THE ROLE OF SEAFLOOR CHARACTERIZATION AND BENTHIC HABITAT MAPPING IN DREDGED MATERIAL MANAGEMENT: A REVIEW

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INTRODUCTION

With the explosive growth of international trade in the past thirty years, maintaining navigable waterways through dredging is increasingly vital to the U.S. and world economies. Statistics provided by the U.S. Army Corps of Engineers' (USACE) Navigation Data Center indicate that 269 million cubic yards of dredged material were removed from USACE-maintained channels in fiscal year 2001, at a cost of $868 million (USACE 2003). According to the American Association of Port Authorities (AAPA), this dredging helps to sustain a public port industry that annually contributes tens of billions of dollars to the U.S. Gross Domestic Product, and the volume of imported cargo moved through U.S. ports by larger and deeper-draft vessels is expected to triple by the year 2020 (AAPA 2002). In addition to maintaining navigable waterways, dredging occurs in coastal waters of the U.S. and other countries to extract commercially valuable mineral resources (e.g., sand, gravel and other construction aggregates). Clearly, as a result of these economic drivers, the need for dredging will continue to be strong on a worldwide scale well into the future.

Both dredging and the aquatic disposal of dredged material are processes that have direct impacts on the environment, primarily the seafloor and benthic habitats. This paper provides a review of how various seafloor characterization and benthic habitat mapping techniques have been used, both in the U.S. and overseas, to evaluate environmental impacts and thereby facilitate the management of dredging and open-water disposal of dredged material. Because the need for seafloor mapping is primarily associated with the aquatic or "open-water" disposal option, other viable dredged material management alternatives (e.g., confined disposal in upland facilities, beneficial use) are not considered herein.

Management of dredging and disposal in the U.S. occurs through a complex system of legislation and authorities (EPA/USACE 1991; 1992). It is necessary at the outset to provide a brief overview of the regulatory/management context within which benthic habitat mapping is conducted (i.e., where in the decision-making process does the need for such mapping arise). Following this are examples from the literature, as well as case studies, that illustrate how various benthic mapping methods have been applied to address the needs arising at various stages in the management framework. This review concludes with a discussion of how advances in benthic mapping technology have resulted in more effective dredged material management and monitoring.

OVERVIEW OF REGULATORY DRIVERS FOR BENTHIC MAPPING

On a global scale, recognition of the need to avoid negative impacts from the disposal of waste in the ocean resulted in the adoption of the London Convention of 1972. While many of the 72 signatory nations to this global treaty have developed disposal regulations of their own, a set of broad guidelines for the assessment and management of dredged material was adopted in 1986 and revised in 1996 (Vellinga 1997). This framework specifies that all dredged material must be characterized with respect to its physical and chemical characteristics, and formal evaluations of the environmental impacts of various disposal options, including monitoring and assessment, must be undertaken.

In the U.S., regulation of dredged material disposal in inland and ocean waters is a shared responsibility of the Environmental Protection Agency (EPA) and USACE. The Marine Protection, Research and Sanctuaries Act (MPRSA) governs ocean disposal and the designation of Ocean Dredged Material Disposal Sites (ODMDS), while the Water Pollution Control Act of 1972 (also called the Clean Water Act, or CWA) governs site designation and the discharge of dredged or fill material into "inland" waters (i.e., inland of and including the territorial sea). All proposed dredged material disposal activities regulated by these laws also must comply with applicable policies of the National Environmental Policy Act (NEPA), as well as with state coastal zone management policies developed pursuant to the Coastal Zone Management Act (CZMA) and approved by the National Oceanic and Atmospheric Administration (NOAA). Additional details on these statutes and their implementing regulations are provided in various technical documents prepared jointly by EPA and USACE (EPA/USACE 1991; 1992).

Regardless of whether the CWA or MPRSA is applicable, a common technical framework has been developed for the testing and evaluation of dredged material being considered for open-water disposal (EPA/USACE 1992). For the purpose of this paper, a simplified version of this framework has been prepared to illustrate the four key points in the decision-making process where the need for seafloor and/or benthic habitat mapping arises: 1) selection of aquatic disposal sites, 2) pre-dredge characterization of dredged material and post-dredge monitoring of dredging sites, 3) environmental impact monitoring at open-water disposal sites, and 4) evaluation of special management techniques, in particular capping (Figure 1). Applications of benthic mapping methods within the context of each of these four areas are reviewed in the following sections.

BENTHIC MAPPING FOR SELECTION OF OPEN-WATER DISPOSAL SITES

General Considerations

The overarching intent of the disposal site selection criteria that exist under both the MPRSA and CWA is to avoid unacceptable, adverse environmental impacts to biota and other amenities (e.g., fishing, shipping, mineral extraction, cultural or historical features). Knowledge of basic site characteristics is necessary for assessing potential physical or contaminant impacts, and primary concern is usually directed to evaluating biological resources in and adjacent to proposed disposal sites. The site selection process typically involves the preparation of an Environmental Assessment (EA) or Environmental Impact Statement (EIS). A number of possible sites may initially be identified within a Zone of Siting Feasibility (ZSF), and through a sequential screening process that relies mainly on existing information about each site’s physical and biological characteristics, many sites can be eliminated from further consideration. Pequegnat et al. (1990) provide a generic description of this process, and several EIS efforts serve to illustrate the effective use of benthic mapping information for preliminary disposal site screening (EPA/USACE 2001; USACE 2001; Palermo et al. 1998a).

Once the number of potential disposal sites is sufficiently narrowed, seafloor mapping may be required to provide the following site-specific information: 1) water depth and bathymetry, 2) sediment physical and chemical characteristics, 3) erosional versus depositional nature, 4) relative abundance of various benthic habitat types, including presence of submerged aquatic vegetation, reefs, or unique, rare or endangered habitats, 5) potential for recolonization of the site by benthos, and 6) impact of any previous disposal operations.

Useful general guidance and procedures for conducting disposal site designation surveys are provided by Pequegnat et al. (1990). The recommended suite of benthic mapping techniques includes bathymetric and side-scan sonar surveys for characterizing gross site bathymetry and large-scale physical characteristics of the seafloor, as well as sampling by box core or grab at discrete stations to provide information on sediment grain size, chemical contaminants, and benthic community structure. Pequegnat et al. (1990) notes that seafloor assessments might be enhanced through the use of photographic techniques, in particular sediment-profile imaging (SPI). This technique, frequently referred to in the literature by the trademark name REMOTS, involves using a specially designed camera to obtain undisturbed cross-section (i.e., profile) images of the top 15 to 20 cm of sediment, with rapid image analysis yielding a suite of measurements that provide information on physical and biological seafloor characteristics and processes (see Rhoads and Germano 1982; 1986).

Taking the guidelines of Pequegnat et al. (1990) a step further, Rhoads and Germano (1990) advocate a hierarchical or tiered approach to conducting disposal site designation surveys that emphasizes the use of SPI in combination with acoustic techniques like bathymetry and side-scan sonar (Figure 2). In this approach, the initial SPI reconnaissance survey effort is directed toward evaluating the containment versus "dispersive" potential of each site under consideration. It is often a desired management goal to locate a disposal site in a low-energy, depositional seafloor environment favoring long-term containment of dredged material on the seafloor, thereby limiting impacts to nearby resources. However, there are a significant number of open-ocean disposal sites (for example, along the U.S southeast coastline) located within a few miles of shore in the higher-energy environment of the inner continental shelf. This can result in significant off-site transport of dredged material, particularly during periodic storm events, and the degree to which this may occur in both space and time should be addressed in the EIS supporting the designation of each dispersive site.

Gradients in sediment texture and bedforms detected by SPI are used to make inferences about dispersion potential: existing silt-clay bottoms are more likely to retain similarly fine-grained dredged material while current-rippled sand bottoms are avoided because they represent higher-energy, erosional areas (Rhoads and Germano 1990). Following this initial reconnaissance assessment, additional SPI and grab sampling combined with precision bathymetry, side-scan sonar and current meter data are used to support management decisions about site suitability (Figure 2).

Both Pequegnat et al. (1990) and Rhoads and Germano (1990) make reference to the potential use of the Benthic Resources Assessment Technique (BRAT) as a routine part of both disposal site selection studies (e.g., Figure 2) and post-disposal monitoring programs. This technique involves simultaneous collection of benthic community and fisheries data to estimate the value of a particular seafloor location as a foraging area for demersal, bottom-feeding fish (see Lunz and Kendall 1982; Fredette et al. 1990a). Despite these early endorsements, the BRAT technique does not appear to have become widely adopted within the context of dredged material management over the past decade, possibly because it is relatively labor- and cost-intensive.

Example Applications

There are over 100 USACE and EPA-designated Ocean Dredged Material Disposal Sites (ODMDS) in open ocean waters around the coast of the continental U.S., Alaska and Hawaii, as well as a number of sites in "inland waters" (e.g. estuaries, lakes, wetlands) where disposal is permitted by USACE under Section 404 of the Clean Water Act. Numerous examples exist of the integrated use of the various seafloor mapping and benthic habitat characterization techniques to aid in the selection of these sites, although many of these are documented only in Environmental Impact Statements and other gray literature (e.g., Battelle Memorial Institute 1990; EPA 1989; USACE 2001; Rhoads and Germano 1990).

A common thread among studies is the use of remote acoustic techniques like bathymetry and side-scan sonar for broad-scale mapping of site topography and seafloor features, but almost always in combination with point-sampling techniques needed to "ground-truth" the acoustic methods and more accurately characterize benthic community structure, habitat types, and/or habitat quality. As used herein, the term “broad-scale mapping” refers to the collection of data over relatively large areas (i.e., hundreds to thousands of square meters), while “ground-truth” refers to using a second, independent method/technique to confirm or verify a seafloor classification derived from a single, primary method/technique.

To characterize benthic community structure, it is necessary to collect sediment grab or core samples, wash the collected sediment through a sieve, preserve the organisms that are retained, and send the samples to experts for taxonomic identification and enumeration. This point-sampling technique is invariably used in every site designation study, but it can be relatively labor- and cost-intensive. For this reason, techniques that involve capturing an image of the seafloor, either in cross-section (SPI) or looking down at the sediment surface (“plan-view” photography using still or video cameras), are also utilized in many studies (Battelle Memorial Institute 1990; EPA 1989; USACE 2001). These techniques have the advantage of combining efficient spatial coverage of an area (e.g., over 50 stations per day can be sampled with SPI) with relatively rapid data turn-around. While excessive turbidity can limit the utility of video or still plan-view images, SPI does not suffer from this limitation and thus has been utilized more routinely. Nonetheless, under ideal conditions both types of imaging techniques allow direct visual observation of sediments and resident organisms useful for characterizing and mapping both benthic habitat types and quality. In combination with taxonomic data from grab sampling, the resulting information is typically employed to: 1) characterize the containment versus dispersive nature of potential disposal sites based on bedforms and sediment grain size, and 2) evaluate potential impacts of dredged material disposal on benthic community structure, habitat types and/or habitat quality.

Amson (1988) provides an account of how a combination of traditional sediment grab sampling, video transects and photographic quadrats (i.e., plan-view photography) aided in site selection and played a decisive role in demonstrating post-disposal recovery of the benthos at an ODMDS in the Gulf of Mexico off of Tampa, FL. Specifically, video transects performed early in the project served to demonstrate that the site ultimately selected as the ODMDS was characterized by flat, barren sandy areas having a minimum of productive hard bottom. Within one year of the cessation of disposal operations, benthic grab sampling and bottom photography showed that clay boulders of dredged material had become heavily recolonized by numerous sessile organisms and was providing habitat for a variety of fish and motile invertebrates, in the same manner as an artificial reef. It was concluded from the extensive benthic monitoring program that complete recovery of the disposal site as a coral, sponge and fish habitat was highly probable.

Revelas et al. (1987) describe an early use of SPI to map benthic habitat characteristics as part of a baseline evaluation of potential dredged material disposal sites in Puget Sound, WA. In this case, the management goal was to identify containment (i.e., low energy) dredged material disposal sites. The reconnaissance SPI data showing physically disturbed sediments and high near-bottom turbidity levels indicated that sediment transport was potentially occurring at one of the sites (Port Gardner). Collection of bottom current data was recommended to evaluate the potential for dredged material dispersion at this site. The SPI reconnaissance sampling further showed that other areas under consideration appeared to be characterized by low disturbance regimes, as evidenced by the presence of intensely bioturbated, fine-grained sediments supporting mature benthic communities (Revelas et al. 1987).

