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LONG TERM STABILITY OF CAPPED DREDGED MATERIAL DISPOSAL MOUNDS: STAMFORD NEW HAVEN NORTH AND CAP SITE 2 IN LONG ISLAND SOUND

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ABSTRACT

The first two open water capped disposal mounds to be engineered (rather than formed by dredging sequence) were created in Long Island Sound in 1979 by the Disposal Area Monitoring System (DAMOS). In 1983, two more mounds were created to further test the approach. In all of these mounds, dredged sediments considered unsuitable for unconfined open water disposal (UDM) were point-dumped. The mounds were surveyed to define the disposal footprint on the seafloor and then covered by controlled disposal of capping dredged material (CDM, material suitable for unconfined open water disposal). Physical, biological and chemical monitoring of the mounds established that UDM layers were isolated from the marine environment; coring studies in 1990 provided additional evidence of stability and isolation.

In 2004, two of these mounds were revisited, cored and subsamples of sediment layers analyzed to compare with previous results. The Stamford-New Haven North mound (STNH-N) provided a 25-year record and the Cap Site 2 mound (CS-2) provided a 19-year record of placement and capping of dredged material.

The results of the coring study provided clear and consistent data showing that the CDM over UDM sequence remained intact with a well-defined interface between the intervals at both mounds. At STHN-N, the thickness of the CDM interval compared well with the distribution of CDM mapped following the original formation of the mound, taking into account the expected long-term consolidation of the hydraulically dredged CDM. At CS-2, the thickness of the CDM was more variable, reflecting the mechanical dredging that was used in the project, but there was no apparent reduction of CDM thickness over time. At both sites, a surficial layer was noted above the CDM, indicating net deposition since formation of the mounds. The maintenance of the CDM thickness over time and the overlying net deposition provide evidence that the UDM interval remains physically isolated from the overlying waters and unaffected by potential erosive events or other surface disturbances.

Sediments in cores were classified visually into horizons (surficial, UDM, CDM, older dredged material, native sediments). Bulk sediment data and detailed sedimentological analysis supported these classifications: physical contacts between layers were distinct and undisturbed. Comparison of 1990 and 2004 sediment data indicated similar horizons were observed in both surveys. The 2004 analytical results did not suggest any physical mixing of sediments from the UDM into the CDM, supporting a conclusion that UDM has been physically stable and isolated within the sediment column of these disposal mounds in Long Island Sound for up to 25 years.

Keywords: Dredging, capping, contaminated sediment, coring, sedimentology.

INTRODUCTION

The formation of discrete mounds of dredged material in subaqueous environments in order to sequester contaminated sediments is now widely practiced (Fredette and French 2004, SAIC 1995, Fredette et al. 1993). In 1977 it was a relatively new concept, and many questions remained regarding the natural and engineering forces involved in successfully isolating harbor sediments in aquatic disposal mounds. In that year, federal and state agencies responsible for navigation and aquatic resources in Long Island Sound began discussing a series of projects designed to isolate inner harbor dredged material (now termed “unsuitably contaminated dredged material”, UDM) beneath layers of cleaner outer harbor material (capping dredged material, CDM), a process now known as “capping”. Monitoring and management of disposal sites had become formally organized under the Disposal Area Monitoring System (DAMOS) and a body of knowledge was building from academic and agency studies of the Long Island Sound disposal sites (Fredette and French 2004).

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Interagency discussions resulted in a decision to place a volume of UDM dredged from Stamford Harbor channel at two sites within the Central Long Island Sound Disposal Site (CLDS, historically referred to as CLIS), termed Stamford-New Haven North (STNH-N) and South (STNH-S) (Figure 1). As part of the project, the two deposits were capped with different types of material; CDM consisting primarily of sands was used at STNH-N, and CDM consisting primarily of silts was used at STNH-S (SAIC 1995).

In 1983, a similar project was initiated as part of a larger study jointly managed by U.S. Environmental Protection Agency (USEPA) and USACE Waterways Experiment Station, entitled the Field Verification Program (FVP). The FVP included laboratory and field investigations of the fate and effects of contaminated dredged material from Black Rock Harbor, CT placed at capped and uncapped subaqueous mounds, confined aquatic disposal sites, and upland (Peddicord 1988, Rogerson et al. 1985). As part of this project UDM from Black Rock Harbor was placed at two sites within CLDS, termed Cap Site 1 (CS-1) and Cap Site 2 (CS-2) (Figure 1). The two sites were capped with different types of CDM dredged from New Haven Harbor; CDM consisting primarily of silts was used at CS-1 and CDM consisting primarily of sands was used at CS-2 (SAIC 1995).

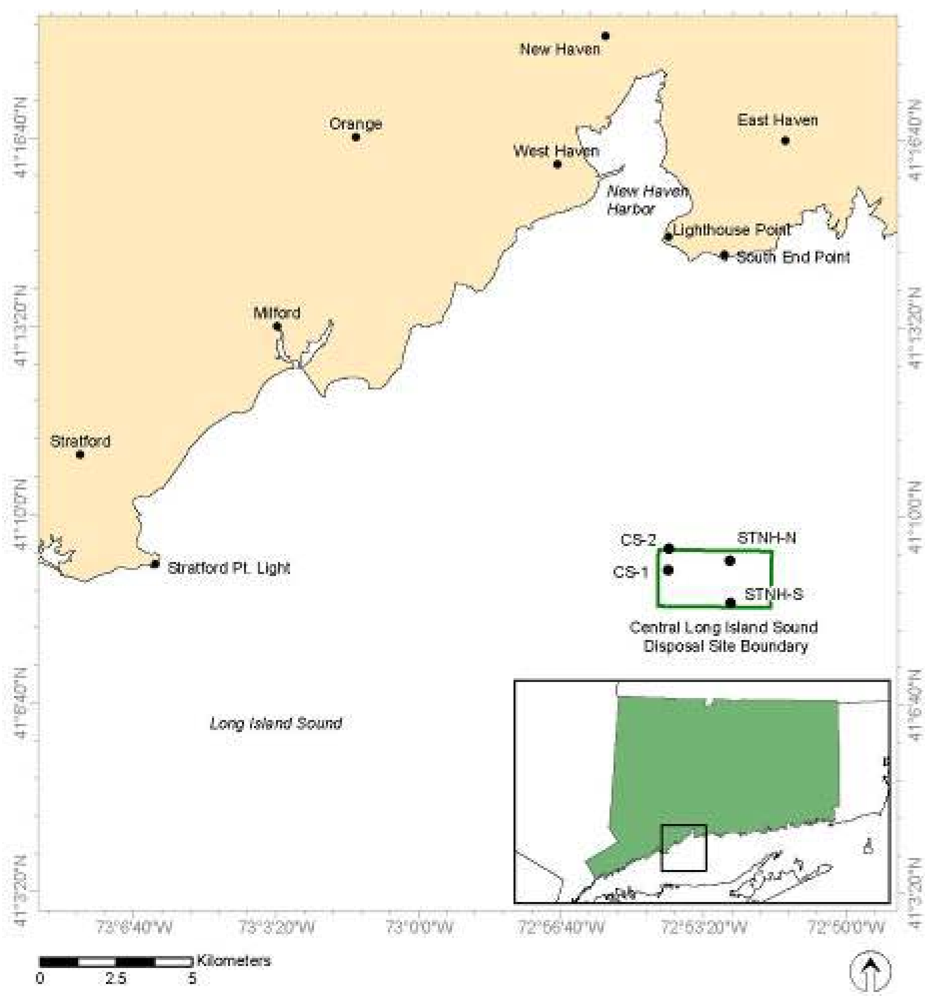

Figure 1. Location of the Central Long Island Sound Disposal Site and the capped mounds Stamford-New Haven North, Stamford-New Haven South, Cap Site 1, and Cap Site 2.

Experimental Capped Mounds in Long Island Sound

The uncertainties about formation and stability of capped mounds in Long Island Sound led to extensive monitoring studies and scientific investigations. This paper provides an overview and results of sedimentological characterization of core data from two of the earliest capped mounds, STNH-N and CS-2 (geochemical results are presented in ENSR 2005). At STNH-N, monitoring surveys were among the first to sequentially document the development and formation of a subaqueous capped mound (SAI 1979 a-f, 1980 a, b). At CS-2, the monitoring surveys were part of a much larger comparative study of the placement of UDM and different management options (Peddicord, 1988). The results of these surveys provide a good record of the initial nature and distribution of UDM and CDM at these two sites (summarized in SAIC 1995).

Follow-up investigations were also performed at both sites to examine the mounds after the deposits had consolidated and weathered for several years. At STNH-N surface grabs were collected in 1983 on an E-W transect across the mound, and in 1986 grabs were collected in a cross-shaped grid over the top of the mound (SAIC 1990). Subsurface cores were collected in 1990 from five locations (SAIC 1995). At CS-2, surface grabs were collected in June 1983, and subsurface cores were collected in July 1983 and July 1990 (SAIC, 1995, Sumeri et al. 1991).

CLDS has remained an active disposal site since the creation of the STNH-N and CS-2 capped mounds, with the creation of additional, and much larger, capped and uncapped disposal mounds across the site (Figure 2).

