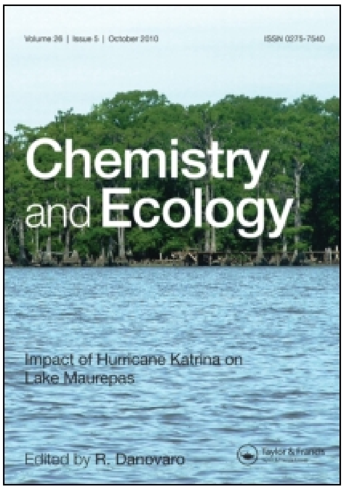

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CHEMICAL STABILITY OF CAPPED DREDGED MATERIAL DISPOSAL MOUNDS IN LONG ISLAND SOUND, USA

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Geochemical analysis and visual inspection of cores collected from capped dredged material mounds revealed that in many cores, cap material was clearly distinguishable, both visually and chemically, from mound material. Contaminated dredged sediments were disposed in Long Island Sound eleven and seven years prior to sampling, and capped with uncontaminated dredged sediments. Core data provided no conclusive evidence of physical disturbance of, or chemical migration from, the contaminated mound sediments. Obvious chemical gradients of contaminant concentrations, which we propose are indicators of chemical migration, were not detected in the cores. Heterogeneity of the cap and mound sediments in some cores made the interface less distinct. We postulate that the preservation of spatial variability of sediment texture and associated contaminants observed within dredged material mounds is a result of the dredging process. Preservation of the textural and contaminant history of dredged sediments within fine-grained cohesive cap materials provides evidence of the absence of physical or chemical disturbance.

INTRODUCTION

In order to confine contaminated sediments deposited in subaqueous environments, dredging and disposal operations have created mounds of contaminated material covered with a cap of cleaner dredged sediments. These 'capping' operations were designed to meet regulatory guidelines under which any contaminants disposed in the ocean must be rapidly rendered harmless (EPA/USACE, 1977, 1991). To ensure continued compliance with regulations, capped mounds have typically been monitored for the presence of physical, biological and chemical indicators of ecosystem exposure to contaminants (e.g. NRC, 1990). Monitoring efforts have not detected any marked environmental impact or breaching of the caps by contaminants, but neither have they provided a clear picture of the fate of contaminants during the disposal operations or after burial (O'Connor and Moese, 1984; SAIC, 1984).

The assumption behind the design of capping operations is that a layer of relatively clean sediment deposited over a stable mound of contaminated sediment will prevent release of contaminants into the water column or benthic ecosystem (Palermo, 1991). The cap constitutes an impenetrable barrier against both physical disturbance and chemical migration. Sufficiently thick caps have been effective in preventing physical disturbance of contaminated sediments by burrowing organisms, powerful storms, and anthropogenic disturbances such as bottom trawlers (e.g. Morton, 1989).

Although many capping studies have included bulk sediment analyses of grab samples of the surface of capped mounds, there have been few detailed studies of chemical profiles within capped mounds (but see: O'Connor and Moese, 1984; Truitt, 1986, Bokuniewicz, 1989; Sumeri *et al.*, 1991). Despite the lack of evidence of cap failure, questions concerning the long-term chemical integrity of mounds have persisted.

The cap is assumed to isolate contaminants chemically through the following processes: a) by increasing the distance over which diffusion must occur if contaminants are to be released to the water column; b) by diluting the contaminant concentrations, and consequently reducing the chemical gradient of the sediments near the sediment-water interface; and c) for metal contaminants covered by sand caps, by increasing the oxygenated zone near the sediment-water interface where iron and manganese oxides coprecipitate and sorb metals from pore waters (O'Connor and O'Connor, 1983).

Bulk chemical analyses and visual inspections of sectioned, vertical cores of some of the earliest mounds created could help establish that caps have effectively isolated contaminants from the environment and that placement of the cap did not disturb the mound. Fragmentary evidence from coring studies conducted thus far has supported this notion and provided impetus to investigate the capped mounds in New England.

Several capping projects have been completed by the New England Division of the Army Corps of Engineers at the Central Long Island Sound Disposal Site (CLIS; Figure 1). The Stamford-New Haven project (STNH), completed in 1979, was the first formal capping project completed in the United States. Subsequent projects at CLIS included: Norwalk (1980–81); Mill-Quinnipiac River (1982); and Experimental Cap Sites 1 and 2 (1983; Figure 1).

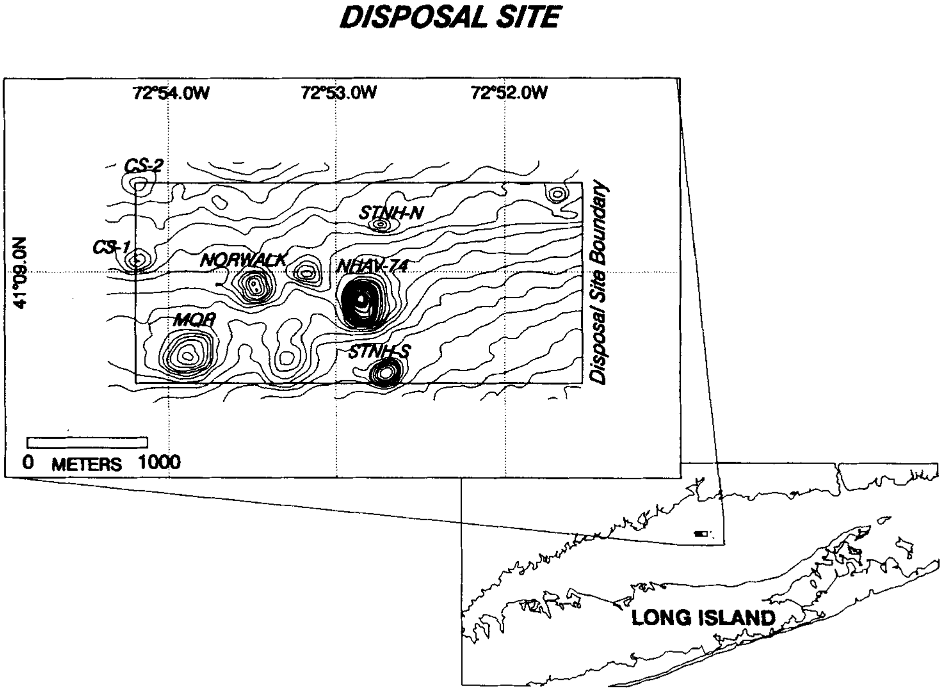


Figure 1 Location of Stamford-New Haven North (STNH-N), Stamford New Haven South (STNH-S) and Experimental Cap Site 2 (CS-2) capped mounds at the Central Long Island Sound Disposal Site. Other disposal mounds at this site include: Norwalk, Mill-Quinnipiac River (MQR), Experimental Cap Site 1 (CS-1), and New Haven 1974 (NHAV-74). Bathymetric contours are 25 cm intervals.