More recently, bathymetric, SPI and grab sampling data have been used effectively to evaluate containment potential and the distribution of benthic habitat types as part of disposal site designation studies in Rhode Island (USACE 2001) and Massachusetts (SAIC 1999a; SAIC 2001a and b). In these cases, initial SPI sampling at numerous candidate sites throughout Narragansett Bay and Rhode Island Sound was used to establish a classification system of benthic habitat types ranging from hard bottom to unconsolidated soft mud (Diaz 1995). As part of the subsequent site screening process, sites with higher numbers of different habitat types (i.e., greater habitat complexity) were ranked as less desirable disposal locations compared to those with greater sediment homogeneity (USACE 2001). Use of the reconnaissance SPI data has served to streamline the screening process, allowing subsequent survey efforts involving more intensive benthic and fisheries sampling to focus only on those sites representing more desirable disposal locations.

Additionally, in both the Rhode Island and Massachusetts efforts, a Geographic Information System (GIS) allowed easy layering of bathymetric and SPI data, resulting in seafloor maps that provide effective visualization of the relationship between bottom topography and sediment types (Figure 3). Large-scale topographic depressions identified in bathymetric contour maps were selected initially as candidate sites because of their higher volumetric capacities and potential long-term containment characteristics. Subsequent SPI and grab sampling was used to determine sediment grain size characteristics, and those topographic depressions dominated by soft, muddy, fine-grained sediments were assumed to represent suitable long-term depositional environments (Figure 3). The SPI and grab sampling also provided data on benthic communities and benthic habitat quality that were used to rank different candidate sites and select preferred alternatives.

BENTHIC MAPPING FOR CHARACTERIZING SEDIMENTS AND EVALUATING IMPACTS AT DREDGING SITES

Dredging of Navigation Channels

Physical and chemical characterization of the sediments to be dredged is essential to the overall decision-making framework for ocean disposal (Figure 1). Grain size analysis is employed to determine the degree of compatibility between the sediments to be dredged and those existing at the disposal site, with the overall goal of avoiding drastic changes in benthic habitat conditions on the seafloor following disposal. It is desirable that the sediments to be disposed have grain size characteristics similar to those at the disposal site, as the overall lack of significant physical change following disposal is expected to result in a similar lack of biological change in the long term. In accordance with this general paradigm, dredged material consisting of clean sand is often used beneficially for beach nourishment in lieu of disposal at an open-water site where the existing sediments are muddy. Chemical analysis of sediments to be dredged is also required to ascertain that contaminant levels are low enough to avoid negative impacts to benthic organisms, through either direct toxicity or bioaccumulation.

The USACE and EPA have jointly developed standard procedures for the testing and evaluation of dredged material proposed for disposal at either ocean sites (EPA/USACE 1991) or in "inland" waters (EPA/USACE 1998). In some situations, existing information may be sufficient to determine suitability of sediments for ocean disposal. Where such information is lacking, samples of the *in-situ* sediment must be collected and evaluated using a "tiered" system of sequential chemical and biological analyses.

In considering the role of benthic mapping at dredging sites, it is necessary to distinguish between two basic types of navigation dredging projects. Construction of new navigation channels (so-called "new work" dredging) involves removal of sediment previously undisturbed. In such situations, there may be concerns about impacts to benthic resources and/or sensitive habitats within or near the new channel that would warrant use of a variety of survey methods (e.g., grab or core sampling, SPI), typically within the context of an EA or EIS.

The majority of projects in the U.S., however, involve maintenance dredging for the repetitive removal of naturally recurring sediment deposits in existing navigation channels. Seafloor characterization at maintenance dredging sites mainly consists of grab or core sampling to determine the physical and chemical characteristics of surface and subsurface sediment layers (down to the depth of the proposed dredging). This seafloor "mapping" is driven by the requirements of the standard testing and evaluation procedures for determining the suitability of the material for various management options, including open-water disposal (EPA/USACE 1991; 1998).

Loss of benthic habitat is not an issue that is commonly addressed in routine maintenance dredging projects. One reason is that many channels were authorized and created decades ago, and therefore are viewed as part of the existing "infrastructure" in a given harbor or estuary. As a result of regular maintenance dredging, such channels generally do not contain critical or protected benthic habitats. For newer channels requiring maintenance dredging, concerns about impacts to benthic resources presumably were addressed as part of the decision-making process that resulted in their authorization and therefore do not need to be revisited. Whatever benthic communities are present presumably became established since the last dredging cycle and therefore can be expected to become re-established following the new dredging.

Dredging to Extract Resources

In addition to channel creation or maintenance, dredging also occurs to extract marine mineral resources (principally sand and gravel) for use either in coastal restoration (e.g., beach nourishment and wetland creation) or as aggregate in the construction industry. In the U.S., the Minerals Management Service (MMS) International Activities and Marine Minerals Division (INTERMAR) has the responsibility for administering the Department of Interior's role in mineral resource development on the outer continental shelf (OCS). Since 1989, this agency has funded a series of studies to evaluate the environmental impacts of OCS sand dredging (MMS 2001). In Europe, the U.K. marine aggregate industry has grown significantly in response to increasing demand over the past 40 years, with concomitant concerns about seafloor impacts leading to increased regulation and a number of environmental studies (see Hitchcock et al. 2002; Newell et al. 1998 and references therein).

Dredging to extract resources has obvious impacts to benthic habitats, including both the physical removal of substratum and associated organisms, as well as deposition of suspended sediment in areas surrounding the dredging operation (Newell et al. 1998). The degree and timing of benthic recolonization following cessation of dredging operations is of particular interest, and the common thread among studies evaluating this process has been the use of grabs or box cores to obtain samples for both granulometric and benthic taxonomic analyses, with subsequent statistical analyses to detect patterns in community response (e.g., Poiner and Kennedy 1984; Seiderer and Newell 1999; Desprez 2000). Kenny and Rees (1994; 1996) supplemented a traditional grab sampling approach with side-scan sonar and underwater still/video photography to better visualize the physical impacts of dredging operations. In this study and several others, side-scan sonar was particularly effective in documenting the different types of larger-scale features (e.g., furrows and/or pits several meters wide) created on the seafloor as a result of various dredging techniques, as well as for monitoring the persistence of such features through time (Kenny and Rees 1994; 1996; Newell et al. 1998; Desprez 2000; Hitchcock et al. 2002).

The significant investigative effort undertaken during the past decade in both the U.S. and overseas (principally but not limited to the U.K.) has culminated in two recent guidance documents advocating the use of a variety of benthic mapping techniques to monitor the environmental impacts of aggregate dredging (CEFAS 2002; MMS 2001). To evaluate benthic community impacts, both documents place primary emphasis on the use of traditional grab sampling and subsequent taxonomic analyses, with careful attention to the statistics used for both sampling design and data analysis. CEFAS (2002) further notes that underwater still and video photography are effective, non-destructive methods for seabed habitat assessments, particularly over hard or consolidated bottoms where the efficiency of grab or core samplers can be low.

Both guidance documents likewise acknowledge the utility of various remote acoustic methods to evaluate physical seafloor impacts and thereby facilitate more accurate interpretation of the biological data. CEFAS (2002) states that side-scan sonar is the most useful and therefore most commonly applied method, but also notes the potential utility of other techniques that have become more readily available in recent years (e.g., single- or multi-beam bathymetry, sub-bottom profiling, and acoustic ground discrimination systems such as RoxAnn^{tm} or QTC-View^{tm}). MMS (2001) focuses more narrowly on the use of either single- or multi-beam bathymetry in combination with side-scan sonar to document physical changes in seabed characteristics associated with aggregate dredging operations.

BENTHIC MAPPING FOR MONITORING OF DISPOSAL SITE IMPACTS

General Considerations

Environmental monitoring of dredged material disposal sites is usually a requirement resulting from the site designation process, or else it may be required as part of an established site management plan (EPA/USACE 1992). The EA or EIS developed to guide the decision on site designation/selection typically describes the impacts expected to occur as a result of site use, such as short-term changes in benthic and fish communities followed by eventual recovery. It is important that monitoring plans be developed to verify these impact predictions and support the assumptions that led to site selection.

Published guidelines emphasize the use of a "tiered" approach in which monitoring is directed toward addressing a hierarchical series of specific, testable hypotheses regarding the impacts of concern (Fredette et al. 1990a; Germano et al. 1994; EPA/USACE 1996). Specific desirable and/or undesirable conditions (e.g., unacceptable adverse effects or unreasonable environmental degradation) are clearly defined *before* sampling is begun. If the initial monitoring at the lowest tiers indicates an absence of significant impacts (e.g., no off-site transport of the dredged material and normal patterns of dredged material recolonization by benthos), then there is no need to expend additional resources for more intensive monitoring at higher tiers (e.g., chemistry or toxicity testing).

The monitoring conducted under this recommended tiered approach may require application of a variety of survey methods, many of which involve seafloor or benthic habitat mapping in one form or another. However, decisions about which physical and biological tools and techniques are most appropriate are case-specific and should not be made until *after* the key monitoring questions or testable hypotheses have been identified (Fredette et al. 1990a and b). In general, concerns about environmental impacts at open-water dredged material disposal sites tend to center around two broad issues: 1) the fate of the material (i.e., does it end up going where it is predicted to go), and 2) impacts to biological resources (i.e., what are the effects of disposal on organisms living in and near the disposal site).

The Disposal Area Monitoring System (DAMOS) program developed by the USACE New England District has been addressing such concerns for over 25 years. This program is unique in terms of both its longevity and its formal documentation of a tiered approach to monitoring that emphasizes collecting only those data useful in making management decisions (Germano et al. 1994). A 1990 study by the National Research Council recognized the effectiveness of the DAMOS approach to monitoring disposal site impacts (NRC 1990). It is mainly within the context of this program, therefore, that examples of benthic mapping applications are presented below.

Mapping Dredged Material Fate: The DAMOS Example

Under the DAMOS program, environmental monitoring surveys are conducted at regular intervals (generally one to five years) at each of 11 open-water dredged material disposal sites located along the coast of New England. Consistent with the general guidelines of Fredette et al. (1990a), this monitoring is conducted within the framework of a tiered approach that makes use of several seafloor mapping techniques to provide data for testing specific hypotheses (Germano et al. 1994). The broad, “first-tier” concern related to determining the fate of the dredged material is addressed through the combined use of precision bathymetry, side-scan sonar, and SPI. In this case, the survey objective is to determine the spatial distribution of dredged material on the seafloor, and the expectation or hypothesis being tested (based on past experience and model predictions) is that this material will be detectable as a discrete deposit or mound within the confines of the site (i.e., no appreciable off-site transport). From a benthic habitat mapping perspective, it is important to document the full area of the seafloor within which habitat conditions may have changed physically as a result of disposal. This includes changes in sediment type, elevation above the seafloor (i.e., depth), and both small-scale and large-scale topography.

To ensure adequate resolution, bathymetric surveys are conducted with vessel tracklines or “lanes” that are spaced relatively close together (25 to 50 m apart) over the designated disposal point within the site boundary. This disposal point is usually marked with a taut-wire moored buoy. The results of year-to-year sequential bathymetric surveys are then compared to produce “depth difference” maps showing the deposit or mound of dredged material formed as a result of disposal during the intervening time period (Figure 4). Sequential single- or multi-beam bathymetric surveys generally are sufficient for detecting mound central or “apex” deposits having a thickness greater than about 0.5 m. However, these acoustic methods typically do not have sufficient resolution for mapping the mound “apron” or “flank” deposits having a thickness of 20 cm or less that can occupy most of the bottom affected by disposal of unconsolidated, fine-grained sediment.

