; Figure 3-17).

3.3.7 Benthic Habitat Classification

The primary benthic habitat classification for the 30 outer harbor and four outfall stations was unconsolidated soft, silty mud (habitat type UN.SI; Table 3-2 and Figure 3-18). Eight of the stations were classified as unconsolidated soft bottom comprised of slightly more sandy mud (habitat type UN.SS), seven as hard, fine sand bottom (habitat type SA.F), and two as very soft mud (habitat type UN.SF). Consistent with the sediment grain size results, the fine sand habitat (SA.F) was found principally on the western side of the outer harbor, including the stations in the vicinity of the former outfall. As previously indicated, the absence of ripples in the sand suggests that this area represents a low-energy sand environment. In general, there was a gradient of increasingly softer, finer-grained sediments (SA.F to UN.SS to UN.SI/SF) moving from west to east and from south to north across the surveyed area (Figure 3-18). The benthic habitat type at Station 08 at the entrance to the outer Harbor was indeterminate (INDET) due to the fact that the camera did not penetrate the seafloor sediments; it is likely that this station had habitat type HR (hard rock/gravel bottom).

Unconsolidated soft, silty sediment (UN.SI) was the primary benthic habitat type found at the CAD cell stations (Table 3-2; Figure 3-18). One exception to this was station 77, which was classified as consisting of soft muddy sediment having a slightly higher fine sand component (UN.SS). Station 78 also had one replicate image that was classified as very soft mud (UN.SF).

4.0 DISCUSSION

4.1 Depth-to-Bedrock and CAD Cell Siting in Gloucester Harbor

The March 2001 sub-bottom survey of outer Gloucester Harbor focused on the area south of Tenpound Island and provided results that serve to augment those of the December 1998 sub-bottom survey of the inner harbor reported previously (SAIC 1999b). Therefore, the results of the December 1998 and March 2001 sub-bottom surveys can be combined to provide a fairly comprehensive picture of depth-to-bedrock in Gloucester Harbor (Figure 4-1). The inner Gloucester Harbor areas previously surveyed in December 1998 generally showed shallow depth-to-bedrock, but the survey results were subsequently reviewed in light of additional existing geotechnical data. The report presenting the results of this review (SAIC 2000) is included herein as Appendix B; it identifies four potential CAD cell sites located west and north of Tenpound Island (sites G-cell-1 through G-cell-4). The location of these candidate CAD cell sites is shown in Figure 4-2 in relation to the sub-bottom survey results.

The March 2001 sub-bottom survey presented herein indicated some relatively prominent bedrock depressions in outer Gloucester Harbor that were well characterized by multiple sub-bottom transects. Two additional potential CAD sites (OG-N and OG-S) have been laid out over these bedrock depressions (Figure 4-2). Table 4-1 provides a summary of the initial, approximate capacity estimates that have been generated for each of the potential CAD sites depicted in Figure 4-2.

Table 4-1. Summary of Approximate Capacity Estimates for Candidate CAD Sites in Gloucester Harbor.

Site Name	Average Depth-to-Bedrock (m)	Estimated Capacity to Bedrock (m^3)
G-Cell-1	6.4	208,015
G-Cell-2	5.5	87,000
G-Cell-3	5.6	138,041
G-Cell-4	6.0	291,114
OG-N	12.0	681,000
OG-S	12.8	1,028,000

In addition to candidate sites OG-N and OG-S, a larger area with potentially deeper bedrock depths was identified in the outer harbor during the March 2001 survey (labeled as the "unknown area" in Figure 4-2). In this area the bedrock layer could not be definitively identified because of the presence of a strong reflector about 5 m below the seafloor surface. Many of the bedrock depths along the edges of this area are quite deep (greater than 20 m in some cases), and if that trend were consistent across the area where the third reflector masks the bedrock layer, then the capacity potential would be very high in this area. However, without any coring or other geophysical data to confirm the depth of the bedrock layer and to assess the composition of the seabed material below this third reflector, it is not possible to make any definitive statement about the CAD site potential of this area.

The presence of a third (or additional) reflector may also have an impact on the potential suitability of sample CAD sites OG-N and OG-S. As the REMOTS® data indicated, most of detailed sub-bottom survey area south of Tenpound Island can be characterized as a depositional area with a seafloor surface comprised primarily of fine-grained silt and clay. It is likely that this same general sediment composition exists down to the sediment boundary layer associated with the third reflector. In sample CAD site OG-N this third reflector averaged about 5 m below the seafloor and in sample CAD site OG-S this third reflector averaged about 10 m below the seafloor.

The composition of the seabed material from this third reflector down to the bedrock layer may be an important factor in the assessment of these locations as potential CAD sites. Based on the geophysical background discussion provided in the previous Gloucester Inner Harbor report (SAIC 2000), it seems likely that this layer between the softer surface sediments and the underlying bedrock layer is comprised of some type of coarser, post-glacial material such as sand, gravel, or till.

The capacity estimates provided for the sample CAD sites in Section 3.2 assumed that the CAD cell could be constructed from the seafloor surface down to the bedrock layer, without consideration for the suitability of seabed material above the bedrock to support the CAD cell creation. If the material in the surface sediment layer turned out to be too soft to support the CAD cell walls or if the material in the underlying coarse layer turned out to be too hard or costly to excavate, then the estimated capacities would be significantly reduced for both of these areas.

4.2 Recommendations for Coring Program

In general, the March 2001 survey identifies the general areas in outer Gloucester Harbor, south of Tenpound Island, that appear to provide sufficient depth-to-bedrock to warrant further consideration as potential CAD sites. Because the actual design and construction of a CAD cell is very dependent upon the properties of the seabed sediments from the bedrock layer up to the seafloor surface, a comprehensive coring survey would need to be conducted to further explore the suitability of these areas. Figure 4-3 shows recommended coring locations in each of the candidate CAD cells that have been identified to date in Gloucester Harbor, as well as in the "unknown area" identified in the March 2001 survey. In general, the recommended core locations were selected around the perimeter of each CAD cell to provide confirmatory geotechnical data on depth to bedrock in these locations. Any coring survey performed will need to confirm the presence, extent, and composition of the soft, coarse, and bedrock boundary layers. These data can then be used to determine the density and permeability of the sediment layers and the ability of these layers to support the CAD cell walls.

4.3 REMOTS® Characterization of Gloucester Harbor

The primary purpose of the March 2001 REMOTS® sediment-profile imaging survey was to characterize seafloor surface conditions (e.g., areas of apparent erosion or deposition) in outer Gloucester Harbor and evaluate the effects of the former sewer outfall on benthic habitat quality. The March 2001 results serve to augment those of the previous REMOTS® survey of the inner harbor conducted in November 1998 (SAIC 1999a). The combined results of the two surveys therefore provide a fairly complete picture of sediment conditions throughout Gloucester Harbor. Two summary contour maps have been prepared to illustrate benthic habitat types (Figure 4-4) and benthic habitat quality (Figure 4-5) in Gloucester Harbor based on the integrated 1998 and 2001 REMOTS® survey results.

In the March 2001 survey, few of the stations in outer Gloucester Harbor showed signs of erosion or scouring from physical processes. A small number of the stations located on the western and southern edges of the survey gird had a sediment grain size major mode of 4 to 3 phi (very fine sand), suggesting that bottom currents are sufficient to winnow finer-grained fractions (i.e., silt and clay) from the heavier sand components. The area with compact sandy sediments on the western side of the outer Harbor is not as protected by the breakwater as the eastern side. The seafloor in this area is therefore likely subject to more scouring by tidal currents and wave action.

The grain size major mode at the majority of the Gloucester Harbor stations sampled in both March 2001 and November 1998 was >4 phi (i.e., mainly silt and clay). Such fine-grained sediments tend to accumulate in more quiescent, depositional areas. Based on both the grain size classification of silt-clay and the relatively deep (i.e., greater than 10 cm) penetration depths of the sediment-profile camera, the benthic habitat at stations in the outer and inner harbor areas was classified as unconsolidated soft bottom, soft mud or silty (habitat types UN.SF or UN.SI; Figure 4-4). In particular, soft, fine-grained sediments were observed in the vicinity of the candidate CAD cells west and north of Tenpound Island (stations 73 through 78), as well as at stations 15 through 19 and stations 25, 26, 27 and 28 located, respectively, in the vicinity of candidate CAD cells OG-N (stations 15 through 19) and OG-S (stations 25, 26, 27 and 28). In general, the 1998 and 2001 REMOTS® results suggest that the sedimentary environment in the vicinity of each of the candidate CAD cells in Gloucester Harbor is largely depositional.

As previously described, the REMOTS® Organism-Sediment Index (OSI) is a summary metric of overall benthic habitat quality. The mapped OSI values based on the combined 1998 and 2000 survey results indicate a gradient of increasingly poorer benthic habitat quality moving from the outer to the inner harbor area (Figure 4-5). In particular, stations 81 and 87 located in the inner-most harbor had highly anoxic sediment, shallow RPD depths, and either azoic conditions or a dominance of low-order successional stages (Stage I) when sampled in November 1998. The combination of these conditions resulted in OSI values less than +3.0, indicating degraded benthic habitat quality (Figure 4-5). Two other inner harbor stations (stations 83 and 85) had OSI values between +3.0 and +6.0, indicating moderately degraded benthic habitat quality. The inner harbor area may have poor water circulation (i.e., restricted tidal flushing) and elevated inputs from runoff and/or local pollution point sources, resulting in the observed degraded sediment quality.

Moving out of the inner harbor, the stations in the vicinity of the candidate CAD cells west and north of Tenpound Island had non-degraded or relatively healthy benthic habitat quality in both the 1998 and 2001 surveys (Figure 4-5). Most of the other outer harbor stations sampled in March 2001 likewise had non-degraded or healthy benthic habitat quality. It is possible to conclude that most of the outer harbor area is characterized by soft, muddy, well-aerated sediments that appear to support a diverse and abundant benthic community. All of the candidate CAD cells are located in areas having relatively healthy benthic habitat quality.

4.4 REMOTS® Characterization of the Former Sewage Outfall Stations

Overall, the stations in the presumed vicinity of the former outfall showed very little indication of lingering impact from the past sewage input in the March 2001 REMOTS® survey. The typical impact of such outfalls is increased organic loading to the surrounding seafloor. Very close to the outfall, such organic loading can overwhelm the assimilative capacity of the seafloor (i.e., eutrophication) and result in degraded benthic habitat quality, while at the same time acting to stimulate benthic production at sufficient distances from the outfall. Stations OF-1 through OF-4 generally were characterized by compact, fine, sandy sediments that typically favor habitation by surface-dwelling Stage I benthic communities as opposed to Stage III. Therefore, the early successional stage observed at these stations is more readily attributed to grain size preferences than to lingering effects of organic loading from the outfall.

The shallow apparent RPD depths at 3 of the 4 outfall stations, coupled with highly anoxic sediment observed at depth at station OF-1 (see Figure 3-14B), may indicate a lingering elevated sediment inventory of organic matter in this area associated with the outfall. However, such conditions were also observed at a few of the other outer Harbor stations located away from the outfall, resulting in OSI values in the range +3 to +6 (moderately degraded). Based on the OSI value of +3.0, outfall station OF-1 was classified as having degraded benthic habitat quality, but the other three outfall stations showed only moderately-degraded (stations OF-2 and OF-3) or non-degraded (station OF-4) benthic habitat quality. Based on these results, any lingering effects of the former sewage input appear to be limited both in magnitude and in spatial extent around the presumed location of the outfall.

4.5 Comparison of the 1998 and 2001 REMOTS® Results at the CAD Cell Stations

The March 2001 REMOTS® survey re-sampled six stations located west and north of Tenpound Island to evaluate existing conditions in the vicinity of the candidate CAD cells and compare these to the conditions observed in the November 1998 survey (SAIC 1999a). This comparison is presented and discussed in the following sections for each REMOTS® parameter.

4.5.1 Sediment Grain Size

In March 2001, the sediment grain size at stations 73 through 78 was found to be >4 phi (Table 4-2; Figure 3-9). The 1998 grain size results for these stations was also >4 phi (Table 4-2). The lack of change in sediment grain size suggests that the sedimentary environment in the area where the candidate CAD cells are located is fairly stable. This area has experienced little or no erosion due to physical processes (i.e., currents) in the period between the two REMOTS® surveys.

Table 4-2. Summary of REMOTS® Sediment-Profile Imaging Results for the 1998 and 2001 Surveys at the Six CAD Cell Stations.

STATION	GRAIN SIZE MAJOR MODE		MEAN CAMERA PENETRATION (cm)		MEAN BOUNDARY ROUGHNESS (cm)		MEAN APPARENT RPD THICKNESS (cm)		SUCCESSIONAL STAGES PRESENT (# of Replicates)		MEAN OSI		BENTHIC HABITATS PRESENT (# of Replicates)	
	1998	**2001**	**1998**	**2001**	**1998**	**2001**	**1998**	**2001**	**1998**	**2001**	**1998**	**2001**	**1998**	**2001**
73	>4	>4	17.4	17.6	0.8	3.5	7.6	11.5	ST I_ON_III (2)	ST_I_TO_II (1), ST_I_ON_III (1)	11.0	9.5	UN.SF (2)	UN.SI (2)
74	>4	>4	15.6	14.6	0.5	2.5	5.3	8.7	ST_I(1), ST_I_ON_III(1)	ST_I_TO_II (1), ST_I_ON_III (1)	9.0	9.5	UN.SF (2)	UN.SI (2)
75	>4	>4	16.3	17.8	0.3	2.1	7.6	16.2	ST_I_ON_III(2)	ST_I_TO_II (1), ST_I_ON_III (1)	11.0	9.5	UN.SF (2)	UN.SI (2)
76	>4	>4	17.2	16.5	1.6	2.3	6.1	11.3	ST_I(1), ST_I_ON_III(1)	ST_I_ON_III (2)	9.0	11.0	UN.SF (1), UN.SI (1)	UN.SI (2)
77	>4	>4	10.3	11.0	1.0	1.7	7.9	6.0	ST I_ON_III (2)	ST_I_TO_II (1), ST_I_ON_III (1)	11.0	9.5	UN.SI (2)	UN.SS (2)
78	>4	>4	16.8	11.8	0.6	4.2	5.8	8.6	ST_I(1), ST_I_ON_III(1)	ST_I_ON_III (2)	9.0	11.0	UN.SF (2)	UN.SI (1), UN.SF (1)

4.5.2 Camera Prism Penetration Depth

In March 2001, the mean camera penetration depths for the six CAD cell stations ranged between 11.0 and 17.8 cm (Table 4-2; Figure 3-11). These values are similar to the values that were reported from the 1998 REMOTS® images at the same stations (Table 4-2). Station 78 showed the greatest difference between surveys (5 cm shallower in 2001). This difference can most likely be attributed to the natural spatial heterogeneity in sediment characteristics at this location compared to the 1998 survey. Although station 78 was ostensibly occupied in both the 1998 and 2001 surveys, differences in navigational precision make it unlikely that exactly the same seafloor location was sampled.

4.5.3 Boundary Roughness

The boundary roughness for the six CAD cell stations in March 2001 ranged from a low of 1.7 cm at station 77 to a high of 4.2 cm at station 78 (Table 4-2; Figure 3-12). The mean for all of the stations was 2.7 cm. The boundary roughness values for the 2001 survey were considerably higher than those reported for the 1998 survey, mainly attributed to increased biological re-working of the surface sediments during the more recent survey.

4.5.4 Apparent RPD Depth

All of the CAD cell stations had mean apparent RPD depths greater than 5 cm in the 2001 survey, with values ranging between 6.0 cm at station 77 to 16.2 cm at station 75 (Table 4-2; Figure 3-13). These very deep apparent RPD depths again are indicative of a higher degree of biological re-working of the surface sediment (i.e., bioturbation activity) in the more recent survey. With the exception of Station 77, the apparent RPD depths increased significantly between the 1998 and 2001 surveys (Table 4-2). In both years, the apparent RPD depths were all greater than 3 cm and considered indicative of extensive sediment aeration. The differences between years probably reflect seasonal differences in organic loading rates and the degree of biological activity.

4.5.5 Infaunal Successional Stage

At least one replicate image at each of the CAD cell stations in 2001 had a Stage I on III successional designation, indicative of an apparent diverse and reasonably well-established benthic community (Table 4-2; Figure 3-15). These results are quite similar to the results from the 1998 survey, when at least one replicate image from each station also showed a successional stage designation of I on III. The results from both the 1998 and 2001 surveys at these stations suggest that the benthic community in the vicinity of the candidate CAD cells is comprised of both surface-dwelling, opportunistic taxa and larger-bodied, deep-dwelling infauna.

4.5.6 Organism-Sediment Index

The mean Organism Sediment Index (OSI) values at the six CAD cell stations in March 2001 were all greater than +6.01, indicative of non-degraded or healthy benthic habitat quality (Table 4-2; Figure 3-17). These values are similar to the values reported from the 1998 survey and suggest that the physical and biological conditions at these stations have remained healthy and stable since 1998.

4.5.7 Benthic Habitat Classification

In March 2001, unconsolidated soft, silty sediment (UN.SI) was the primary benthic habitat type found at the CAD cell stations (Table 4-2; Figure 3-18). One exception to this was station 77, which was classified as consisting of soft muddy sediment having a slightly higher fine sand component (UN.SS). Station 78 also had one replicate image that was classified as very soft mud (UN.SF). The predominant benthic habitat type reported at the CAD cell stations in 1998 was unconsolidated, very soft mud (UN.SF). Station 77 and one replicate image at station 76 were reported as silty (UN.SI) in 1998. Although these results suggest a change in habitat types over time, it should be noted that there is very little practical difference between habitat classifications UN.SF and UN.SI. Small changes in the water content of the sediment over time (a function of the degree of bioturbation) can result in subtle differences in the appearance of the sediment texture in the profile images. In the case of the CAD cell stations, the sediment appeared to have slightly more texture (i.e., siltier) in 2001 compared to 1998, but the basic habitat type (unconsolidated soft, muddy sediment) remained the same (Figure 4-6).

Overall, the candidate CAD cell stations in March 2001 continued to be characterized by fine-grained sediments and relatively healthy overall benthic habitat quality. Benthic activity during the March 2001 survey appears to have been somewhat higher than in November 1998, resulting in higher surface boundary roughness, deeper apparent RPD depths, and minor changes in the apparent texture of the sediment in the profile images. Overall, however, there was little significant change in basic seafloor characteristics in the vicinity of the candidate CAD cells between the two surveys.

5.0 REFERENCES

Fredette, T. J., Bohlen, W. F., Rhoads, D. C., and Morton, R. W. 1988. Erosion and resuspension effects of Hurricane Gloria at Long Island Sound dredged material disposal sites. Proceedings of the U.S. Army Corps of Engineers Seminar on "Water Quality '88", Davis, California, February, 1988. U.S. ACOE, Hydraulic Engineering Center, Charleston, SC.

Germano, J. D. 1983. Infaunal succession in Long Island Sound: Animal-sediment interactions and the effects of predation. Ph.D. diss., Yale Univ., New Haven, CT.

Germano, J. D., and Rhoads D. C. 1984. REMOTS® sediment profiling at the Field Verification Program (FVP) disposal site. pp. 536-544. R. L. Montgomery and J. W. Leach eds. *Dredging and Dredged Material Disposal*. Volume 1. Am. Soc. Civil Engineers. New York.

Johnson, R. G. 1972. Conceptual models of benthic marine communities. *Models of Paleobiology* T. J. M. Schopf, ed., Freeman, Cooper, and Co., San Francisco, pp. 145-159.

Revelas, E. C., Germano, J. D., and Rhoads, D. C. 1987. REMOTS® Reconnaissance of benthic environments. Coastal Zone '87: Proceedings of the Conference, WW Div/ASCE/May 26-29, Seattle, WA, pp. 2069-2083.

Rhoads, D. C. 1974. Organism-sediment relations on the muddy sea floor. *Oceanogr. Mar. Biol.* Ann. Rev. 12: 263-300.

Rhoads, D. C., and Boyer, L. F. 1982. The effects of marine benthos on physical properties of sediments. In: *Animal-Sediment Relations* (P. L. McCall and M. J. S. Tevesz, eds.), Plenum Press, New York, pp. 3-52.

Rhoads, D. C., and Germano, J. D. 1982. Characterization of organism-sediment relations using sediment profile imaging: An efficient method of Remote Ecological Monitoring of the Seafloor (REMOTS® System). *Mar. Ecol. Prog. Ser*. 8:115-128.

Rhoads, D. C., and Germano, J. D. 1986. Interpreting long-term changes in benthic community structure: a new protocol. *Hydrobiologia* 142: 291-308.

Santos, S. L., and Simon, J. L. 1980a. Marine soft-bottom community establishment following annual defaunation: Larval or adult recruitment? *Mar. Ecol. Prog.* Ser. 2:235-241.

Santos, S. L., and Simon, J. L. 1980b. Response of soft-bottom benthos to annual catastrophic disturbance in a south Florida estuary. *Mar. Ecol. Prog.* Ser. 3:347-355.

Science Applications International Corporation (SAIC). 1999a. Habitat Characterization of the DMMP Candidate Aquatic Disposal Sites. SAIC Report No. 463 submitted by Maguire Group, Inc. to Massachusetts Coastal Zone Management Agency, Boston, MA.

Science Applications International Corporation (SAIC). 1999b. Capacity Analysis of CAD Cells within Salem, Gloucester, and New Bedford Harbors. SAIC Report No. 467 submitted by Maguire Group, Inc. to Massachusetts Coastal Zone Management Agency, Boston, MA.

Science Applications International Corporation (SAIC). 2000. Review of Depth to Bedrock in Gloucester Harbor. SAIC Report No. 483 submitted by Maguire Group, Inc. to Massachusetts Coastal Zone Management Agency, Boston, MA.

Valente, R. M., D. C. Rhoads, J. D. Germano and V. J. Cabelli. 1992. Mapping of benthic enrichment patterns in Narragansett Bay, Rhode Island. Estuaries 15:1-17.

FIGURES

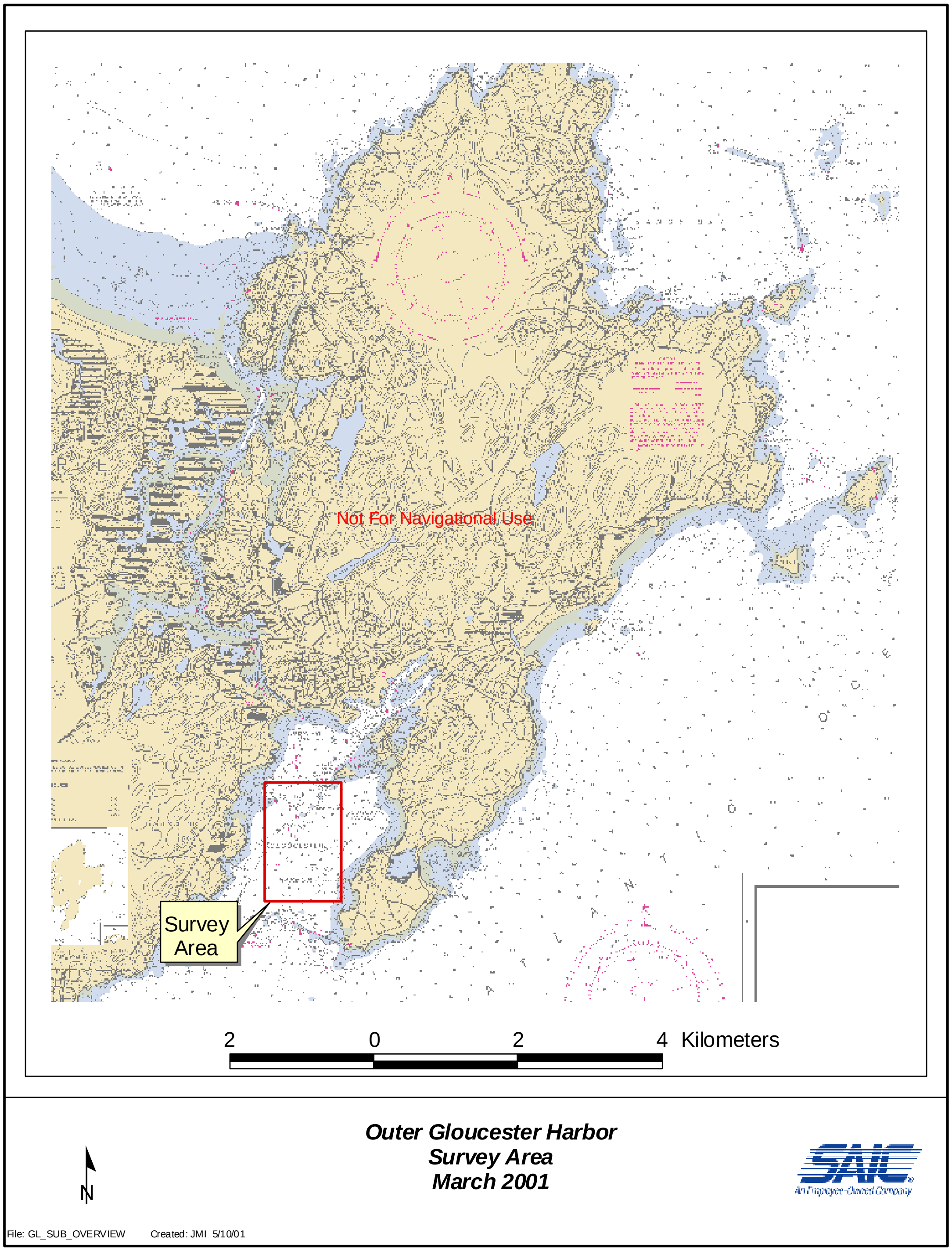


Figure 1-1. An overview chartlet of the Outer Gloucester Harbor survey area.