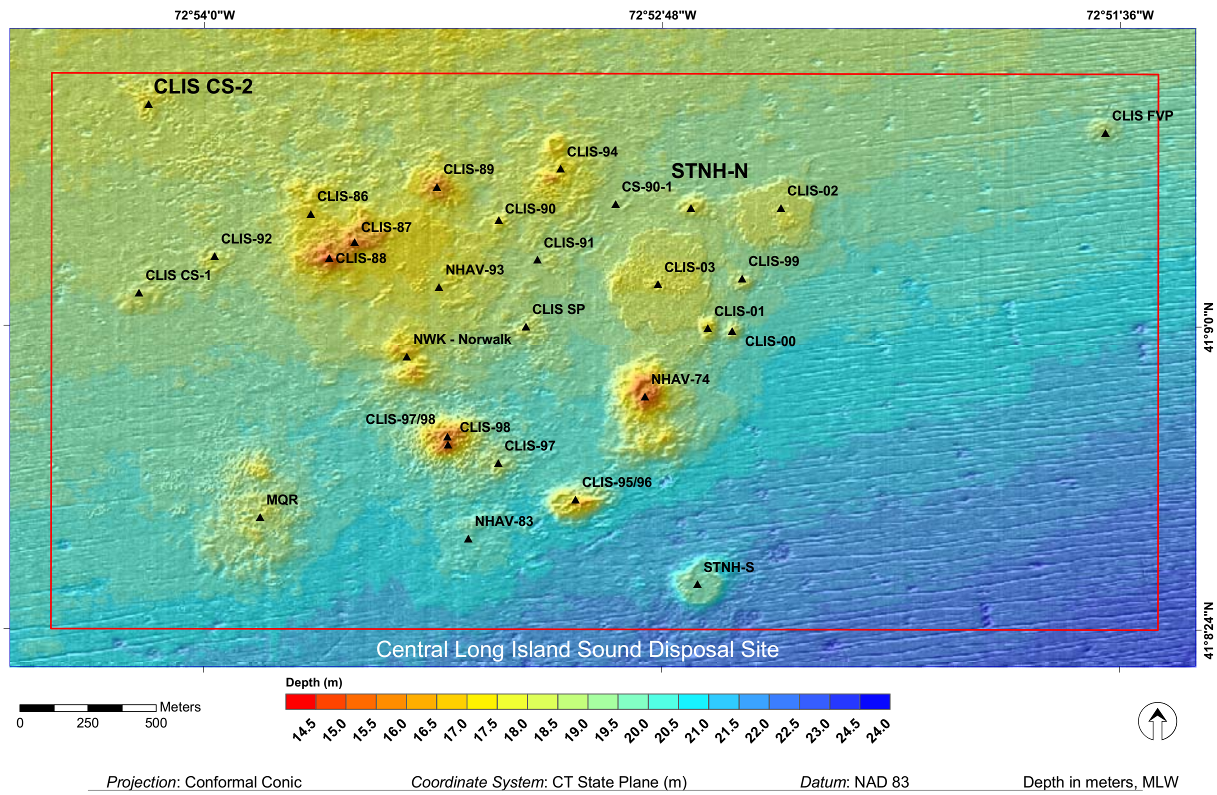

Figure 2. Disposal mounds and seafloor topography at the Central Long Island Sound Disposal Site.

A variety of techniques have been used to distinguish dredged materials placed in aquatic environments from ambient or native sediments (Fredette et al. 1992, 1993, SAIC 1995, Germano et al. 1994). Most rely upon a combination of characteristics (acoustic and optical signatures, bulk sediment analysis) to identify a mix of harbor or channel sediments (including surface and deeper layers) that have been placed in deeper water on relatively uniform surface sediments. Dredged material is removed from New England harbors with mechanical buckets and a single disposal barge may have a wide mix of materials, textures and water content. Original sedimentological features (bedding, biological material, biological traces) and features created during dredging, transport and disposal (clasts, mixing, size gradation, rip-up textures, liquefaction, "puzzle fabric", dewatering pipes) may be preserved in deposited dredged material. The DAMOS program pioneered the use of sequential single-beam bathymetric surveys and grids of sediment profile imagery (SPI) to map the distribution of fresh dredged material to monitor disposal activities and place cap material over mound deposits (SAIC 1995). Consolidation of placed dredged material due to dewatering reduces the height of mounds and has led to concerns that dewatering and seafloor currents may expose underlying unsuitable material to the benthic environment. A key to successful monitoring and management of disposal mounds is the development of diagnostic characteristics of dredged material and the sedimentological and landscape patterns that result from disposal activity. This paper presents descriptions and characterizations of layers formed during the engineering of capped disposal mounds. The results were part of a study conducted to revisit capped mounds to investigate physical and chemical stability of the capping process. The chemistry results will be discussed in a future paper but are presented in a DAMOS Contribution (ENSR 2005) and are discussed here where they provide support for the sedimentological analyses.

APPROACH

Five vibracores plus one replicate were collected at both the STNH-N and CS-2 capped disposal mounds on 24-25 May 2004 (Figures 3, 4). Pneumatic vibracoring was performed at the selected stations using OSI's VC 1500 coring unit outfitted with a 10-cm (4-inch) steel barrel and stainless steel cutter head. The sediment samples were collected in new, clear lexan liners (8.9 cm (3.5 inch) ID). OSI's coring barge (R/V Candu) was equipped with differential global positioning system (DGPS), multipoint anchoring system, and central moon pool for accurate positioning of cores.

The May 2004 coring at STNH-N and CS-2 and subsequent analyses were performed by ENSR International, Ocean Surveys Inc. (OSI), CoastalVision, and a team of laboratories. The approach and methods used to collect and analyze the cores were detailed in a project Sampling and Analysis Plan/Quality Assurance Project Plan (QAPP, ENSR 2005, Appendix A). Cores were collected using vibracoring equipment and were subsequently split, imaged, and subsampled at the University of Rhode Island, Department of Ocean Engineering. Analyses included total organic carbon (TOC), total petroleum hydrocarbons (TPH), and polycyclic aromatic hydrocarbons (PAHs) performed by Katahdin Analytical Services Inc.; metals (copper and zinc) performed by STL-Pittsburgh; and grain size performed by Geo\Plan Associates.

Coring Survey

For shipboard storage and subsequent transport of the collected cores, water overlying the sediment was drained by drilling a hole near the sediment water interface followed by cutting the lexan liner to within 1 cm of the sediment surface using a hack saw. The entire 2 to 3 meter long core was labeled, logged, and cut into manageable subsections of approximately 1 to 2 meters in length. Each subsection was capped, sealed with tape, and secured in an upright position.

The initial set of 12 cores, subsequently split in the field into shorter sections for transport and storage, resulted in a set of more than 30 core sections. At the end of each day, the core sections were off-loaded upright into insulated boxes and iced for storage. Following completion of the field effort, the cores were transported to the Marine Geomechanics Laboratory (MGL) at the University of Rhode Island (URI) and stored upright in a walk-in refrigerator.

Core Processing

Processing of the cores was performed at MGL. Before splitting commenced, any void existing above the sediment water interface was filled with a high density, low permeability foam material to prevent sediment/water migration and to maintain the core configuration and shape during the splitting process. This prevented loss of material from the uppermost surface sediment slurry. Each core tube was labeled at intervals from the sediment water interface before splitting.

Core sections were split length-wise using a device designed to cut the hard plastic liner without disturbing the sediment core. This device cut each core liner axially, using a set of laterally adjustable routers, pushed along the core using an electric motor and wire/pulley system. To avoid disturbance, the routers did not cut through the entire liner. Straight blades were then used to manually finish the cut. Following the splitting of the lexan core liner, each sediment core section was split lengthwise by hand by pulling a titanium wire through the core beginning at the uppermost sediment surface and continuing down through each successive (lower) sediment layer.