Therefore, SPI sampling at a regular grid of stations centered at the disposal buoy is usually performed in conjunction with the bathymetric surveys to detect the thinner layers of dredged material on the mound flanks and thereby delineate the full “footprint” of the deposit (Figure 4). Experience has shown that the flank or apron regions that are detected and mapped using SPI can account for over 80% of the seafloor area affected by disposal and over 45% of the total volume of disposed material (Germano and Rhoads 1984; Rhoads and Germano 1990). In experimental studies on the use of thin-layer (i.e., 15 to 20 cm) disposal to limit overburden thickness and thereby reduce environmental impacts, SPI sampling likewise was effective in mapping the full area of dredged material coverage (Wilber 1992).

Side-scan sonar is sometimes used in conjunction with bathymetry and/or SPI to better visualize the changes in seafloor morphology and sediment texture associated with dredged material disposal (Figure 5). This technique provides a view of such changes at a relatively broad scale, on the order of hundreds of meters representing the diameter of a typical DAMOS dredged material disposal mound. Changes in reflectance detected in side-scan sonar maps are often associated with increased surface roughness imparted to the bottom as a result of disposal of larger clumps of cohesive mud. When sediments are dredged by mechanical means (e.g., clamshell bucket), such clumps of cohesive fine-grained sediment can remain intact during both dredging and subsequent disposal. Because they fall quickly to the bottom, they tend to accumulate at the mound center or apex. Side-scan sonar is not always effective at detecting the flatter layers of unconsolidated fine-grained sediment that can accumulate on the flanks of a mound during its creation, especially when the ambient bottom also consists of fine-grained sediments that lack significant surface relief. For this reason, SPI is usually used in conjunction with side-scan sonar to provide essential "ground-truth" information on dredged material distribution while also providing insights into the nature of the habitat change at a scale that is relevant to benthic organisms (Figure 5). Germano et al. (1989) demonstrate how SPI and side-scan sonar were used in combination to efficiently map physical and biological properties of the seafloor at a dredged material disposal site in Buzzards Bay, MA.

Monitoring the Biological Impacts of Disposal

The other broad concern surrounding open-water dredged material disposal is related to impacts on biological resources living in and near the disposal site. In simple conceptual terms, the basic environmental impact of placing dredged material on the seafloor at an aquatic disposal site is a change in the existing benthic habitat to something new. Some degree of mortality of the existing benthos as a result of burial is expected (although this can vary among taxa as a function of burial depth; see Nichols et al. 1978; Maurer et al. 1981a and b; 1982), and the surface of the dredged material deposit represents a new, uninhabited substrate that is available for colonization by organisms.

Benthic organisms inhabiting shallow-water estuarine and near-coastal environments are well adapted to maintaining populations despite frequent physical disturbance from a variety of sources (see reviews by Hall 1994 and Newell et al. 1998), and it is not surprising, therefore, that numerous studies have documented the ability of such organisms to recolonize seafloor areas affected by either dredging (Rosenberg 1977; Kenny and Rees 1994; 1996; Lopez-Jamar and Mejuto 1988; Hall 1994; Newell et al. 1998; DeGrave and Whitaker 1999; Seiderer and Newell 1999; Desprez 2000) or dredged material disposal (Oliver et al. 1977; Van Dolah et al. 1984; Engler et al. 1991; Somerfield et al. 1995; Harvey et al. 1998; Valente et al. 2000).

Biological Impact Monitoring under DAMOS

Under the DAMOS program, benthic grab sampling and SPI are the main monitoring tools that have been used for evaluating the impacts of disposal on benthic communities within and near disposal sites, with a primary emphasis on SPI. One of the main reasons SPI has been employed preferentially is that it is more cost-effective and provides more rapid data turnaround than traditional grab sampling and taxonomic analysis. For example, a single day of SPI sampling involving the collection of images at up to 50 stations is estimated to cost on the order of $5,000 to $10,000 (inclusive of subsequent image analysis and report preparation costs), with a report generated within weeks of the field effort. Because taxonomic analysis of benthic grab samples can range in cost from $500 to $1,000 per sample and require many months, simply analyzing such samples at the same 50 stations would be significantly more expensive and time-consuming than SPI, without even considering data analysis/reporting costs and the extra time needed for collecting and sieving such samples in the field. In terms of impact assessment, SPI is extremely powerful because of its ability to image in-situ organism-sediment relationships in the undisturbed sediment profile. It thus provides direct viewing not only of the physical habitat changes that have occurred as a result of disposal (e.g., changes in sediment grain size, texture, and/or oxidative state), but also the organisms' response to and interaction with this changed habitat through time.

Based on imaging of the organism-sediment couple, SPI is used to make inferences about the degree of benthic recolonization and overall benthic habitat quality in seafloor areas effected by dredged material disposal. Benthic recolonization is evaluated through the mapping of infaunal successional stages, based on the theory that organism-sediment interactions follow a predictable sequence after a major seafloor perturbation like dredged material disposal. The model of soft-bottom infaunal succession that underlies the interpretation of SPI images is illustrated in Figure 6. Pioneering, Stage I assemblages that can appear within days to weeks of a dredged material disposal event consist of dense aggregations of near-surface living, tube-dwelling, opportunistic polychaetes. Stage I may be associated with a shallow redox boundary; and bioturbation depths are shallow, particularly in the earliest stages of colonization (Figure 6).

In the absence of further disturbance, the early successional assemblages are eventually replaced by infaunal deposit feeders; the start of this "infaunalization" process is designated arbitrarily as Stage II. A mature community dominated by Stage III taxa may require many months to years to become fully established. Stage III organisms are larger-bodied, infaunal and typically found in low-disturbance regimes; many feed at depth in a head-down orientation that results in distinctive subsurface excavations called feeding voids. Bioturbation by these deposit-feeders is responsible for aerating the sediment and causing the redox horizon (defined as the *apparent* redox-potential discontinuity, or aRPD, in SPI images based on the visual distinction between the lighter-colored, aerobic surface sediment layer and darker subsurface sediment) to be located several centimeters below the sediment-water interface. The end-member stages (Stages I and III) are easily recognized in SPI images by the presence of dense assemblages of near-surface polychaetes (Stage I) or the presence of subsurface feeding voids (Stage III; Figure 6).

As described in greater detail in Rhoads and Germano (1982; 1986), a multi-parameter Organism-Sediment Index (OSI) has been constructed to characterize overall benthic habitat quality based on analysis of SPI images (Table 1). More recently, Nilsson and Rosenberg (1997) have developed an index of Benthic Habitat Quality (BHQ) based on the same SPI infaunal successional model (Figure 6) but utilizing a more quantitative determination of the relative densities of surface and subsurface organisms (Table 1). Rigorous comparative studies of these two similar indices have yet to be performed, but because the OSI precedes the BHQ by at least a decade and therefore has been used much more extensively in dredged material monitoring programs, it is the focus of the following discussion.

In the calculation of the OSI (Table 1), habitat quality is defined relative to two end-member standards: the lowest possible value of –10 (highly disturbed/degraded benthic habitat quality) indicates highly anoxic sediments lacking a visible redox layer, no apparent macrofaunal life, and methane gas present (e.g., image A in Figure 6). At the other end of the scale, oxidized sediments having deep, well-developed redox depth, evidence of a mature, Stage III macrofaunal assemblage, and no apparent methane gas bubbles at depth (e.g., image D in Figure 6) will have an OSI value of +11 (Table 1). Experience has shown that OSI values of +6 or greater are generally indicative of undisturbed or non-degraded benthic habitat quality; this parameter has proven to be effective 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).

Integral to disposal management under DAMOS and other programs is the use of a taut-wire moored buoy to mark the required location within each disposal site where each barge load of dredge material is to be released. The buoy location within the site boundary is changed at regular intervals, typically once each year at sites that are used intensively. This facilitates the formation of discrete deposits or mounds on the seafloor during each disposal season, and these mounds can then be monitored individually through time to ensure that recovery of benthic communities and overall habitat quality proceeds in a manner consistent with expectations (i.e., consistent with the conceptual model depicted in Figure 6). Grids of SPI stations are established over each disposal mound, as well as in nearby reference areas unaffected by disposal. Surveys conducted every few years are designed to test the hypothesis that as infaunal succession proceeds, aRPD depths will become deeper and overall benthic habitat quality (as indicated by the mapped OSI values at each mound) will eventually become comparable to that at the reference areas (Figure 7). Evaluating the effects of dredged material disposal on benthic habitats under DAMOS, therefore, relies primarily on mapping aRPD depths, infaunal successional stages and OSI values.

Hypothesis testing involving comparison of OSI values between mound and reference stations is performed within the decision-making framework of the DAMOS tiered monitoring approach. If progressive infaunal succession and concomitant increases in OSI values over the disposal mounds are not observed within expected timeframes, a number of potential management actions may ensue. These can range from more intensive monitoring to assess the contaminant or toxicological properties of the disposed sediment, to placement of additional sediment over the mounds in question (i.e., capping). In this way, the benthic mapping data collected as part of routine DAMOS monitoring is used for early identification of potential negative impacts and proactive management actions (Fredette et al. 1990a; Germano et al. 1994). Additional examples of the combined use of precision bathymetry, side-scan sonar and/or SPI for mapping both the spatial distribution of dredged material and benthic impacts are provided in numerous DAMOS technical reports available from the following program website: http://www.nae.usace.army.mil/environm/damos/splash_page.htm and in Rhoads and Germano (1990).

Impact Monitoring in Other Locales

The use of acoustic mapping techniques like bathymetry and side-scan sonar in combination with point sampling techniques like SPI or grab/core collection has not been limited to the monitoring of DAMOS disposal sites in New England. Over the past two decades, monitoring activities involving various combinations of these techniques have occurred at open-water disposal sites in Puget Sound (Revelas et al. 1987; SAIC/Battelle 2000), off-shore San Francisco (Blake et al. 1994; SAIC 1999b), the southern California Bight (SAIC 2001c), Mobile Bay (Clarke and Miller-Way 1992; Wilber 1992), Chesapeake Bay (Nichols et al. 1990), the New York Bight (Greges 1994; May et al. 1994; Valente et al. 1998), as well as in New Zealand (Gowing et al 1997) and Hong Kong (Valente et al. 2000).

It has been possible to use SPI in these locations because the disposal activities have largely involved fine-grained sediments (silt-clay and fine sands) being placed on equally fine-grained seafloors. This is the case at many disposal sites because muddy sediments are the ones that tend to accumulate in channels, and coarser sediments (e.g., sand, cobble or rocks) requiring dredging are often used for beneficial purposes like beach nourishment or artificial reef creation. The SPI camera must be able to penetrate into the bottom at both the disposal location and in the surrounding area to be effective in assessing the nature of the benthic habitat change that has occurred as a result of dredged material disposal. Furthermore, evaluating the *response* of benthic communities to this habitat change using SPI hinges upon application of the successional paradigm (Figure 6) developed for fine-grained, soft-bottom benthic habitats.

In situations where the material placed at an open-water disposal site consists of coarser sediment (e.g., coarse sand or gravel), video or still photography can be effective means of viewing both the nature of the habitat change and the benthic community response. In recent years, the United States Geological Survey has performed a number of seafloor mapping studies at dredged material disposal sites in the U.S. (Torresan et al. 1995; Schwab et al. 1997; Valentine et al. 1998; Torreson and Gardner 2000; Butman et al. 2000). These investigations have employed a variety of broad-scale acoustic mapping methods (bathymetry, side-scan, sub-bottom profiling) in combination with both sediment grab/core sampling and plan-view photography using video or still cameras. In one such study, plan-view photography was effective in showing that piles of rock debris from excavation of the Third Harbor Tunnel in Boston were only sparsely populated by epifauna three years after being placed on the seafloor at the Massachusetts Bay Disposal Site (Figure 8).

Numerous investigations have effectively evaluated the impacts of dredged material disposal on soft-bottom benthic communities without employing photographic techniques; these studies have relied upon the traditional approach of using grab or core sampling alone to assess spatial and/or temporal changes in benthic community composition (e.g., Van Dolah et al. 1984; Harvey et al. 1998; Roberts et al. 1998; Boyd et al. 2000). In such studies, analysis of the collected sediment for parameters such as grain size or organic carbon provides some information on the nature of the habitat change associated with dredged material disposal, but without the insight gained from viewing *in-situ* organism-sediment relationships through photography.