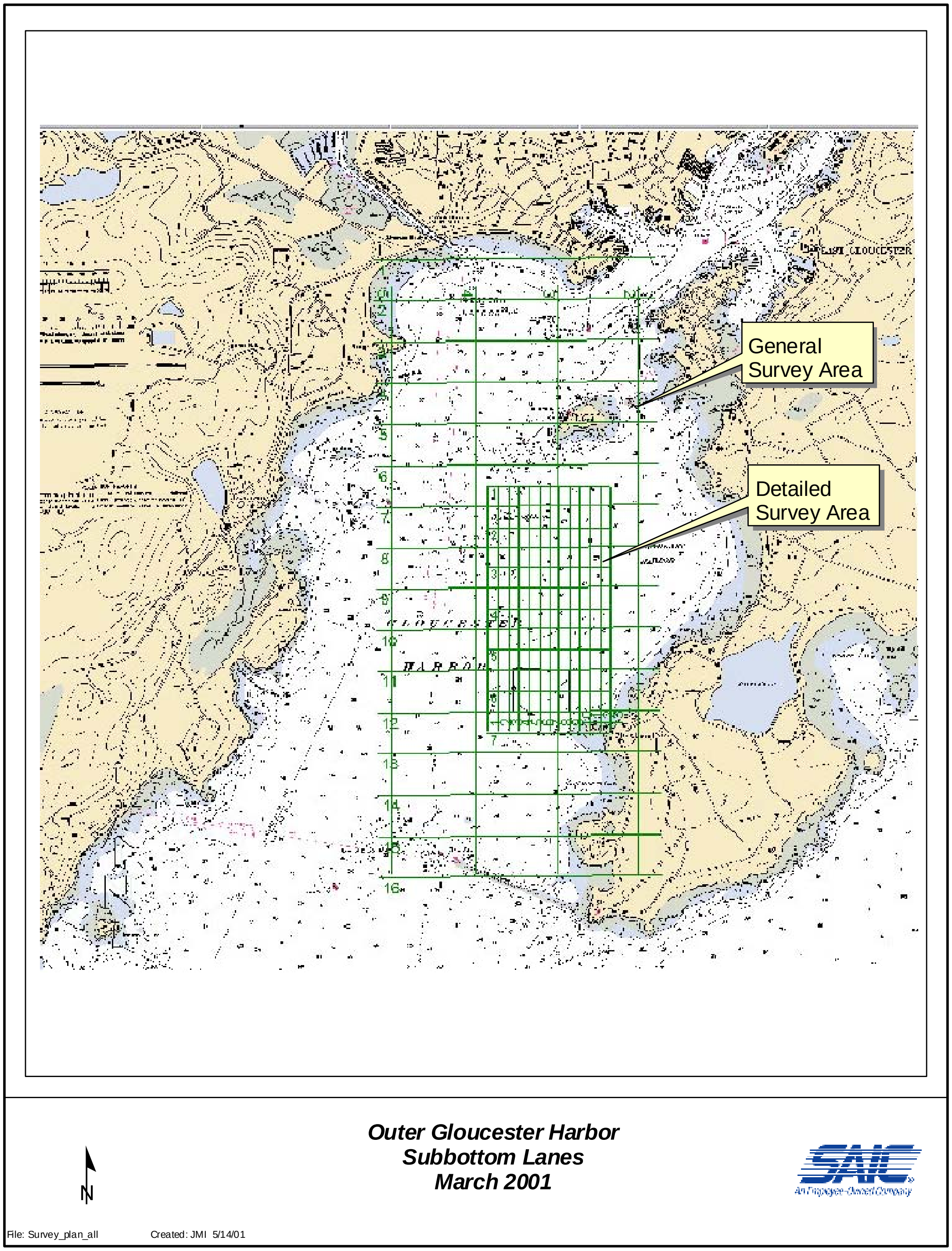


Figure 2-1. General schematic of survey lanes for the Outer Gloucester Harbor sub-bottom survey.

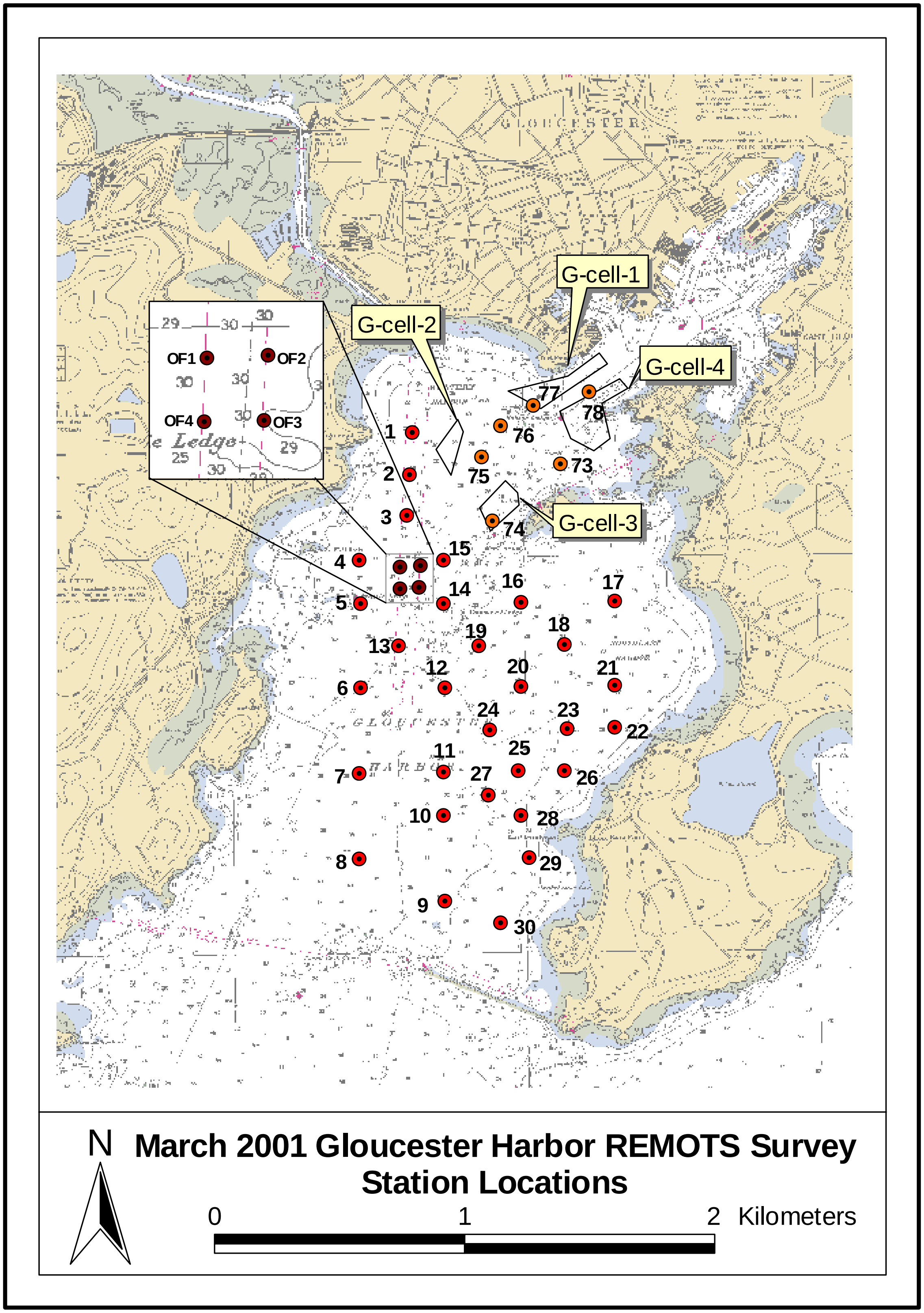


Figure 2-2. Sampling stations for the Outer Gloucester Harbor REMOTS® survey.

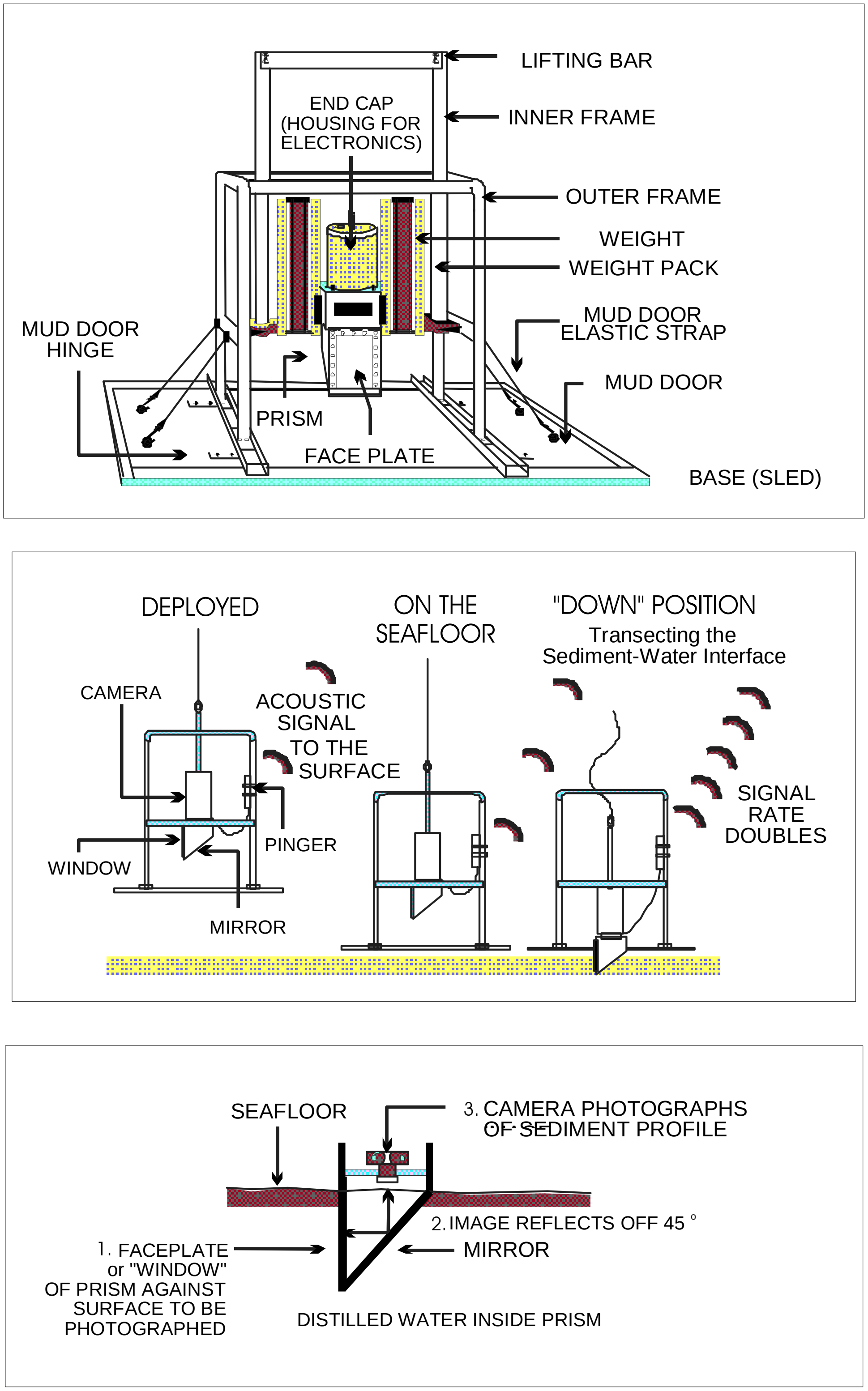


Figure 2-3. Schematic diagram of Benthos, Inc. Model 3731 REMOTS® sediment-profile camera and sequence of operation on deployment

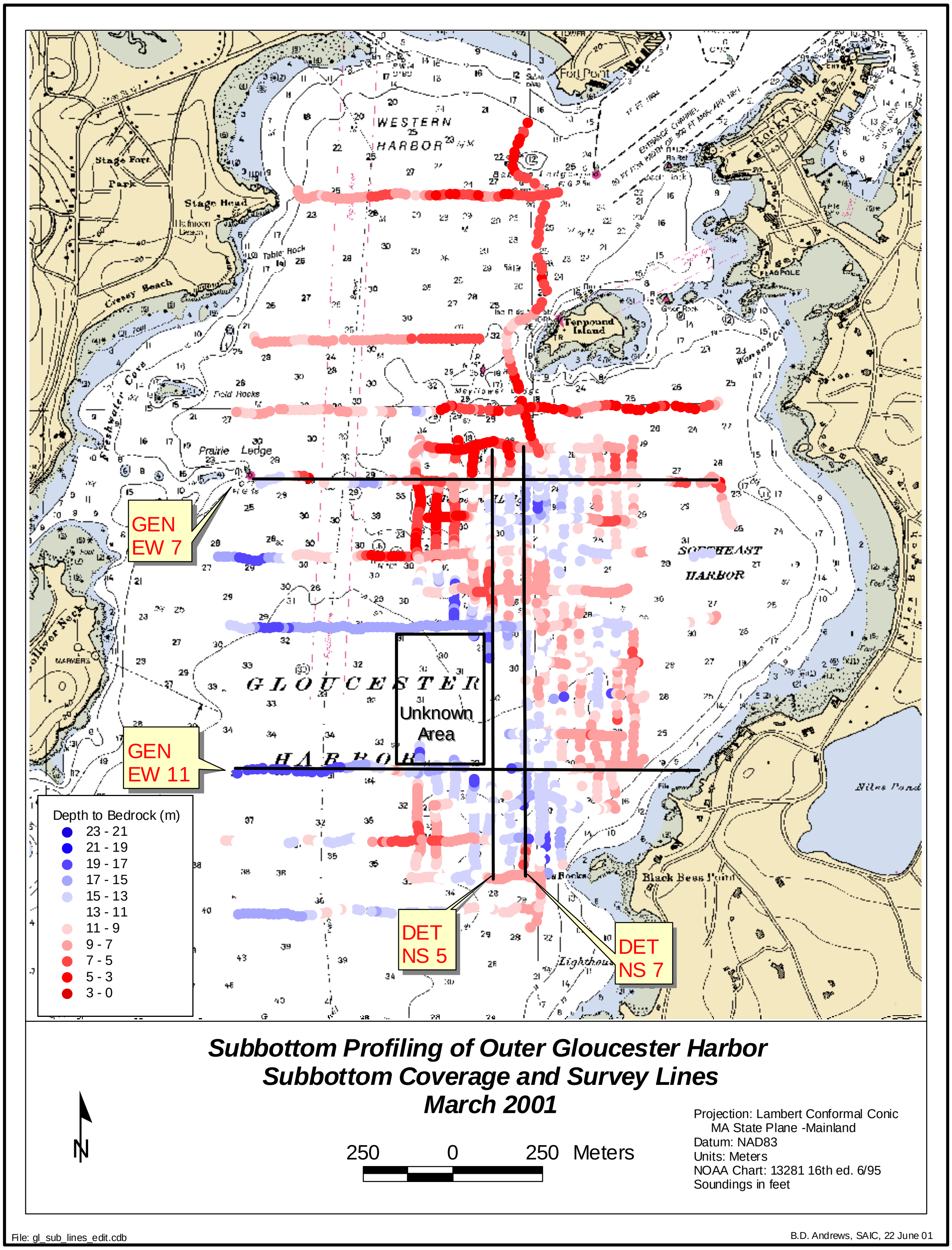


Figure 3-1. Color-coded depth-to-bedrock sub-bottom trackline data for the Outer Gloucester Harbor survey area. This figure also shows the locations of the four sample sub-bottom transects that are presented in Figures 3-2 thru 3-5.

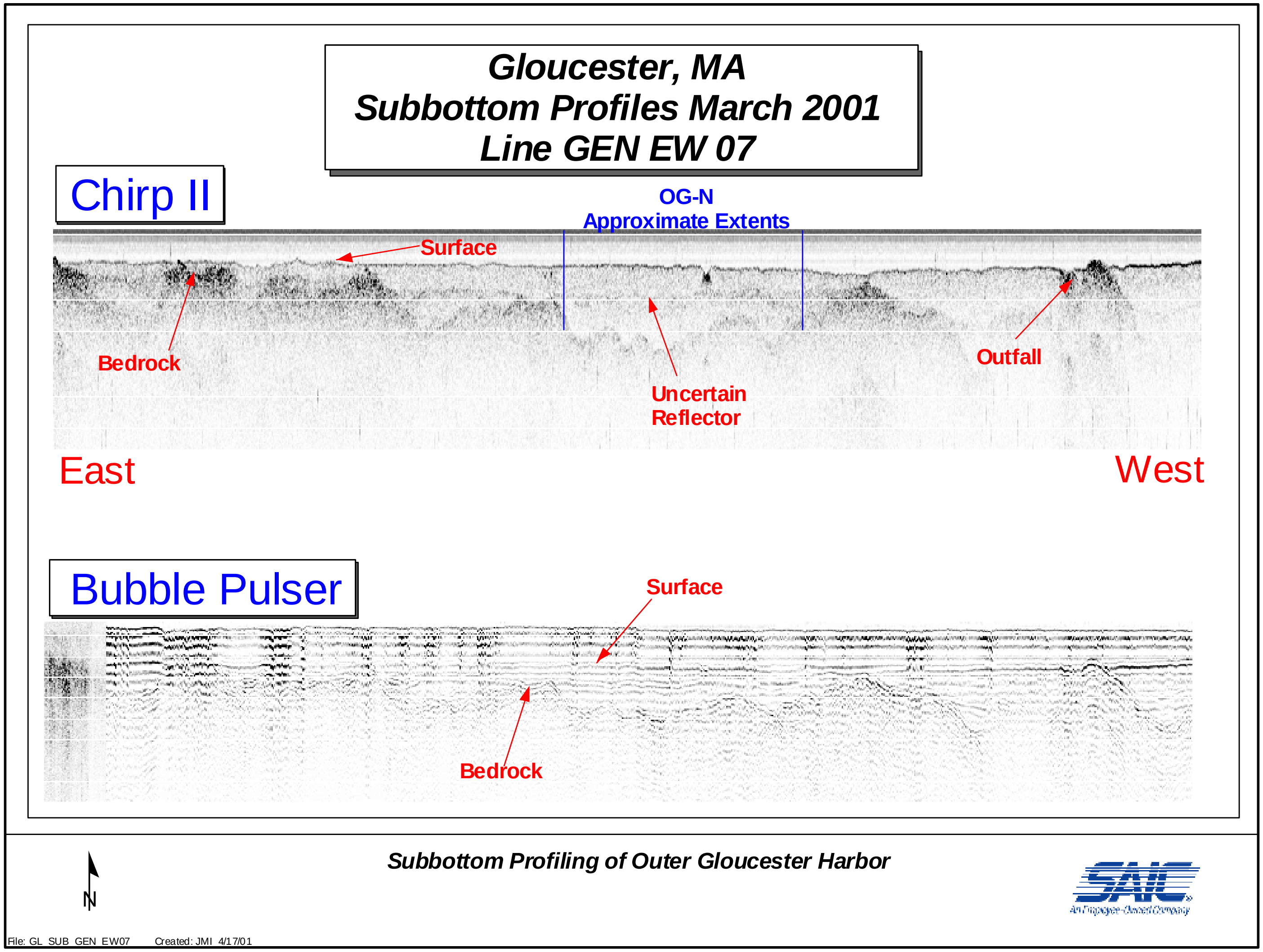


Figure 3-2. Sample sub-bottom transect GEN EW 07 (see Figure 3-1 for relative location on area map).

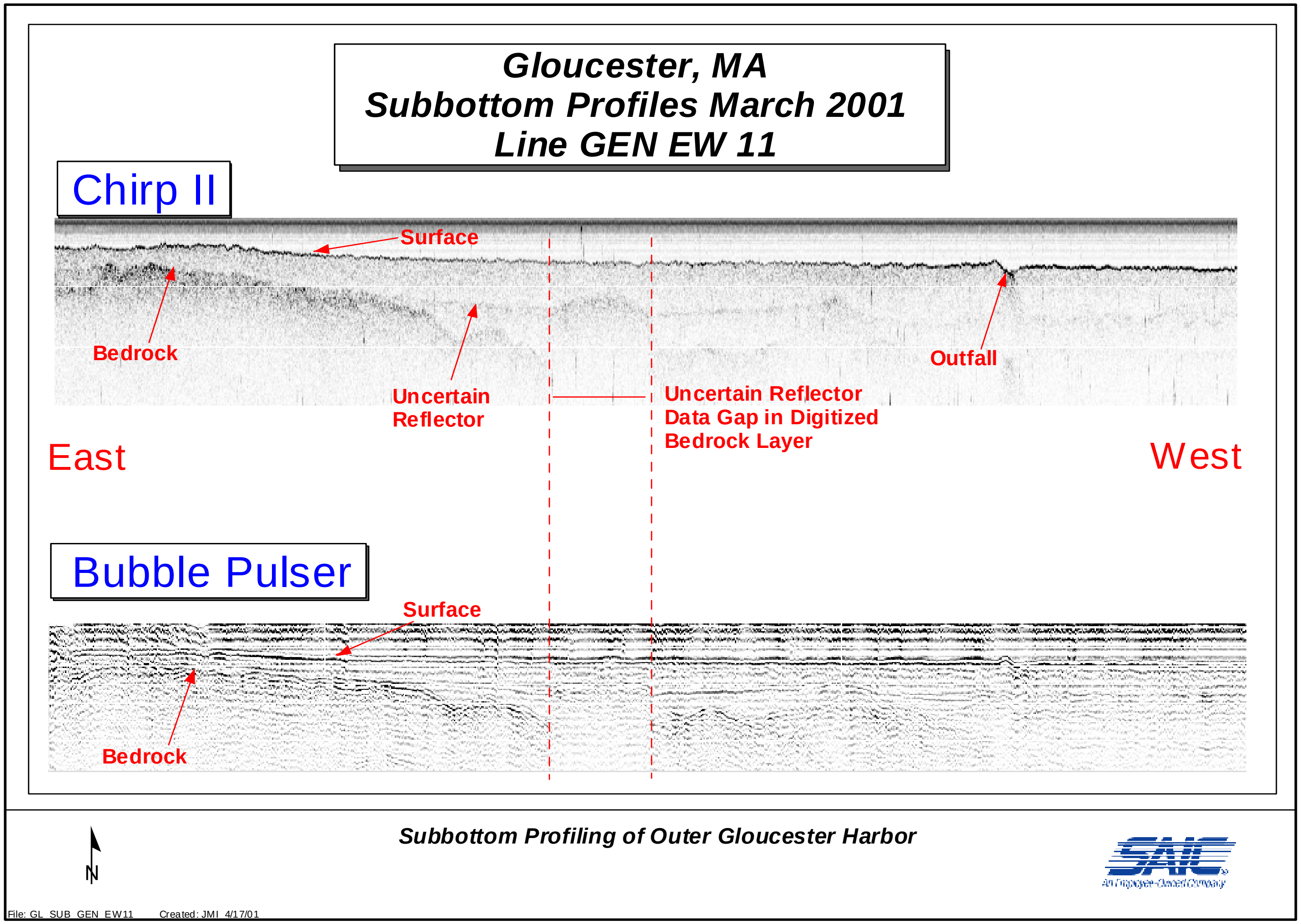


Figure 3-3. Sample sub-bottom transect GEN EW 11 (see Figure 3-1 for relative location on area map).