Coring investigations of an experimentally capped mound at the New York Bight Mud Dumpsite revealed that the sand-mud interface was distinct visually and could be recovered with vibracoring operations (Bokuniewicz, 1989). Grain-size analysis of cores showed that the transition from sand to mud occurred over a distance of less than a few centimeters.

The preliminary results of vertical core studies conducted by the Waterways Experiment Station on a capped mound in the Duwamish waterway indicated the potential for obtaining quantitative data on the chemical isolation of capped mounds (Truitt, 1986). The interface between the cap materials (sand) and the mound materials (sandy, clayey silt) was distinct, visually and chemically. Samples were collected at 4 cm intervals on either side of the visual interface (ten in the cap, seven in the mound) and analyzed for total concentrations of polychlorinated biphenyls (PCBs), copper (Cu), lead (Pb), and zinc (Zn). Profiles of lead and Arochlor 1242 PCB in one core showed sharp increases in concentration at the interface from the cap to the mound. These results supported the conclusion that the mound and cap materials formed a sharp, relatively unmixed interface.

The results of these previous studies indicated that capped mounds could be effective at short-term chemical isolation. They also suggested that coring old mounds could provide a longer-term perspective; this insight helped prompt reinvestigation of the capping operations in Long Island Sound. A coring investigation was initiated in 1990 to revisit three of the capped mounds located at CLIS: Stamford-New Haven North (STNH-N) and South (STNH-S), and Cap Site 2 (CS-2).

Assumptions

Based on the evidence from the New York and Duwamish studies, the initial assumptions of this investigation were that the sand caps should have relatively low levels of contaminants and should be chemically and/or visually distinct from the underlying contaminated material. Silt caps were not expected to be as visually distinct due to the similarity of grain size between the clean and contaminated sediments. Capping materials used at CLIS reflected a wide variety of sources, textures and contaminant levels, based on pre-dredging analysis of surface samples from source areas (Table 1). Despite the apparent heterogeneity of material available for capping, the range of measured contaminant values in cap materials were, in each case, at or below the minimum values measured in materials to be isolated (Table 1).

With these assumptions in mind, the following working hypotheses formed the basis of the investigation:

1. If the interface is distinct visually, then the mound materials have been physically isolated by the capping operation.
2. If the interface is distinct chemically, then the mound materials have been chemically isolated by the capping operation.
3. If chemical gradients exist in the cap, then contaminants may be capable of migrating from mound to cap.

These hypotheses were implicit in the objectives of the study. We can examine the results with these two hypotheses in mind:

H1: The interface between the cap and mound is visually distinct.

Table 1 Bulk sediment contaminant levels from pre-dredging cap and mound sources (all concentrations are ppm).

	Cap sources			*Mound sources*	
		New Haven		*Stamford*	*Black Rock*
	STNH-N	*CS-2*	*STNH-S*	*STNH-N, STNH-S*	*CS-2*
	Coarse Silty, clayey, fine-medium sand with shell fragments	Coarse Dark grey sands	Fine clay and silt	Black-grey organic clay silt, sand	Dark grey to black organic clayey silt; oil odour
Number		1 sample	3 samples	3 samples	1 sample
Oil and grease**	*	340	1750–3235	3560–28,900	8400–44,000
Cd	*	0.1	2.3–4.8	4.9–45.3	7.5–58
Cu	*	59	154–192	342–1167	890–3400
Zn	*	41	234–250	441–2417	560–1180

* No chemistry data available for outer harbour sediments, units in ppm.
** EPA method 9070A

H2: The interface between the cap and mound is chemically distinct.

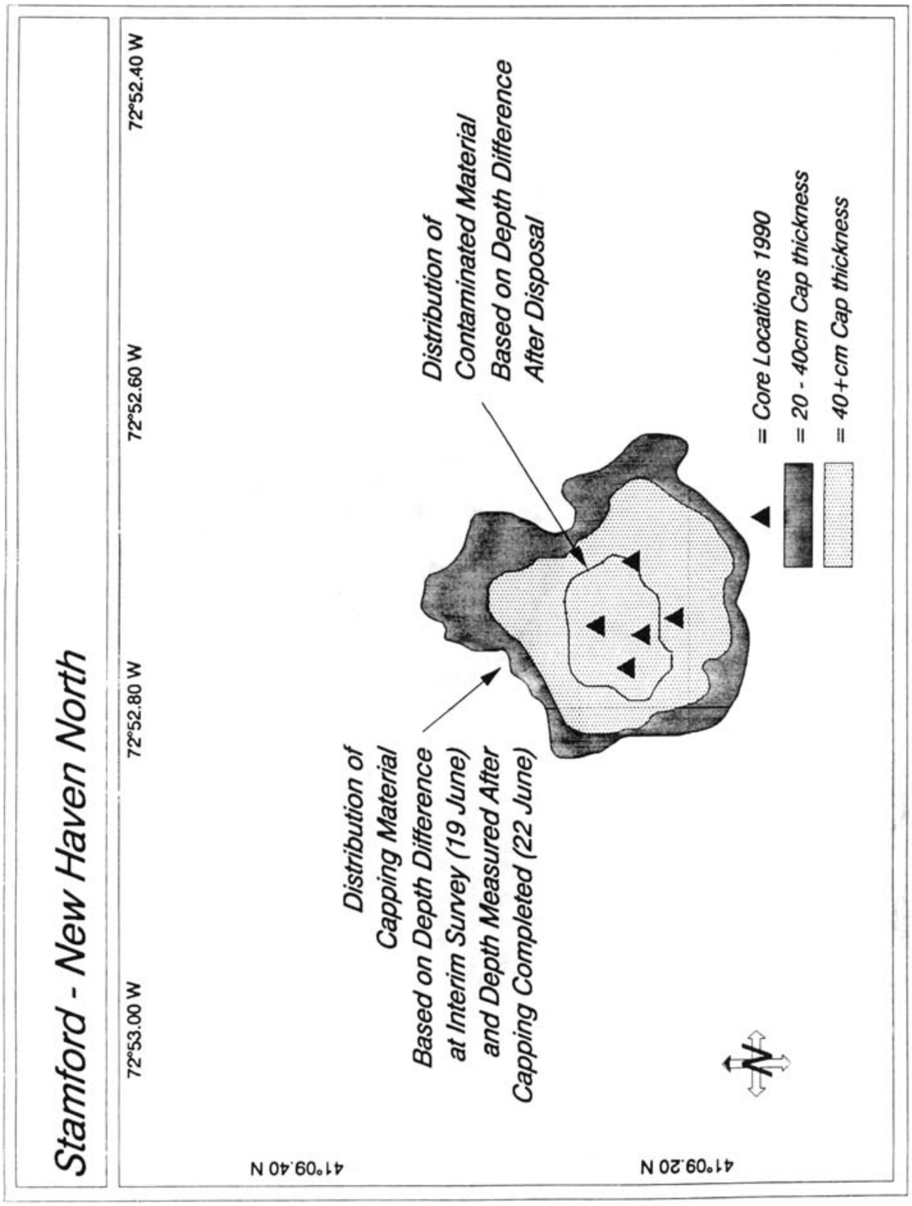
It is important to note two additional points: these hypotheses are separate, but there was no independent criterion for distinguishing the interface. Because these two hypotheses are independent, their validity does not depend on them both being true and congruent. This point raises a number of possibilities that will be discussed below. Also, because there were no independent means of identifying the interface, it is impossible to know whether it represented the original interface between mound and cap without some diagnostic marker (such as an immobile compound only present in the mound material). Consequently, testing the above hypotheses can lead to circular arguments. Nevertheless, distinct interfaces are discernible, and in many cores are coincident chemically and visually; it is these interfaces which are important in documenting the effectiveness of contaminant containment.