The main emphasis in taxonomic studies is on characterizing benthic community response to the habitat change, the ecological indicator that is ultimately of interest regardless of which technique is employed. The advantage over photographic techniques is that the response of individual taxa can be examined, if desired, and this may be an important monitoring objective. SPI does not allow such assessment, but instead evaluates community response in terms of the “functional groups” represented by the different successional stages (Rhoads and Germano 1982; 1986). It is often desirable or necessary to collect grab samples for benthic community analysis simultaneously with SPI or plan-view images, providing a valuable means of verifying or reinforcing the image interpretation for more effective impact assessment (Valente et al. 2000; Valente and Fredette 2002).

BENTHIC MAPPING FOR EVALUATING EFFICACY OF MANAGEMENT OPTIONS (CAPPING)

General Considerations

The initial testing of dredged material may indicate that it unsuitable for unconfined open-water disposal due to elevated levels of chemical contaminants. Within the broad management framework for open-water disposal (Figure 1), capping represents a contaminant control measure that may be instituted to reduce impacts to acceptable levels. Capping is the controlled, accurate placement of contaminated dredged material at an open-water disposal site, followed by a covering or cap of clean material to isolate the contaminants from the overlying water column and biota. Level-bottom capping (LBC) involves the placement of the contaminated material in a mounded configuration and the subsequent covering of the mound with clean sediment; contained aquatic disposal (CAD) is similar to LBC but with some form of lateral confinement (e.g., placement in natural-bottom depressions, constructed subaqueous pits, or behind subaqueous berms) to minimize spread of the materials on the bottom

(Palermo et al. 1998b). A distinction also is made between capping of dredged material, which is often only marginally contaminated in comparison with other sediments in an area, and in-situ capping of contaminated sediments for remediation purposes (Palermo et al. 1998b).

Monitoring is required to ensure that capping acts as an effective control measure. The monitoring considerations discussed in the USACE guidelines (Palermo et al. 1998b) parallel those for open-water disposal sites, with emphasis on the use of a multi-tiered monitoring approach involving sequential hypothesis testing and predefined thresholds for taking management actions. The tiered monitoring program (Table 2) may include a wide variety of seafloor mapping techniques, to be employed for either "construction" monitoring (which takes place before, during and immediately after placement of the contaminated and capping material to ensure that an effective cap has been constructed) or "long-term" monitoring (to ensure long-term cap stability and effectiveness in contaminant isolation).

Example Applications

Subaqueous capping of contaminated dredged material at open-water sites began in the late 1970s, and the capping projects that have since been completed under a variety of disposal conditions are too numerous for exhaustive review here. Palermo et al. (1998b) present numerous case studies, and the experience gained under the DAMOS program from over 15 years of capping operations in New England is summarized in Kullberg and Fredette (1993) and SAIC (1995). In 1993 and again in 1997, dioxin-contaminated sediments dredged from container ports in Newark Bay, NJ were placed in two separate mounds in 24 m of water at the southern end of Mud Dump Site in the New York Bight. A summary of benthic mapping techniques employed in the monitoring and management of these two capping projects follows; details are provided in McDowell et al. (1994), May et al. (1994), Greges (1994), Valente et al. (1998) and Clausner et al. (1998).

A combination of sequential bathymetric surveys and SPI proved extremely useful for monitoring the construction of both the 1993 and 1997 capped mounds. Depth differencing of baseline and post-disposal bathymetric surveys allowed detection of the thicker layers of contaminated dredged material comprising the central mound deposits, while transects of SPI stations were used to detect thin layers of material on the mound aprons that required capping (Figure 9). The capping plans developed jointly by USACE and EPA required that the full footprint of contaminated dredged material be capped with at least one-meter of clean sand, and a post-cap bathymetric survey confirmed that this goal was largely achieved (Figure 9).

Following the completion of the capping operations over both mounds, a variety of techniques have been applied for long-term monitoring of cap stability and effectiveness. Bathymetric surveys have been performed periodically; depth differing of sequential surveys has indicated no significant changes in mound topography. These results have been reinforced by several vibracoring and sub-bottom profiling surveys that have consistently detected over one meter of sand cap material overlying the fine-grained dredged material across the entire surface of both mounds. Chemical analyses of sediment and tissue samples have shown negligible levels of dioxin in the sand cap layer. Finally, SPI has demonstrated the consistent presence of clean cap sand over the surface of the mounds (Figure 10A). This capping sand has favored the establishment of a benthic community dominated by surface-dwelling suspension feeders (Stage I), while discouraging recolonization by the larger-bodied, deposit-feeding organisms (Stage III) that dominate in nearby areas having fine-grained, organic-rich dredged material (Figure 10C). Ideally, caps should be comprised of suitably coarse sediments and/or be thick enough to prevent extensive bioturbation by Stage III organisms that can disrupt cap integrity over the long term.

Consistent with the guidelines of Palermo et al. (1998b), the monitoring of both the 1993 and 1997 capping projects was undertaken within the context of a carefully designed monitoring and management plan (May et al. 1994). The various seafloor mapping techniques were employed to address specific questions and objectives associated with both cap construction and long-term monitoring. The mapping results were used at several times during the cap construction phase to make changes in the operational approach, and lessons learned during the 1993 project facilitated efficient planning and implementation of the 1997 project (Valente et al. 1998; Clausner et al. 1998). Both capping projects provide excellent examples, therefore, of using seafloor mapping for more effective dredged material management.

Capping is also used as a remediation technique in areas where surface sediments have elevated levels of chemical contaminants. A monitoring program currently underway in the New York Bight is relying on precision bathymetry, side-scan sonar and SPI to determine the spatial distribution, thickness, and benthic recolonization status of cap material being placed over the 9 square mile Historic Area Remediation Site (HARS). This same suite of techniques, combined with extensive coring, was employed in 2000 to evaluate the feasibility of capping an extensive area of DDT-contaminated sediments on the Palos Verdes Shelf off of Los Angeles (Valente et al. 2001; Fredette et al. 2002). SPI has been particularly effective on these programs both for mapping the distribution and thickness of cap material layers and evaluating changes in benthic habitat conditions associated with cap placement (Figure 11).

DISCUSSION AND CONCLUSIONS

Seafloor characterization and benthic mapping data are collected to support decisions at several points in the overall management of open-water dredged material disposal (Figure 1). In deciding which seafloor mapping techniques are most appropriate in a given situation, it is important that the study or monitoring program objectives be articulated clearly at the outset, particularly with respect to the common concerns related to the fate of the material on the seafloor and biological impacts. Several key guidance documents prepared by the regulatory agencies provide essential advice and should be consulted (e.g., Fredette et al. 1990a and b; Pequegnat et al. 1990; Palermo et al. 1998b). The overarching message of this guidance is that seafloor mapping (or any other data collection activity) will not be effective unless it is done within a pre-defined decision-making framework that clearly identifies the hypotheses being tested and the management actions to be taken at each outcome.

Within the context of dredged material management, bathymetry and side-scan sonar are the two main acoustic methods providing information on benthic habitat characteristics at relatively broad scales (i.e., on the order of hundreds of meters). In disposal site selection studies, these two techniques furnish reconnaissance mapping information useful for evaluating the potential containment versus dispersive characteristics of candidate seafloor areas and the degree of habitat complexity. Collection of samples at discrete points (e.g., grabs or cores, sediment-profile or plan-view images) is usually necessary to ground-truth the acoustic data in evaluating both containment potential and benthic habitat characteristics (e.g., Figure 2).

In disposal site monitoring programs, bathymetric and side-scan sonar are employed to detect changes in seafloor topography, surface roughness and/or hardness useful for mapping the broad-scale distribution of dredged material or capping material on the seafloor. This provides information on *where* and to some extent *how* the benthic habitat may have changed within or outside the disposal site but fails to offer any insight on actual impacts to benthic communities. Point sampling is again necessary, and benthic community assessment based on taxonomic analyses of grab or core samples traditionally has been the most widely employed technique. Grain size analysis performed in conjunction with such sampling provides information on how the benthic habitat has changed in terms of sediment *composition*. However, important insights on how sediment *structure* (e.g., degree of consolidation, layering, small-scale relief) may have influenced the benthic community response are lost in the act of sieving samples for taxonomic analysis. Non-destructive photographic techniques like SPI or plan-view imaging therefore have proven to be particularly useful in disposal site monitoring because they provide direct visualization of both the nature of the habitat change and the response of organisms to this change.

In the case of SPI, evaluating the response of benthic communities to the habitat change resulting from disposal relies on application of a successional model developed for soft-bottom habitats (Figure 6). This technique therefore has proven to be quite useful for monitoring impacts at the majority of sites where both the dredged material and ambient sediments are fine-grained. In situations where the dredged material or ambient bottom consists of sandy or rocky sediments, it becomes more difficult to evaluate community response using SPI because the soft-bottom successional model is not applicable. Evaluating overall benthic habitat quality using either the OSI or BHQ summary statistic (each derived in part from the successional stage designation) is equally problematic in anything other than a muddy seafloor environment. Thus, SPI is not universally applicable for monitoring the impacts of disposal on benthic habitat types or quality. Where sediments are coarse or hard, alternate photographic techniques (e.g., sediment plan-view imaging using still or video cameras) combined with traditional grab sampling are probably the best choices.

The survey techniques discussed in this review generally have proven to be quite effective in visualizing both the physical changes associated with dredged material placement on the seafloor and the response of benthic communities to such changes. As technology has advanced over time and improved this visualization capability, the management and monitoring of dredged material has likewise evolved. For example, steady advancements have been made in the ability to perform precision bathymetric surveys having sufficient resolution to detect relatively thin (down to 0.5 m) depositional layers of dredged material. In many monitoring programs (e.g., DAMOS in New England), bathymetric survey results have provided confirmation that the repeated placement of dredged material at a single release point results in the formation of a discrete mound or deposit on the seafloor. Thus the management technique has evolved of marking the release point with a buoy and changing its location within the disposal site every few years to create a series of individual mounds on the bottom. This serves to limit the area of seafloor that is affected by dredged material placement during any given disposal season, and subsequent bathymetric surveys are used to provide confirmatory feedback that such mounds remain as stable seafloor features over the long term.

The development of the infaunal successional model (Figure 6), and the ability to view the different stages of this model using SPI technology, are intertwined advances that have likewise had a significant influence on the way in which the biological impacts of dredged material disposal are monitored. The model allows predictions to be made about the expected timing and sequence of benthic recolonization following disposal; SPI gives managers the ability to evaluate the accuracy of such predictions in a timely and cost-efficient manner. Having both this predictive and confirmatory capability has in turn supported the development of advanced, multi-tiered, *prospective* monitoring designs, as advocated by Fredette et al. (1990a) and implemented under the DAMOS program (Germano et al. 1994). Prospective means that specific desirable and undesirable conditions are clearly defined prior to sampling, with the resultant monitoring focused on detection of changes in specific conditions rather than identifying any or all detectable changes. SPI is therefore used routinely under DAMOS and numerous other programs to verify the prediction that recolonization will proceed to the point that habitat conditions (as measured using the OSI or BHQ statistic) over dredged material mounds ultimately will become similar to those at nearby reference areas.

When changes in basic habitat conditions resulting from dredged material disposal are not drastic (e.g., muddy sediments being placed on a muddy seafloor), numerous studies have demonstrated that benthic communities are resilient and successful in recolonizing the area of impact. Even when dredging or disposal causes a significant change in habitat conditions, it may improve or stimulate rather than disturb or limit benthic production. For example, placement of sandy dredged material on the muddy seafloor in Hong Kong acted to enhance sediment stability and habitat complexity, resulting in significant increases in benthic abundance and diversity (Valente et al. 2000). Likewise, the organic-rich, muddy dredged material placed within the predominantly sandy, organic-poor seafloor environment of the New York Bight supports a thriving Stage III infaunal community (SAIC 2001d).

Results such as these illustrate why dredging and the open-water disposal of dredged material have been and likely will remain controversial environmental issues. Because our knowledge of the functioning of most estuarine and coastal systems is limited at best, particularly with respect to the link between benthic production and fisheries resources, it is difficult to judge whether some of the benthic habitat changes associated dredging or disposal are acceptable or not from a broader ecological perspective. The approach that has evolved to date is to manage dredged material within the context of a decision-making framework that at least attempts to minimize adverse impacts based on existing knowledge of ecosystem function. Benthic mapping has and will continue to play a key role within this framework.