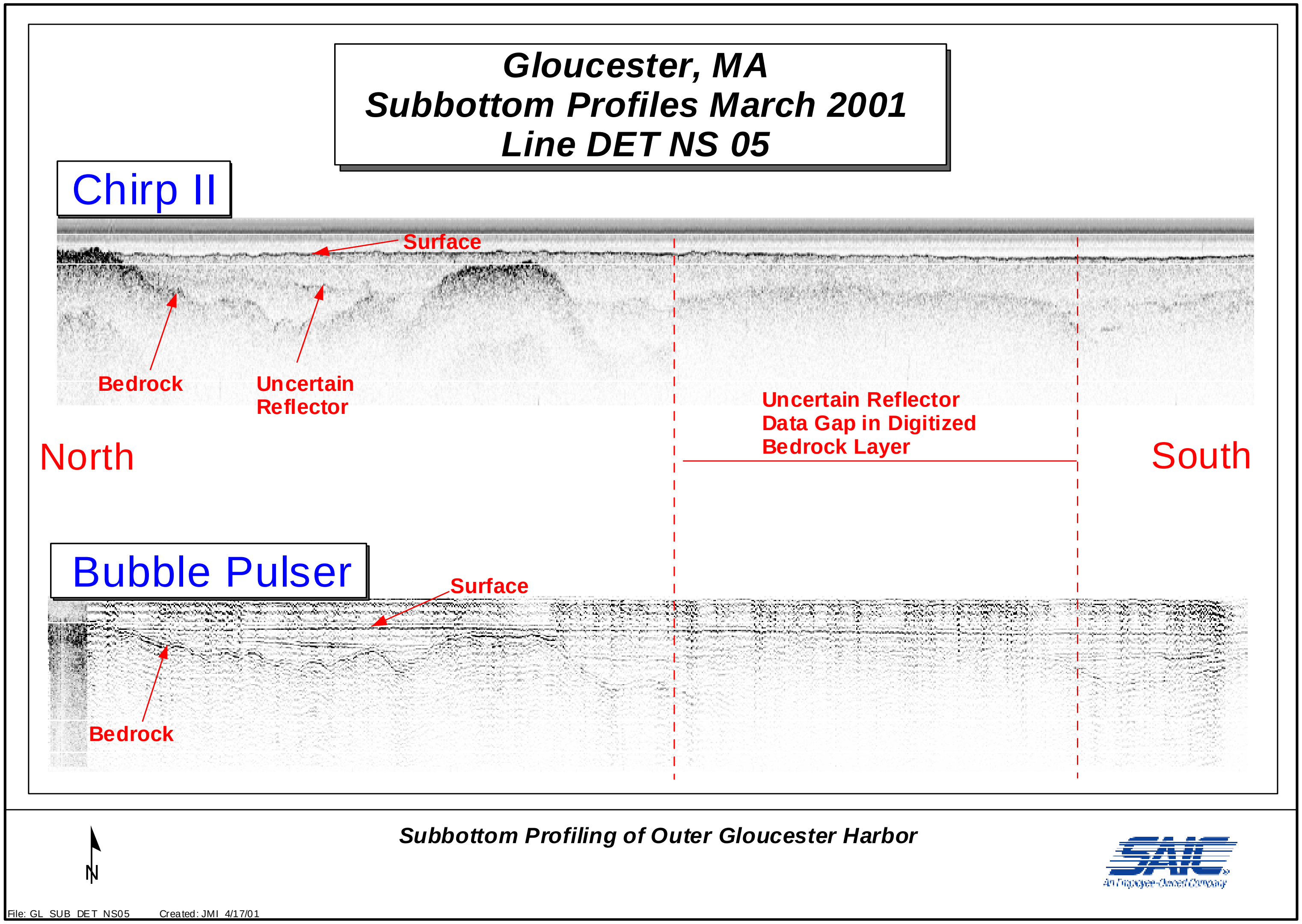


Figure 3-4. Sample sub-bottom transect DET NS 05 (see Figure 3-1 for relative location on area map).

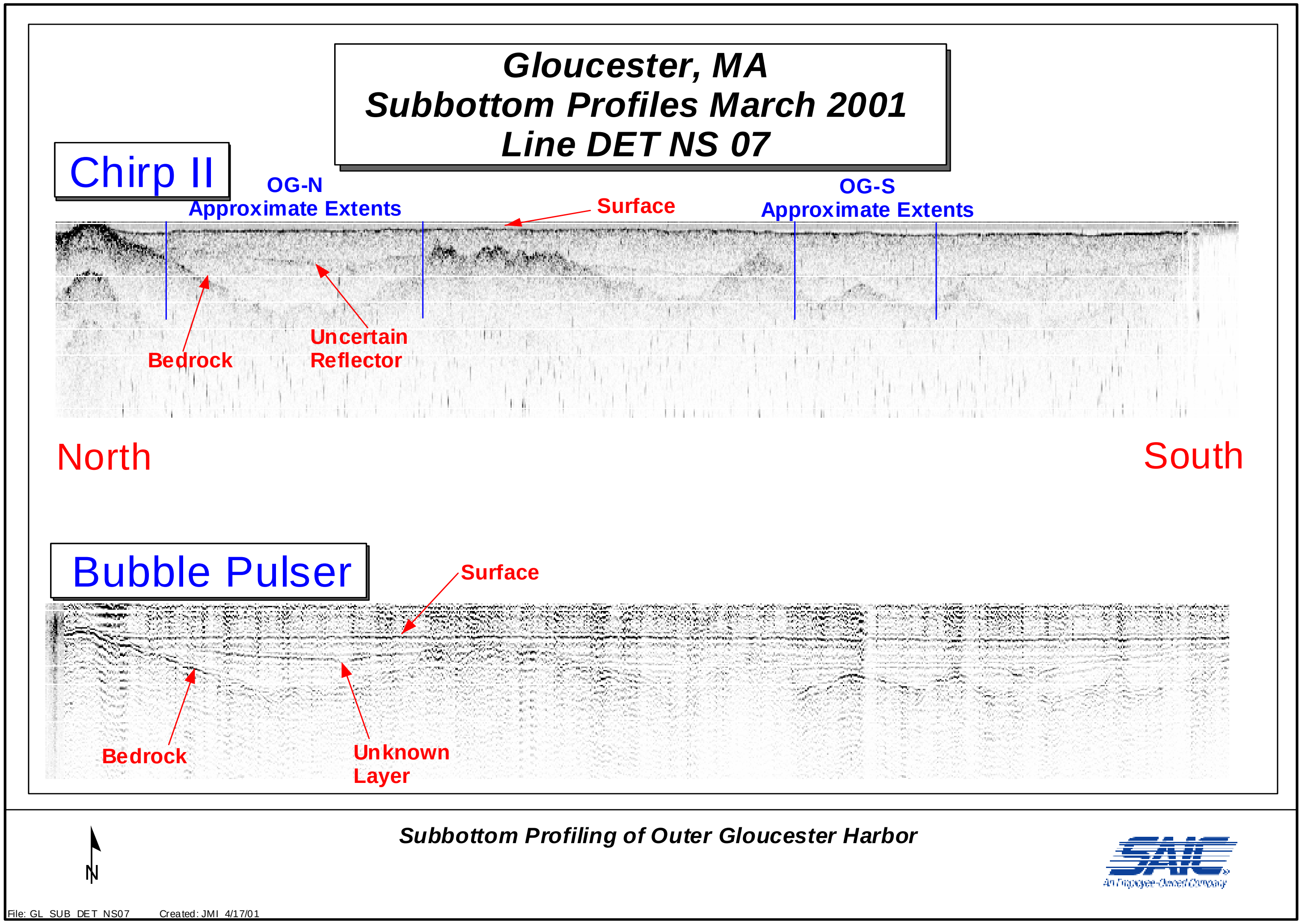


Figure 3-5. Sample sub-bottom transect DET NS 07 (see Figure 3-1 for relative location on area map).

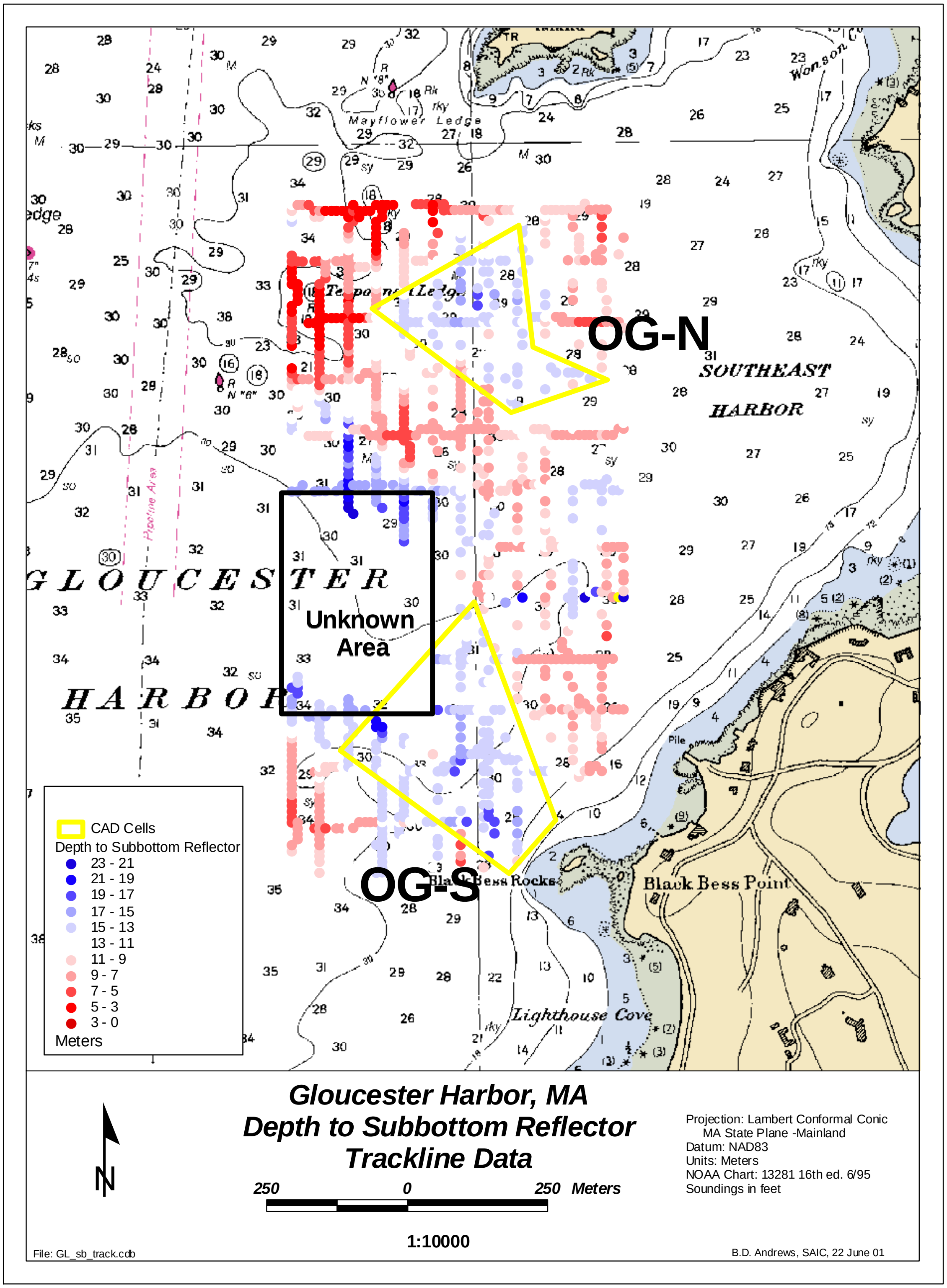


Figure 3-6. Sample CAD sites, OG-N and OG-S, overlaid on color-coded depth-to-bedrock sub-bottom trackline data.

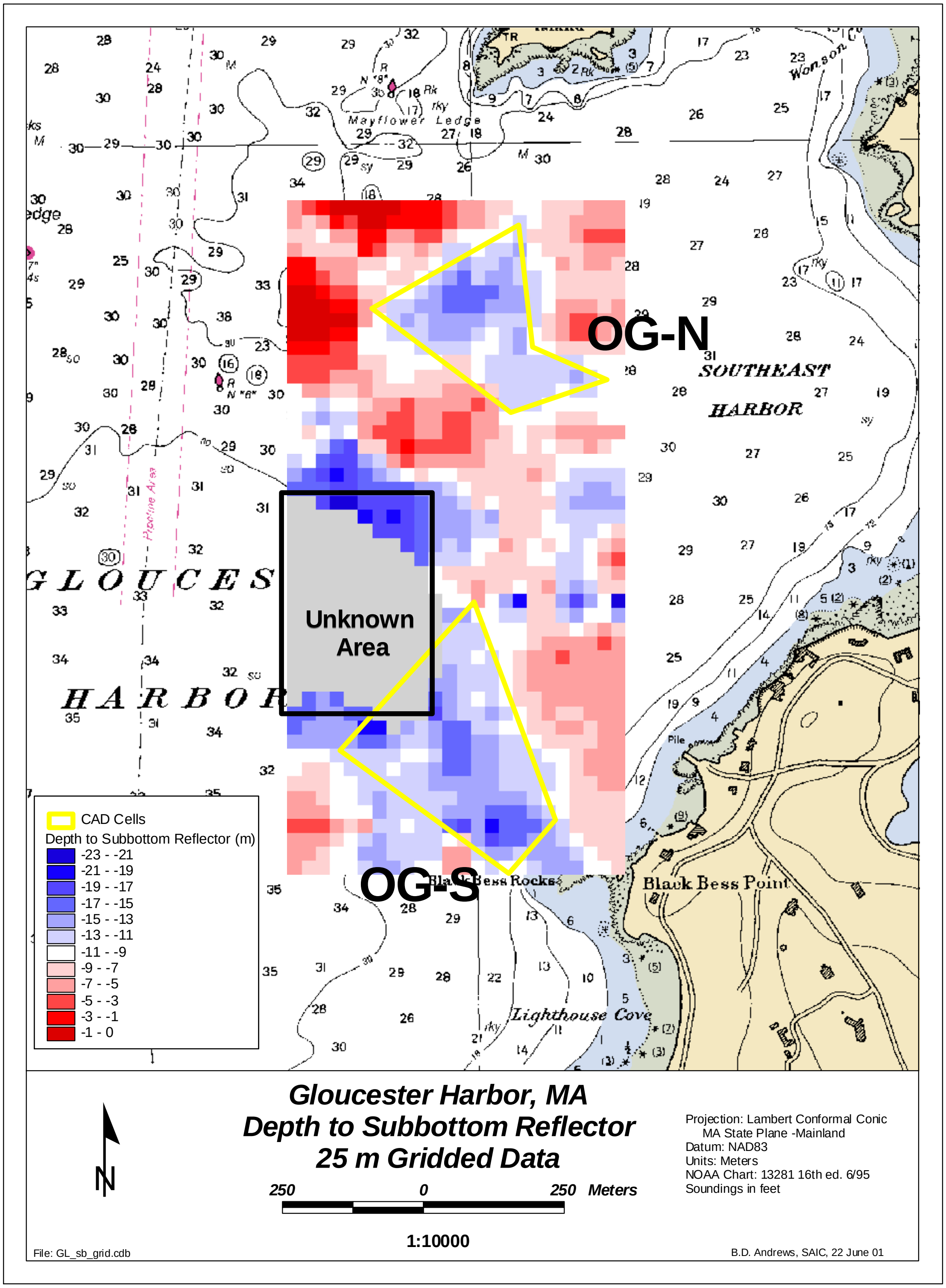


Figure 3-7. Sample CAD sites, OG-N and OG-S, overlaid on 25m gridded depth-to-bedrock surface model.

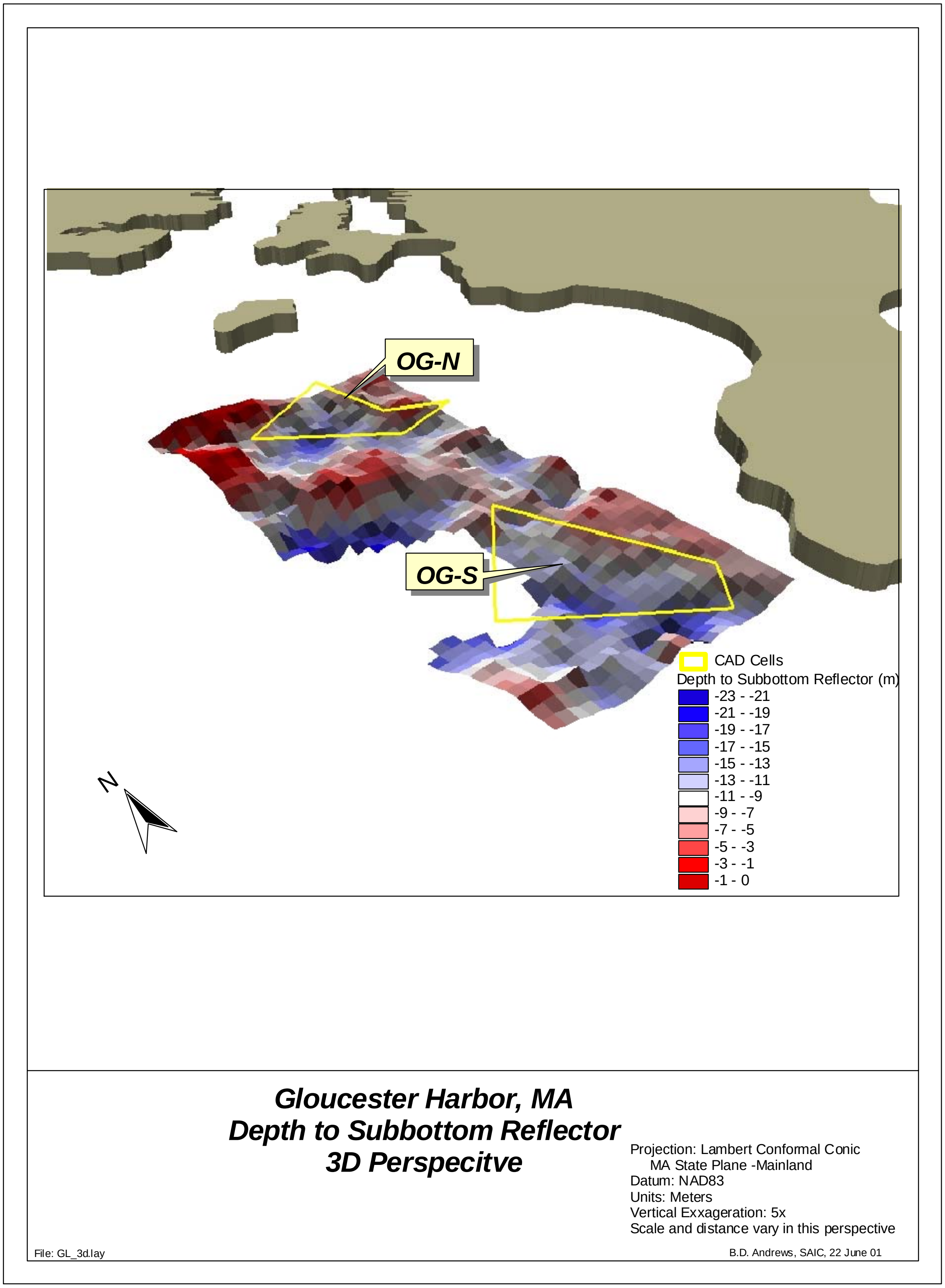


Figure 3-8. Sample CAD sites, OG-N and OG-S, overlaid on 3-D view of the 25m gridded depth-to-bedrock surface model.

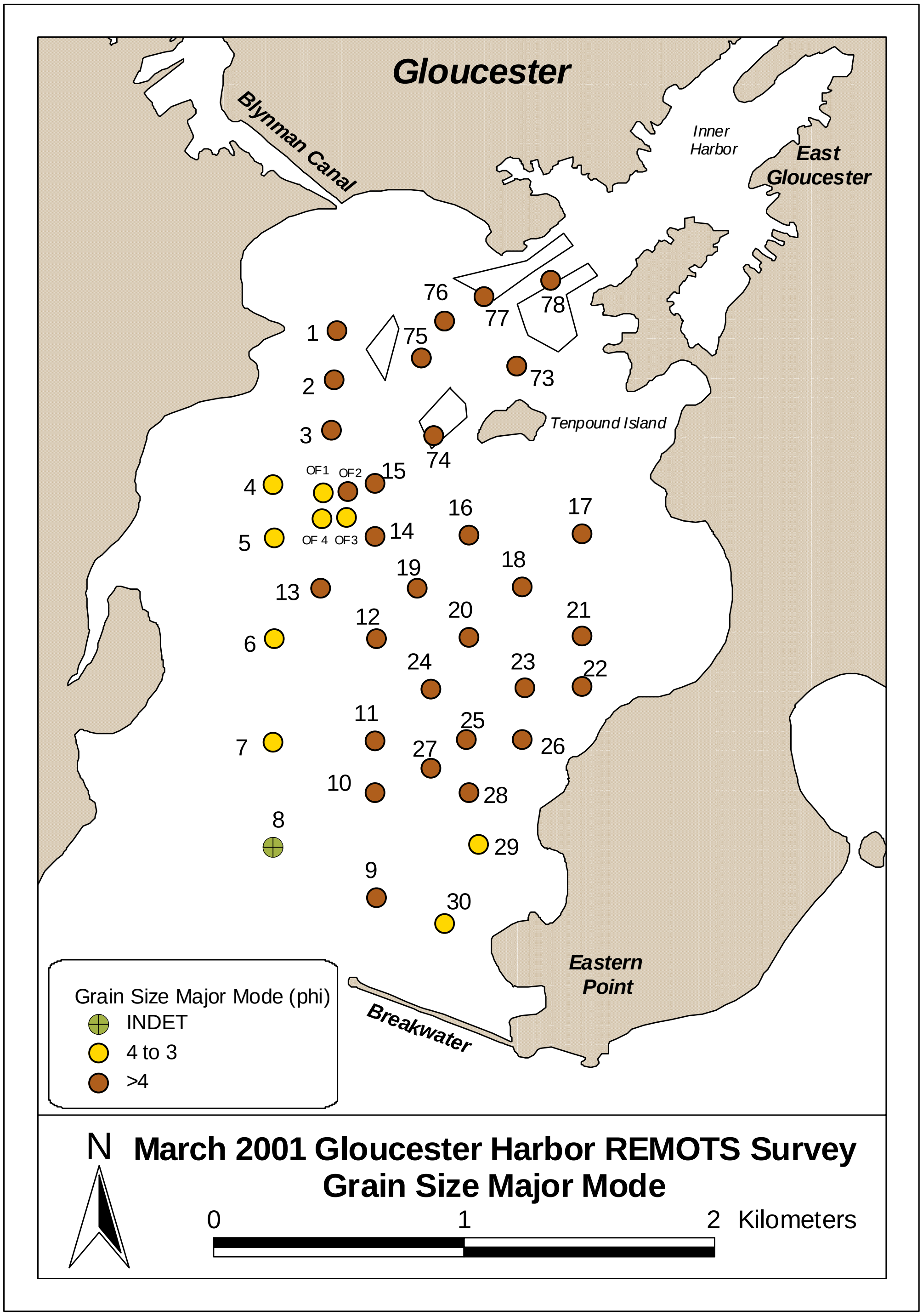


Figure 3-9. Map showing grain size major mode at the REMOTS® stations in Outer Gloucester Harbor.

Figure 3-10. Two REMOTS® sediment profile images illustrating the two predominant sediment types observed in outer Gloucester Harbor. Image A from Station 04 on the western side of the surveyed area shows compact, very fine sand (grain size major mode 4 to 3 phi). Image B from Station 25 on the eastern side of the outer harbor shows relatively soft, muddy sediment (grain size major of >4 phi). Note the difference in camera penetration depth between the compact fine sand and softer, fine-grained sediment.

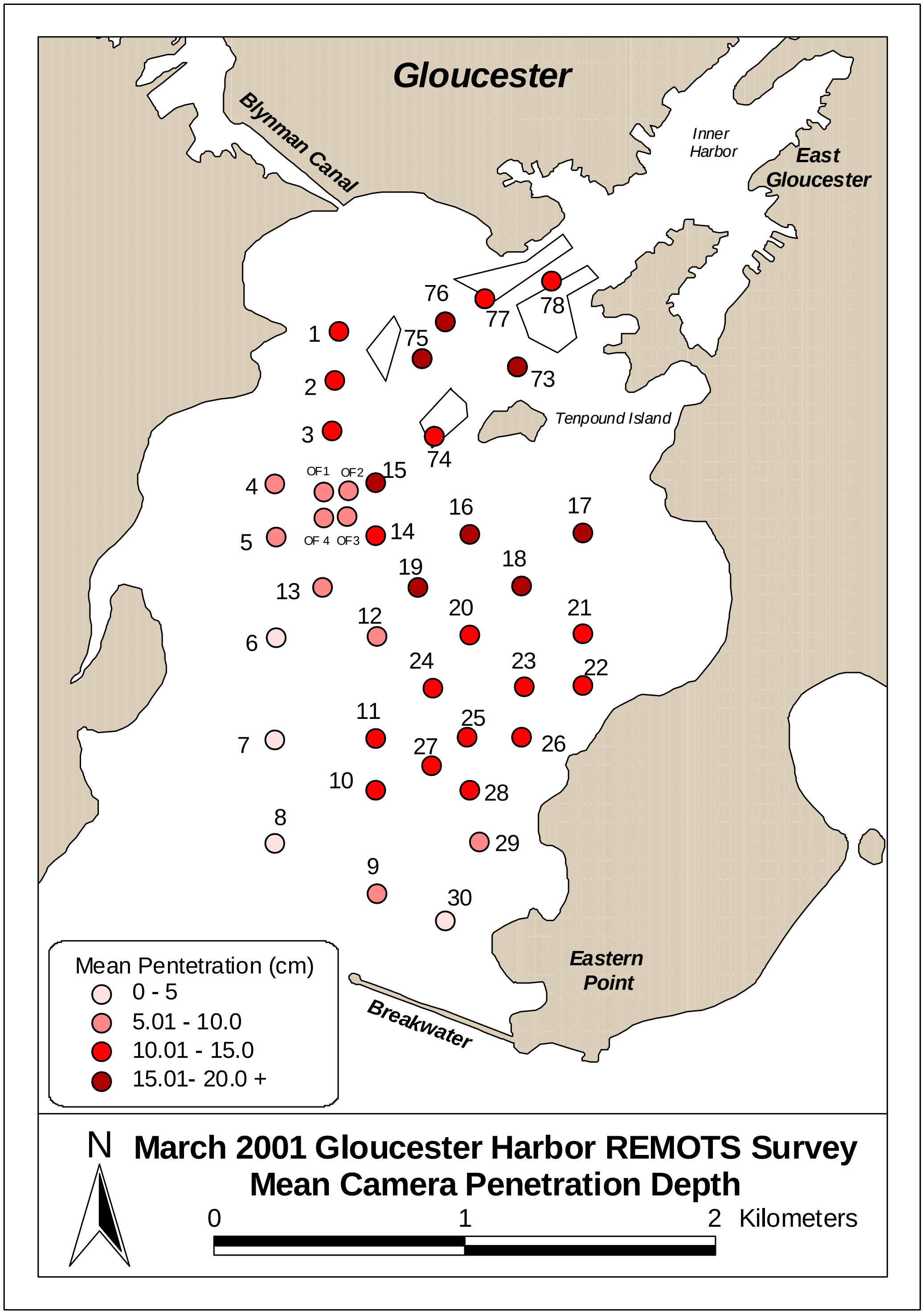


Figure 3-11. Map of mean prism penetration depths in Outer Gloucester Harbor.