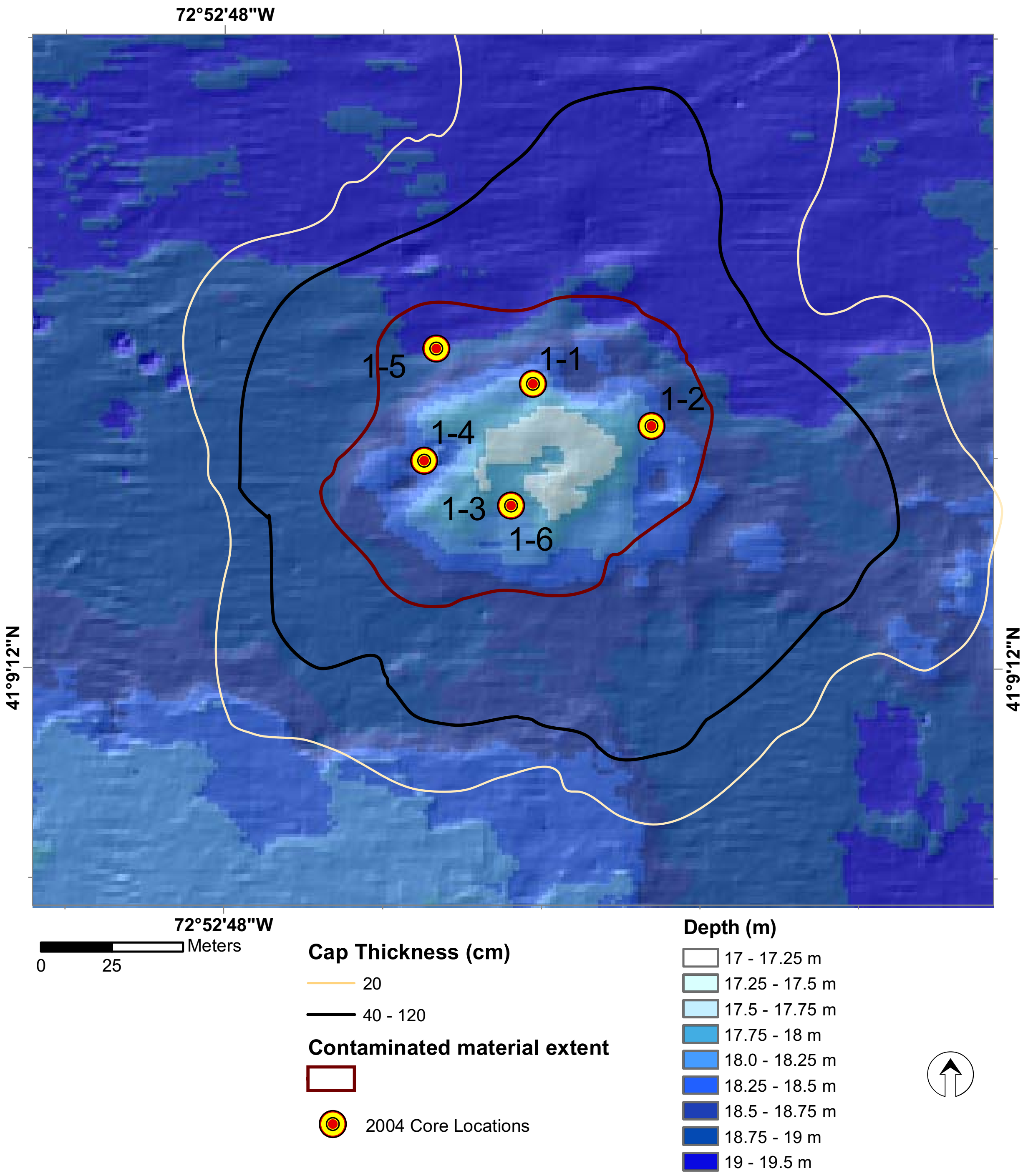

Figure 3. Core locations collected in 2004 from STNH-N. Colored lines represent the footprints of layers of UDM (red) and overlying CDM (yellow and black). Background is hillshaded bathymetry from 2005.

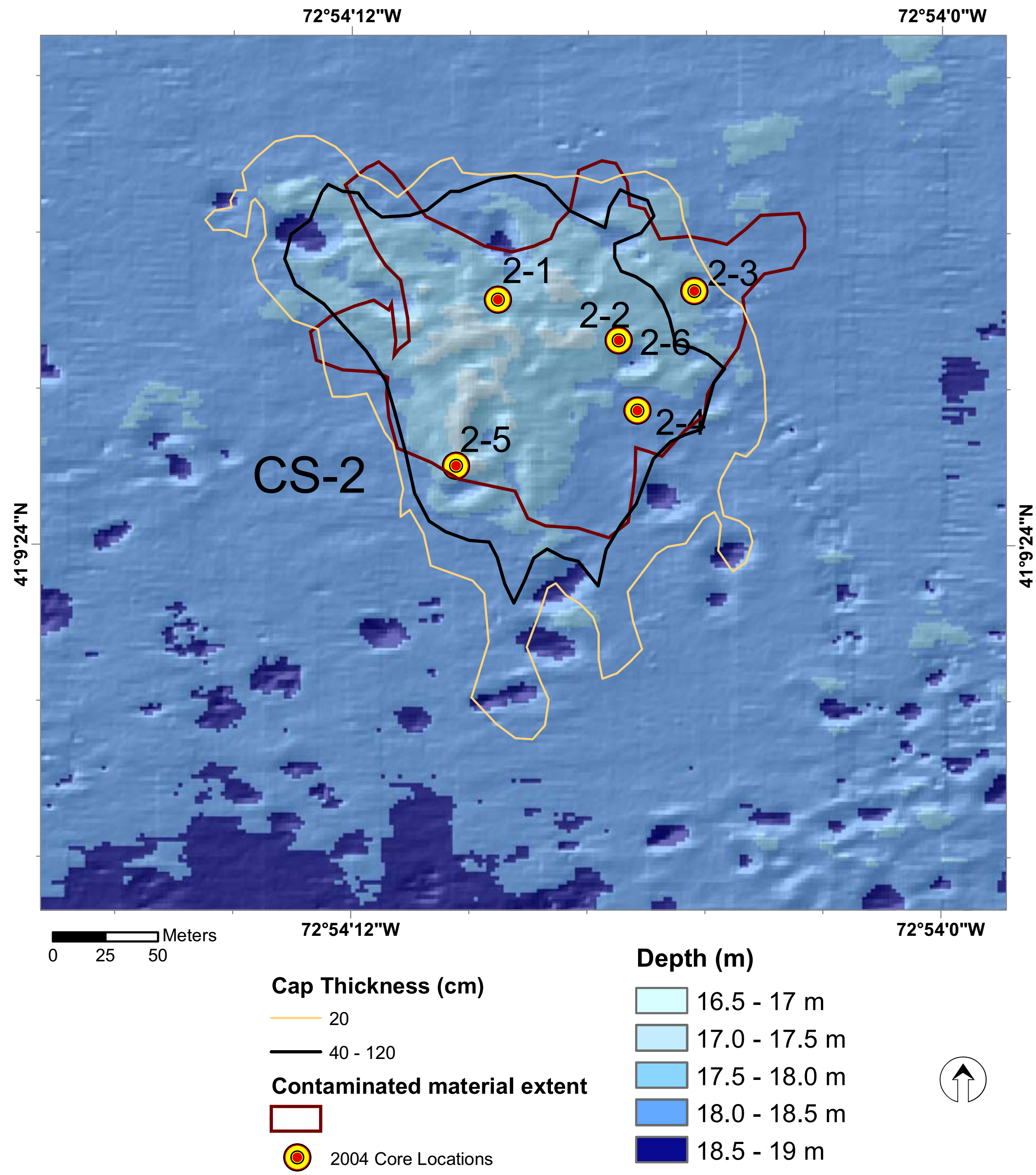

Figure 4. Core locations collected in 2004 from CS-2. Colored lines represent the footprints of layers of UDM (red) and overlying CDM (yellow and black). Background is hillshaded bathymetry from 2005.

After each core was split lengthwise (resulting in two core halves), one half was transferred to the imaging laboratory for high-resolution filming, subsampling for grain size analysis, and p-wave analysis. Because the imaging process required surface smoothing that could have caused chemical cross contamination along the length of the core, only grain size subsamples were collected from the imaged core splits. The remaining half of the core was described by examining the open surface of the core, labeled, and subsampled for chemical analysis.

Subsamples collected for grain size were transferred to plastic zip-lock bags, labeled, and delivered to the physical testing laboratory for homogenization and analysis. Details of sample handling and containerization are provided in the project QAPP (ENSR 2005, Appendix A).

Core Descriptions

Core descriptions were conducted by MGL staff with oversight by ENSR and CoastalVision. Each core was examined to document surface texture, odor, coloration, stratigraphic changes, and unique features or anthropogenic materials (e.g., plastic) on log forms (ENSR 2005, Appendix C). Details of selected split core sections were also photographed. Based on this examination, select 10-cm horizons were identified in each core for subsampling and chemical analysis, and 20-cm horizons were identified for quality control analyses. Each subsample was homogenized before containerization and transfer to the analytical laboratory. Details of sample handling and containerization are provided in the project QAPP (ENSR 2005, Appendix A).

Core Imaging

Core imaging was performed at URI by MGL staff using a GeoTek GeoScan III, digital video camera mounted on a core logger. The sediment surface along the core split was smoothed laterally with a plastic plate to minimize changes in focal length, prior to imaging.

Core Grain size and Chemistry

Sediments were analyzed for PAHs (extraction by EPA SW-846 method 3550B and analysis using method 8270C modified to utilize selected ion mass spectrometer mode). Samples designated for TPH analysis were prepared using EPA SW-846 method 3540C (Soxlet) and analyzed using method 8015B (GC/FID).

Copper and zinc were selected for metals analysis to complement available historical information that largely focused on these two metals as reliable tracers of UDM. Metals that are typically used in describing sediment geochemical terms (such as Al or Fe) were not included because the horizons of interest are man-made features largely consisting of UDM or older dredged material overlain by coarse-grained cap material. Metals samples were prepared according to EPA SW-846 method 3050B and analyzed using method 6010B (ICP/AES). The preparation method (3050B) is a rigorous acid digestion method using HNO3 and H2O2 followed by an HCl acid reflux step. TOC measurements were analyzed using a combustion method (Kahn 1988) which is preferred for TOC analysis in marine sediments.

Sediment grain size analysis was performed combining sieving and pipetting methods (Folk 1974). The data are presented here as percent silt and clay. All other chemistry results are reported elsewhere (ENSR 2005).

Layer Classification

As a preliminary step in data analysis the core descriptions and images were used to classify the horizons of the cores based on historical records of disposal (SAIC 1995). The initial classification guided the sampling and allocation of samples for analysis or archival storage. The most prominent core features were related to basic color and appearance and provided initial evidence for classification of a core section. The understanding of mound creation (e.g., coarse CDM placement above UDM) provided clues during the classification process. Some layers were quite uniform, indicative, for example, of native sediments underlying the mound. The existence of anthropogenic material (plastic, foil, etc.) or biological material (preserved plant material) at depth provided a clear indication that the sediment section was within one of the disturbed dredged material layers. A distinctive thin horizon of coarse, red sand observed within multiple cores provided a useful marker for assessing cross-mound core layers. The fact that many cores penetrated native sediments also aided the classification process by providing a point of reference between cores across the mounds. After the results of grain size analysis and sediment chemistry were available, the initial classification was tested and reassessed. Final classification and description incorporated all lines of evidence available.