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TABLES AND FIGURES

Table 1.

Calculation of the Organism Sediment Index (OSI) value based on analysis of certain measured parameters in each SPI image (from Rhoads and Germano 1982; 1986).

A. CHOOSE ONE VALUE:		
	Mean aRPD 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 ® II	2
	Stage II	3
	Stage II ® 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)	
POTENTIAL RANGE OF OSI: -10 to +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.

Sample tiered monitoring program for a capping project (from Palermo et al. 1998)

Monitoring Program	Monitoring Frequency	Threshold	Management (Threshold Not Exceeded)	Options (Threshold Exceeded)
Consult site designation surveys, technical advisory committee, and EIS for physical and chemical baseline conditions.				
TIER I • Bathymetry • Sub-bottom profiles • Side-scan sonar • Surface grab samples • Cores • Water samples	Pre, Post Placement, Annually	• Mound within 5 ft of nav. hazard. • Cap thickness decreased 0.5 ft. • Contaminant exceeds limit in sediment or water sample.	• Continued to monitor at same level. • Reduce monitoring level. • Stop monitoring.	• Go to next tier. • Stop use of site. • Increase cap thickness.
TIER II • Bathymetry • Sub-bottom profiles • Side-scan sonar • Sediment-profile camera • Cores • Water samples • Consolidation instru.	Quarterly to Semi-Annually	• Cap thickness decreases 1 ft. • Contaminant exceeds limit in sediment or water sample.	• Continued to monitor at same level. • Reduce monitoring level.	• Go to next tier. • Replace cap material. • Increase cap thickness. • Stop use of site.
TIER III • Bathymetry • Sub-bottom profiles • Side-scan sonar • Sediment-profile camera • Surface grab samples • Cores • Water samples • Tissue samples	Monthly to Semi-Annually	• Cap thickness decreases 1 ft. • Contaminant exceeds limit in sediment or water sample. • Contaminant exceeds limit in tissue.	• Continued to monitor at same level. • Reduce monitoring level.	• Replace cap material. • Increase cap thickness. • Stop use of site. • Change cap sediment. • Redredge and remove.

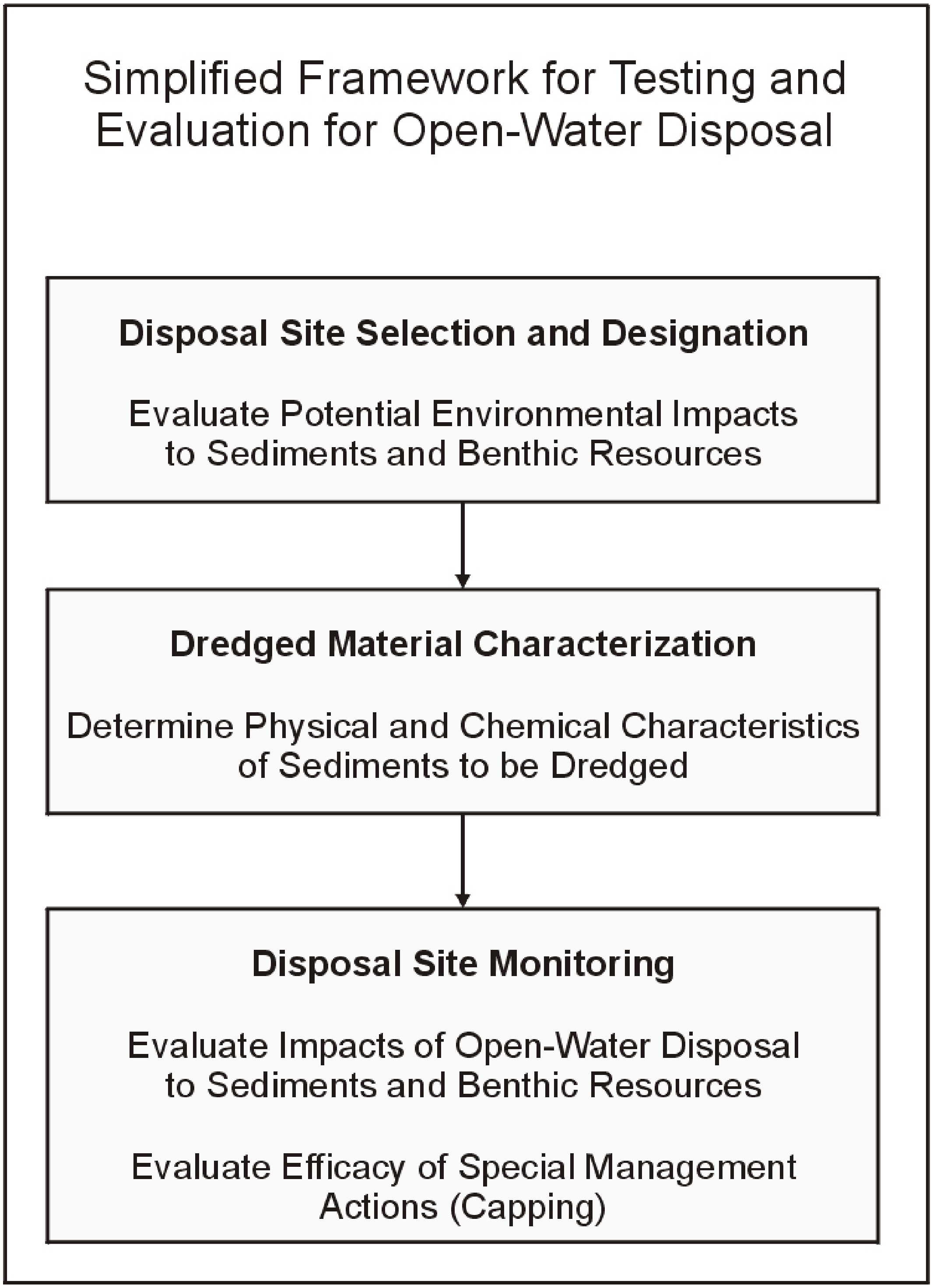

Figure 1. Simplified framework for testing and evaluation of dredged material being considered for open-water disposal (adapted from EPA/USACE 1992).

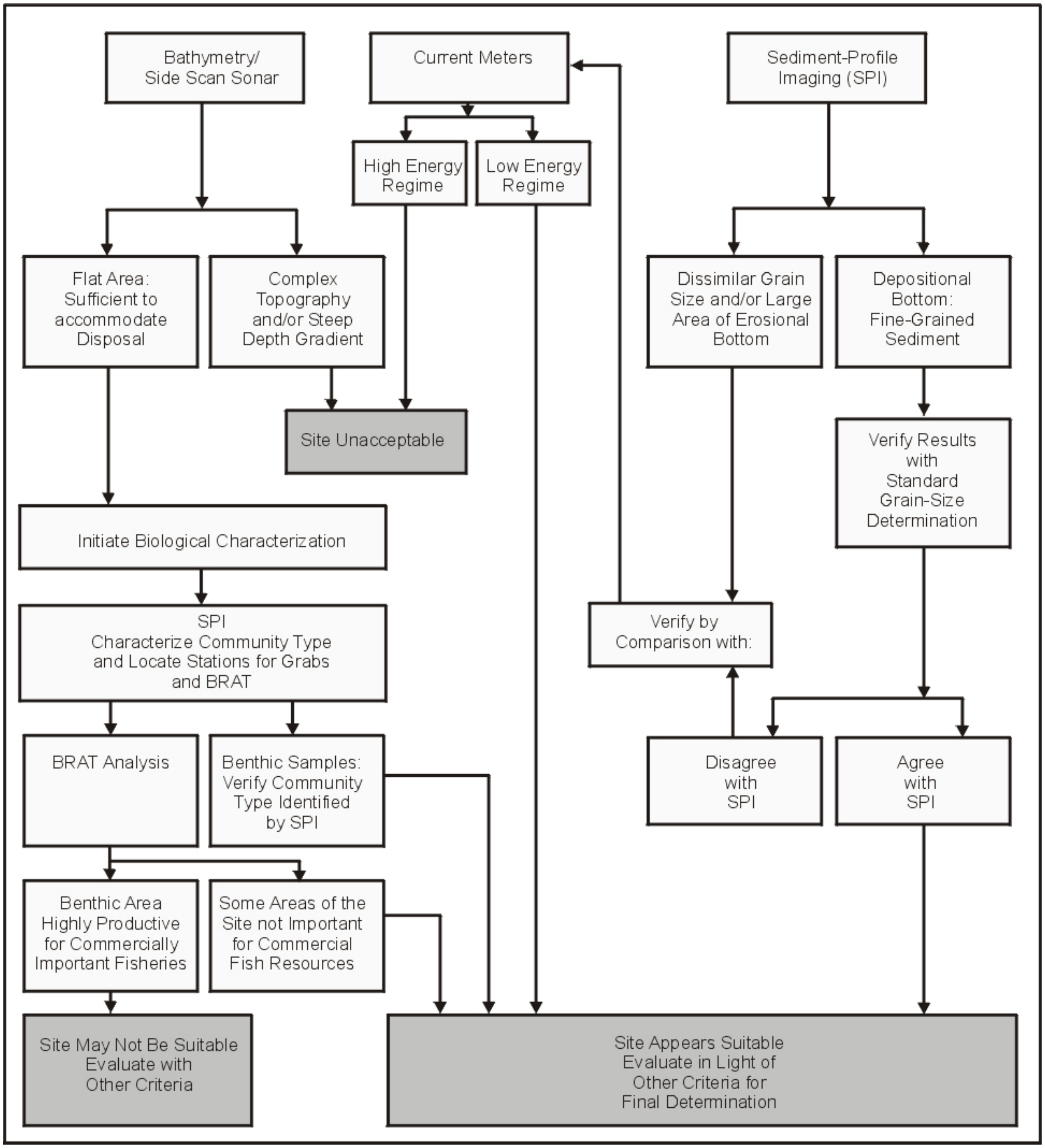

Figure 2. Example of a tiered monitoring approach for dredged material disposal site designation studies; management decisions are contained within shaded boxes (from Rhoads and Germano 1990).