For management purposes, these distinctions are not crucial as long as the contaminants remain isolated from the biotic communities. However, it is useful to be able to investigate the fine-scale distribution of sediments and contaminants within historical mounds. This information can be used to evaluate the assumptions behind the design of capped mounds and to guide future investigations and capping operations.

METHODS

Core Recovery and Sampling

Capped mounds were cored in roughly cross-shaped sampling arrays (Figures 2–4) located away from the peak mound heights in an attempt to sample three distinct layers from each mound (cap, mound, base). During the summer of 1990, cores were collected aboard the R/V *Shock* (University of Rhode Island) with URI's large-diameter gravity corer and a vibracorer. Both of these corers had an inside diameter of 10.2 cm (4.0 in). A total of forty cores were recovered successfully from three mounds (STNH-H, STNH-S, CS-2); of these, fifteen were sampled for chemical analysis. The mean length of the cores was 1.74 m (range 1.16–2.5 m). Cores were identified by relative position; for example, STNH-N-CTR was recovered from the centre station on the STNH-N mound, CS-2-60W was recovered


Stamford - New Haven North
72°53.00 W
72°52.80 W
72°52.60 W
72°52.40 W
41°09.40 N
41°09.20 N
Distribution of Capping Material Based on Depth Difference at Interim Survey (19 June) and Depth Measured After Capping Completed (22 June)
Distribution of Contaminated Material Based on Depth Difference After Disposal
▲ = Core Locations 1990
▨ = 20 - 40cm Cap thickness
░ = 40+cm Cap thickness
N

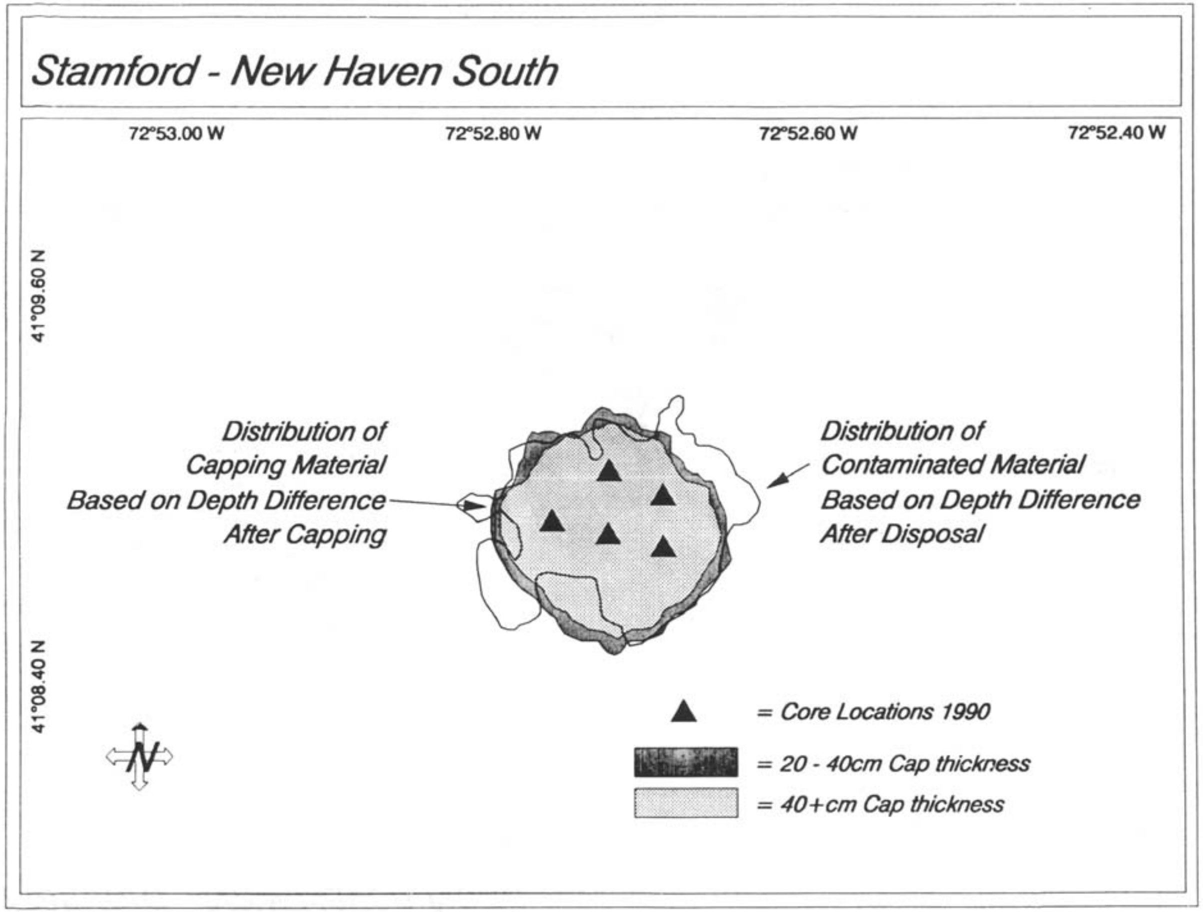
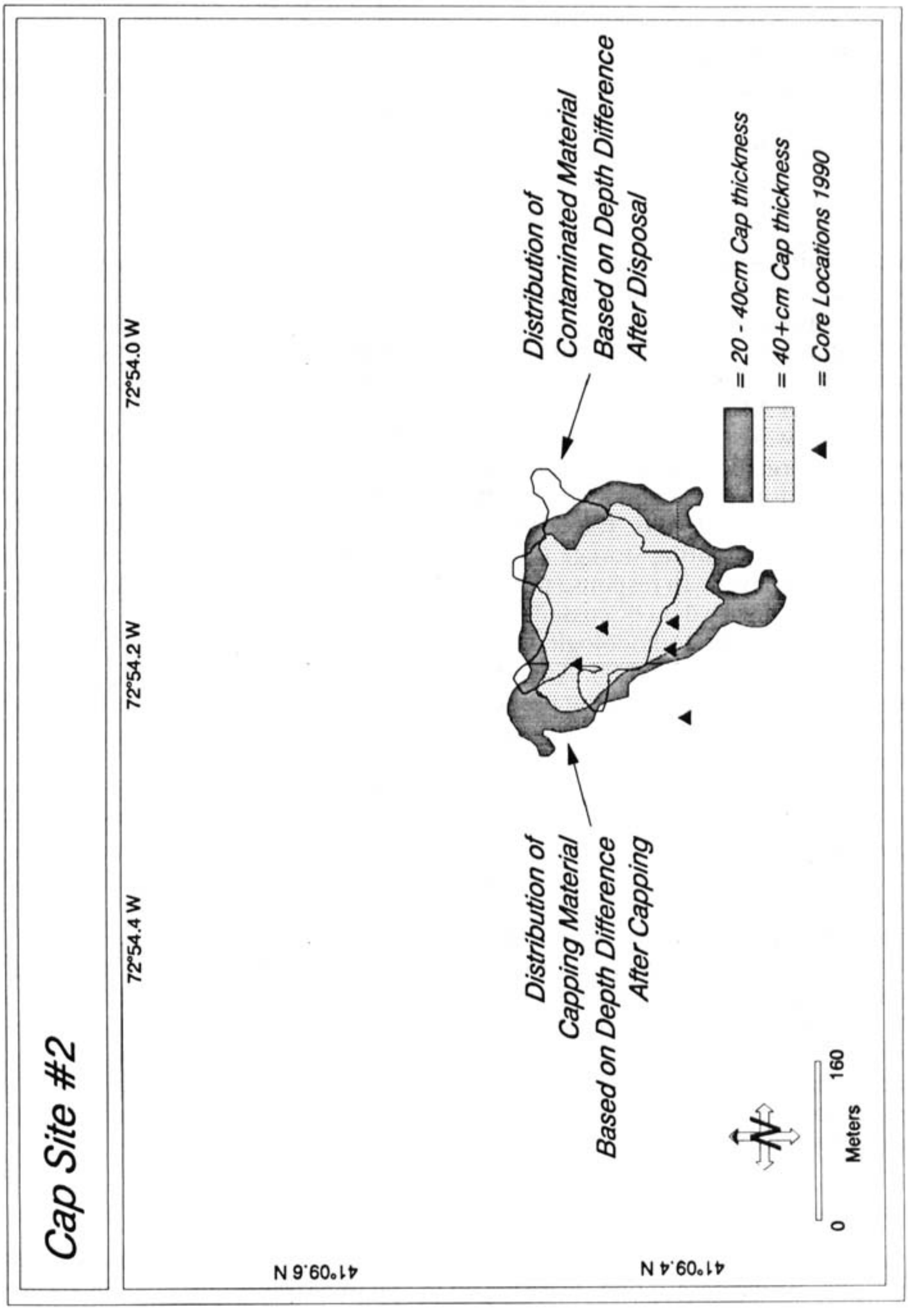