RESULTS

Field Collection

Sediment cores were successfully collected in May 2004 at the five target and two replicate locations at each of the two capped mounds. At STNH-N recovered sediment cores ranged in length from 282 to 296 cm and were distributed across the mound within the area assumed to contain underlying UDM material based on bathymetric studies conducted prior to and following mound formation (Figure 3). Core 1-1 was collected from the northern edge of the upper mound surface; Core 1-2 was collected from the eastern mound slope; Cores 1-3 and 1-6 were collected as field replicates from the southern slope; and Cores 1-4 and 1-5 were collected from the western and northwestern mound flank, in outer, thinner mound areas.

The cores recovered from the CS-2 mound ranged in length from 235 to 289 cm and were distributed across the more irregular CS-2 mound footprint (Figure 4). Core 2-1 and 2-2 and field replicate 2-6 were collected across the thickest area of the mound; Cores 2-3 and 2-4 were collected along the eastern slope of the mound; and Core 2-5 was collected along the southwestern margin of the mound where a thick UDM layer had been noted during the 1990 survey (Core "CS-2 Center", SAIC, 1995).

Mound Sediment Classifications

To evaluate large scale mound characteristics, the predominant layers observed within each core were classified (Table 1).

Table 1. Core layer classification.

Classified layer	Interpretation	Sediment color	Grain size	Texture	Features
Surficial layer	Cap material mixed with ambient deposition	Dark brown to light tan	Fine – medium sand; more silt at STNH-N	Uniform, well-mixed	Soft, unconsolidated
CDM	Outer harbor dredged material used to cap the mound.	Brown to light tan	Fine – coarse sand; layers of silt at CS-2	Chaotic with alternating layers of coarse and fine sand	Shells, plant material, plastic
UDM	Inner harbor silts and sands unsuitable for unconfined aquatic disposal	Black to dark brown	Fine sand - silt	Disturbed, chaotic layering	Clasts of black or grey silt, plant material, oily smell
DM	Dredged material disposed at CLDS prior to the placement of STNH-N and CS-2 mounds	Dark brown to olive green	Silt with some layers of fine sand at CS-2	Disturbed chaotic layering	Clasts of black or grey silt, lack of oily smell
Native sediment	Native Long Island Sound sediments in place prior to disposal of dredged material	Olive green	Fine silt	Uniform, lack of bedding, some isolated layers	Burrow halos, thin sand layers

STHN-N

Physical Characteristics and Observations

Distinct and consistent strata were observed in the six cores from STNH-N. A dark, fine-grained surface layer was observed at the top of all the cores (Figure 5). This layer ranged from approximately 20 to 30 cm in thickness, with up to 94% fines and TOC ranging from 1.4 to 4.4% (Figure 7). Core 1-1, collected on the upper portion of the mound was the exception, where the upper fine-grained layer appeared less than 10 cm in thickness and was not captured in the first sampling interval.

The dark, fine-grained surface layer graded into an interval of much lighter and coarser grained material, assumed to be the New Haven CDM placed at the site (Figure 5). This interval ranged in thickness from approximately 50 cm for the cores located closer to the mound edge (Cores 1-4, 1-5) to over 100 cm near the top of the mound (Core 1-1). This interval was quite variable in appearance with numerous shells, shell hash, and pockets of fine material. Three 10-cm sections were sampled in this interval for most cores. Sand was the dominant grain size, with the sand and shell fraction generally over 70% (Figure 7). TOC was low, ranging from 0.1 to 2.3% with a median of 0.7%.

Beneath the lighter colored, coarse-grained material there was a sharp transition to a very dark gray-black silt and sand which gave off a strong petroleum odor in four cores. This interval ranged in thickness from approximately 20 to 80 cm and was assumed to be the Stamford Harbor UDM placed at the site. The dark sand and silt was interspersed with pockets of gravel and shell and occasionally interlayered with lighter olive silt. Two or three 10-cm sections were sampled in this interval for each core. Silt and clay content ranged from 12 to 84%, with a median of 45% (Figure 7). Samples from this interval consistently had the highest TOC of each core, ranging from 2.9 to 11%, with a median of 5.0%.

The dark UDM horizon was underlain by a layer that was predominantly a lighter olive silt and clay but had pockets of sand and gravel as well as shell and wood fragments. Some layering of darker material was apparent, as were some irregular contact angles between sediment types. The mixed properties and disturbed nature of this material indicated older dredged material disposed at the site prior to the STNH-N mound formation. One or two 10-cm sections were sampled in this interval for most cores. In addition to the lighter color and texture change, analysis revealed that this interval was further distinguished from the overlying UDM by moderate TOC content, ranging from 1.6 to 3%. This older dredged material interval ranged in thickness from approximately 10 cm at Core 1-4 on the outer flank of the mound to >100 cm at Core 1-1.

In four cores, layers of what appeared to be native Long Island Sound sediments were identified below the older dredged material. This material was generally logged as light olive clay silt. A distinctive thin sand lens was embedded within the silt in three of the cores. There appeared to be a gradation from the overlying older dredged material to the native sediment rather than a sharp transition. The two samples collected from this interval had very high silt and clay content (85-98%) and lower TOC (1.3-2.6%) (Figure 7).

STHN-N Mound Sediment Classification Summary

The Stamford Harbor UDM was identified as a distinct interval in all six cores collected at STNH-N. A minimum UDM thickness of approximately 20 cm was found in Core 1-5, collected near the edge of the original mapped mound. The thickness of the UDM interval increased in cores collected farther up the mound, with a maximum of approximately 80 cm in Cores 1-4 and 1-6. Although the UDM was generally dark in appearance and contained elevated contaminant concentrations, there was some variability both between and within individual cores. This variability is best characterized in the field replicate Cores 1-3 and 1-6, collected within several meters of each other. The overall thickness of the UDM interval was similar for the two cores, but in Core 1-6, the interval contained a much larger component of lighter olive silt (Figure 5).

Above the UDM, there was a sharp transition to the overlying cap in all cores. The cap consisted of distinct, coarse-grained CDM directly above the UDM with a surficial interval of finer-grained material worked into the CDM. The overall cap thickness ranged from approximately 80 cm on the mound flank to nearly 150 cm near the top of the mound.

Lighter colored material with increased fines and occasional shells and gravel was found beneath the UDM in all six cores. Given the disturbed nature of this sediment and slightly elevated contaminant levels, it was considered to be older dredged material historically disposed at the site prior to STNH-N mound formation. A gradual transition to apparent native Long Island Sound sediments was noted beneath the older dredged material in four cores. The native material consisted of a relatively uniform olive to gray silt, with occasional imbedded coarser horizons.

Cap Site 2

Physical Characteristics and Observations

Distinct vertical strata were observed in the six cores from CS-2 (Figure 6). However, consistency of these strata among cores was not as strong as for STNH-N. The surficial interval was typically dark olive-gray with a nearly even sand-silt content (Figure 8). TOC for the 10-20 cm interval was low, ranging from 1.1 to 1.7%. This sand and silt surficial interval extended to 30 to 40 cm in all cores except Core 2-5 where surficial sediments were coarser.

In four cores (2-1, 2-2, 2-3, 2-4) the surficial interval was underlain by a sharp transition to coarser material with shells and shell hash, ranging from 20 to 50 cm in thickness (Figure 6). Cores 2-5 and 2-6 transitioned to finer, lighter colored material beneath the surficial interval. This finer material was approximately 40 cm thick with imbedded shells in Core 2-5 and was approximately 20 cm thick in Core 2-6. All of this material was classified as CDM, with the variability in grain size consistent with the source of the cap material (New Haven) and method of removal (mechanical dredging). Two 10-cm sections were sampled in this CDM interval for most cores, with a median sand and shell fraction of 78% and median TOC of 1.4% (Figure 8).

Beneath the varied CDM, there was a sharp transition to a very dark mixture of silty sand and sandy silt in four cores (2-1, 2-2, 2-4, 2-6). This interval contained some horizons of lighter olive silt, and a strong petroleum odor was noted in two cores. This interval ranged in thickness from approximately 35 to 100 cm and was assumed to be the Black Rock Harbor UDM placed at the site. Three or four 10-cm sections were sampled in this UDM interval in each core. Silt and clay content ranged from 21 to 94%, with a median of 43%. TOC was lowest (0.8% minimum) in the lighter horizons and highest (8.6%) in the darker sections, with a median of 2.8% (Figure 8).

The UDM interval was not apparent in two cores (2-3, 2-5). In these cores the CDM transitioned to a chaotic mixture of silt, sand, and shells that was lighter in color than the UDM and assumed to be older dredged material disposed at the site prior to the CS-2 mound formation. This interval was approximately 50 cm in length in both cores. A total of seven 10-cm sections were sampled in this interval for the two cores. Silt and clay content ranged from 25 to 97%, with a median of 67%. TOC was low, ranging from 0.9 to 2.2%. This older dredged material was apparent beneath the UDM in the other four cores, ranging in thickness from approximately 15 to 35 cm.

In all six cores, native Long Island Sound sediments were apparent below the older dredged material. Similar to the STNH-N cores, this material was generally logged as light olive clay silt, but evidence of episodic deposition of coarser sediments was not as apparent beneath CS-2. In general, the exact boundary between the older dredged material and underlying native material was difficult to discern, with a gradual transition from the disturbed and heterogeneous older dredged material to the more uniform native material below. One 10-cm interval was sampled within this interval for each core. Silt and clay content was over 90% for all but one sample, and TOC ranged from 1.5 to 2.8% (Figure 8).

CS-2 Mound Sediment Classification Summary

The Black Rock Harbor UDM was identified as a distinct interval in four cores collected closer to the top of the CS-2 mound, with thicknesses ranging from approximately 35 to 100 cm. Although the UDM was generally dark in appearance and contained elevated contaminant concentrations, there was some interlayering of lighter, finer-grained, and less contaminated material.