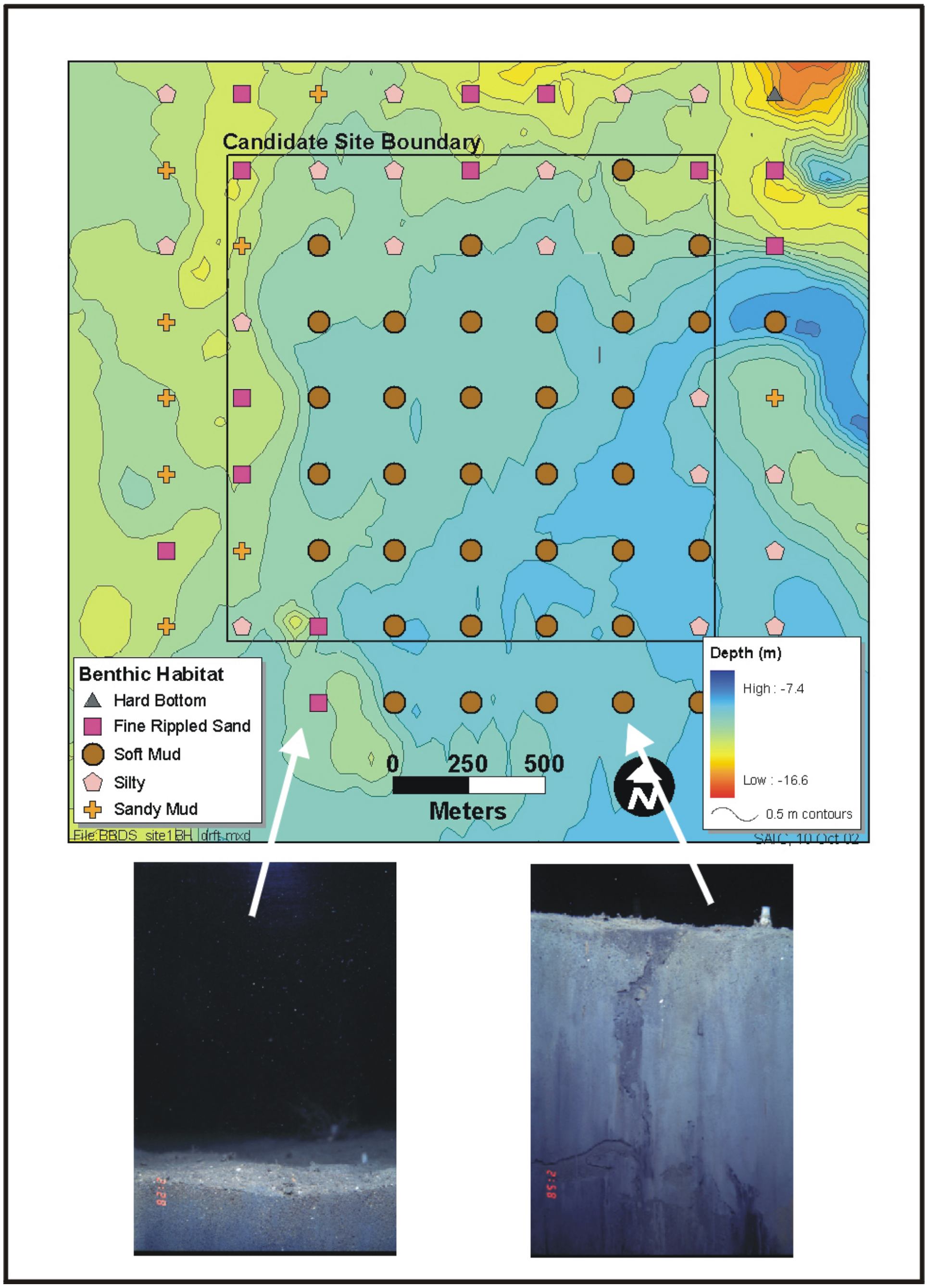

Figure 3. Map of benthic habitat types determined by SPI overlaid on bathymetric contours at a candidate dredged material disposal site in Buzzards Bay, MA. Representative sediment-profile images below the map provide examples of the fine rippled sand (left image) and soft mud (right image) habitat types. Throughout most of the candidate site, soft mud occurred within a topographic depression, leading to the conclusion that this site is predominantly a depositional seafloor environment favoring long-term containment of fine-grained sediment.

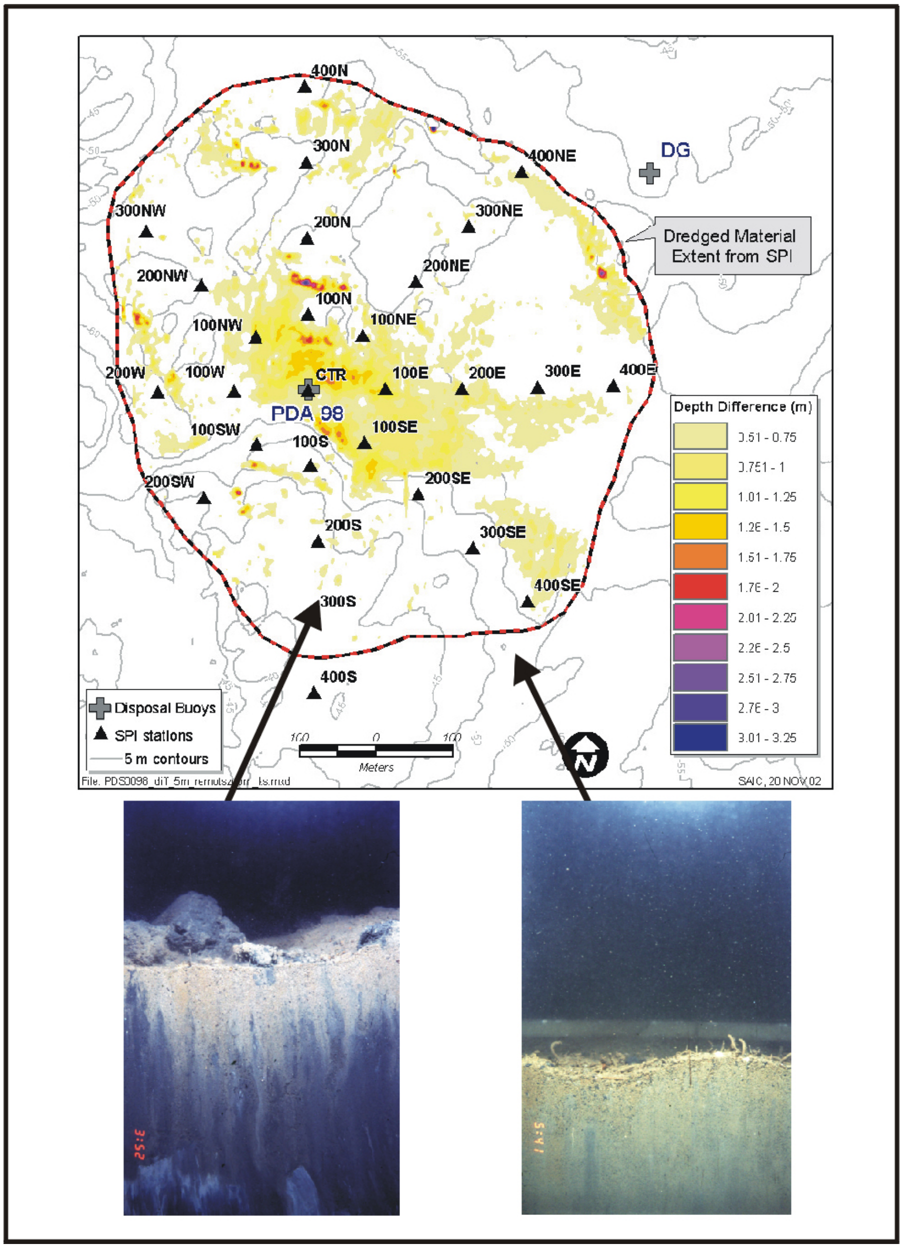

Figure 4. Map showing the spatial distribution and thickness of dredged material on the seafloor following one year of disposal activity at the Portland Disposal Site in Maine. Depth differencing of sequential bathymetric surveys allowed detection of the thickest accumulations of dredged material in the immediate vicinity of the PDA-98 buoy (colored depth difference results). Layers of dredged material that were too thin to be detected acoustically were found at SPI stations arranged in radial transects around the buoy. The spatial distribution of dredged material determined by SPI therefore was significantly wider than detected by bathymetry alone. Representative SPI images show cohesive, fine-grained dredged material comprising the deposit (left image) compared to ambient sediment with dense surface polychaete tubes found outside the deposit (right image).

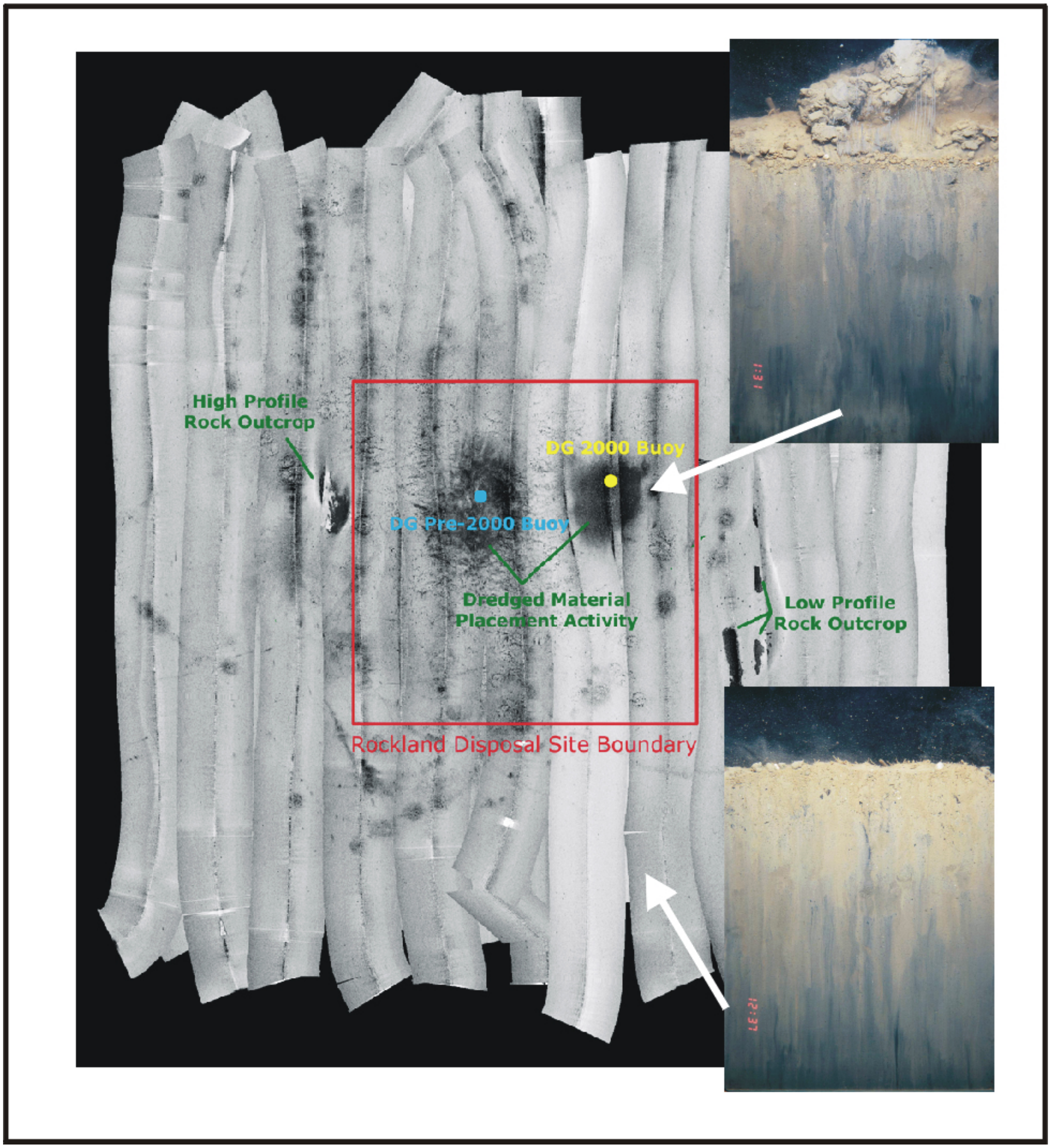

Figure 5. Side-scan sonar mosaic showing clear evidence of dredged material disposal activity on the seafloor in the immediate vicinity of former buoy locations at the Rockland Disposal Site in Maine. The dark, circular patches within the disposal site boundary are areas of increased surface roughness imparted to the bottom as a result of disposal of cohesive mud clumps. The sediment-profile image in the upper right corner shows a large, cohesive mud clast at the surface of the dredged material layer; the image in the lower right corner illustrates the relatively flat, muddy seafloor surrounding the disposal site.