Figure 3 Location of geochemistry cores taken at the STNH-S capped mound.


Cap Site #2
72°54.4 W
72°54.2 W
72°54.0 W
41°09.6 N
41°09.4 N
Distribution of Capping Material Based on Depth Difference After Capping
Distribution of Contaminated Material Based on Depth Difference After Disposal
= 20 - 40cm Cap thickness
= 40+cm Cap thickness
= Core Locations 1990
N
0
160
Meters

60 m west of the centre station on the CS-2 mound.

The cores selected for geochemical analysis were split lengthwise, described, and measured. One split from each core was divided into 20 cm intervals, homogenized, stored in polyethylene bags, and refrigerated for later analysis of grain size and chemical contaminants. There was no evidence of organic contamination because of the use of plastic in storing samples. Proper chain-of-custody procedures were followed for all samples.

Analysis

Chemical analyses were conducted by the Army Corps of Engineers, New England Division, and associated contract laboratories. All core samples were analyzed for cadmium, copper and zinc as well as for total recoverable petroleum hydrocarbons (TRPHs) and grain size. One core from each mound was analyzed for pesticides and PCBs and three cores from each mound were analyzed for a suite of polyaromatic hydrocarbons (PAHs).

All analyses were performed within allowable holding times except for PAHs and semi-volatile organics (including the suite of pesticides). The 14 day maximum holding time before extraction was exceeded by 2–24 days for semi-volatile organics, and by 20–25 days for PAHs. Exceeding these holding times could have resulted in analyte degradation during storage with the potential to lower the measured levels below the actual levels. In response to this potential problem, the metals and TRPH results are the primary data discussed in this paper.

Standard US EPA methodologies were used for all analyses with only minor deviations (EPA/USACE, 1991). An in-house developed sulphuric acid cleanup was used for the PCB analysis, and the pesticide extracts were cleaned using a modified Florisil® procedure. The trace metal digestion procedure was modified to accommodate microwave energy instead of radiant heat.

Method blanks were below detection for all compounds measured except for five blanks of zinc (0.06–0.12 ppm) and two blanks of TRPHs (4.2 and 5.9 ppm). In addition, traces of several semi-volatile compounds (three phthalate compounds, phenanthrene and pyrene) were detected. These minor detections should have had no impact on the sample data.

Method blanks, surrogate recoveries, replicate analyses and matrix spike recoveries indicated good precision for the analyses except for one PAH and three zinc spike recoveries. These unacceptable spike recoveries were probably due to sample inhomogeneity since the direction and magnitude of the deviations were inconsistent. However, it is not possible to rule out some systematic problem with the accuracy of the zinc test. Poor spike recoveries for three pesticides (lindane, dieldrin and endrin) provided evidence that there could be some negative bias to the pesticide values due to matrix effects.

Limit of Data Interpretation

Profiles of contaminant levels were compared to visual descriptions and photographs. Visual descriptions were keyed to apparent transitions in grain-size or texture; these transitions were related to measured lengths of core contents. The measured contaminant levels represented homogenized 20 cm sections collected sequentially from the top of the core. In most cases, the visual transition points did not coincide with divisions between sampled sections. This limited definition of chemical transition intervals to 20 cm increments.

The hypothesis that the contaminants are chemically isolated is dependent, in our model, on a visual and chemical boundary between cap and mound, and the lack of chemical gradients in the sediment samples. This hypothesis is constrained largely by sampling. For example, it is impossible to distinguish whether an intermediate level of contamination results from an actual gradient in the sediment (which may indicate remobilization of contaminants) or artificial mixing, during the sampling process, of a sharp chemical boundary.

Statistical analyses were conducted in order to document the presence or absence of a sharp chemical boundary between sample intervals (Appendix A). Initially a principal components analysis (PCA) was conducted to reduce the large number of chemical analytes to a smaller, more workable number of uncorrelated variables (PCA axes). Each PCA axis represents a set of analytes which co-vary. Scores from the PCA axes then were examined for the presence of a sharp chemical boundary using regression analysis, conducted between the PCA axes and a set of dummy variables, each of which simulated a sharp boundary at a different depth interval. A single sharp chemical boundary was considered present when the R^2 value for a PCA axis and a dummy variable was close to 1. In addition, PCA axis scores for each depth interval were plotted to confirm the regression results.