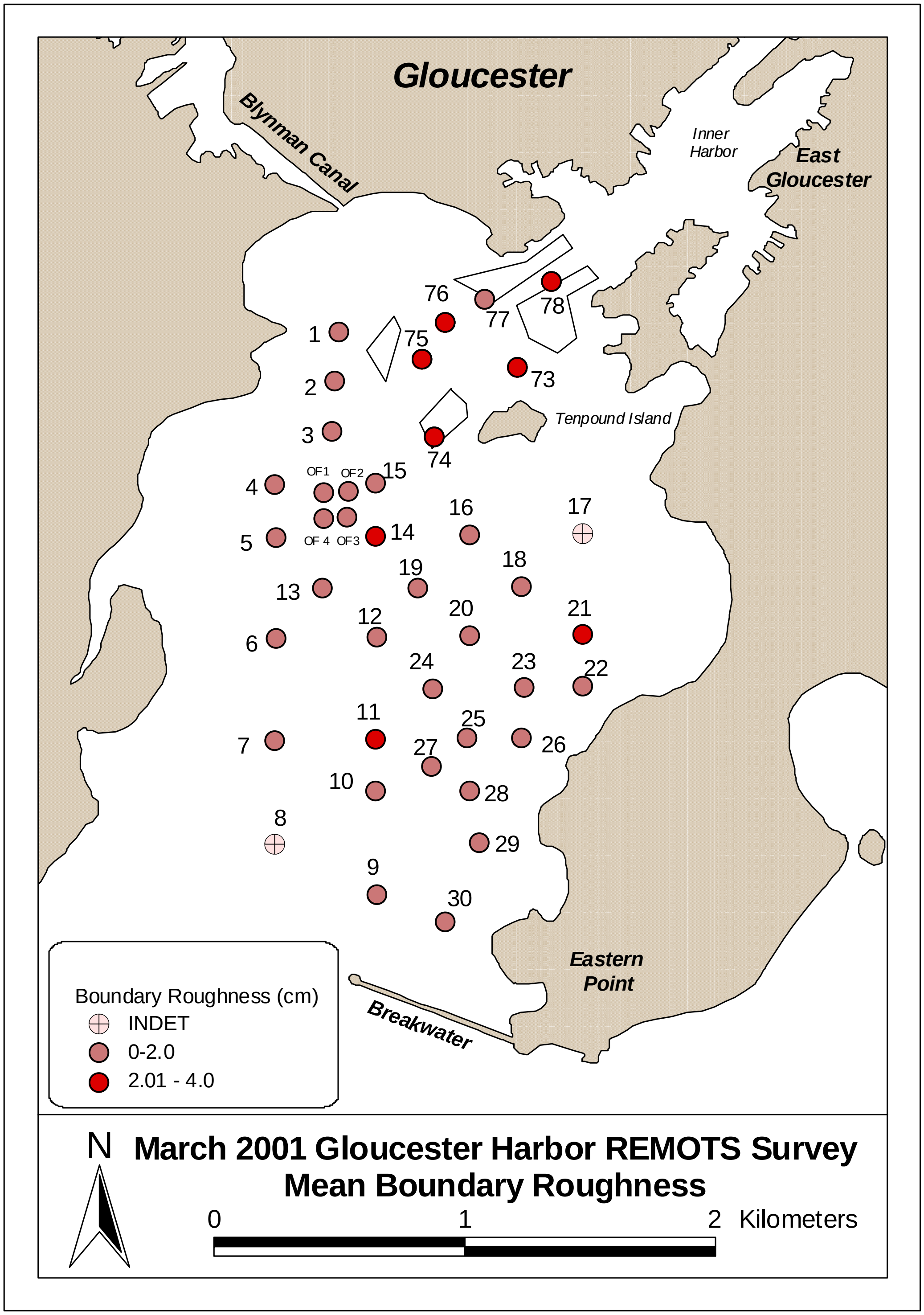


Figure 3-12. Map of mean boundary roughness values in Outer Gloucester Harbor.

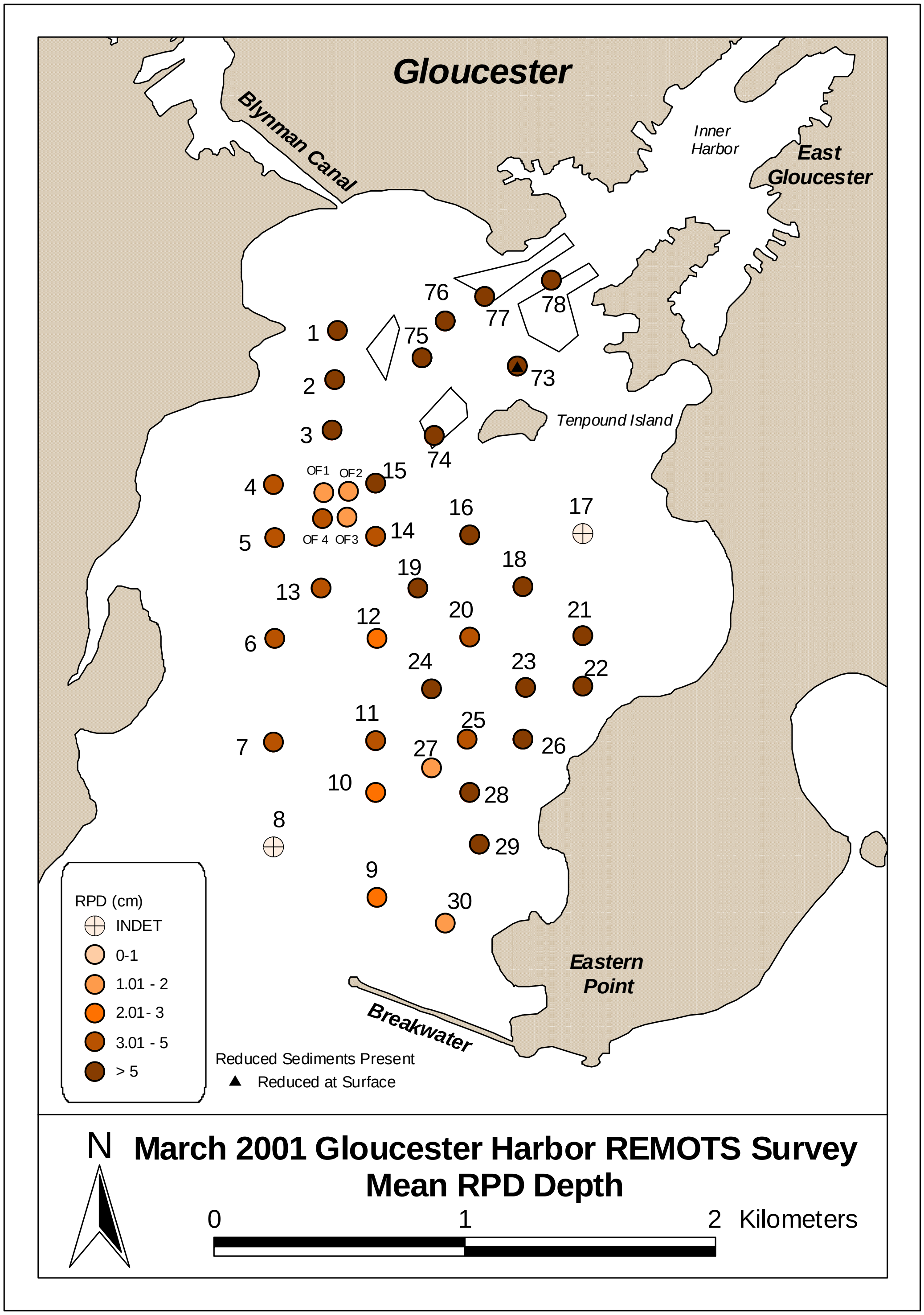
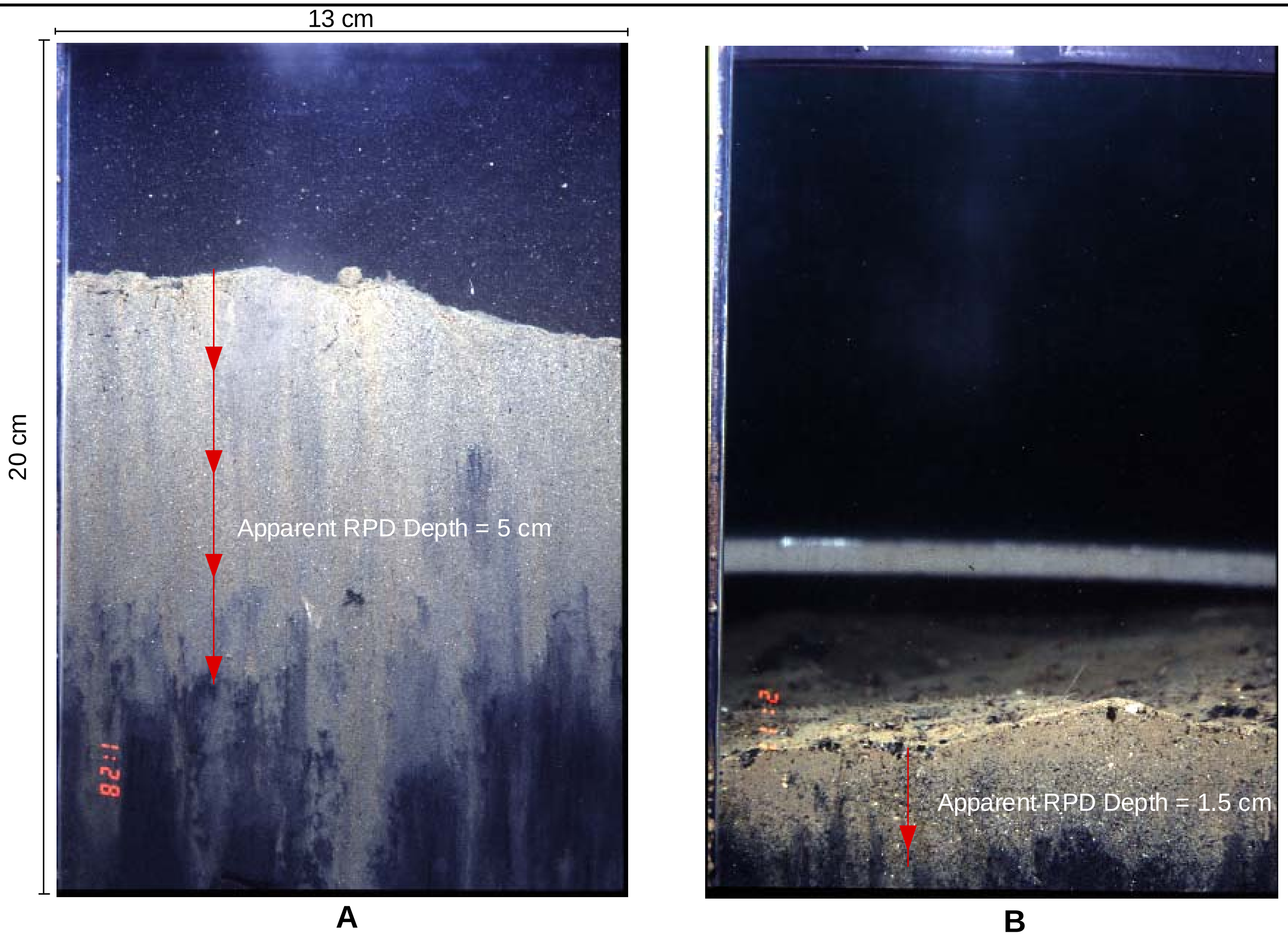


Figure 3-13. Map showing mean apparent RPD depths in Outer Gloucester Harbor.



Outer Gloucester Harbor
REMOTS Images
March 2001

Figure 3-14. REMOTS® image A shows a relatively deep, well-developed apparent RPD of 5.0 cm at station 20. Image B shows a much shallower RPD of 1.5 cm at sewer outfall station OF-1. In both images, the light-colored surface layer of oxidized sediment overlies very black, anoxic sediment at depth.

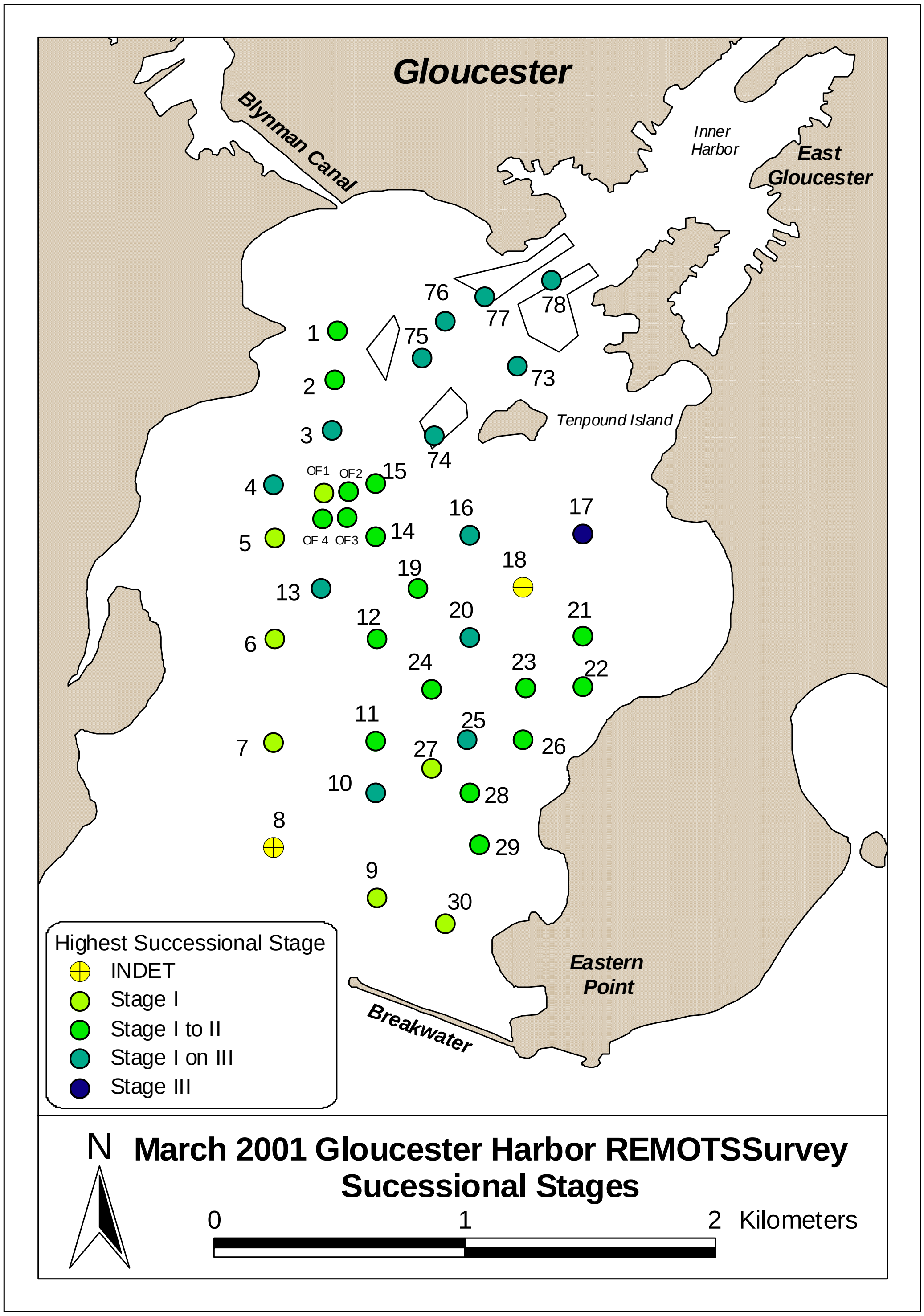
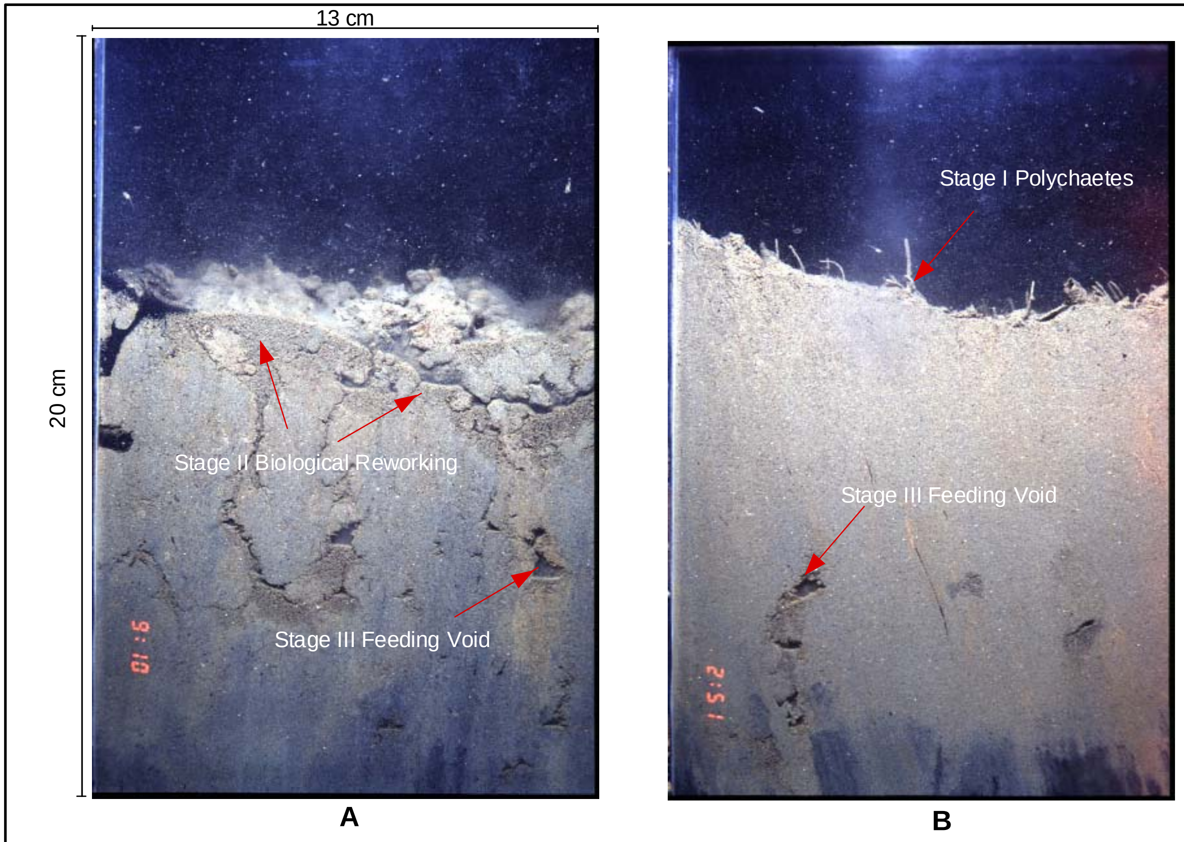


Figure 3-15. Map showing the highest infaunal successional stage present at each of the REMOTS® stations in Outer Gloucester Harbor.



Outer Gloucester Harbor
REMOTS Images
March 2001

Figure 3-16. REMOTS® sediment profile images showing typical infaunal successional stages found throughout outer Gloucester Harbor. Image A from station 74 provides an example of a Stage II on III biological community, produced most likely by shallow dwelling bivalves and/or tubicolous amphipods (Stage II) and infaunal deposit feeders (Stage III). The stage II organisms are responsible for the shallower re-working of the surface sediments. The presence of Stage III organisms is evidenced by the sub-surface feeding voids found at depth. Image B from station 78 shows a classic Stage I on III biological community; denoted by the surface dwelling polychaetes (Stage I) at the sediment-water interface coupled with the Stage III organism feeding voids at depth.

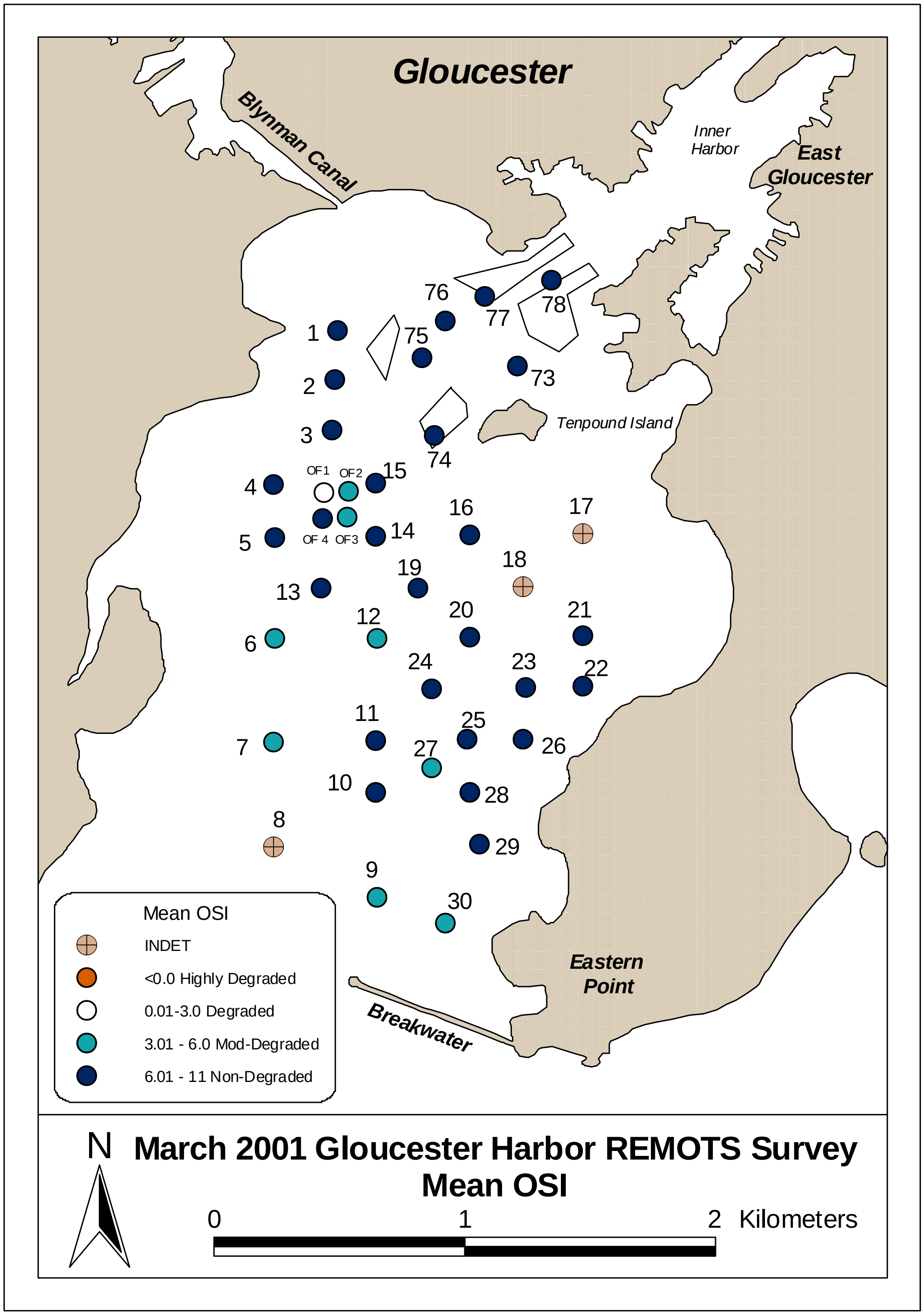


Figure 3-17. Map of Organism-Sediment Index (OSI) values in Outer Gloucester Harbor.