Above the UDM, there was a sharp transition to the overlying cap in all four of the cores. The cap consisted of CDM with variable appearance and grain size directly above the UDM with a more uniform surficial interval of finer-grained material worked into the CDM. The variable nature of the CDM was highlighted by the replicate cores collected at CS-2. Core 2-2 had the greatest overall cap thickness (approximately 90 cm) with an extended sequence of coarse-grained material (Figure 6). Replicate Core 2-6, collected several meters away had the least overall cap thickness (approximately 50 cm) with very limited coarse-grained material (Figure 6).

Cap material was also present at the two cores with no identified UDM interval. Beneath the cap material, both cores had an approximately 50-cm thick interval of heterogeneous and/or disturbed material that was apparently older dredged material historically disposed at the site prior to CS-2 mound formation. Shorter sequences of this older dredged material were apparent beneath the UDM at the other four cores. A gradual transition to apparent native Long Island Sound sediments was noted beneath the older dredged material in all six cores. Similar to STNH-N, the native material consisted of a relatively uniform olive to gray silt, but with limited imbedded coarser material.

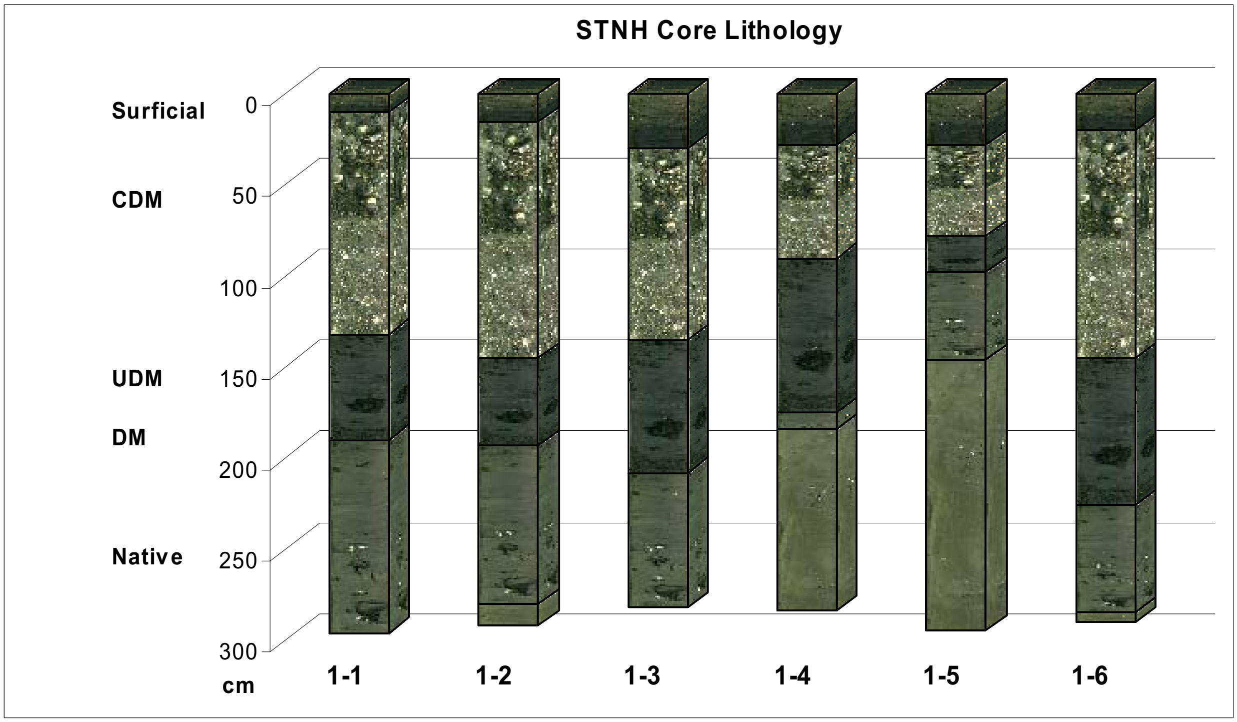

Figure 5. Thickness of sediment layers in cores from STNH-N mound. Layer descriptions in Table 1.

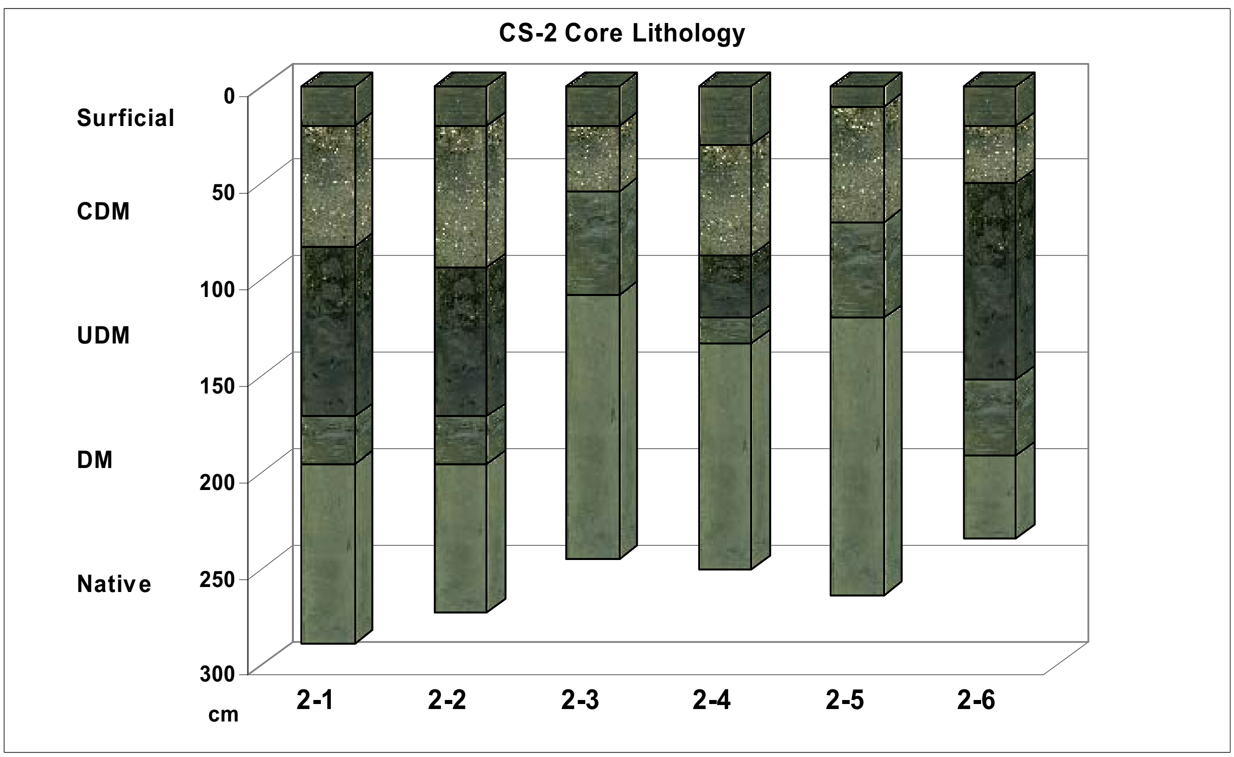

Figure 6. Thickness of sediment layers in cores from CS-2 mound. Layer descriptions in Table 1.