Three different principal components analyses were conducted in this study. The first was run on all of the samples and included only those analytes sampled in all cores (three metals and TRPH). The second was run on nine of the cores which were sampled for three metals, TRPH, and PAHs. The third was conducted on only three cores and included all of the analytes. From these analyses, sharp boundaries were found for some cores using PCA axes generated from metals and TRPH data. The results indicate that metals and TRPH are the best boundary indicators for the cores examined. R^2 values for several of these PCA axes and their dummy variables are presented in the following discussion.

The frequency distribution of the resulting R^2 values, representing different combinations of metal and TRPH concentrations, was similar for all three sites. Plotting the R^2 data results in a biomodal distribution of values less than 0.5, and greater than 0.9 (Figure 5). This division is convenient for using the PCA analyses to describe the relative presence (> 0.9) or absence (< 0.5) of a boundary between sample intervals.

RESULTS

STNH-N

At STNH-N, the coarse-grained cap (sand and shells) was fairly uniform in texture (some bands of shell hash) and had low levels of contaminants (Figure 6). There was a sharp visual transition from the cap to the mound sediments. The mound sediments were relatively uniform in texture (black organic silty clay) with high levels of contaminants. Statistical analyses confirm the presence of well-correlated chemical boundaries at the visual cap/mound interfaces.

The ranges of contaminants measured in material visually identified as cap in three of the cores (CTR, 40S, 40N) at STNH-N were significantly lower than the concentrations measured in the underlying dredged material. These low values are attributed to the abundance of sand in STNH-N cap material, as fine-grained material tends to accumulate more contaminants. In these three cores, the visual and

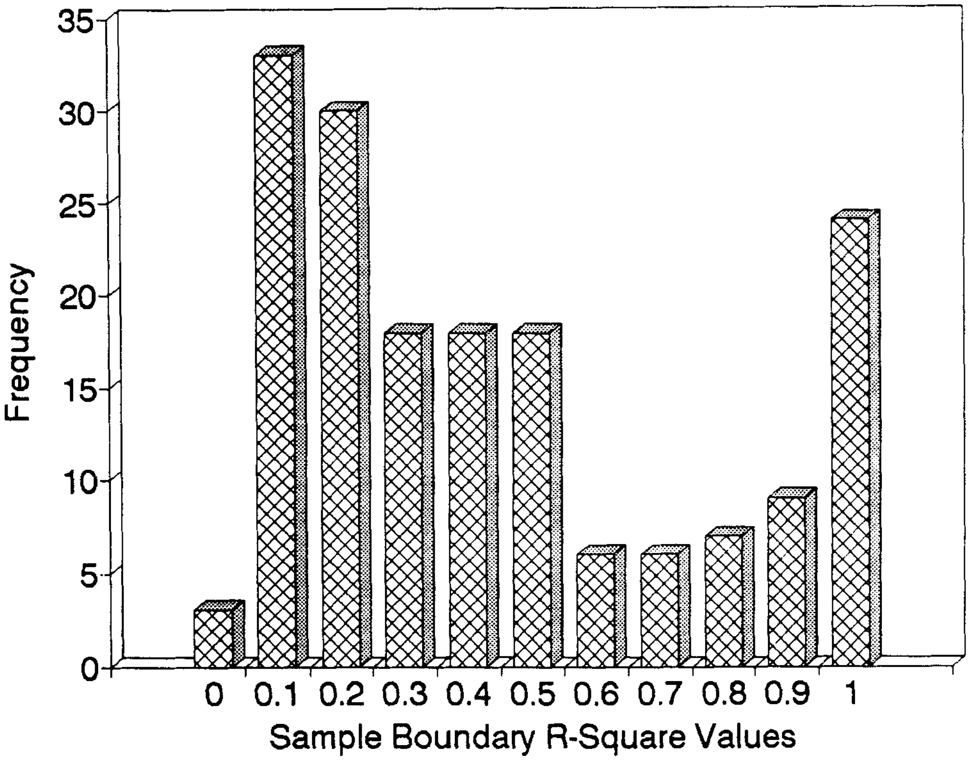


Figure 5 Frequency distribution of R^2 values resulting from boundary analysis of chemical components from STNH-N core samples. Values on x axis represent the maximum value of that interval.

chemical cap/mound boundary seem to be coincident. R^2 values for the cap/mound boundary documented in visual core descriptions are 0.984 at CTR, 0.915 at 40N and 0.613 at 40S. The relatively low R^2 of the boundary at 40S is probably an effect of the narrow band of apparent mound material documented in visual core descriptions.

A relatively high zinc concentration of 122 ppm in the 20–40 cm sampling interval of 60E was out of the range of zinc concentrations measured in the rest of the cap material at STNH-N (10–68 ppm). The concentrations of all other contaminants in 60E were typical of the low STNH-N cap material values. Quality analysis of the zinc data showed trace detections in some of the method blanks and high spike recoveries. However, it is possible that the detected zinc can be attributed to natural contaminant variation of dredged material, as 122 ppm is within the range of zinc measured in New Haven Harbor at sites destined for other disposal mounds (Table 1).

An R^2 of 0.989 occurs at 80 cm depth at 60E, above the visual cap/mound boundary, and appears to occur at a transition area between cap and mound (80–100 cm; sandy material with clay lumps). This transition zone is a potential mixed interface which extends over a maximum depth of 20 cm. No sample was taken below this transition zone.