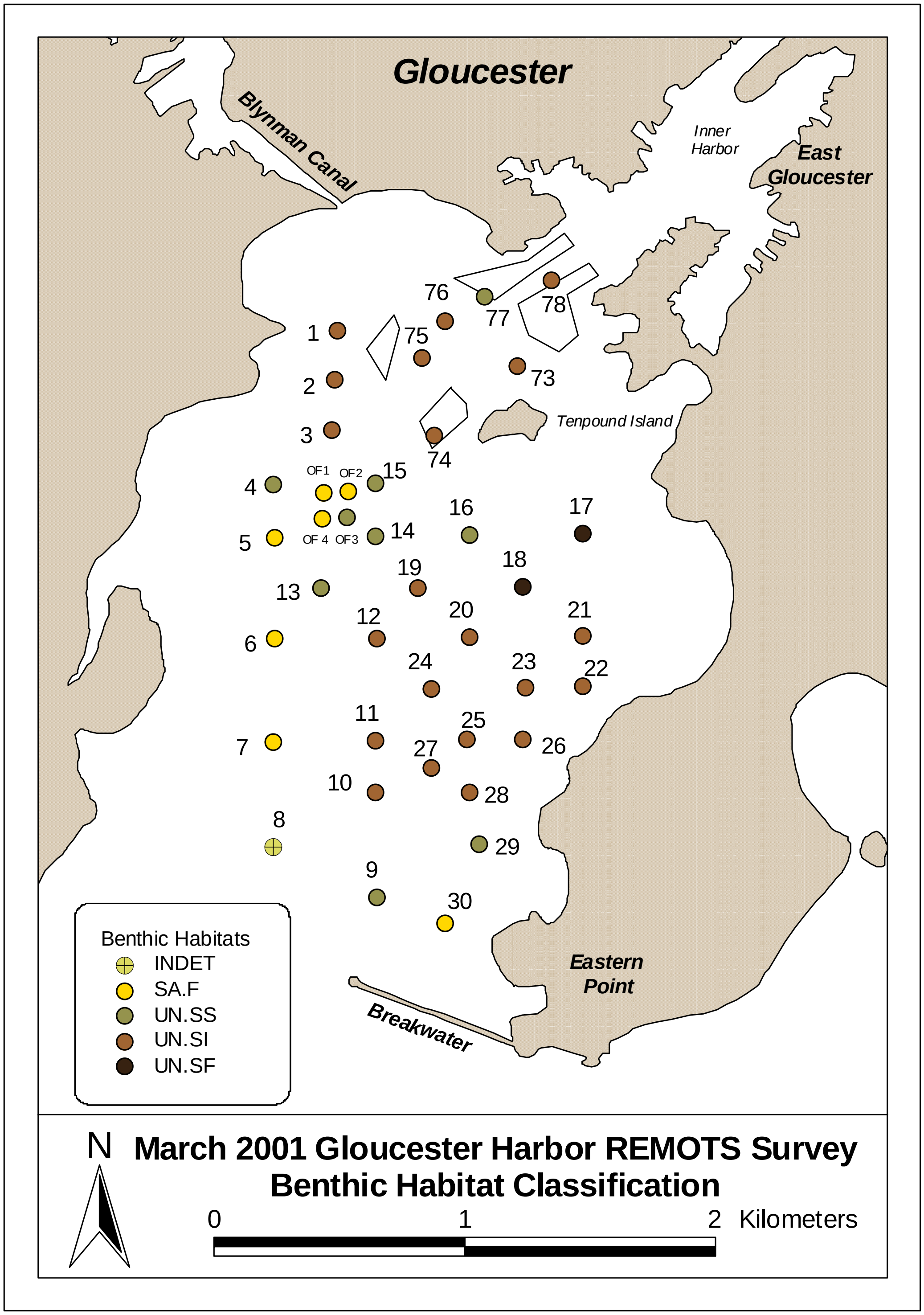


Figure 3-18. Map of benthic habitat types at the outer Gloucester Harbor REMOTS® stations.

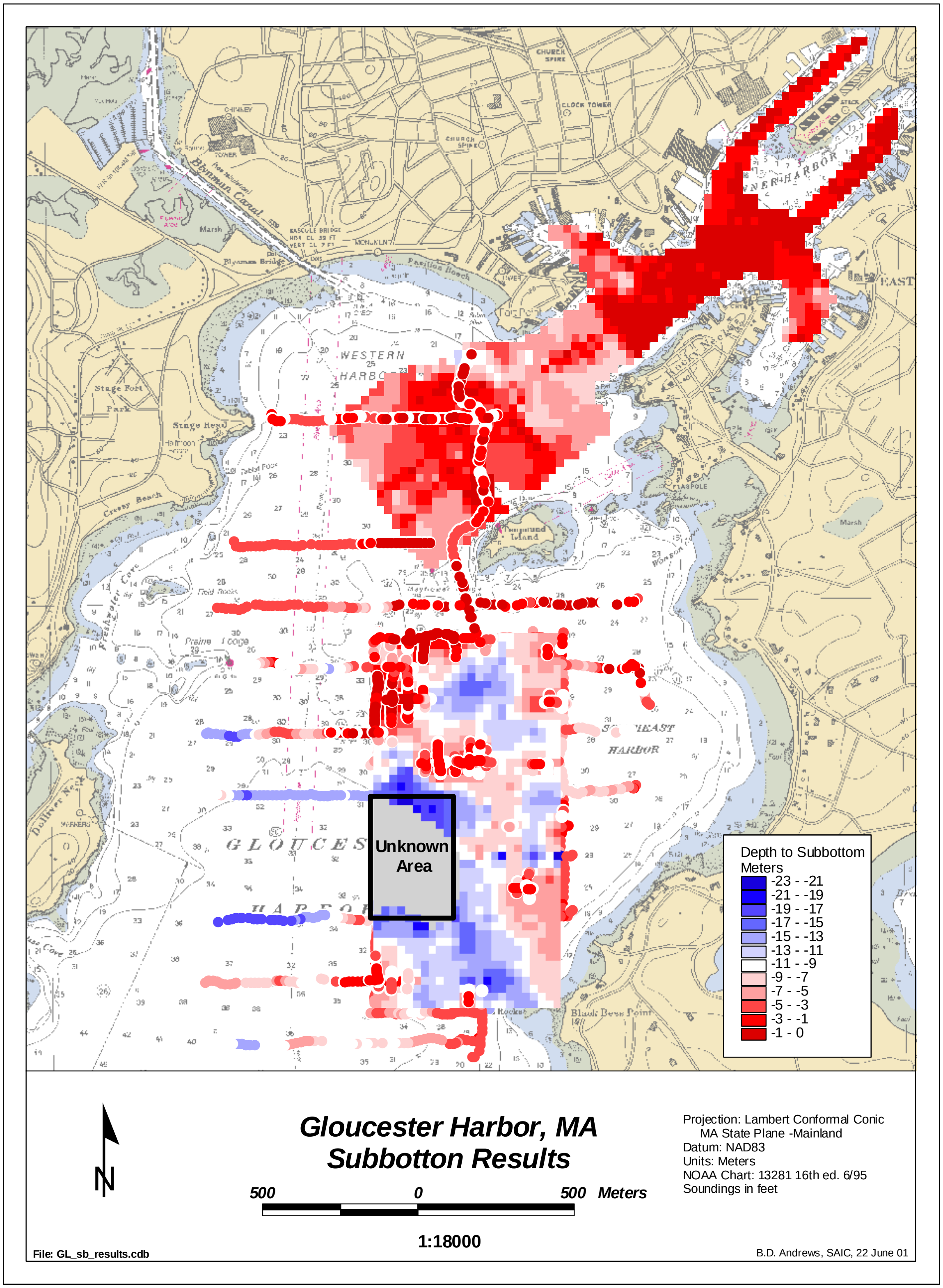


Figure 4-1. Combined results of the December 1998 and March 2001 sub-bottom surveys showing depth-to-bedrock in Gloucester Harbor.

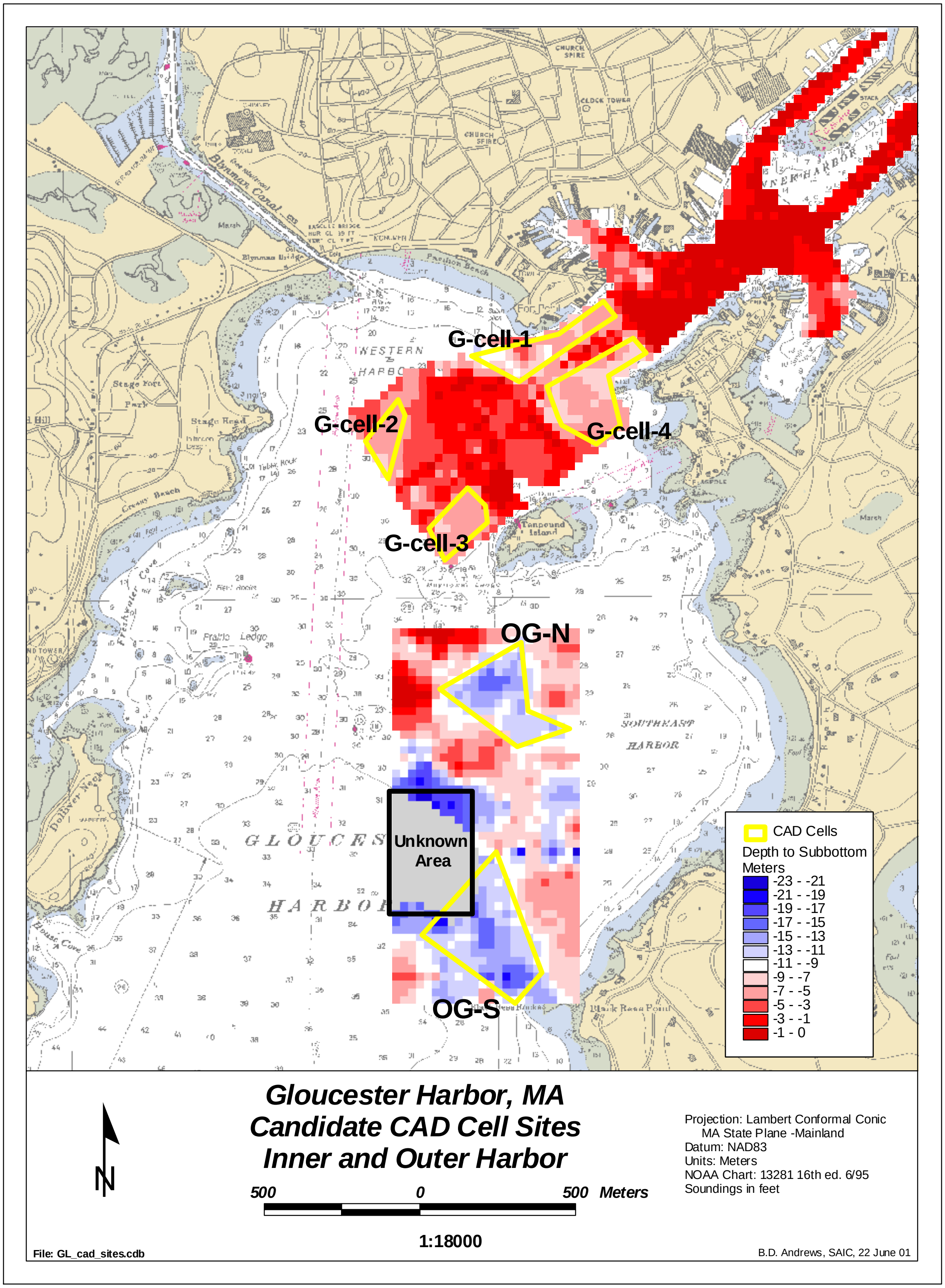


Figure 4-2. Location of candidate CAD cell sites in relation to sub-bottom survey results.

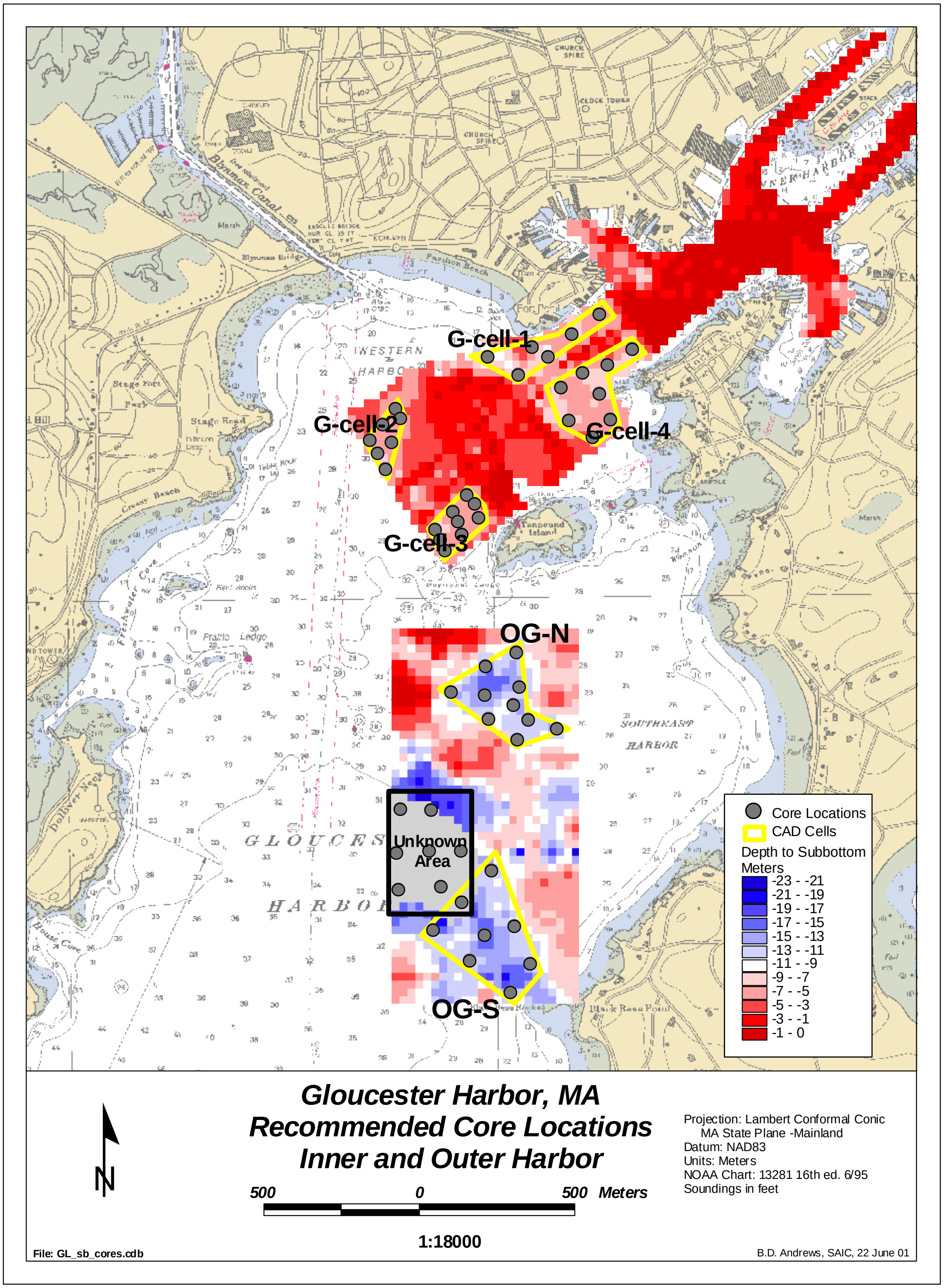


Figure 4-3. Recommended coring locations in each of the candidate CAD cells sites and in the "unknown area" identified in the March 2001 survey.

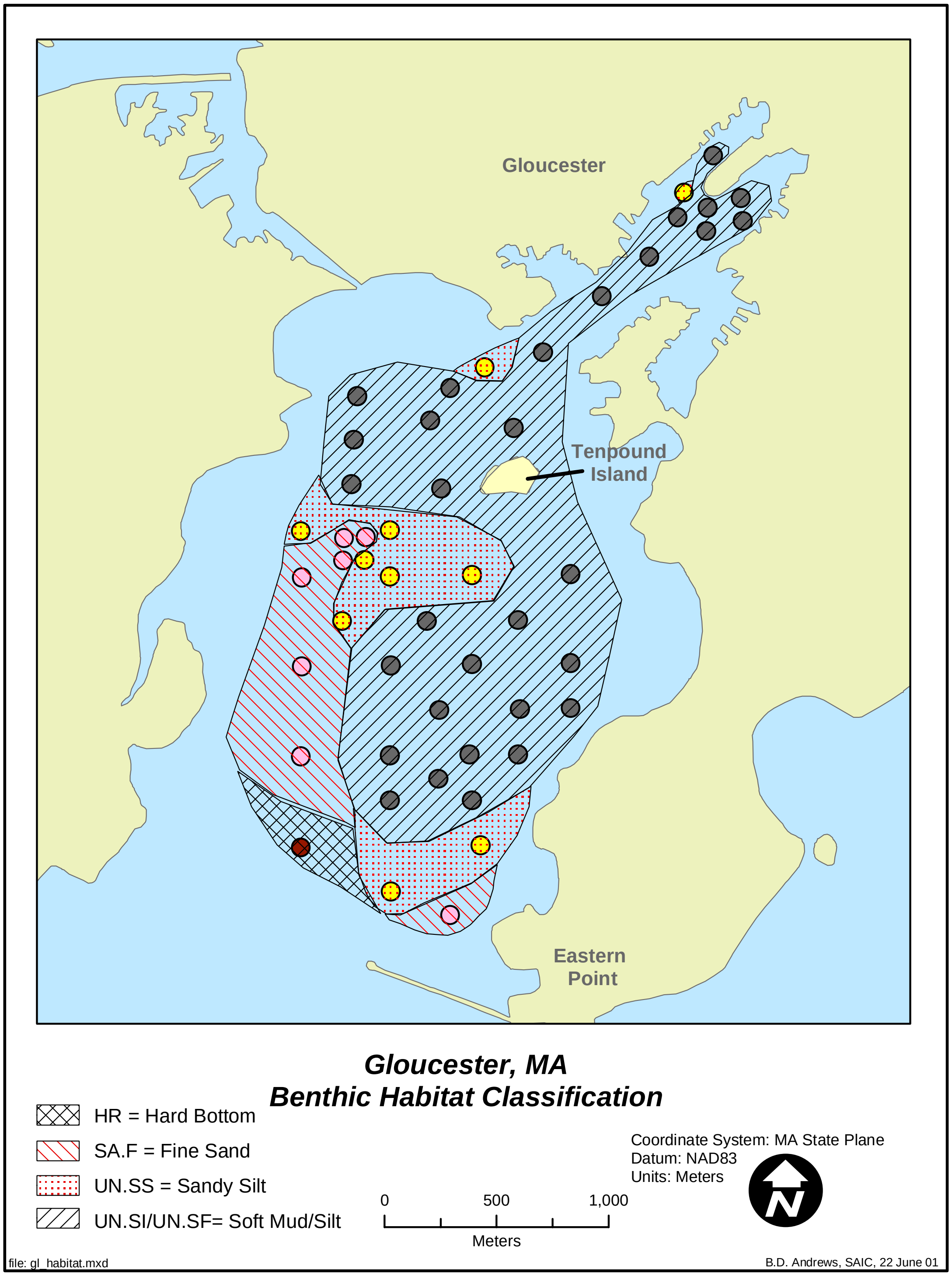


Figure 4-4. Contour map of benthic habitat types in Gloucester Harbor based on the integrated 1998 and 2001 REMOTS® survey results.

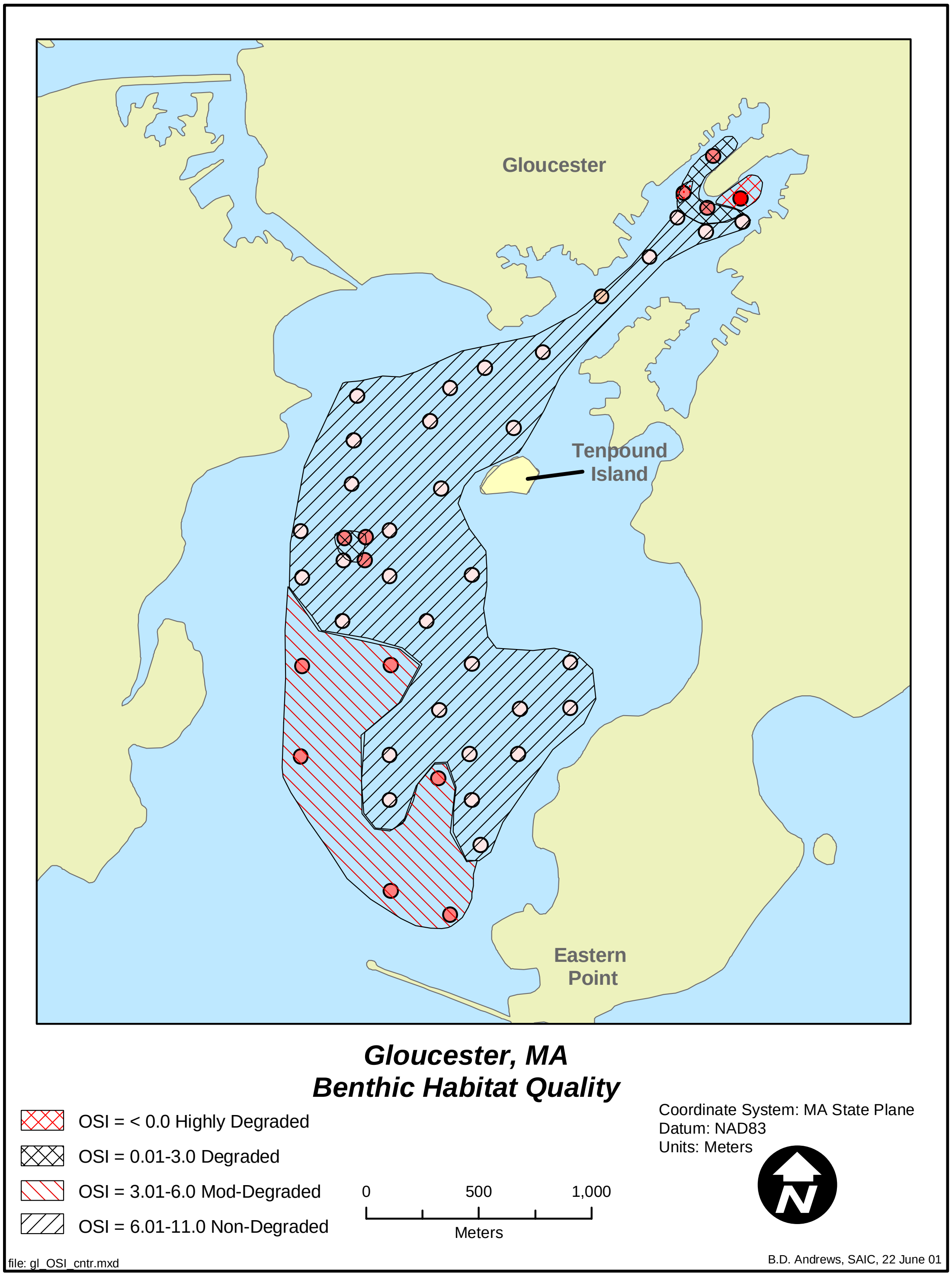
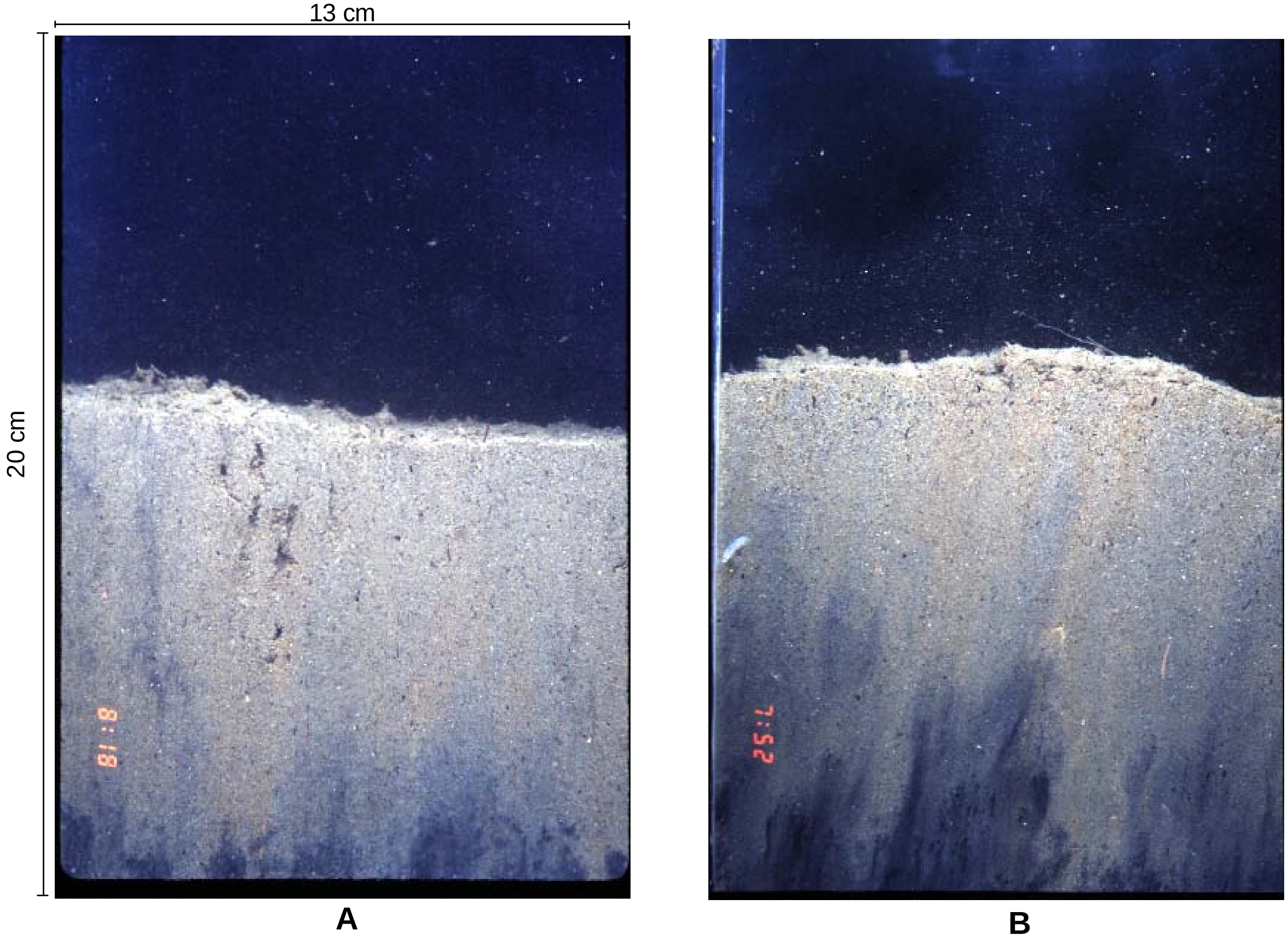


Figure 4-5. Contour map of benthic habitat quality in Gloucester Harbor (based on the average REMOTS Organism-Sediment Index value at each station) for the integrated 1998 and 2001 REMOTS® survey dataset.