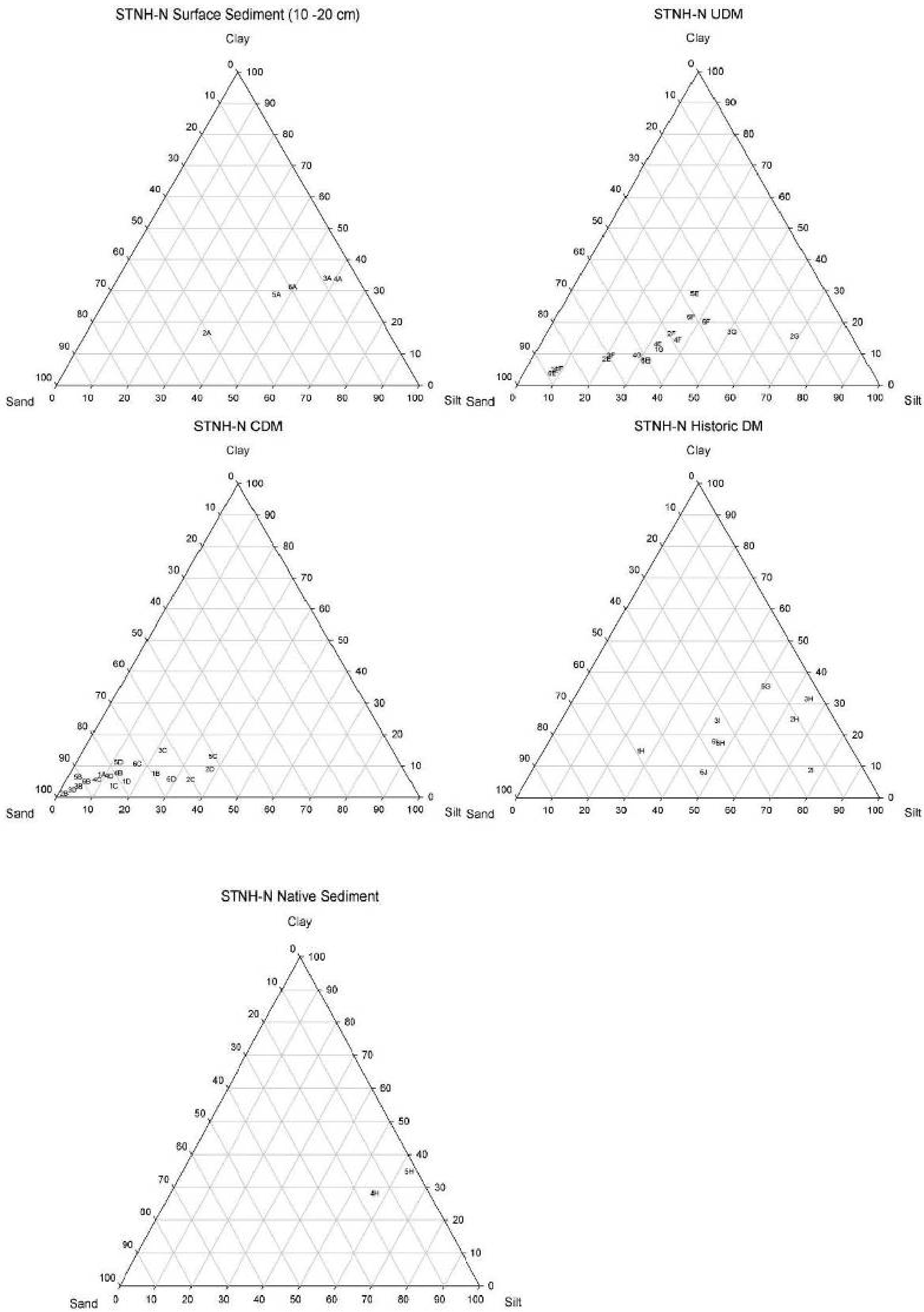

Figure 7. Ternary grain size plots of the STNH-N mound layers

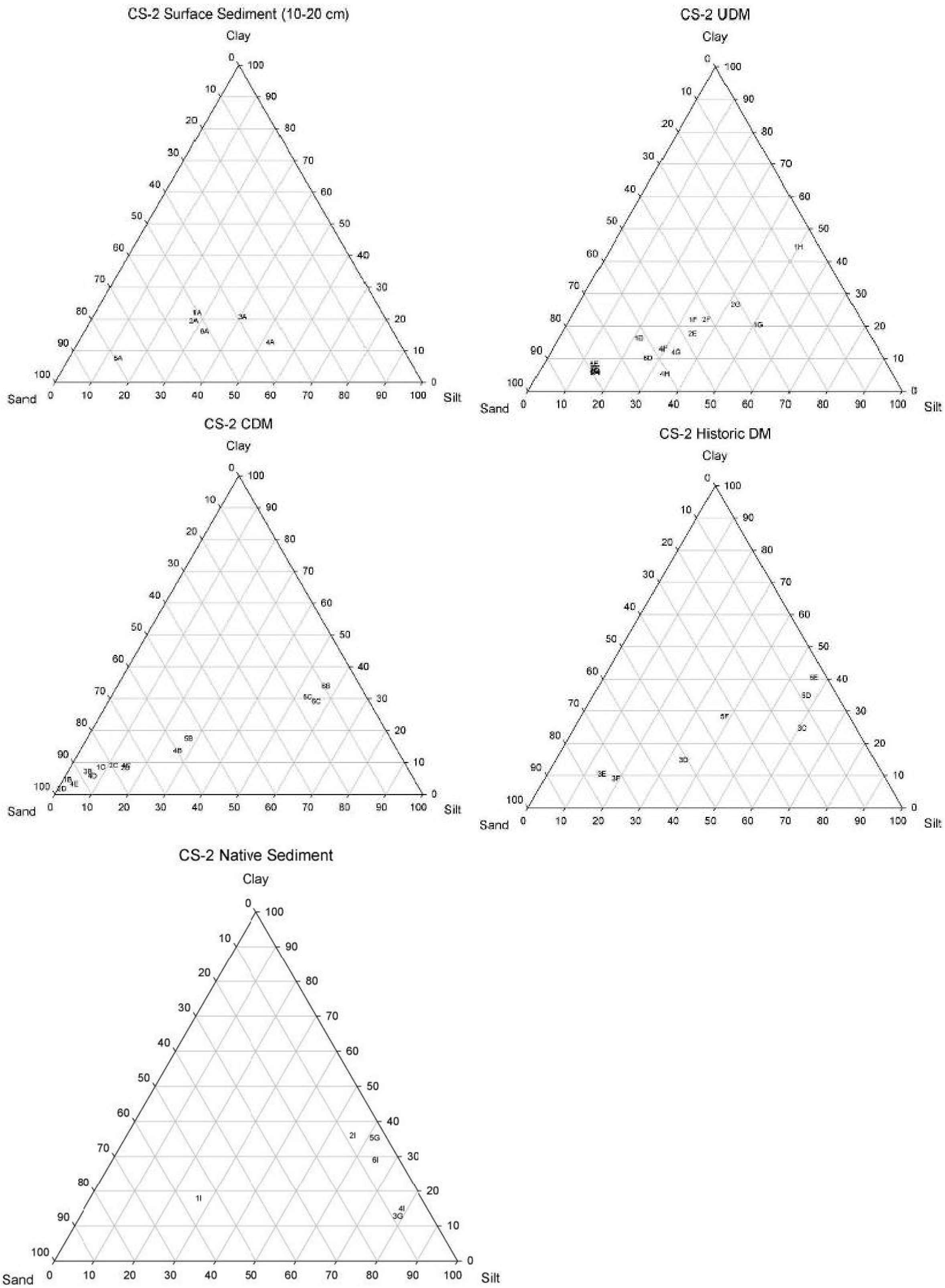

Figure 8. Ternary grain size plots of the CS-2 mound layers.

DISCUSSION

The STNH-N and CS-2 capped mounds at CLDS are among the earliest engineered open-water caps. As such, they have been studied periodically to assess the long-term stability of this dredged material management technique. There are two sets of processes governing the movement of contaminants within buried sediments and into overlying waters where they might be available to the ecosystem. Physical processes, such as scouring of bottom sediments by tidal or storm-related currents, disturbance by trawling, or mixing resulting from burrowing of organisms, can cause redistribution of sediments. This is of potential concern for capped mound settings where the sediment redistribution could result in UDM at or near the sediment-water interface. Chemical processes, such as dissolution of contaminants into surrounding pore water, can allow previously sediment-bound contaminants to move into the pore space of the sediment. If pore waters can actively exchange with near-surface pore water or overlying water, contaminants might become available to biota. This type of pore water exchange process has been shown to be virtually non-existent for a capped mound setting where there is no mechanism for active flux of water through the mound, such as exists at STNH-N and CS-2 (Murray et al. 1994).

Previous investigations have shown both the STNH-N and CS-2 mounds to be stable, with no evidence of physical disturbance of mound components or chemical migration (Sumeri et al. 1991, Fredette et al. 1992, Murray et al. 1994, Silva et al. 1994). This paper reports on physical results of the May 2004 coring investigation which was designed to provide additional assurance of mound stability 20+ years after formation of the STNH-N and CS-2 mounds with the following objective: Compare the physical distribution of sediment intervals within the cores with expected values based on core location on the mound and on previous data to assess the physical integrity of the caps. A separate paper will address the results of chemistry profiles of the cores compared to original mound constituents.

To provide a context for discussing the physical condition of the STNH-N and CS-2 mounds, a review of the formation of the mounds is presented below. Maps of mound configuration, generated as part of the original mound construction, were used to select coring locations in the May 2004 study and as a context to evaluate the resulting data. The mound horizons were evaluated as an independent data set and compared with historical data to address the objective. These data also allowed addressing an ancillary objective, identifying mound variability over a short (meters) distance scale.

Review of Mound Formation

The distribution and characteristics of sediment at each capped mound represent the net product of a series of events, both natural and anthropogenic. Some of these events took many years (e.g., natural deposition of fine-grained sediment), and others were completed within a single day (e.g., disposal of a barge load). Natural transport and accumulation of sediments occur throughout Long Island Sound and would have occurred before, during, and after discrete dredged material disposal events. Disposal of dredged material in the vicinity of CLDS took place throughout much of the twentieth century, prior to detailed record keeping of dredging and disposal activities. Hence, the presence of historic dredged material from a number of potential sources was expected in the vicinity of both cap sites. The disposal events for the STNH-N and CS-2 capping projects were grouped around taut-wire moored buoys or specified disposal targets, and the dates, sources, and volumes of disposed material are reasonably well-known. Subsequent deposition and reworking of surface material is assumed to have occurred following the completion of disposal activity (1979 for STNH-N and 1983 for CS-2) until the present. Recently, during the 2003-2004 season, disposal at the CDA03 buoy, located approximately 300 m to the southwest of the STNH-N mound, could have resulted in accumulation of dredged material on top of the cap (Figures 2 and 3).

For interpretation and discussion, the depositional stratigraphy identified in the 2004 cores was grouped into presumed horizons: base material of native Long Island Sound sediment, older dredged material (DM) with unknown source characteristics, dredged material unsuitable for unconfined open ocean disposal (UDM), capping dredged material (CDM) placed at the sites to sequester the contaminated UDM, and surface sediment representing recent deposition and reworked upper CDM (Table 1). Our knowledge of the characteristics and distribution of material in each of these horizons is uneven given the lack of records for the historic DM and given the heterogeneous nature of the UDM and CDM, which were collected from several harbors, depths, and locations and deposited in bulk on the seafloor over existing historical deposits. The following provides a review of the chronology of mound formation and the known characteristics of materials used in the two capping projects.

STNH-N History

The Stamford-New Haven project was the first planned open water capping operation performed in the United States. The seafloor of the area was surveyed prior to mound development to establish depths across the intended site (SAI 1979a). The seafloor had some irregular topography, likely the result of historical disposal, but the pre-placement surveys were not designed to document the older dredged material. Development and capping of the STNH-N mound was performed in 1979 and is summarized below.