The only evidence for a chemical gradient at STNH-N is at 40W. The sampling

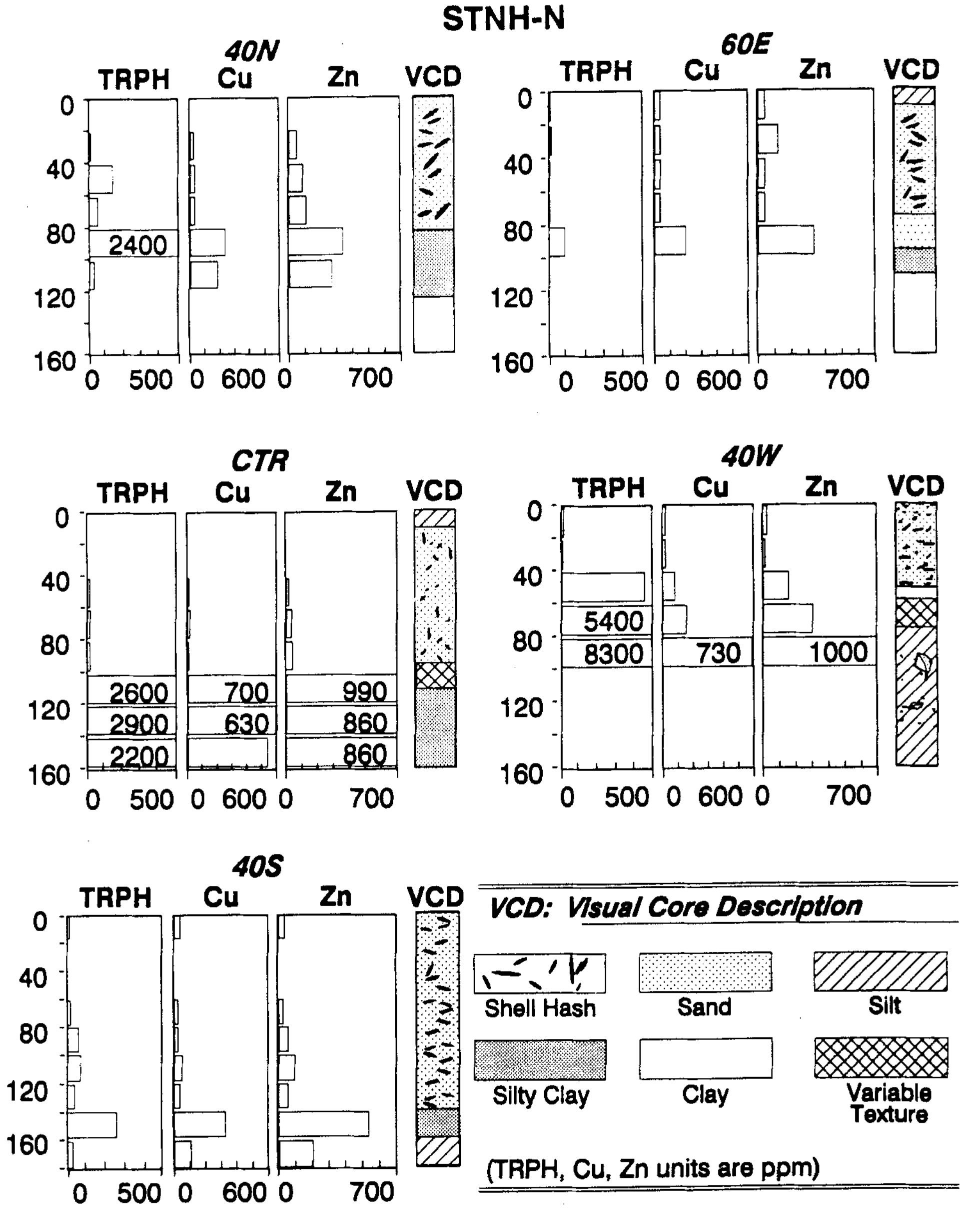


Figure 6 Core descriptions and selected geochemistry results from cores collected at STNH-N. "Variable texture" is used to describe interlayered sediments of different grain sizes.

intervals overlapped all of the visual transitions, which complicates the choosing of a discrete boundary. The increasing contaminant values from 40 to 100 cm in the 40W core is coincident with the described variable texture. This coincidence of variable texture and contaminant concentrations is one noted commonly in the coring investigation, and is discussed more fully below. The greatest R^2 value occurs at 80 cm (0.879), which indicates that material below 80 cm is indeed mound material.

A small peak of TRPHs (as well as some of the PAHs and pesticides) occurs from 40–60 cm at 40N, well within the cap sediments. In addition, these compounds are low or below detection in the 60–80 cm interval. This suggests that either there has been vertical movement of organic contaminants without accompanying movement of metals, or, more likely, that New Haven dredged material has pockets of relatively more contaminated sediments.

CS-2

In comparison to STNH-N, the cap material at this site had increased variability of sediment texture (sand, shell, and silt) and contaminant loading (Figure 7). In addition to within-horizon variability, the visual transition from the cap material to the mound was not obvious in every core. In one core (80NE) the zone of transition appeared to extend over 30 cm (60–90 cm); the implications of this "transition zone" are discussed below. In another core (40E) the apparent mound material had very low contaminant levels. The mound material was also variable in texture (shell and silt) and contaminant loading.

Based on chemical results, it is apparent that potential mound material was recovered only at 80NE and CTR, although it was recorded as being present at 40E. The visual transition from the cap to the mound was not as obvious as at STNH-N. The zone of transition at 80NE appeared to extend over 30 cm. The transition in contaminant levels occurred within the bottom of a sand layer, which had been defined visually as cap material. The highest R^2 value at CS-2 (0.965) occurs at the 60 cm interval at 80NE, whereas the visual boundary is located at approximately 80 cm.

The CTR station at CS-2 is the most problematic. PCA analyses showed no boundary with an R^2 greater than 0.7; however, the visual distinction between shell hash and black mud described as mound material occurred at approximately 40 cm. A dramatic increase in TRPH values at this interval agrees with the visual cap/mound distinction. However, metal contaminant concentrations at the CTR station fall between normal CS-2 cap material ranges and those measured at Black Rock Harbor where the mound material was obtained (Figure 8). These intermediate values also extend throughout most of the core (20–120 cm), but no material with metal concentrations within Black Rock Harbor ranges was recovered at CTR.

The intermediate metal contaminant values of samples recovered at CS-2 CTR could be material remnant of mixing of cap and mound, evidence of contaminant mobilization, or an isolated pile of more contaminated New Haven material. Mixing is unlikely since this core was taken at the centre of the mound where presumably the cap is thickest, and there is no evidence of mound material at three of the other five cores. If chemical migration did occur at the CTR station, it leads to the question of why these intermediate values were not measured at the other core which recovered mound material at CS-2 (80NE). The most realistic possibility is that the material recovered at CS-2 was New Haven cap material. The concentrations of metals are within the ranges of New Haven material disposed elsewhere (e.g. Cap Site 1, Mill-