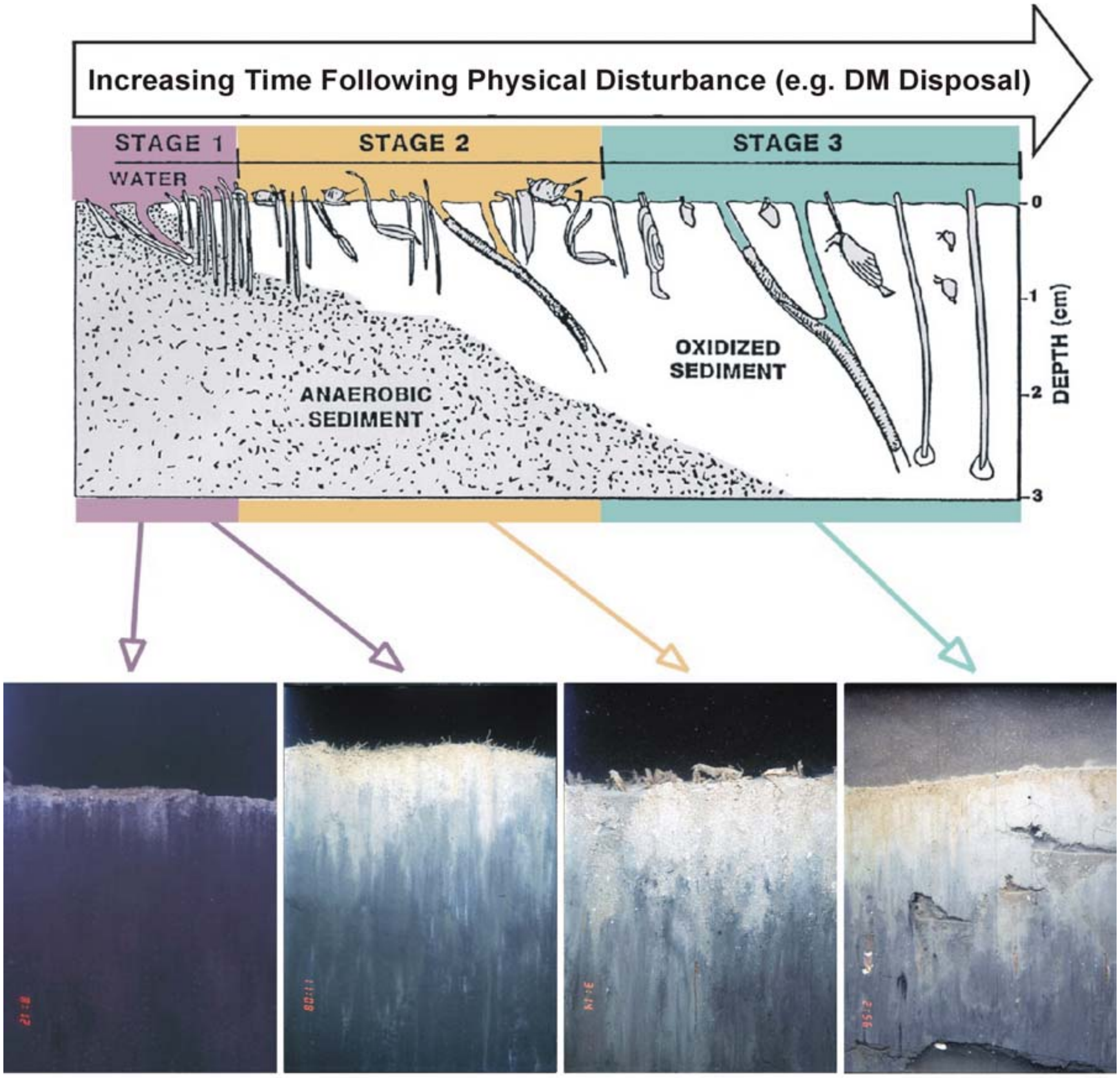

Figure 6. The conceptual drawing at top illustrates the development of infaunal successional stages over time in a sediment cross-section following the physical disturbance associated with dredged material disposal (from Rhoads and Germano 1986). The SPI images below the drawing provide examples of the different successional stages. Image A shows highly anoxic sediment with a very shallow redox layer and little evidence of infauna (azoic conditions); this is typical of many organic-rich, dredged harbor muds immediately following disposal. Numerous small polychaete tubes are visible at the sediment surface (Stage I) in image B, and organism activity results in a deeper redox depth. A mixture of polychaete and amphipod tubes occurs at the sediment surface in image C (Stage II). Image D shows numerous burrow openings and feeding pockets (voids) at depth within the sediment; these are evidence of deposit-feeding, Stage III infauna. The redox depth is relatively deep in this image, as bioturbation by the Stage III organisms has resulted in increased sediment aeration.

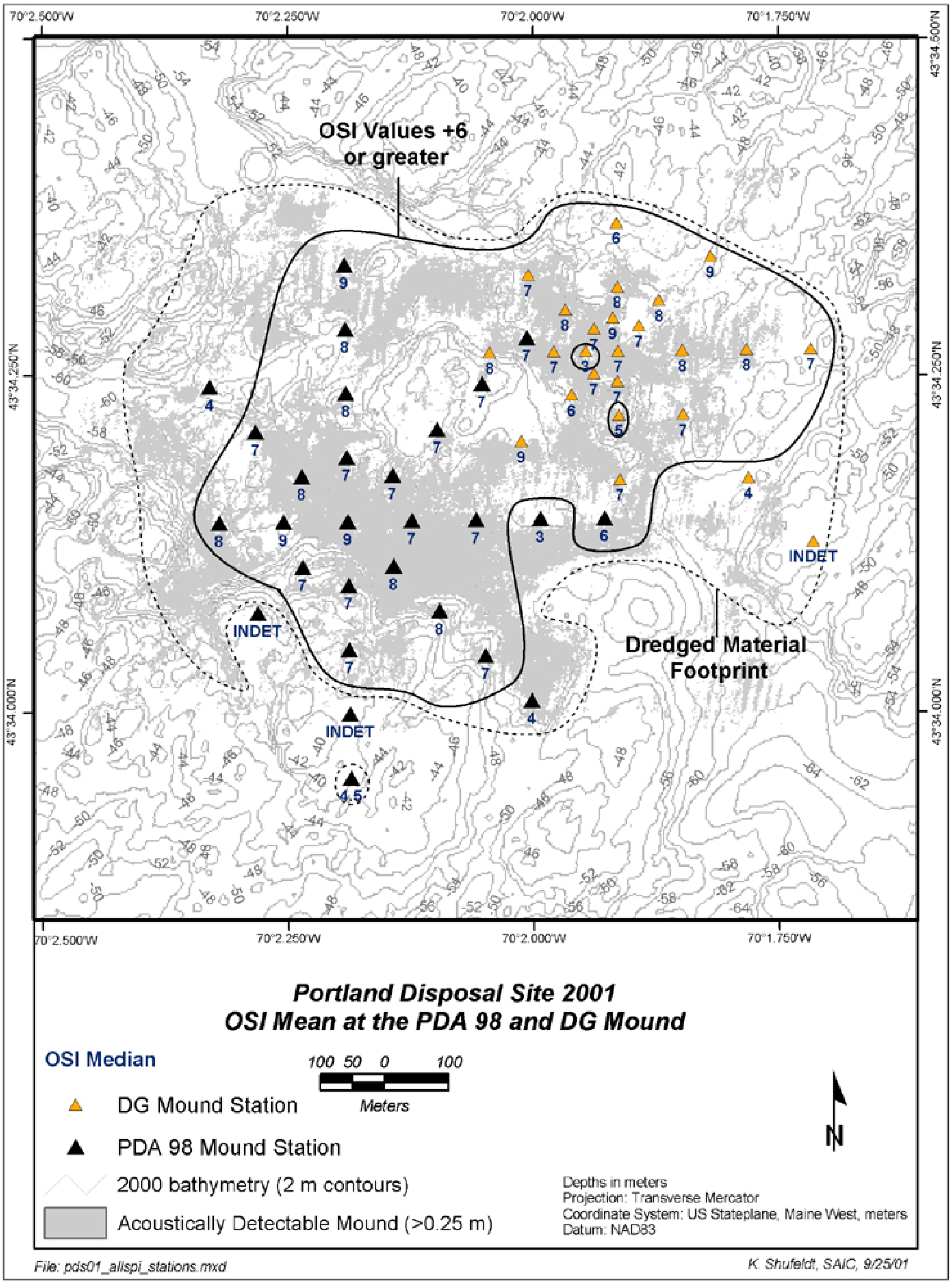

Figure 7. Map of average OSI values at SPI stations located over dredged material deposits at the Portland Disposal Site in Maine. Values of +6 or greater indicate non-degraded benthic habitat quality, similar to that found at reference stations in nearby areas unaffected by dredged material disposal.

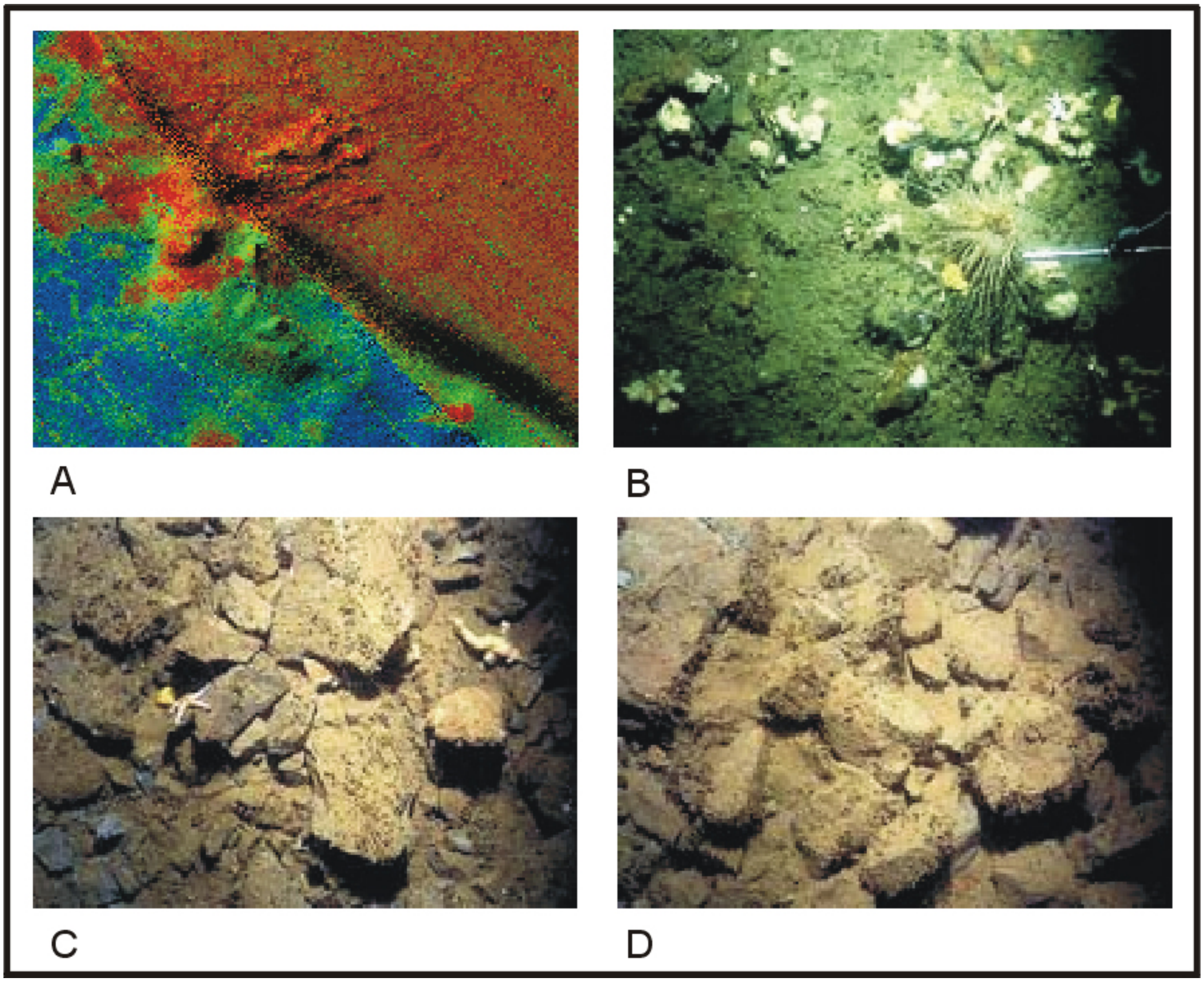

Figure 8. Images of the seafloor at the Massachusetts Bay dredged material disposal site (from Valentine et al. 1998). A) false-color image showing rock piles at the edge of Stellwagen Bank near the disposal site boundary; B) plan-view image showing ambient seafloor sediments consisting of gravel with abundant sponges; C and D) plan-view images of rock piles showing a lack of significant epifaunal recolonization more than three years following disposal.