Outer Gloucester Harbor
REMOTS Images
March 2001

Figure 4-6. REMOTS® sediment profile images obtained at CAD cell station 77 in November 1998 (image A) and March 2001 (image B) showing the general similarity in the appearance of the surface sediments between the two years.

APPENDIX A

Table 1

REMOTS® Image Analysis Results for Outer Gloucester Harbor Stations 1 - 30

STATION	REPLICATE	DATE	GRAIN SIZE (PHI)			MUD CLASTS		CAMERA PENETRATION (cm)				APPARENT RPD			SUCCESSIONAL STAGE	OSI	BENTHIC HABITAT	SURFACE ROUGHNESS	COMMENTS
			MIN	MAX	MAJOR MODE	COUNT	AVG. DIA.	MIN	MAX	RANGE	MEAN	MIN	MAX	MEAN					
1	A	3/15/1901	>4	2	>4	0	0.66	13.63	15.95	2.32	14.79	4.05	14.79	12.9	ST_I_TO_II	8	UN.SI	PHYSICAL	MUD>P;ST I TUBES;DEEP RPD
1	B	3/15/1901	>4	2	>4	0	0	11.68	12.68	1	12.18	4.47	12.21	10.76	ST_I_TO_II	8	UN.SI	PHYSICAL	SILTY MUD>P;ST I TUBES;VERTICAL BURROWS
2	C	3/15/1901	>4	2	>4	0	1.23	13.16	14.63	1.48	13.9	3.63	11.68	8.98	ST_I	7	UN.SI	PHYSICAL	SILTY MUD>P;ST I TUBES
2	D	3/15/1901	>4	2	>4	0	0.68	8	10	1.42	9	NA	NA	NA	ST_I_TO_II	99	UN.SI	BIOGENIC	PULL AWAY;SILTY MUD>P
3	B	3/15/1901	>4	2	>4	0	1	11.63	11.95	0.32	11.79	9	11	10	ST_I_ON_III	11	UN.SI	PHYSICAL	SILTY MUD>P;DENSE SURF TUBES;VOID/BURROW
3	D	3/15/1901	>4	2	>4	0	0.76	12.96	14.03	1.08	13.49	6.29	10.91	9.29	ST_I_TO_II	8	UN.SI	BIOGENIC	SILTY MUD>P;DENSE ST I;SURF REWORKING
4	A	3/15/1901	>4	2	4 to 3	0	0	6.77	7.31	0.54	7.04	1.04	4.08	2.75	ST_I_TO_II	6	UN.SS	PHYSICAL	MUDDY;V FINE SAND>P
4	D	3/15/1901	>4	2	4 to 3	0	0	6.45	8.28	1.83	7.37	2.96	8.12	5.13	ST_I_ON_III	11	UN.SS	PHYSICAL	MUDDY V FINE SAND>P;VOID/BURROW;GREEN ALGAE
5	A	3/15/1901	3	2	4 to 3	0	0	5	5.01	0.01	5.4	2.96	5.7	4.69	ST_I	7	SA.F	PHYSICAL	V FINE SAND>P;SAND DOLLAR;ST I TUBES
6	A	3/15/1901	3	2	4 to 3	0	0	3.33	4.25	0.91	3.79	3.28	4.62	3.7	ST_I	6	SA.F	PHYSICAL	MUDDY;V FINE SAND>P;ALGAE;ST I TUBES
6	B	3/15/1901	3	2	4 to 3	0	0	1.72	4.68	2.96	3.2	1.88	4.35	2.96	ST_I	5	SA.F	BIOGENIC	V FINE SAND>P;SAND DOLLARS
7	C	3/15/1901	3	2	4 to 3	0	0	2.9	3.92	1.02	3.41	1.34	3.87	3.21	ST_I	6	SA.F	PHYSICAL	V FINE SAND>P;ST I TUBES
7	D	3/15/1901	>4	2	4 to 3	0	0	3.17	4.46	1.29	3.82	3.06	4.3	3.73	ST_I	6	SA.F	PHYSICAL	V FINE SAND>P
8	A	3/15/1901	NA	NA	NA	0	0	0	0	0	0	NA	NA	NA	INDET	99	N/A	INDET	NO PEN=>HARD BOTTOM
8	C	3/15/1901	NA	NA	NA	0	0	0	0	0	0	NA	NA	NA	INDET	99	N/A	INDET	NO PEN=>HARD BOTTOM
9	B	3/15/1901	>4	2	>4	0	0	8.71	9.41	0.7	9.06	1.5	3.52	2.5	ST_I	5	UN.SS	PHYSICAL	V SANDY MUD>P;RED SED@DEPTH
9	C	3/15/1901	>4	2	>4	0	0	9.78	11.08	1.29	10.43	1	3	2.5	ST_I	5	UN.SS	PHYSICAL	SANDY MUD>P;REDUCED SED@DEPTH; DENSE ST I
10	A	3/15/1901	>4	2	>4	0	0	8.45	10.11	1.66	9.28	0.53	3	1.75	ST_I_TO_II	5	UN.SI	BIOGENIC	SANDY MUD>P;RED SED@DEPTH;BURROW
10	B	3/15/1901	>4	2	>4	0	0	12.3	12.89	0.59	12.59	1.6	6.79	4.12	ST_I_ON_III	11	UN.SI	BIOGENIC	SANDY MUD>P;RED SED@DEPTH;VOID;ALGAE
11	B	3/15/1901	>4	2	>4	0	0	13.96	14.76	0.8	14.36	1.93	6.95	4.72	ST_I	7	UN.SI	PHYSICAL	SILTY MUD>P;RED SED@DEPTH
11	D	3/15/1901	>4	3	>4	0	0	7.01	12.19	5.19	9.6	0.53	5.56	3.87	ST_I_TO_II	8	UN.SI	BIOGENIC	SANDY MUD>P;LG VERTICAL BURROW;RED SED@DEPTH
12	A	3/15/1901	>4	2	>4	0	0	11.66	12.73	1.07	12.19	0.05	2.5	0.5	ST_I	2	UN.SI	PHYSICAL	MUD>P; RED SED@SURF RPD;ALGAE (SMOTHERED BOTTOM)?
12	D	3/15/1901	>4	2	>4	0	1.17	6.04	7.01	1.76	6.93	3	7.27	5.45	ST_I_TO_II	8	UN.SS	BIOGENIC	SANDY MUD>P;LG FILLED DISECTED BURROW;DENSE TUBES@SURF;ALGAE
13	A	3/15/1901	>4	2	>4	0	0	6.79	6.9	0.11	6.84	0.48	3.96	2.09	ST_I_ON_III	8	UN.SS	PHYSICAL	SANDY MUD>P;WORMS@Z;VOID;DENSE TUBES@SURF
13	D	3/15/1901	>4	2	>4	0	0	6.53	7.68	1.16	7.11	1.53	8.26	6.86	ST_I_ON_III	11	UN.SS	BIOGENIC	SANDY MUD>P;SAND DOLLAR;VOID
14	B	3/15/1901	>4	2	>4	1	0.67	14.26	14.89	0.63	14.58	2.05	5	3.5	ST_I_TO_II	7	UN.SI	PHYSICAL	SILTY MUD>P;SM WORMS@Z
14	C	3/15/1901	>4	3	>4	0	0	7	13.11	6.11	10.05	NA	NA	NA	ST_I_TO_II	99	UN.SI	PHYSICAL	REDUCED MUD>P;V SHALLOW RPD;SM WORMS@Z;TUBES@SURF
15	C	3/15/1901	>4	2	>4	0	0	15.63	17.63	2	16.63	3.11	16.58	13.55	ST_I_TO_II	8	UN.SI	PHYSICAL	MUD>PEN;SOME MUD;SM WORMS@Z;TUBES@SURF
15	D	3/15/1901	>4	2	>4	0	0	14.89	16.84	1.95	15.87	4.42	8.42	7.16	ST_I_TO_II	8	UN.SI	PHYSICAL	SANDY MUD>P;RED SED@DEPTH
16	B	3/15/1901	>4	2	>4	0	0	16.74	17.89	1.16	17.32	9.42	12.84	11.27	ST_I_ON_III	11	UN.SI	PHYSICAL	SANDY MUD>P;SM WORMS@Z;DEEP VOIDS
16	D	3/15/1901	>4	2	>4	6	0.53	17.58	18.68	1.11	18.13	5.21	17.74	15.04	ST_I_ON_III	11	UN.SI	PHYSICAL	SILTY MUD>P;DEEP VOID
17	D	3/15/1901	>4	3	>4	0	0	20.53	20.53	0	20.53	NA	NA	NA	ST_III	99	UN.SF	INDET	O.P.;VERY SOFT MUD>P
17	E	3/15/1901	>4	3	>4	0	0	20.58	20.58	0	20.58	NA	NA	NA	ST_III	99	UN.SF	INDET	O.P.;VERY SOFT MUD>P
18	A	3/15/1901	>4	2	>4	0	0	19.74	20.79	1.05	20.26	10	12.11	10.35	INDET	99	UN.SF	BIOGENIC	O.P.;VERY SOFT MUD>P;RED SED@DEPTH
18	B	3/15/1901	>4	2	>4	0	0	20.37	20.37	0	20.37	NA	NA	NA	INDET	99	UN.SF	INDET	O.P.;SOFT MUD>P;RED SED@Z
19	B	3/15/1901	>4	2	>4	0	0	17.42	18.74	1.32	18.08	3.89	18.37	16.74	ST_I_TO_II	8	UN.SI	PHYSICAL	SANDY MUD>P;SM WORMS@Z;TUBES&SAND DOLLAR@SURF
19	E	3/15/1901	>4	2	>4	0	0.37	12.42	13.74	1.32	13.08	5.26	12.84	10.09	ST_I_TO_II	8	UN.SI	PHYSICAL	SANDY MUD>P;SM WORMS@Z
20	C	3/15/1901	>4	2	>4	0	0	11.37	12.26	0.89	11.82	0.05	6.47	3.71	ST_I_TO_II	7	UN.SI	PHYSICAL	SANDY MUD>P;REDUCED SED@SURF;WORMS@Z;TUBES@SURF;AMP STALK
20	D	3/15/1901	>4	2	>4	1	0.67	13.63	15.21	1.58	14.42	2.5	10.11	5	ST_I_ON_III	11	UN.SI	PHYSICAL	SANDY MUD>P;DEEP VOID;RED SED@DEPTH
21	B	3/15/1901	>4	3	>4	2	0.37	11.18	14.87	3.69	13.02	0.86	14.6	11.8	ST_I_TO_II	8	UN.SI	BIOGENIC	MUD>P;SM WORMS@Z;DISECTED BURROW;V LG RED SED PATCH
22	A	3/15/1901	>4	2	>4	2	0.65	16.36	17.86	1.5	17.11	12	15	13	ST_I_TO_II	8	UN.SI	PHYSICAL	SANDY MUD>P;SM WORMS@Z
22	B	3/15/1901	>4	2	>4	1	0.59	10.7	11.6	0.91	11.15	11	11.34	10.46	ST_I_TO_II	8	UN.SI	PHYSICAL	SILTY MUD>P;RPD>PEN;SM WORMS@Z;CLASTS&VEGETATION FF;FECAL MOUND
23	C	3/15/1901	>4	2	>4	0	0	11.66	13.05	1.39	12.35	1.6	5.72	4.63	ST_I_TO_II	8	UN.SI	BIOGENIC	SANDY MUD>P;VERTICAL BURROW; RED SED@DEPTH
23	D	3/15/1901	>4	2	>4	0	0.77	13.26	14.65	1.39	13.96	3.8	7.38	5.85	ST_I_TO_II	8	UN.SI	PHYSICAL	SANDY MUD>P;SM WORMS@Z; RED SED@Z
24	B	3/15/1901	>4	2	>4	0	0	10.16	11.6	1.44	10.88	2.14	8.98	5.4	ST_I_TO_II	8	UN.SI	PHYSICAL	SANDY MUD>P;AMPHIPOD STALK;ST I TUBES
24	C	3/15/1901	>4	2	>4	0	0	8.4	10.59	2.19	9.49	4.92	7	6	ST_I_TO_II	8	UN.SS	PHYSICAL	SANDY MUD>P;DENSE ST I
25	B	3/15/1901	>4	2	>4	0	0.75	11.34	12.19	0.86	11.76	1.39	4.17	3.05	ST_I_TO_II	7	UN.SI	PHYSICAL	SILTY MUD>P;RED SED@DEPTH
25	D	3/15/1901	>4	2	>4	0	0	17.97	18.56	0.59	18.26	3	7	6	ST_I_ON_III	11	UN.SI	PHYSICAL	MUD>P;VOID@DEPTH;RED SED@DEPTH;DEEP RPD
26	B	3/15/1901	>4	2	>4	0	0	9.89	10.48	0.59	10.19	3.42	7.65	5.78	ST_I_TO_II	8	UN.SI	PHYSICAL	SANDY MUD>P;SM WORMS@Z
26	D	3/15/1901	>4	2	>4	0	0.59	9.89	10.05	0.16	9.97	0.16	10.05	9.03	ST_I_TO_II	8	UN.SI	PHYSICAL	SANDY MUD>P;SM SURF BURROWS
27	A	3/15/1901	>4	2	>4	0	1.45	11.34	12.41	1.07	11.87	0.2	4	1.75	ST_I	4	UN.SI	PHYSICAL	MUD>P;PATCHY RPD;RED SED@DEPTH
27	B	3/15/1901	>4	2	>4	0	0.53	8.24	8.93	0.7	8.58	0.27	2	1	ST_I	3	UN.SI	PHYSICAL	MUD>P;RED SED@SURF;PATCHY RPD
28	A	3/15/1901	>4	2	>4	0	0	9.41	10.16	0.75	9.79	3.21	7.49	5.86	ST_I	7	UN.SI	PHYSICAL	SANDYMUD>P;RED SED@DEPTH
28	D	3/15/1901	>4	2	>4	0	0	10.86	11.12	0.27	10.99	5	9.89	7.44	ST_I_TO_II	8	UN.SI	PHYSICAL	SANDY MUD>P;MANY SM WORMS@DEPTH;ST I TUBES
29	A	3/15/1901	3	2	4 to 3	0	0	5.29	7.11	1.82	6.2	5.35	7.43	6.09	ST_I	7	UN.SS	PHYSICAL	MUDDY SILT>P;DENSE ST I;RPD>P
29	C	3/15/1901	3	2	4 to 3	0	0	5.19	5.4	0.21	5.29	4.12	5.61	5.28	ST_I_TO_II	8	UN.SS	PHYSICAL	MUDDY V FINE SAND>P;ST I TUBES;RPD>P
30	A	3/15/1901	>4	2	4 to 3	0	0	3.82	4.62	0.01	4.22	0.43	3.28	1.67	ST_I	4	SA.F	PHYSICAL	V FINE SAND>P;RED SED@DEPTH;ALGAE
30	B	3/15/1901	>4	2	4 to 3	0	0	3.74	4.6	0.86	4.17	0.1	3.5	1.75	ST_I	4	UN.SS	PHYSICAL	MUDDY V FINE SAND>P;RED SED@DEPTH;DENSE ST I

Table 2

REMOTS® Image Analysis Results for the Outfall and CAD Cell Stations

STATION	REPLICATE	DATE	GRAIN SIZE (PHI)			MUD CLASTS		CAMERA PENETRATION (cm)				APPARENT RPD			SUCCESSIONAL STAGE	OSI	BENTHIC HABITAT	SURFACE ROUGHNESS	COMMENTS
			MIN	MAX	MAJOR MODE	COUNT	AVG. DIA.	MIN	MAX	RANGE	MEAN	MIN	MAX	MEAN					
OF1	B	3/15/1901	>4	2	4 to 3	0	0	3.32	4.63	1.32	3.97	0.5	2	1.5	ST_I	3	SA.F	PHYSICAL	MUDDY SAND>P; V RED SED@DEPTH
OF2	A	3/15/1901	4	2	4 to 3	0	0	6.89	7.63	0.74	7.26	0	2.5	2	ST_I	4	SA.F	PHYSICAL	LIGHT SAND/YELLOW SAND/GRAY SILTY SAND;SM WORM@Z;TUBES@SURF
OF2	B	3/15/1901	4	2	>4	0	0	7.37	8.26	0.89	7.82	0.53	2.63	1.59	ST_I_TO_II	5	UN.SS	PHYSICAL	MUDDY FINE SAND>P;DENSE ST I TUBES;WORM@Z
OF3	B	3/15/1901	4	3	4 to 3	0	0	7.26	7.63	0.37	7.45	0.2	2	1	ST_I	3	UN.SS	PHYSICAL	MUDDY FINE SAND>P;WORMS@Z;TUBES@SURF
OF3	C	3/15/1901	4	2	4 to 3	0	0	11.37	12.42	1.05	11.89	2	3	2.5	ST_I_TO_II	6	UN.SS	PHYSICAL	MUDDY LT SAND/YELLOW SAND/GRAY SAND;WORMS@Z;VOIDS;TUBES@SURF
OF4	A	3/15/1901	4	2	4 to 3	0	0	3.84	4.58	0.74	4.21	1.37	3	2.75	ST_I_TO_II	6	SA.F	PHYSICAL	RIPPLED VF SAND>P; WORMS@Z; ST I TUBES
OF4	C	3/15/1901	>4	3	>4	0	0	6.47	7.21	0.74	6.84	0.5	5.32	4.23	ST_I_TO_II	8	UN.SS	PHYSICAL	MUDDY SAND>P;SM WORMS@Z;TUBES@SURF

STATION	REPLICATE	DATE	GRAIN SIZE (PHI)			MUD CLASTS		CAMERA PENETRATION (cm)				APPARENT RPD			SUCCESSIONAL STAGE	OSI	BENTHIC HABITAT	SURFACE ROUGHNESS	COMMENTS
			MIN	MAX	MAJOR MODE	COUNT	AVG. DIA.	MIN	MAX	RANGE	MEAN	MIN	MAX	MEAN					
73	C	3/15/1901	>4	2	>4	0	0.9	15.37	19.47	4.11	17.42	8.32	16.26	12.38	ST_I_TO_II	8	UN.SI	PHYSICAL	SILTY MUD>P;REDEUCED PATCHES@SURF
73	D	3/15/1901	>4	2	>4	0	1.17	16.37	19.16	2.79	17.76	10.47	14	10.57	ST_I_ON_III	11	UN.SI	PHYSICAL	SILTY MUD>P;SURF REWORKING;DEEP VOID
74	B	3/15/1901	>4	2	>4	0	0	16.58	18.79	2.21	17.68	10.16	14.63	12.52	ST_I_TO_II	8	UN.SI	PHYSICAL	SILTY SOFT MUD>P;THIN WORM IN MUD
74	D	3/15/1901	>4	2	>4	0	0.88	10.11	12.95	2.84	11.53	0.95	7.84	4.85	ST_II_ON_III	11	UN.SI	BIOGENIC	SILTY MUD>P;MANY VOIDS/BURROWS;OXIDIZED BURROW
75	B	3/15/1901	>4	2	>4	0	0.39	16.63	19.21	2.58	17.92	14.37	17.79	16.33	ST_I_ON_III	11	UN.SI	BIOGENIC	SILTY MUD>P;LG BURROW/VOID;SURF BUURROW
75	D	3/15/1901	>4	2	>4	0	0.78	16.89	18.47	1.58	17.68	0.42	18.79	16.16	ST_I_TO_II	8	UN.SI	BIOGENIC	SOFT MUD>P; SURF REWORKING
76	B	3/15/1901	>4	2	>4	0	0	15.64	16.74	1.1	16.19	10	12	11	ST_I_ON_III	11	UN.SI	PHYSICAL	SILTY MUD>P;DEEP VOIDS;DEEP RPD
76	D	3/15/1901	>4	2	>4	5	0.71	15.11	18.63	3.53	16.87	10	15.47	11.62	ST_I_ON_III	11	UN.SI	PHYSICAL	SILTY MUD>P;DEEP VOID
77	A	3/15/1901	>4	2	>4	0	0	11.37	12.84	1.47	12.11	1.74	7.05	4.44	ST_I_TO_II	8	UN.SS	PHYSICAL	SANDY MUD>P;SIG FINE SAND COMPONENTS
77	D	3/15/1901	>4	2	>4	0	0	9.05	10.89	1.84	9.97	2.47	9.84	7.64	ST_I_ON_III	11	UN.SS	BIOGENIC	SANDY MUD>P;LOTS OF SURF BIO REWORKING
78	C	3/15/1901	>4	2	>4	2	1.36	9.47	13.95	4.47	11.71	0.32	12.26	8.61	ST_I_ON_III	11	UN.SI	BIOGENIC	MUD>P;BIO REWORKING;FLUID MUD
78	F	3/15/1901	>4	3	>4	0	0	13	15.42	2.42	14.21	10	15	12.22	ST_I_ON_III	11	UN.SF	PHYSICAL	SOFT MUD>P;VOIDS;WORMS@Z;MANY TUBES@SURF;DEEP RPD

APPENDIX B

REVIEW OF DEPTH TO BEDROCK IN GLOUCESTER INNER HARBOR

Prepared for:

Maguire Group, Inc.
One Court Street
New Britain, CT 06051

Prepared by:

Science Applications
International Corporation
Admiral's Gate
221 Third Street
Newport, RI 02840

In association with:
CoastalVision
215 Eustis Avenue
Newport, RI 02840

January 2000

Massachusetts Coastal Zone Management Office
Dredged Material Management Plan
Phase 2C Program

SAIC Project No. 01-0440-04-4391-500
SAIC Report No. 483

Table of Contents

List of Figures

1.0 INTRODUCTION

The Gloucester Harbor Committee, after several discussions with the DMMP technical team, felt that it would be valuable to investigate any potential for siting Confined Aquatic Disposal (CAD) cells in the inner harbor of Gloucester.

The construction of CAD cells requires the excavation of aquatic sediments (generally silt and/or sand) below the existing sediment surface. The size of the cell that can be constructed will depend on the properties of sediments in the area proposed (the depth of soft sediment, the ability of the sediments to support a side slope, the permeability of the sediments). In many areas of the northeastern United States, there is a highly variable thickness of sediment accumulated over irregular bedrock surfaces. Just as the land surface in Cape Ann is formed of hills and lowlands, the harbor areas represent drowned topography that has accumulated sediments since the last glacier left New England. These sediments have covered these drowned hills and lowlands leaving a relatively smooth layer of silt of varying depths.

The primary limitation in defining potential locations for, and capacities of, CAD cells was the unknown depth of soft sediment throughout much of the harbor. Information available in the Phase 1 and Phase 2 reviews of candidate disposal sites (subbottom survey data, geotechnical review) was insufficient to provide detailed recommendations for locations of CAD cells within the harbor. There were two primary difficulties: the subbottom survey data were obscured throughout much of the harbor by the characteristics of the silt in the harbor (gas bubbles or surface reflectors), and the geotechnical data (ledge areas, borehole data, bathymetry) was not entered into a common reference format. The committee recommended further exploration of all available information on bedrock depth in the Gloucester Harbor area.

We reviewed all available geological literature, Corps of Engineers documents, and the subbottom records to develop GIS layers of local geological features (faults, bedrock units), ledge removal areas, bathymetry and depth to bedrock. The geological data were consistent with the ledge removal areas and bedrock depth mapping. The subbottom data were carefully reviewed to draw inferences on bedrock depth in areas obscured by strong reflectors or gas deposits. The subbottom data were analyzed to confirm all reported or inferred depths and were then remapped onto a GIS layer. This provided the most accurate depiction (with relative confidence levels) of areas of the harbor that might have sufficient depth to bedrock to merit additional direct sampling.

2.0 GEOLOGICAL INFORMATION

Recent geologic maps and articles were reviewed to provide the best understanding of the underlying fabric of the rocks expected to lay beneath the inner harbor of Gloucester. While there has been no detailed investigation of the bedrock geology within the inner harbor, the information available from the surrounding area is quite helpful.

In the most basic sense, the area of Gloucester inner harbor (or for that matter the entire Cape Ann area) was formed through two major geologic processes: placement and fracturing of the igneous rocks deep within the mantle of the earth and erosion of this bedrock by glacial activity. The glacial activity smoothed the existing bedrock and in places deposited sand, silt and till (a compact, concrete-like sediment). For the purposes of predicting the depth to bedrock within the harbor, the distribution of these processes in the area is quite important.

The landscape of the Cape Ann area and much of New England is controlled by the underlying bedrock (Denny 1982). While the erosion and deposition associated with the glacial episodes of the Quaternary Era have altered the topography and created large landforms (e.g., Cape Cod, Stellwagen Bank), for the most part the shape of New England and location of harbors is related to bedrock distribution. In the determination of the most likely locations for CAD cells we need to account for bedrock geology, glacial deposits and recent estuarine deposits.