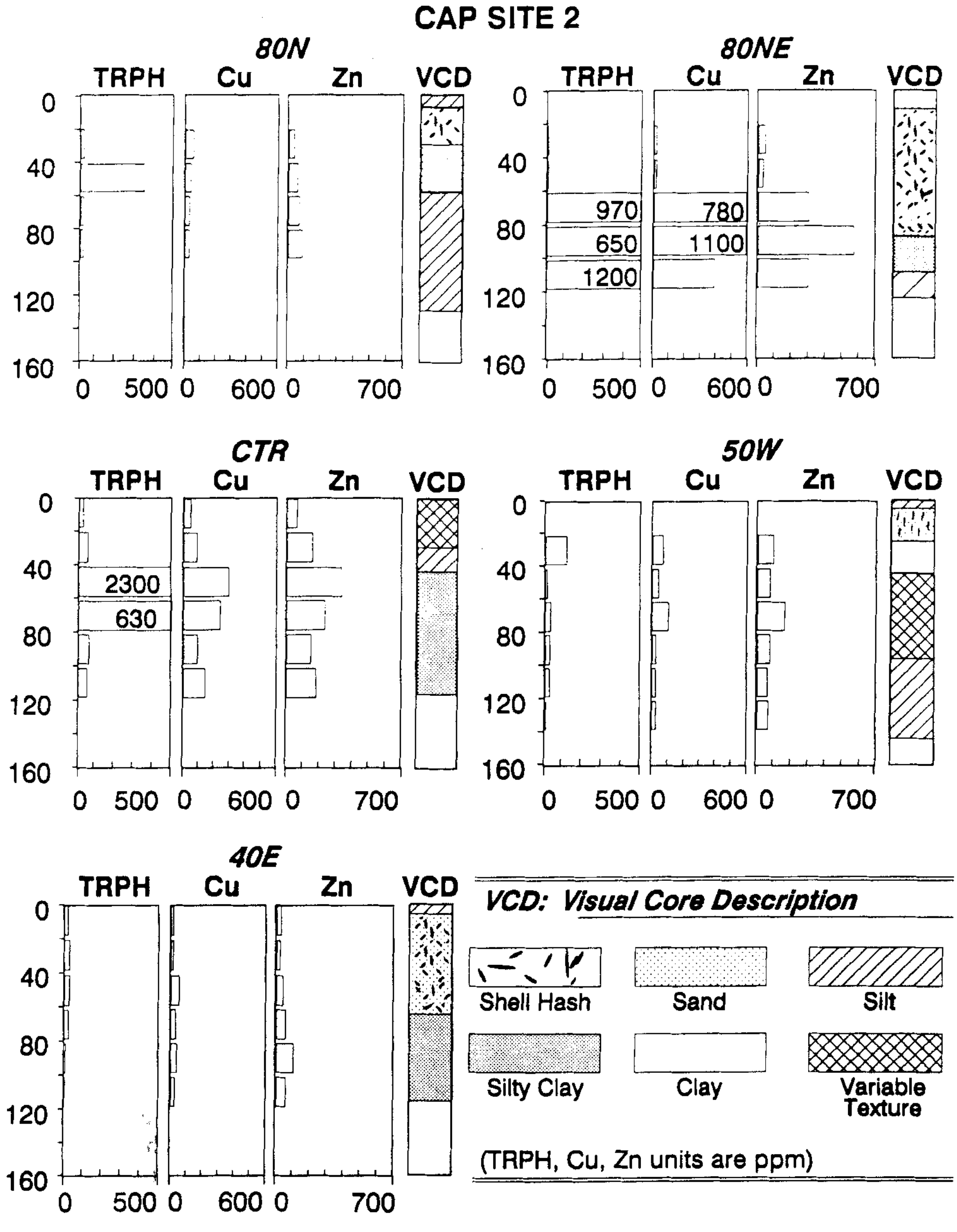


Figure 7 Core descriptions and selected geochemistry results from cores collected at CS-2. "Variable texture" is used to describe interlayered sediments of different grain sizes.

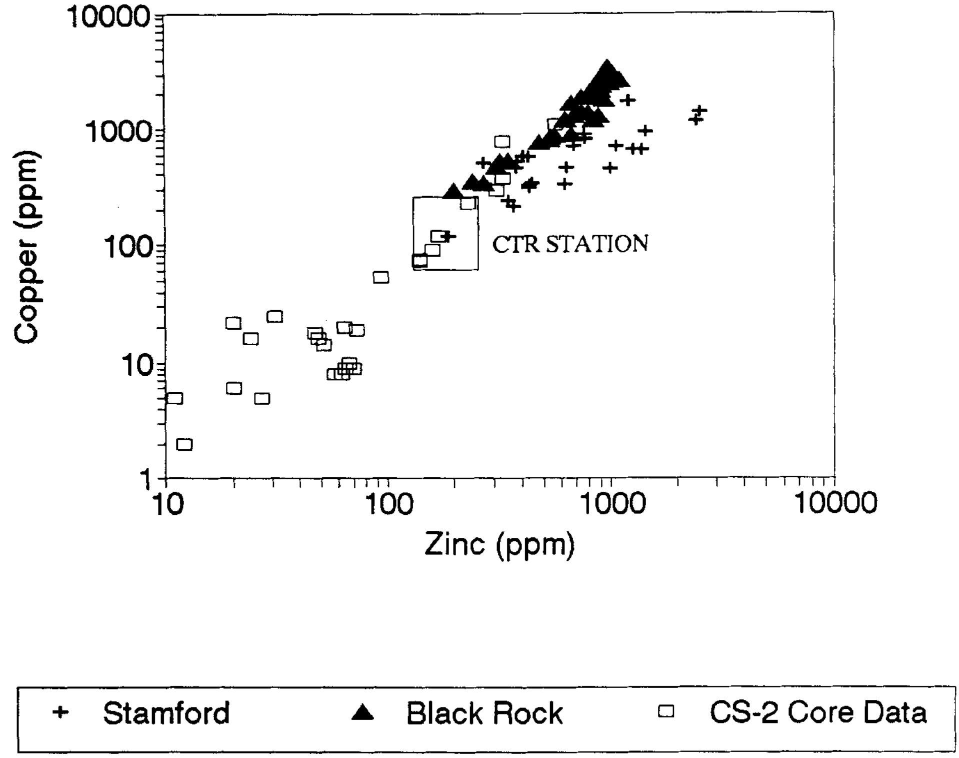


Figure 8 Zinc and copper concentrations measured in CS-2 core samples as compared with the two mound material source areas (Stamford and Black Rock Harbors).

Quinnipiac River), and the cap material disposed at CS-2 was siltier than the sand and shell-rich material at STNH-N.

Three of the five cores taken at CS-2 did not penetrate obvious mound material (80N, 50W, and 40E), and resulted in correspondingly low chemical contaminant concentrations. As at STNH-N, the low concentrations are indicative of the sand material used as a cap at both of these mounds. A relatively high R^2 value of 0.800 occurs at the 60 cm interval of 80N and is due to the base material having higher values of vanadium and zinc, and a peak in TRPHs in the 40–60 cm interval of the cap. The peak of TRPH concentration without a corresponding peak of metal contaminants suggests again that cap material may have isolated patches of higher contaminant concentrations. The 60 cm interval of 80N is coincident with the apparent boundary between base material and cap (Figure 7). This boundary suggests that cap material was deposited where there was no mound material, and resulted in little or no mixing with base sediments.