Approximately 31,000 m^3 of UDM was deposited at a taut-wire marker buoy at STNH-N in April-June 1979. The material was mechanically dredged from Stamford Harbor and transported and disposed at STNH-N using split-hulled barges. Pre-dredging sediment sampling characterized this UDM as predominantly silts and clays with elevated levels of oil and grease, volatile organics, and metals.

Following placement of the UDM, a bathymetric survey revealed a well-defined mound rising approximately 2 m off the bottom with some elongation of the peak to the southwest and a more extensive mound apron extending to the east and southeast (Figure 3 and Figure 4-1 from SAI 1979d). Comparison of the post-disposal survey results with the pre-disposal bathymetry allowed for mapping of the UDM thickness (Figure 3). Note that the outer 20-cm contour in the figure is approximate given the presumed accuracy of the bathymetry measurements in 1979. Diver and grab sampling surveys identified the mound surface as gray cohesive clay clumps 20-30 cm in diameter scattered within a matrix of black oily silt and watery clay (SAI 1979d, e). These surveys provided an additional assessment of the full extent of the mound. The black silty material was spread as a thin layer over oxidized sediment at the margin of the mound. The apron of UDM rapidly thinned from approximately 50 cm thick at the mound margin to 3-6 cm thick at a distance of 50 m and to 1-3 cm thick at a distance of 100 m beyond the mound margin (SAI 1979d).

Following placement of the UDM, approximately 112,000 m^3 of coarse-grained CDM was deposited over the STNH-N mound in June 1979. The material was hydraulically dredged from the mouth of New Haven Harbor and transported and disposed at STNH-N using a hopper dredge. The CDM was not analyzed for chemistry but was characterized as silty, clayey, fine-medium sand with shell fragments (Fredette et al. 1992). Approximately 65,000 m^3 of the CDM was placed near the center of the mound, and the remainder was placed within a band approximately 100 to 300 m from the mound center. Comparison of a bathymetric survey performed after cap placement with the pre-cap survey indicated an estimated cap thickness of 1-2 m over the majority of the mound (Figure 3).

Comparison of the bathymetry survey performed following STNH-N formation (SAI 1979e) with a follow-up survey performed 12 years later (Silva et al. 1991) revealed that the overall morphology of the mound remained the same, but that the height above the seafloor was reduced by approximately 1 m. Given that cores recovered from the mound during the 1990 survey revealed an intact cap layer, the reduction in mound height was attributed to consolidation of mound components and the underlying seafloor (Silva et al. 1991, Fredette et al. 1992, Silva et al. 1994). The results of a 2005 bathymetric survey (ENSR 2006) are presented in Figure 3 along with overlays of the previously mapped primary UDM mound extent and CDM cap thickness. This survey, performed 26 years after the formation of STNH-N, is similar to the 1991 survey; the mound retained its original morphology of a nearly 2 m rise above the surrounding seafloor.

CS-2 History

The CS-2 mound was formed in 1983, four years after STNH-N, as part of an extensively monitored follow-up capping study. Baseline surveys at CS-2 prior to mound formation included bathymetry, sediment-profile imaging (SPI), side-scan sonar, and diver observations. The bathymetric survey indicated complex topography with relief of approximately 1 m and apparent coarse dredged material in the northeast portion of the survey area (Morton 1983). SPI survey data indicated habitat disturbance at several stations on the eastern margin of the survey area (200 and 400 m east of the disposal buoy) consistent with older dredged material. Diver surveys conducted near the center of the site reported cohesive oxygenated silt with very few shell fragments and no evidence of recent dredged material disposal (Morton et al. 1984). The side-scan survey revealed large patches of high reflectance material consistent with older dredged material deposits in the eastern portion of the survey area (Morton et al. 1984). Development and capping of the CS-2 mound was performed in 1983 and is summarized below.

Approximately 30,000 m^3 of UDM was placed at CS-2 in April 1983. The material was mechanically dredged from Reach 1 in Black Rock Harbor and transported and disposed at CS-2 using split-hulled barges (Morton et al. 1984). Pre-dredging sampling characterized the Black Rock material as highly contaminated with both organic and inorganic compounds, including oil and grease, PAH, copper, and zinc (Rogerson et al. 1985 and Fredette et al. 1992).

Following UDM placement, a bathymetric survey documented the presence of an elliptical shallow mound, approximately 200 m east-west and 100 m north-south with a maximum elevation of 1 m above the surrounding sea floor (Figure 4-4 from Morton et al. 1984). This mound contrasted with the initial UDM deposit at STNH-N (which had a similar volume of UDM) with a lower height and broader dimensions indicating that the Black Rock material was less cohesive than Stamford Harbor material, and tended to spread out more following placement on the sea floor. Diver observations and a side-scan sonar survey noted a flat deposit of dredged material with clay clumps, wood fragments, shells and coarse-grained material centered on the disposal buoy. Following characterization of the CS-2 UDM mound, an additional 8000 m^3 of material from Reach 3 in Black Rock Harbor was placed at CS-2 in May 1983.

Following placement of the UDM, approximately 42,000 m^3 of coarse-grained CDM was deposited over the CS-2 mound in May-June 1983. The material was mechanically dredged from outside the New Haven Harbor breakwater and transported and disposed at CS-2 using split-hulled barges. The material was characterized as dark grey coarse sand (Fredette et al. 1992). A bathymetric survey conducted to assess the distribution of CDM over CS-2 indicated that most of the capping material was placed south and west of the disposal buoy, while the UDM was more closely centered and slightly to the east. During capping operations at CS-2, there were some problems with the operation of the Loran receivers used for locating capping points, and tug operators instead used the buoy as a reference point for most of the barge loads (Morton et al. 1984). The resulting cap layer varied in thickness from 20 to 140 cm and formed roughly an equilateral triangle pointing south with sides approximately 250 m long (Figure 4). The thickest deposits were over the southern point of the triangle, but the cap at the center of the mound was at least 80 cm thick over a broad area (Morton et al. 1984).

Following the completion of the cap, the surface of the mound was surveyed extensively with side-scan, SPI, and divers. Side-scan results showed high reflectance material centered on the mound and evidence of cratering from individual barge loads (Morton et al. 1984). Divers observed a 2-cm layer of fine sand over sandy gravel with ripples and patchy distribution of shell fragments, clay clumps and wood debris at the center of the mound. They also observed rapid changes in elevation of 1-2 m over the surface of the mound in the recently-deposited dredged material. The results of the SPI survey indicated that the CDM was thicker than camera penetration from the center of the site to the margin of the bathymetrically observable mound. Beyond the margin of the mound, the thickness of the CDM decreased quickly to thin layers (1 to 4 cm) over thin layers of UDM (1 to 9 cm) (Morton et al. 1984).

Another round of surveys was performed one to two months following completion of the cap, which included collection of sediment cores, bathymetry, SPI, and diver observations. The bathymetric survey indicated consolidation in the thickest portion of the mound, and divers noted a 2-cm deposit of flocculent soft sediment over the CDM and relatively flat topography compared with the previous survey. The surface was scattered with clay clumps with some peat, and the western region was littered with chunks of wood, fishing gear and rope (Morton et al. 1984). The SPI survey also reported a 2 cm layer of silt on top of the CDM and a similar distribution of CDM and UDM compared to the previous SPI survey. The flanks of the mound had thin layers of UDM (<2 cm) covered by thin layers of sand that were beginning to be mixed by bioturbation (Morton et al. 1984).

Comparison of the bathymetry from the survey performed following CS-2 formation (Morton et al. 1984) with a follow-up survey performed eight years later (Silva et al. 1991) revealed that the overall morphology of the mound remained the same. Similar to STNH-N, cores recovered from the CS-2 during the 1990 survey revealed an intact cap layer (Fredette et al. 1992). The results of a 2005 bathymetric survey (ENSR 2006) are presented in Figure 4 along with overlays of the previously mapped primary UDM mound extent and CDM cap thickness. This survey, performed 22 years after the formation of CS-2, was similar to the 1990 survey; the mound still retained its original morphology of approximately a 0.75 m rise above the surrounding seafloor.

Physical Distribution of Mound Sediments

The physical characteristics of the CDM generally differed from those of the UDM at both STNH-N and CS-2. These characteristics (color, texture, organic content, and odor) were used to classify the layering within the 2004 cores and to assess the physical integrity of the CDM over UDM mound structure 20+ years after formation. The earlier investigations that characterized the mound structure following formation were used to select a range of locations over the mounds for coring in the 2004 study to ensure representative coverage. Cores were of sufficient length to capture the full mound stratigraphy at each location.

STNH-N

All six of the STNH-N cores showed clearly differentiable CDM and UDM intervals. The overall cap thickness ranged from approximately 75 cm to 145 cm (Table 2). The cap was made up primarily of CDM, but also contained a surficial layer ranging in thickness from 10 to 30 cm and consisting of fine sediment grading into CDM. This surficial layer was assumed to be the result of deposition occurring since mound formation that has been reworked into the CDM through biological activity and surface disturbance.

Taking into account the overall mound consolidation that was documented following formation, the thickness of the CDM recorded in the 2004 cores (ranging from 45 at Core 1-5 to 130 at Core 1-2) was in good agreement with the original estimated CDM thickness at each location (ranging from just under 100 cm at Core 1-5 to just over 200 cm at Core 1-2). For 2004 cores collected in close proximity to cores from the 1990 study, a thicker CDM layer was recorded in two of the 2004 cores relative to the 1990 cores (Table 3). This may have been due to recent dredged material that may have accumulated on the mound during the 2003-2004 disposal season, when the CDA03 disposal buoy was located approximately 300 m to the southwest of the STNH-N mound. Minor differences in CDM thickness may also be due to natural variation within the intervals or to differences in vibracore equipment or techniques between the two studies that resulted in increased compaction of the 1990 cores. The lack of a trend toward reduced CDM thickness in 2004 coupled with the record of deposition of fine-grained sediment over the CDM provided evidence that surficial erosion and disturbances had not occurred at a level that would affect the CDM layer.