Three features of the bedrock geology may help define potential locations for CAD cells: the nature of the bedrock (any variations in bedrock might produce lows or highs in topography); the locations of dikes (potentially zones of softer or harder rock); and the location of faults (generally areas of weakness that may have been preferentially eroded by glaciers).

In the Cape Ann area, the bedrock is remarkably uniform, composed of Ordovician Era (450 million years before present) intrusive igneous rocks known as the Cape Ann Granite (Dennen 1992, [Cape Ann Complex of Zen et al. 1983]). These rocks were formed when molten rock from deep within the earth’s mantle rose and partially melted rocks in the lower and intermediate crust. Variations within the Cape Ann Granite suite of rocks (see Figure 1) are likely to be a result of incorporation of different proportions of crust material into the magma (represented by proportion of quartz in the rock). During the cooling of the granite, the material was split and allowed deeper liquid rock to flow into the splits and form “dikes” of different composition. Some of these may have fed extrusion of the magma in the form of volcanic vents creating ash and lava deposits (Lynn rhyolite). Much later the cooled granite and dike material was split during an episode when large areas of rock were subject to strain and fractured in large faults. These are regional faults with a very distinct trend (direction) and angle (Barosh et al. 1977, Barosh 1984). The faults are part of a layered “thrust” zone of eastern Massachusetts (Bell 1968) with northeast trending high angle faults where the western side of the fault rode over the eastern side (Figure 2).

One branch of the local major north-northeast fault, trends east-northeast from Freshwater Cove through the Inner Harbor of Gloucester where it branches again (Figure 1). This fault is likely to be the controlling geological factor in the shape of the harbor itself. The axis of the harbor and the two inner segments of the harbor parallel the trend of the fault. While this might offer hope for deep areas of bedrock, other evidence (presence of ledge, acoustic survey) suggests that while the inner harbor was clearly formed by removal of material along the fault line, it was not removed to great depth.

One interesting aspect of the local geology is the theory that because the Cape Ann Granite was never subjected to the regional alteration (metamorphism) seen in rocks to the north and west, Cape Ann (and the Boston area) was not part of present North America until long after its formation (Barosh 1984, Hon et al. 1993). Many authors agree that it was likely formed during the closure of the "proto-Atlantic" or Iapetus Ocean. The present Atlantic was formed by a rifting of the continents during which the area represented by Cape Ann became part of the North American continent and the ocean opened further east. This theory has no practical relevance to the location of CAD cells in Gloucester Harbor but the lack of metamorphism does. The limited folding and deformation seen in the granites of Cape Ann may not have provided conditions for deep excavation of the bedrock along folds or seams between rock types.

The bedrock geology was modified by fluvial (river) erosion, probably during a period of low sea level (Oldale and Wommack 1987) and then by several sequences of glaciation. The episodes of glaciation were accompanied by drowning of the land by the sea (the weight of the ice depresses the crust and the melting of the ice creates a rise in sea level) and subsequent draining of the land (shore regression) when the crust rebounded following the removal of the weight of the ice. This complex combination of events may remove much of the overlying soil horizon and deposit sands and gravels, till, silt or clay. These deposits can fill glacially scoured depressions with tens of meters of unconsolidated materials (Oldale and Wommack 1987). Based on borehole data, Gloucester Harbor appears to have glacial deposits under the recent silt (USACE 1995 and associated borehole logs). Sand and clay deposits of glacial origin have been used for CAD cell development in Massachusetts (Boston Harbor and Hyannis Harbor).

Following the period of glaciation, the coastal areas of Cape Ann were inundated by the sea and recent marine deposits have accumulated (harbor silts, sands). These recent deposits tend to be fine-grained inside bedrock harbors (such as Gloucester) and often have high organic contents. The organic content can lead to creation of methane gas below the surface of the sediments and the surface can be modified by biological activity and winnowing from vessel wakes. Both of these conditions can interfere with acoustic methods of determining sediment depth (see below).

Significance:

The geological results suggest that locally, bedrock contours should reflect the general patterns seen on the land surface, with the location of faults or dikes serving as indicators of potential topographic lows in the bedrock contours. Because there is little variation in the type of bedrock seen in Cape Ann, it is unlikely that there are significant areas of softer rocks that might have been eroded more extensively by glaciation.

The distribution of glacial deposits is difficult to predict from available evidence, but much of the marine sediment probably covers some thickness of glacial drift or till. An example is the results of borings taken on land and in the nearshore zone during reconstruction of the Coast Guard dock and helipad in 1972. These borings show an average of 10-15 feet of unconsolidated material (fine sand and silt) before refusal of probes (nearshore) or encountering rock (land) (USCG 1972). Further evidence is seen in the borehole data from 1964 (USACE 1964). The 1964 data concentrated on areas suspected of ledge, but most boreholes contained 5–10 feet of sand, gravel or till.

The recent marine silts, which are easily penetrated by probes, appear to mantle the glacial deposits and in some cases, rock outcrops (USCG 1972, USACE 1995).

3.0 CONDITION SURVEYS

Dredging projects have been conducted in Gloucester Harbor since the late 1800's to deepen the channel and remove rock obstructions (USACE 1995). The history of the identification of ledge areas and their removal provides important clues to the likelihood of bedrock depth in the inner harbor area. Between 1870 and 1916 a total of 3,536 cy of rock were removed in the inner harbor to a depth of –15 feet MLW. After the channel was authorized to –20 feet MLW, 1,000 cy of ledge were removed in 1964. Recent studies to determine the feasibility of deepening the existing channel and turning basin to either –24 or –26 feet MLW reviewed existing probe and borehole data to determine ledge areas that might need to be removed (Figure 3). This data review does not provide evidence for any areas of deep sediment layers above bedrock, but the majority of the probe studies only determined conditions to –23 feet MLW. However, there are numerous areas within the inner harbor (Ledge areas A, B, C, D, and E) where probe studies met refusal (hard sediment or rock) at –18 to –20 feet MLW. Probe and borehole data from 1959 and 1964 were reviewed in this study and compared to acoustic data (see below).

The map constructed by the Corps to delineate contours of subsurface ledge was placed as an image in the GIS database to aid interpretation of acoustic records and evaluation of the potential for location of CAD cells (Figure 3). In addition, searches were made of the microfiche records at the Concord office of the New England District, U.S. Army Corps of Engineers to locate additional historical survey maps. Sketch maps from ca. 1900 and 1929 showed significant areas of ledge had been removed adjacent to the present Coast Guard station and in the North Channel of the Inner Harbor. These historical maps lend further support for the conclusion that much of the inner harbor area is underlain with shallow bedrock with a thin (<5 foot) layer of sediment.

4.0 ACOUSTIC SURVEYS

In addition to the circumstantial evidence compiled from geological and condition surveys, there is direct evidence of depth to bedrock compiled from acoustic subbottom surveys. Subbottom seismic (or acoustic) profiling is a standard technique for determining changes in acoustic impedance below the sediment/water interface. The acoustic impedance, while a product of the velocity and density of sound in a sediment layer, is also affected by differences in surface roughness, porosity, and grain size, among other factors (Hamilton 1970; LeBlanc et al. 1992). In general, sound penetrates further into fine-grained sediment because the impedance of high-water content silt and clay is closer to that of the water column. The ability to detect subbottom layers is similarly dependent on the acoustic impedance contrast between sediment layers (Myre and DeAngelo 1999).

The presence of subbottom reflectors depends on changes in acoustic impedance between the water column and the sediment (first bottom reflector), and between subbottom layers of different lithologies. In general, the basement reflector (bedrock) is a dark (high amplitude) subbottom reflector because of the acoustic contrast between the basement rock and overlying sediments.

Acoustic surveys were conducted from 19–20 December, 1998 and consisted of 31 lanes oriented perpendicular to the main channel and spaced at 50 m intervals (Myre and DeAngelo 1999). In addition, subbottom data were collected along four evenly spaced lanes in each of the two forks of the innermost harbor. Survey operations were conducted in the ATC areas and in the OD area from Ten Pound Island midway into the harbor (Figure 4). Details of the acquisition and processing of the subbottom acoustic records are available in Myre and DeAngelo (1999).

The records from 1998 were reexamined in light of the renewed interest in locating CAD cells within Gloucester inner harbor. Each survey lane was reviewed to distinguish clear horizons of bedrock, those obscured by artifacts and those with no discernable bedrock. In general the subbottom profile records provided the ability to detect and map the basement bedrock layer. Two basic factors impeded the ability to confidently trace subbottom reflectors. The first problem in measuring subbottom reflectors was the presence of natural gas. The presence of gas in sediments is common, usually attributable to the decomposition of organic matter (commonly methane and other similar gasses). These gas “wipe-outs” prevent any distinction of subbottom layers. The second problem was in areas of coarse surface sediments; commonly the resolution below these sediments varied greatly from a complete loss of subbottom reflectors to a fair ability to distinguish the basement reflector. Subbottom data directly below these coarse sediments, frequently below the shipping channel, showed the presence of “multiples” that obscured the subbottom reflectors. The term “multiple” refers to strong reflections of sound from the sediment/water interface that arrive after an additional round trip through the water column. These multiples are easily identified because they arrive at specific multiples of time (travel time round trip through the water column), imitate the surface reflector, but appear to be a discrete distance “below” the sediment/water interface (Myre and DeAngelo 1999).

The reviewed data was gridded and each grid was assigned values for depth (Figure 5). A depth interval was assigned 0-1 meters if it was clear based on acoustic and ledge data that bedrock protruded at the surface. This re-gridded data revealed that while the general pattern of bedrock depth distribution was the same as the 1999 report, there were important differences. In some areas, multiple reflectors had been digitized as bedrock reflectors exaggerating the potential depth. In other areas the data from along channel was obscured completely by the channel reflector, while cross channel data could be interpreted more clearly (each end of the lane had clear bedrock reflector outside the channel). The resultant grid has less small-scale variation in depth for two reasons: one, a more conservative gridding routine; two, elimination of some data conflicts.

The most significant area of deep bedrock occurs near the entrance to the harbor (Figure 5). This area is the most complex geologically (cut by a fault, dikes and several groups of Cape Ann granite) and appears to have some buried topography. An example of the acoustic data from a lane through this area reveals that the channel area is all but obscured by the surface reflector while a clear bedrock reflector can be seen at one end of the record (Figure 6). An additional area of deep bedrock occurs southwest of Ten Pound Island in a section of the record that was not originally digitized (a turn between lanes, Figure 4). While the depth to bedrock may be as much as 10 m, we currently have fragmentary evidence of the scale of the area with this depth.

5.0 FINDINGS

1. Subbottom records provide additional information when examined in relation to maps of ledge, bedrock geology and the USACE condition survey.

2. Much of the inner harbor subbottom has a characteristic bottom type that provides a strong surface reflection and obscures deeper subbottom information. This appears to be related to ship traffic, as it occurs in the authorized channel but outside of the area dredged to maintain navigation depth (shipping lanes).

3. Where the feature is present, we can only speculate on depth to bedrock. In some cases adjacent areas provide depth to bedrock and some extrapolation is possible.

4. Most of the inner harbor shows no evidence for significant sediment depth (>3m) based on ledge distribution, bedrock geology, and fragmentary subbottom evidence. An exception is Smith Cove which is visible on the subbottom records and may have as much as 3-5 m depth to bedrock.

5. Outside the harbor there are distinct areas of shallow and deep bedrock - which can be clearly seen on subbottom records. Southwest of Ten Pound Island there is an area which shows evidence of at least 10 m of depth to bedrock (not shown on grid).

6. Some areas previously mapped with extensive depth to bedrock (near entrance to harbor) appear to have a much smaller area of deep bedrock surface. This may limit their utility for CAD cells.

6.0 RECOMMENDATIONS

In Gloucester, the bedrock depth is relatively shallow, and quite variable in the area near the entrance to the harbor, as shown by all of the data reviewed here. Despite careful re-analysis, some of the information contains a level of uncertainty due to loss of subbottom information. Some of the noise of the data was due to the presence of an acoustic reflecting surface layer associated with the shipping channel. This reflector was persistent in the shipping lanes even in the areas outside of the dredged channel. These results suggest that ship traffic may produce a slightly coarse lag deposit in the channel that acts as an acoustic “ringer” obscuring the penetration of the acoustic signal. Therefore, in general, the estimates of bedrock depth from the channel area may be highly uncertain due to the need to extrapolate bedrock depth from the margins of the channel.

All of the evidence (acoustic, condition surveys, geology) are consistent with an expectation that the bedrock depth in the inner harbor is quite shallow (less than 5 feet below sediment surface). While this area was identified by the committee as the most desirable region to locate a CAD cell, apart from Smith Cove, there do not appear to be any significant areas of depth within the inner harbor.

Recommended subsurface data collection

We do not recommend collection of borehole data in the inner harbor area (apart from Smith Cove) as the evidence for shallow bedrock is sufficiently compelling in our professional judgement to remove this area from consideration.

Because of the difficulty in collecting reliable acoustic data within the harbor it will be necessary to collect ground-truth borehole data in any cell that is proposed as a preferred alternative (Figure 7). The areas in Smith Cove may be too small to serve as CAD cells, but if they are considered a small number of boreholes (2-3 for each cell) could provide sufficient design information to conduct an alternatives analysis. The depth to bedrock in the areas near the entrance to the harbor (G-Cell-1 and -4) is highly speculative, although there are some points within the dataset that are well-characterized. These areas are the areas with the greatest need for data collection, if the cells are deemed to be Preferred Alternative Disposal Sites. The areas outside the harbor (G-Cell-2, and –3) are relatively well-characterized and should not need confirmatory borehole exploration. It might be worthwhile to investigate the area to the southwest of Ten Pound Island with direct exploration as there was fragmentary evidence of significant depth to bedrock

Recommended disposal cells

The suggested disposal cell locations are modifications of the outlines of the Proposed Preferred Alternative Disposal Sites of Phase 2 (Figure 8). Rather than presume any interaction with other resource issues, these locations are based on the physical possibilities of CAD cell development. Therefore they still need to be evaluated in the same manner as the Proposed Preferred Alternative Disposal Sites.

G-Cell-1 This proposed cell is a revised outline that corresponds to G3-ATC-A
The average depth to bedrock is 6.4 m over an area of 48,973 m^2

G-Cell-2 This proposed cell is a revised outline that corresponds to G3-ATC-B
The average depth to bedrock is 5.5 m over an area of 22,969 m^2

G-Cell-3 This proposed cell is a revised outline that corresponds to G3-ATC-C
The average depth to bedrock is 5.6 m over an area of 30,215 m^2

G-Cell-4 This proposed cell is a revised outline that corresponds to G3-ATC-D and includes area in the channel. The average depth to bedrock is 6 m over an area of 62,617 m^2

G-Cell-5 This is a new cell located in Smith Cove that is quite small but might be used for small volumes, particularly if any maintenance or new dredging was conducted in the Cove
The average depth to bedrock is 5.7 m over an area of 3,937 m^2

G-Cell-6 This is a new cell located in Smith Cove that is quite small but might be used for small volumes, particularly if any maintenance or new dredging was conducted in the Cove
The average depth to bedrock is 5.6 m over an area of 5,710 m^2

7.0 REFERENCES

Barosh, P.J., Fahey, R.J., and Pease, M.H., Jr., 1977. Preliminary Compilation of the Bedrock Geology of the Land Area of the Boston Two Degree Sheet, New England Seismotectonic Study Report, Weston Observatory, Boston College.

Barosh, P.J. 1984. Regional Geology and tectonic history of southeastern New England, in Hanson, S.L. ed.: New England Intercoll. Geol. Conf. 76th ann. Meeting Salem State College, Salem, Massachusetts, p. I-1 to I-35.

Bell, K.G. 1968. Faults in eastern Massachusetts [abs.]: Geological Society of America Special Paper 115, NE Section, 2nd Annual Meeting, Boston, Mass., 1967, p. 250.

Dennen, W.H. 1992. Bedrock Geologic Map of the Gloucester and Rockport Quadrangles, Essex County, Massachusetts: U.S. Geological Survey Miscellaneous Investigations Series Map I-2285.

Denny, C.S. 1982. Geomorphology of New England: U.S. Geological Survey Professional Paper 1208, 18 p.

Hamilton, E. L. (1970). Reflection coefficients and bottom losses at normal incidence computed from pacific sediment properties. Geophysics, 35:995-1004.

Hon, R., Paige, M.L., and Loftenius, C.J. 1993. Petrogenesis of two diverse mid-paleozoic complexes for eastern Massachusetts: A-Type Cape Ann Granite and I-Type Sharpners Pond Quartz Diorite, in Cheney, J.T. and Hepburn, J.C. ed: Field Trip Guidebook for the Northeastern United States: 1993 Geological Society of America Annual Meeting and 85th Annual New England Intercollegiate Geological Conference, October 25-28 Boston, Massachusetts.

LeBlanc, L. R., L. Mayer, M. Rufino, S. Schock, and J. King. (1992). Marine sediment classification using the chirp sonar. J. Acoust. Soc. Am., 91(1):107-115.

Maguire Group. (1997a). Preliminary geotechnical investigations, Dredged Material Management Plan Task B. Submitted to Massachusetts Coastal Zone Management Agency, Boston, MA. Submitted by GEI Consultants, Inc., Winchester, MA.

Myre, P.L. and DeAngelo, E.C. 1999. Capacity analysis of CAD sites within Salem, Gloucester, and New Bedford Harbors. Report submitted by Maguire Group to Massachusetts Coastal Zone Management Agency, March 1999, SAIC Report No. 467.

Oldale, R.N. and Wommack, L.E. 1987. Maps and seismic profiles showing geology of the inner continental shelf, Cape Ann, Massachusetts to New Hampshire. U.S. Geological Survey Miscellaneous Field Studies Map MF-1892.

Ocean Surveys Inc. 1991. Hydrographic chart, post dredge survey-outfall extension Gloucester Harbor, Gloucester, MA. Prepared for Maitland Brothers., Co.

USACE 1964. Gloucester Harbor, Gloucester, Massachusetts. Record of Explorations. Drawing number 266-Dr. 37, 7 sheets. U.S. Army Corps of Engineers, Waltham, MA, June 1964.

USACE 1995. Gloucester Harbor, Gloucester, Massachusetts, Navigation Improvement Study Reconnaissance Report. Department of the Army Corps of Engineers, New England Division, July 1995.

- Appendix D and associated Condition surveys and subsurface data obtained from microfiche collections held at New England District (NAE). Data includes borehole results and probe surveys within the inner harbor (1884-1965).
- Bathymetric condition survey sheets (1994 & 1999)

USCG 1972. U.S. Coast Guard Station, Gloucester, Massachusetts Boring Plan, Boring Log On-shore, Boring Log Off-shore. C.G. Drawings No. 6250, L-2,L-3,L-4. U.S. Coast Guard First District, Boston, Massachusetts, February 1972.

Zen, E-an, ed., Goldsmith, Richard, Ratcliffe, N.M., Robinson, Peter, and Stanley, R.S. compilers. 1983. Bedrock Geologic Map of Massachusetts: U.S. Geological Survey Scale 1:250,000. Open-File Report 81-1327.

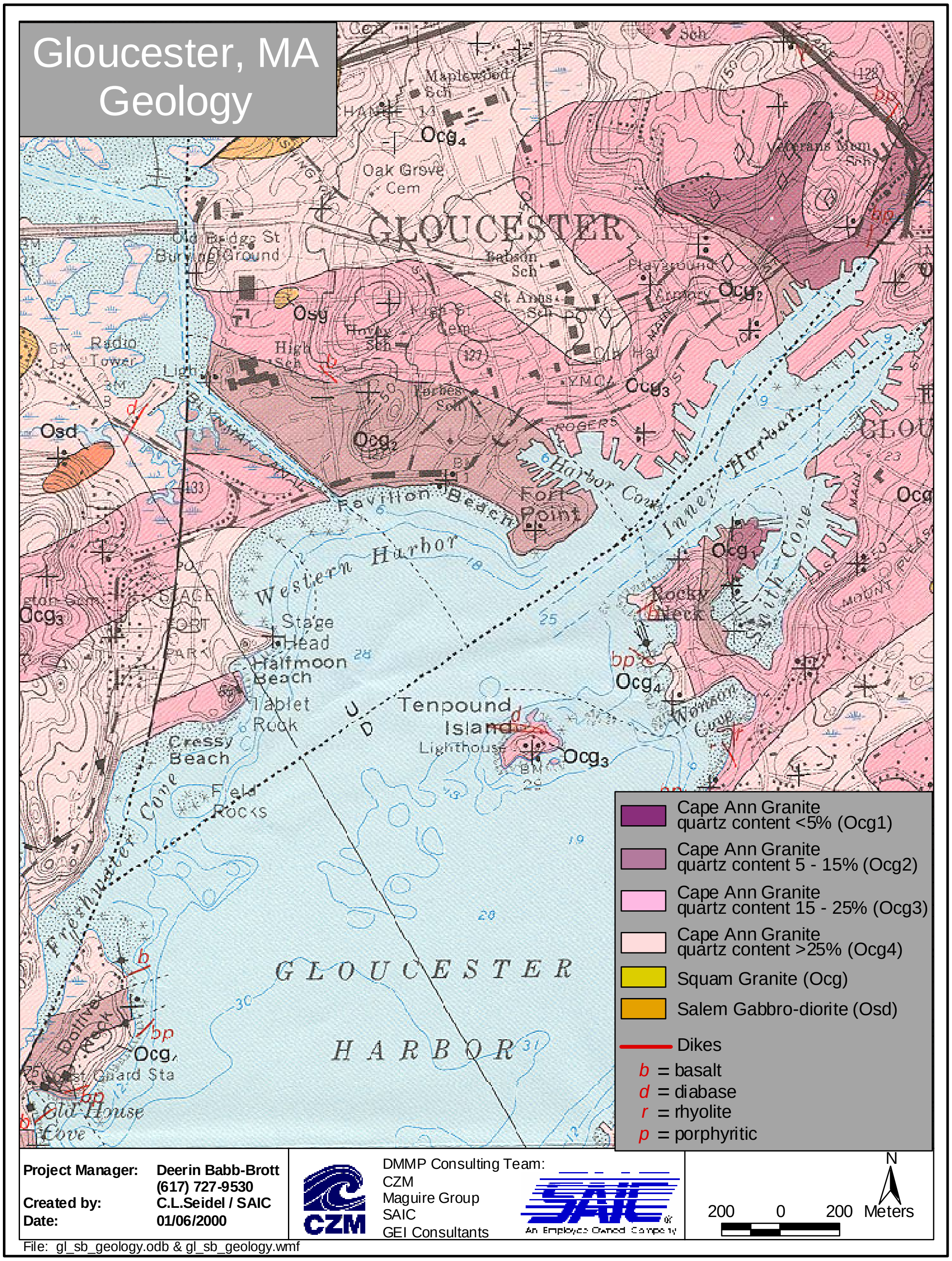


Figure 1. Geological map of bedrock surrounding Gloucester Inner Harbor.

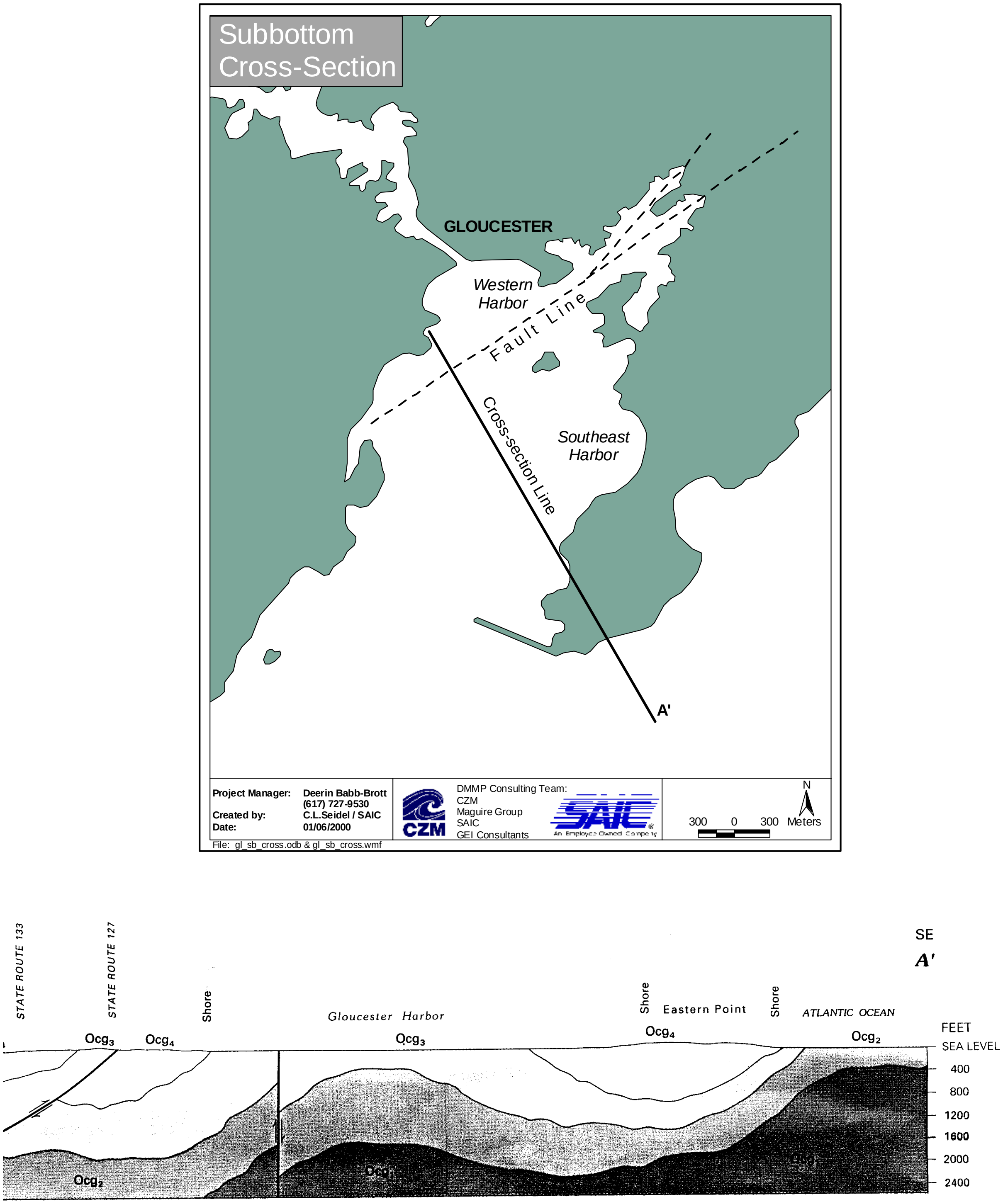


Figure 2. Cross-section of Gloucester Harbor. The cross-section shows the high angle thrust fault that runs along the axis of Gloucester Harbor.