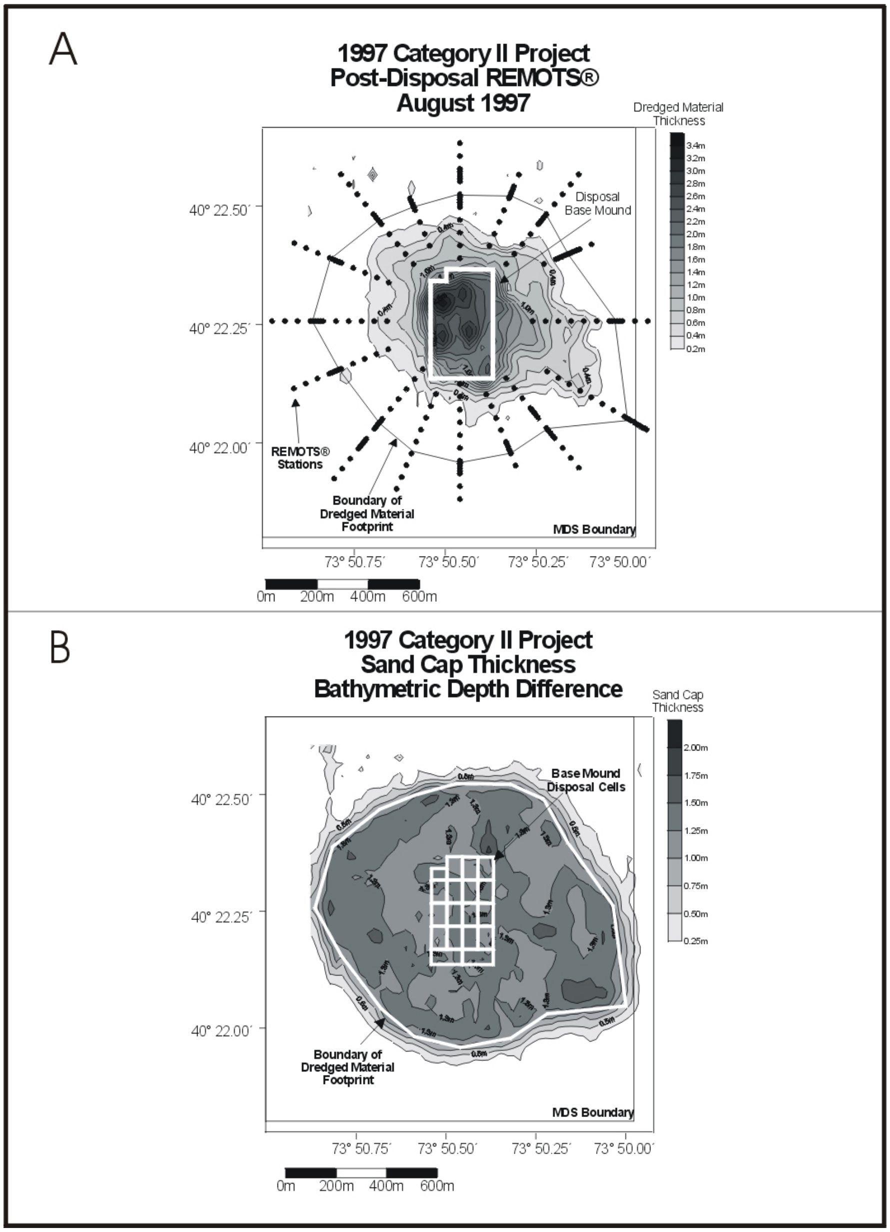

Figure 9. Maps of the 1997 dioxin capping project at the former Mud Dump Site in the New York Bight. A) Sequential bathymetric surveys in combination with SPI were used to determine the thickness and distribution of the dioxin-contaminated dredged material on the seafloor. Bathymetric depth differencing detected the thickest layers of dredged material near the mound center, while transects of SPI stations were used to detect thinner layers of material on the mound flanks and thereby map the full dredged material footprint. B) Following the capping operations, bathymetric depth differencing was used to confirm that the full footprint of dredged material had been covered with at least one meter of clean sand.

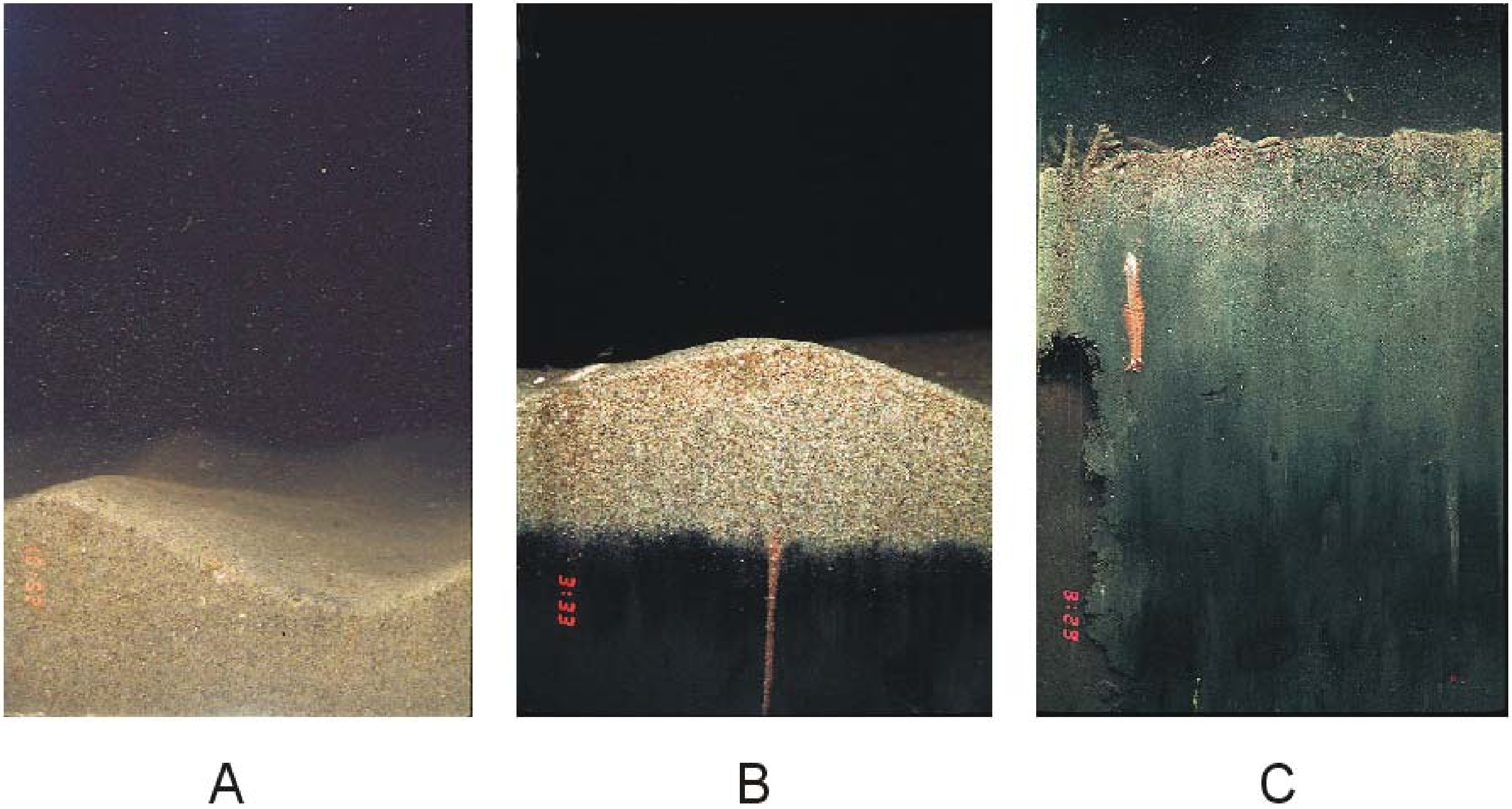

Figure 10. Example SPI images from monitoring of capped dredged material disposal mounds at the former Mud Dump Site in the New York Bight. A) homogenous fine sand dominated by small, surface-dwelling organisms is found consistently over the surface of the sand caps, B) at the outer edge of the sand caps, a distinct stratigraphy is sometimes observed in which thinner layers of cap sand (ca. 5 cm in this image) are visible over fine-grained, historic dredged material, C) uncapped, fine-grained dredged material from past disposal activities occurs in the area surrounding the capped mounds; this organic-rich sediment supports an abundant community of deposit feeding, Stage III organisms.

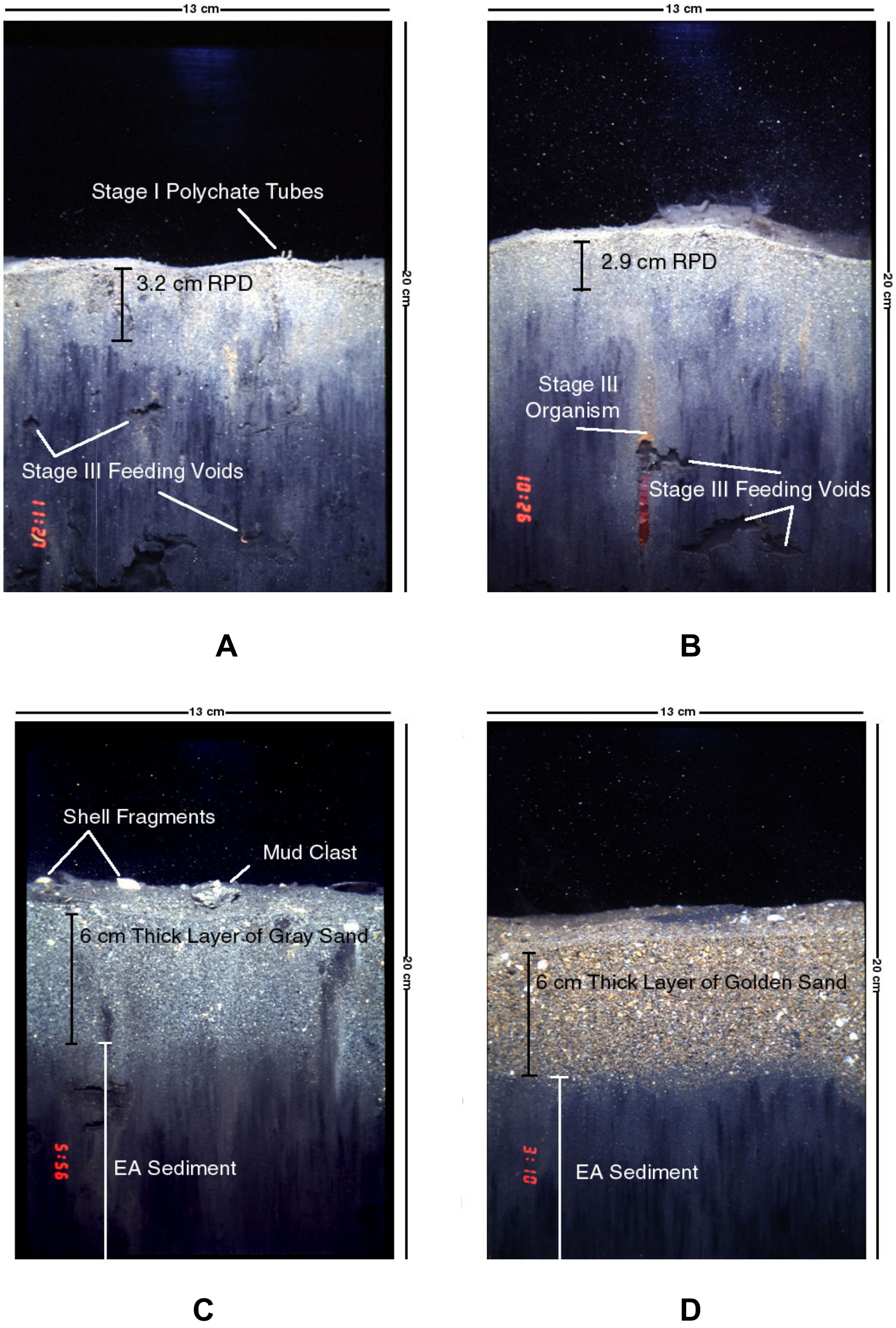

Figure 11. SPI images illustrating changes in benthic habitat conditions resulting from sand capping of contaminated (i.e., effluent-affected or EA) sediments on the Palos Verdes shelf off of Los Angeles (from Valente et al. 2001). Images A and B show typical baseline (i.e., pre-capping) conditions; sediments are predominantly silt-clay mixed with very fine sand, with a well-developed redox depth (RPD) and abundant Stage I and Stage III organisms. Images C and D (post-capping) each show a distinct 6 cm depositional layer of cap material (grey or golden sand) over the EA sediment.