The transition from CDM to underlying UDM was visually quite distinct in all six of the cores based on color and texture (Figures 5 and 7). Banding of CDM and UDM, indicating potential interlayering or mixing at the time of formation, was only noted in the lower cap interval of Core 1-5. Although the fines content was similar between the CDM and UDM in some samples, the CDM had a larger fraction of shells and very coarse material (Figure 7). The UDM was generally dark in color and uniform in appearance, but with some variability of color and texture within the interval. The transition from UDM to underlying historic dredged material was generally less defined than the UDM-CDM interface.

The UDM interval was identified in all of the 2004 cores and ranged in thickness from approximately 20 cm in Core 1-5 to 85 cm in Core 1-4 (Table 2). Once again taking mound consolidation into account, these UDM thicknesses were in good agreement with the original estimated UDM thickness at each location (ranging from just over 60 cm at Core 1-5 to 120 cm at Core 1-4). For 2004 cores collected in close proximity to cores from the 1990 study, a thicker UDM layer was recorded in both of the 2004 cores relative to the 1990 cores (Tables 2 and 3), again potentially due to natural variation or greater compaction of the 1990 cores during collection.

Historic dredged material was identified beneath the UDM in all six of the cores. Four of the cores penetrated through the dredged material into base material of native Long Island Sound sediments. The boundary between the historic dredged material and underlying native sediment was not well-defined, likely because the disposal of historic dredged material occurred intermittently over an extended period of time (decades).

Table 2. Thickness of sedimentary horizons (cm) in cores collected from capped mounds in 2004.

Mound	Layer	Core ID/Layer thickness					
STNH-N		**1-1**	**1-2**	**1-3**[R]	**1-4**	**1-5**	**1-6**[R]
	CAP-Surficial	10	15	30	30	30	20
	CAP-CDM	120	130	105	60	45	125
	UDM	60	55	75	85	20	80
	DM	105	80	75	10	50	60
	Native Sediment	0	10	0	95	145	5
CS-2		**2-1**	**2-2**[R]	**2-3**	**2-4**	**2-5**	**2-6**[R]
	CAP-Surficial	20	20	20	30	10	20
	CAP-CDM	65	75	35	55	60	30
	UDM	85	75	0	35	0	100
	DM	25	30	55	15	50	35
	Native Sediment	95	70	135	115	145	45

[R] Field Replicate

Table 3. Thickness of sedimentary horizons (cm) in cores collected from capped mounds in 1990.

Mound	Layer	Core ID/Layer thickness				
STNH-N		**40N**	**40W**	**CTR**	**60E**	**40S**
	CAP-CDM	80	50	110	75	140
	UDM	40	40+	50	20-40	20
	Core length	125	160	160	110	180
CS-2		**80N**	**CTR**	**80NE**	**40E**	**50W**
	CAP-CDM	60	40	80	65	25
	UDM	0	40-80[1]	35	0	0
	Core length	130	120	125	120	140

[1] The bottom 40 cm may be historic dredged material

CS-2

The CDM over UDM sequence was identified in four of the six CS-2 cores. In the remaining two cores, a CDM interval was identified with no apparent underlying UDM interval. The overall cap thickness ranged from approximately 50 to 95 cm (Table 2). Similar to STNH-N, the cap was made up primarily of CDM, but also contained a surficial layer, ranging in thickness from approximately 10 to 30 cm. The surficial layer was coarser in texture than at STNH-N, consisting of nearly even sand and silt-clay content (Figure 8). In addition, the CDM layer at CS-2 showed more variability in color and texture than at STNH-N, making it harder to differentiate from the surficial material (Figure 8).

The 2004 core locations are shown on the original cap thickness map prepared following mound formation/capping (Figure 6). Comparison of the thickness of the CDM recorded in the 2004 cores (Table 2) with the original mapped CDM thickness (Figure 6) revealed greater variability but no consistent trend, i.e., there was no observable trend toward reduced CDM thickness in the 2004 cores relative to the original estimates. None of the 2004 cores were collected in close proximity to those in the 1990 study, and a direct comparison of CDM thickness cannot be made.

The transition from CDM to underlying UDM was visually distinct in the four cores in which UDM was present based on color and texture (Figures 6 and 8). Similar to STNH-N, the fines content in the UDM was sometimes similar to the CDM, but the CDM had a larger fraction of shells and very coarse material (Figure 8). Also similar to STNH-N, there was some variability of color and texture within the UDM interval, and the transition to underlying historic dredged material was generally less defined than the UDM-CDM interface.

The UDM interval identified in the four cores ranged in thickness from 35 cm in Core 2-4 to 100 cm in Core 2-6 (Table 2). Similar to the CDM, these interval lengths showed more variability than the STNH-N cores when compared to the original estimated UDM thickness at each location (Figure 6). This variability was highlighted by comparison of the 2004 replicate cores and comparison with the 1990 core data (Tables 2 and 3). Cores 2-2 and 2-6 were collected within several meters of each other (Figure 6), but the UDM thickness measured in the two cores varied by about 25 cm (Table 2, Figure 6). Core 2-5 was positioned in the general direction of the 1990 Core CTR but closer to the mound center. A relatively thick, 40+ cm layer of UDM was recorded for Core CTR, and a similar or greater thickness was expected at Core 2-5, positioned closer to the mound center. However, no UDM interval was found in Core 2-5.

Historic dredged material was identified beneath the UDM or CDM in all six of the cores, varying in thickness from 15 to 50 cm (Table 2). As expected, this material was variable in texture (Figure 8). All six of the cores penetrated into base material of native Long Island Sound sediments. Similar to STNH-N, the transition from the overlying historic dredged material to the underlying native sediment was not well-defined.

Cores 2-2 and 2-6 were collected as replicates within several meters of each other. In addition to the variability in the UDM intervals for the two cores noted above, the overall cap thickness varied by 45 cm between the two cores (Table 2, Figure 6). This variability was expected given that both the CDM and UDM at CS-2 were placed using mechanical dredging/split-hulled barge disposal (Fredette et al. 1992).

Sediment Distribution Summary

The cores collected in the 2004 study at STNH-N and CS-2 provide clear and consistent data showing that the CDM over UDM sequence remains intact with a well-defined interface between the intervals at both mounds. At STNH-N, the thickness of the CDM interval compared well with the distribution of the CDM mapped following the original formation of the mound, taking into account the expected long-term consolidation of the hydraulically dredged CDM. At CS-2, the thickness of the CDM was more variable, reflecting the mechanical dredging that was used in the project, but there was no apparent reduction of CDM thickness over time. At both sites, a surficial layer was noted above the CDM, indicating net deposition since formation of the mounds. This layer was more distinct and thicker at STNH-N, potentially the result of its location near the center of CLDS, with significant dredged material disposal over the past 25 years (see disposal mounds noted on Figure 2). In the 2003-2004 disposal season, the disposal buoy was located approximately 300 m to the southwest of STNH-N, and depth-difference maps calculated from subsequent bathymetric surveys indicated a thin layer (up to 0.25 m) of deposition over at least the southern portion of the mound (Figure 5). Taken together, the maintenance of the CDM thickness over time and the overlying net deposition provide evidence that the UDM interval remains physically isolated from the overlying waters and unaffected by potential erosive events or other surface disturbances.

CONCLUSIONS

The STNH-N mound is one of two capped mounds created in 1979 as the first engineered open water caps in the United States. The CS-2 mound was created in 1983 as part of a follow-up capping project. Extensive investigations performed during and following formation of these mounds revealed that the contaminated UDM had been successfully capped at both sites. The May 2004 survey included collection of six long cores from each of the mounds, covering areas with a range of expected UDM and CDM thicknesses. Follow-up investigations included detailed logging of core stratigraphy and chemical analyses of selected core intervals. The primary objective reported here was to: Compare the physical distribution of sediment intervals within the cores with expected values based on core location on the mound and on previous data to assess the physical integrity of the caps. Chemical profiles within the cores will be compared to previous data to assess the maintenance of chemical isolation of contaminants within the UDM interval.

The cores collected in the 2004 study at STNH-N and CS-2 provide clear and consistent data showing that the CDM over UDM sequence remains intact with a well-defined interface between the intervals at both mounds. At STNH-N, the thickness of the CDM interval compared well with the distribution of the CDM mapped following the original formation of the mound, taking into account the expected long-term consolidation of the hydraulically dredged CDM. At CS-2, the thickness of the CDM was more variable, reflecting the mechanical dredging that was used in the project, but there was no apparent reduction of CDM thickness over time. At both sites, a surficial layer was noted above the CDM, indicating net deposition since formation of the mounds. This layer was more distinct and thicker at STNH-N, where recent dredged material has likely been deposited. Taken together, the maintenance of the CDM thickness over time and the overlying net deposition provide evidence that the UDM interval remains physically isolated from the overlying waters and unaffected by potential erosive events or other surface disturbances. These physical results are consistent with chemistry profiles reported elsewhere (ENSR 2005). The long cores also sampled historical dredged material and native sediments underlying the capped mounds, the sedimentological characteristics and chemical profiles of these layers will provide valuable insights into pre-1979 conditions in Long Island Sound and processes associated with dredged material management.

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