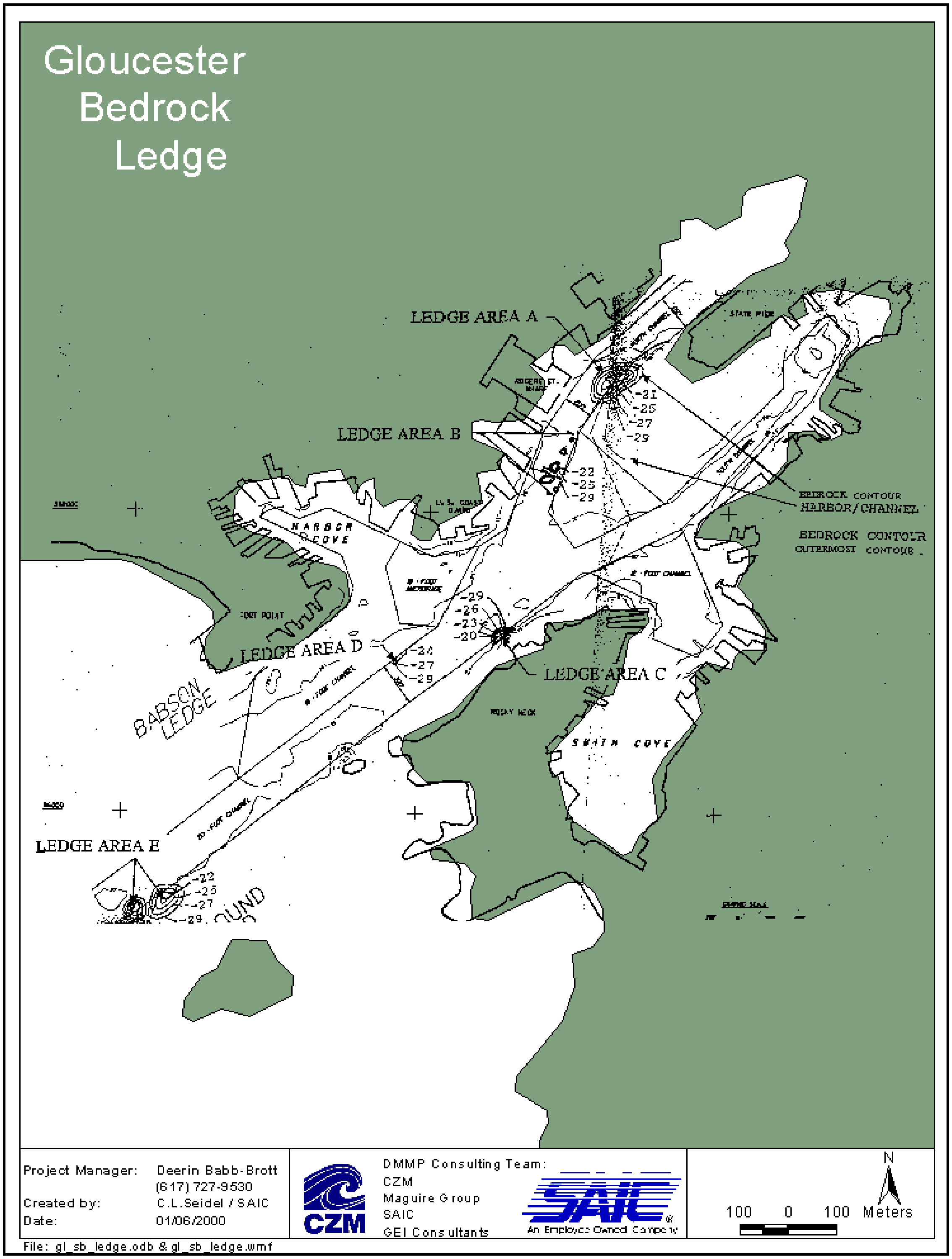


Figure 3. Ledge identified in 1995 by U.S. Army Corps of Engineers.

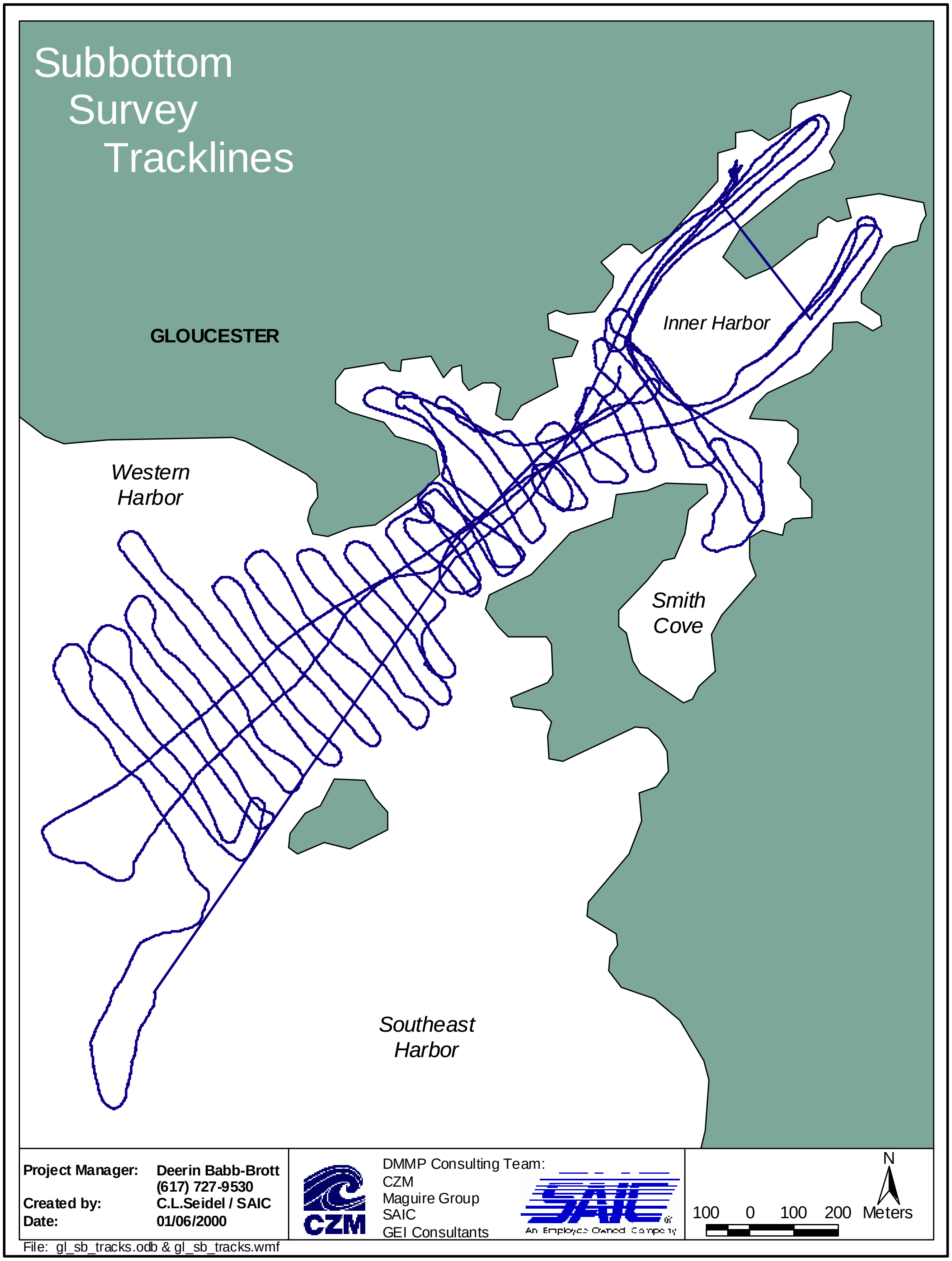


Figure 4. Tracklines of subbottom surveys in Gloucester Harbor.

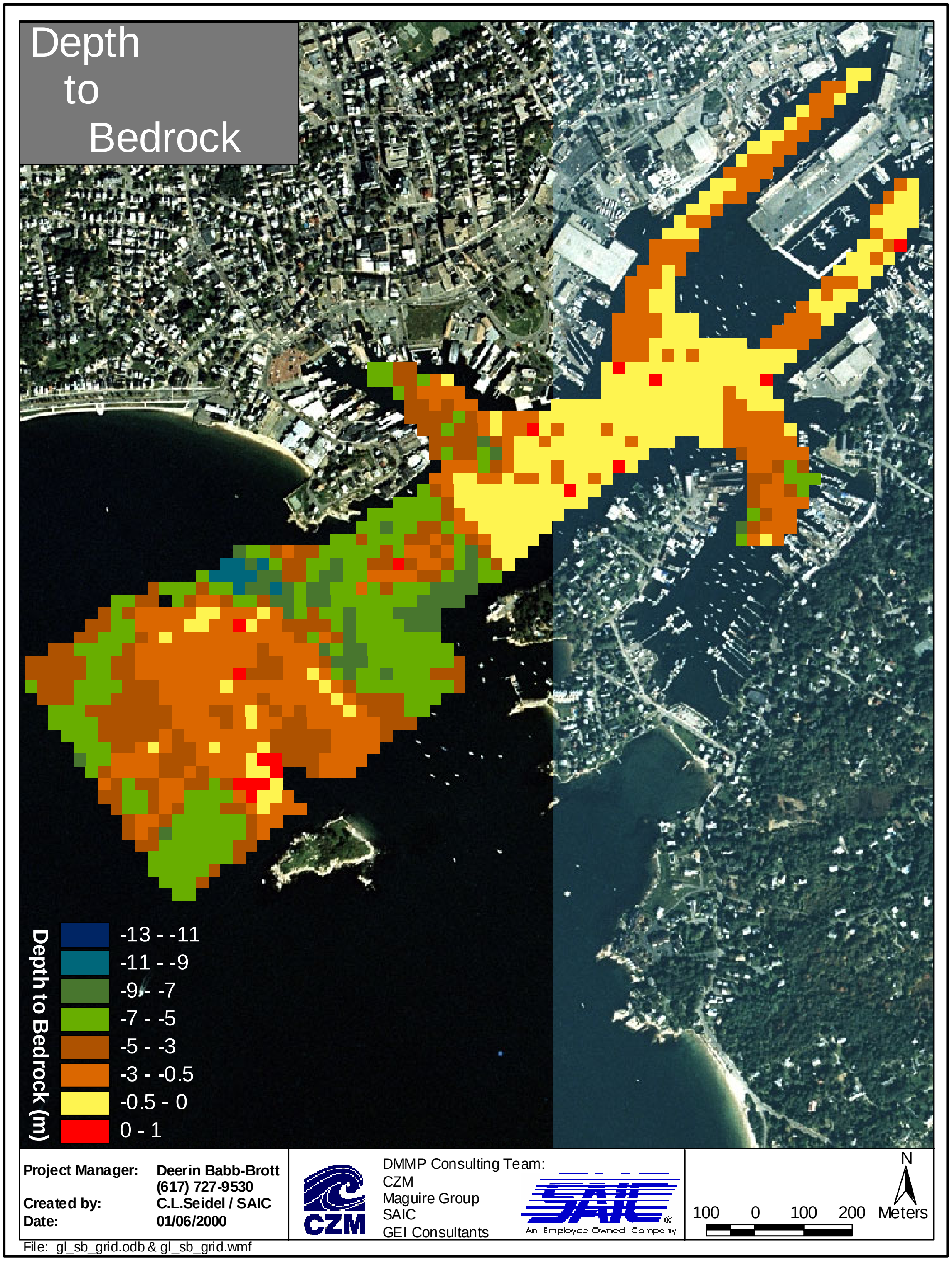


Figure 5. Interpreted depth to bedrock based on acoustic surveys.

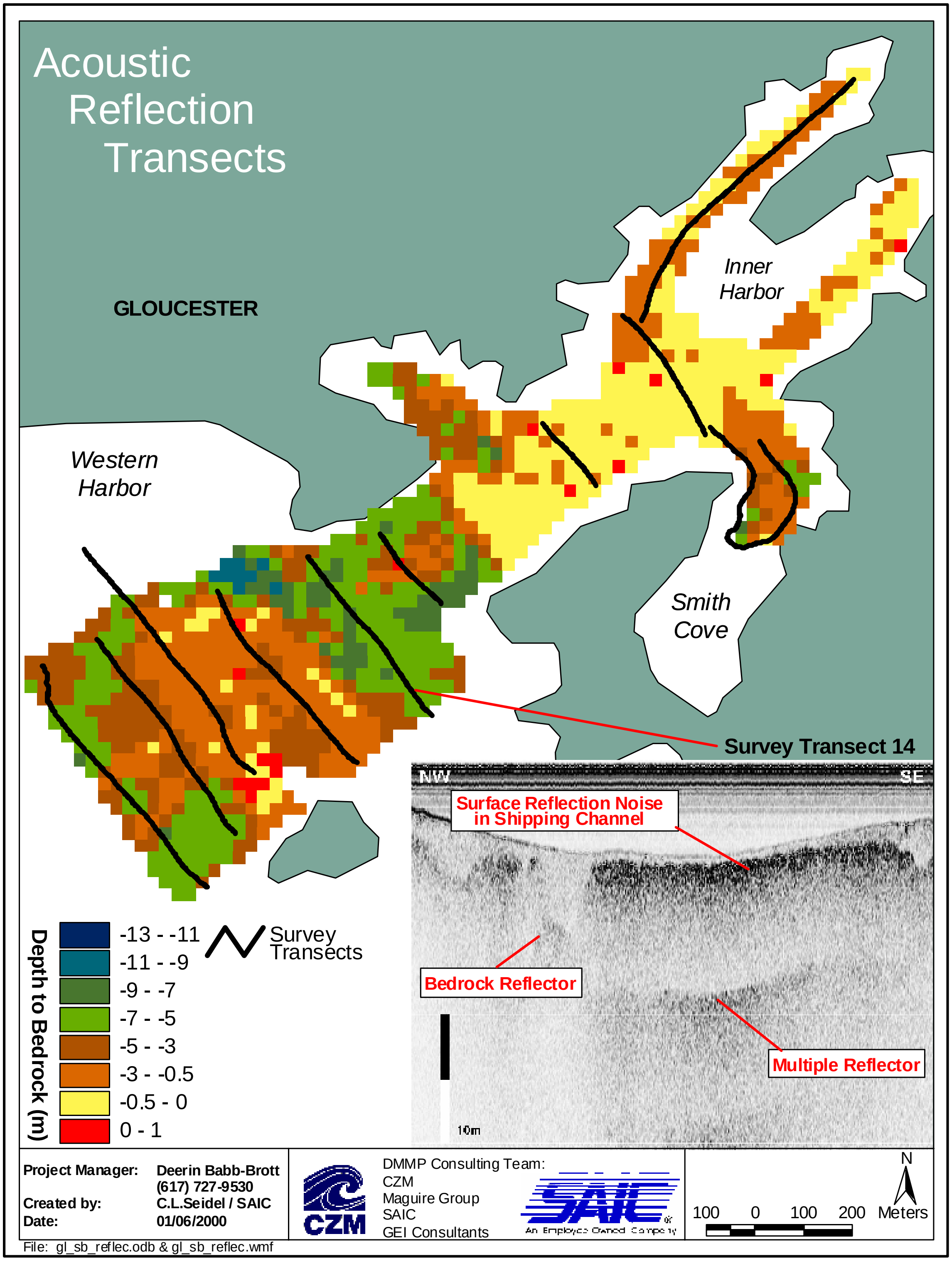


Figure 6. Example acoustic reflection transect.

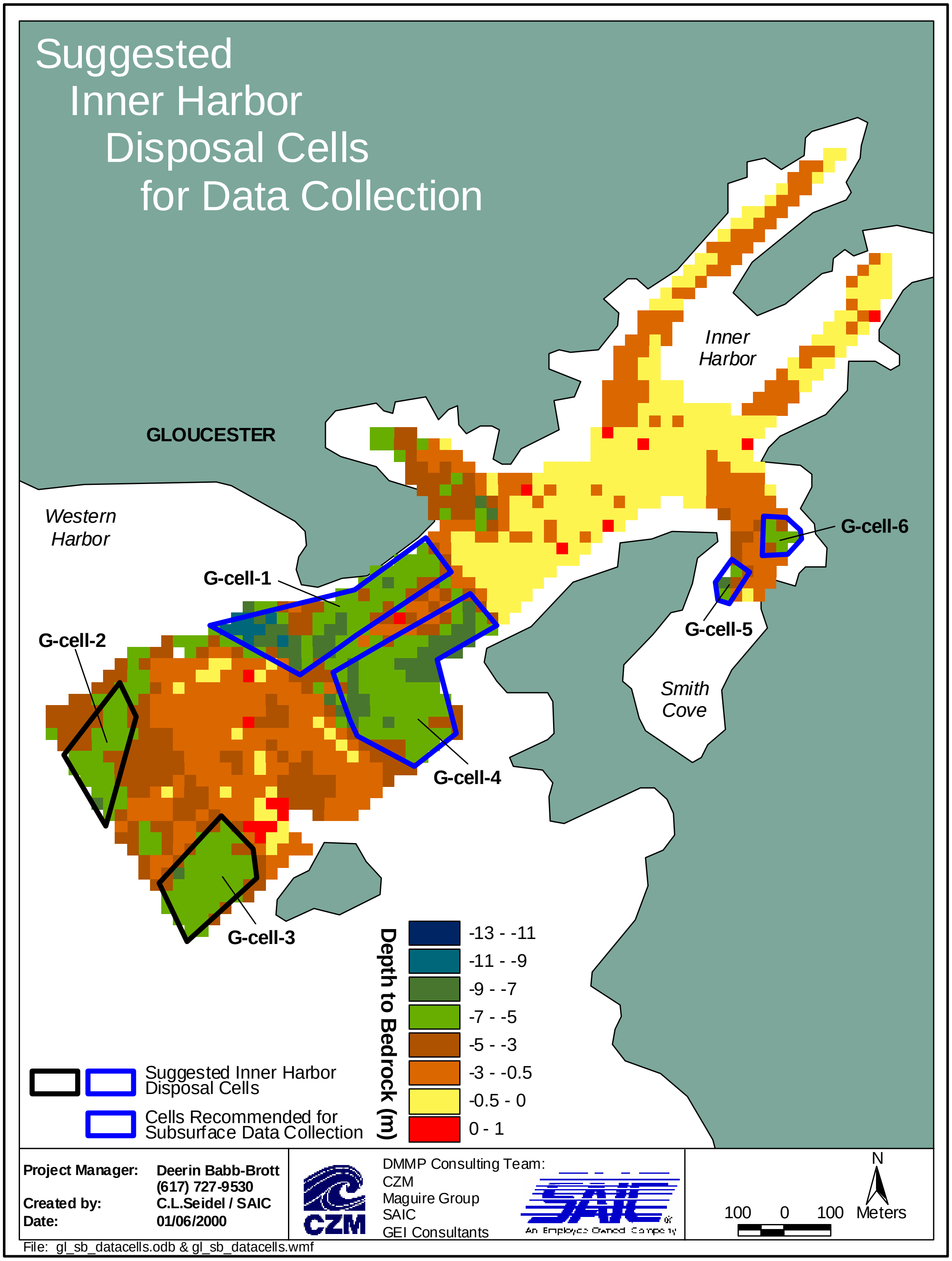
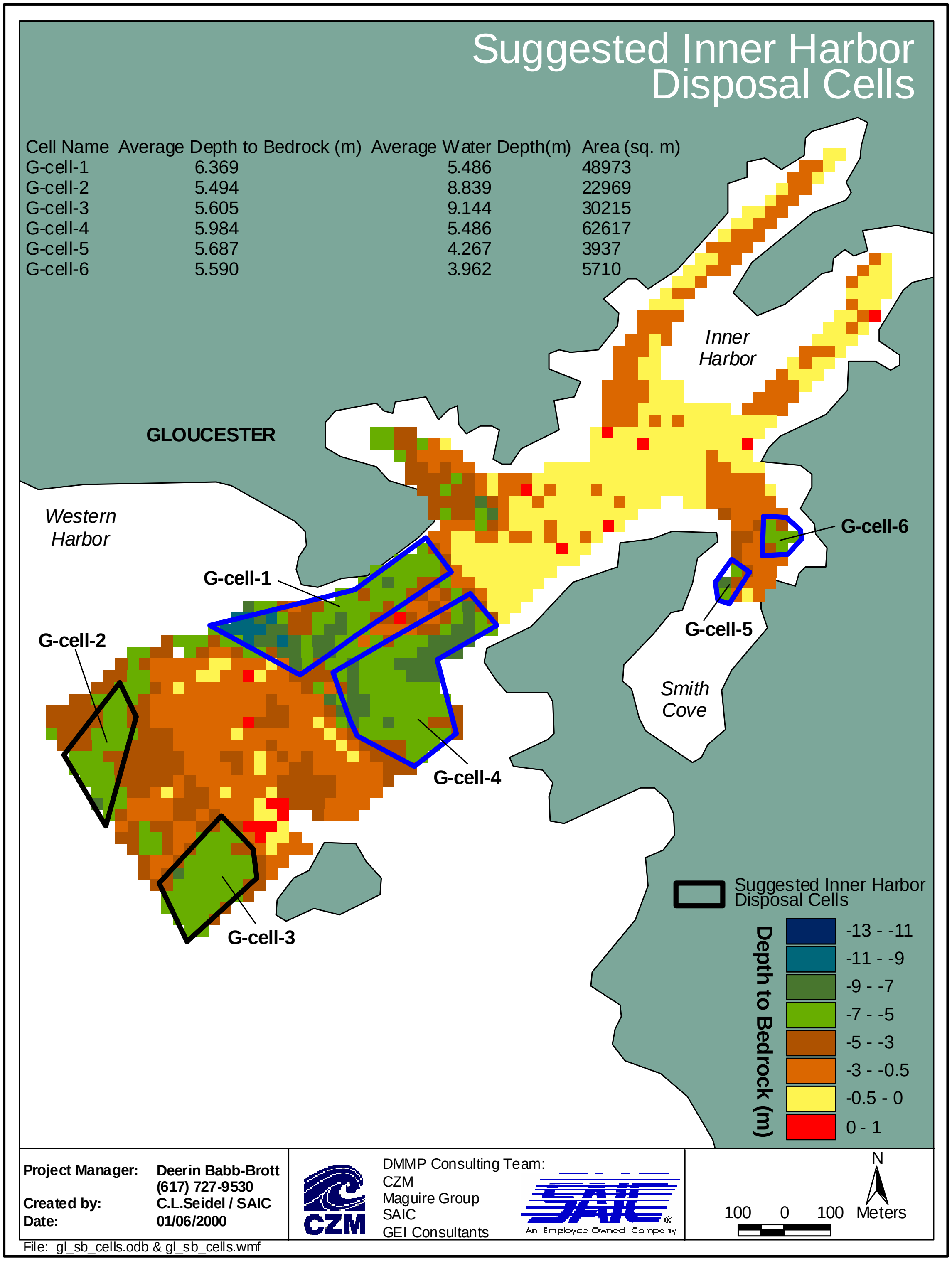


Figure 7. Recommended subsurface data collection.



Suggested Inner Harbor Disposal Cells

Cell Name	Average Depth to Bedrock (m)	Average Water Depth(m)	Area (sq. m)
G-cell-1	6.369	5.486	48973
G-cell-2	5.494	8.839	22969
G-cell-3	5.605	9.144	30215
G-cell-4	5.984	5.486	62617
G-cell-5	5.687	4.267	3937
G-cell-6	5.590	3.962	5710

Project Manager: **Deerin Babb-Brott**
(617) 727-9530
Created by: **C.L.Seidel / SAIC**
Date: **01/06/2000**

DMMP Consulting Team:
CZM
Maguire Group
SAIC
GEI Consultants

File: gl_sb_cells.odb & gl_sb_cells.wmf

Figure 8. Suggested inner harbor disposal cells with average depth below MLW for fill surface.