STNH-S

The fine-grained cap material on the STNH-S mound was highly variable in sediment texture (Figure 9). The visual appearance was one of very distinct bands of high

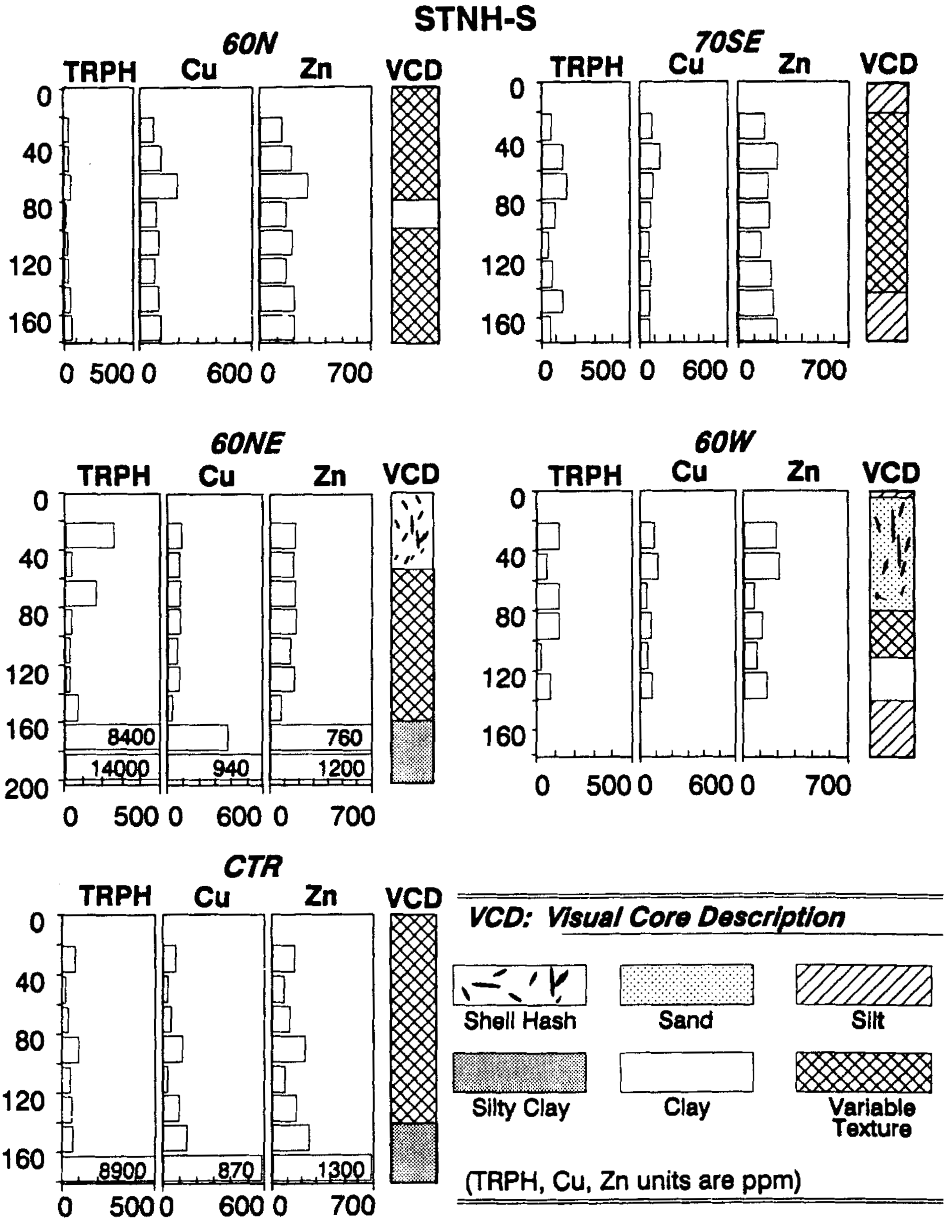


Figure 9 Core descriptions and selected geochemistry results from cores collected at STNH-S. "Variable texture" is used to describe interlayered sediments of different grain sizes.

organic (black) and low organic (grey) silt and clay, with some intervals of shell hash. The contaminant loading was moderate but also highly variable. Despite this variability, the visual and chemical transition to mound materials was distinct. The mound material contained high levels of contaminants and a uniform texture of dry, black organic silt. In this case (in contrast to STNH-N and CS-2), the variability of the cap material made it distinctive and recognizable and the uniformity of the mound material made it easier to distinguish.

One of the original concerns for success of the capping project was that a silt cap would make cap/mound distinction difficult. However, cores from STNH-S showed very clear chemical and visual boundaries (Figure 9). Both metals and organic data show a bimodal distribution between the three samples taken from areas in the core documented in the visual core descriptions as being mound material (160–200 cm at 60NE and 160–180 at CTR) and cap material (Figure 10). R^2 values are 0.841 at 60NE and 0.93 at CTR. This suggests that silt caps are just as effective at containing contaminants and may cause even less disturbance than sand caps deposited on silt. There was also no evidence of a gradient in contaminant levels within the cap material.

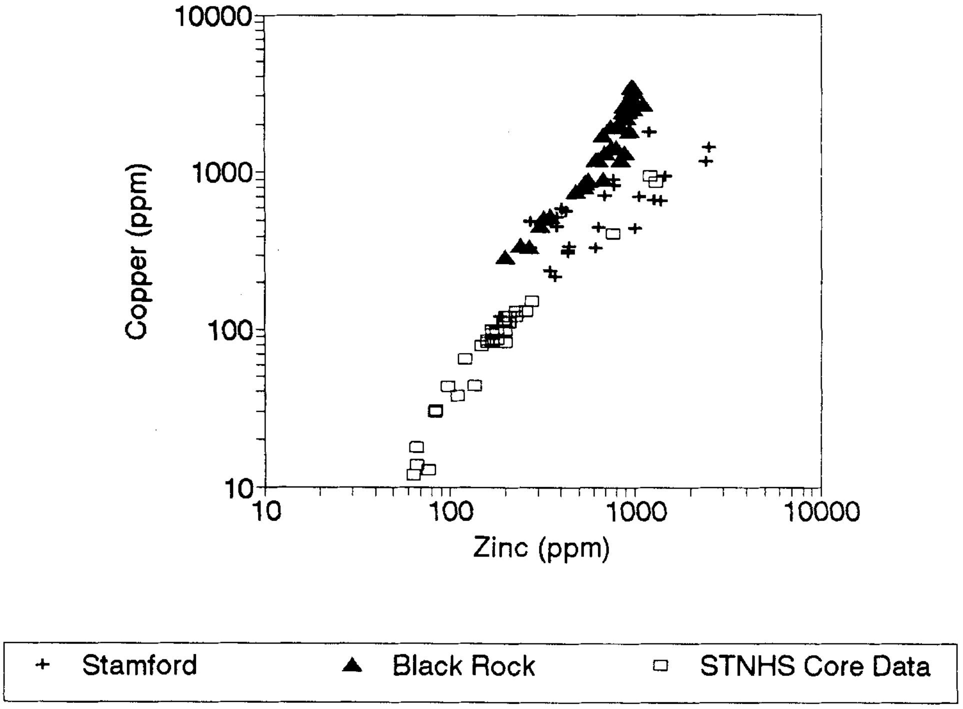


Figure 10 Zinc and copper concentrations measured in STNH-S core samples as compared with the two mound material source areas (Stamford and Black Rock Harbors).

Three cores did not contain apparent mound material (60N, 60W, 70SE). This site received a large amount of cohesive cap material (see below) which formed a relatively high cap on the mound. Despite success in taking long cores, most of the material recovered was cap material. However, the distinctive nature of the cap material was established by comparing profiles from all of the cores.

DISCUSSION

Evidence provided in this study supports the hypothesis that sediment caps can effectively isolate contaminants from the marine environment. It was possible to distinguish clearly cap material from mound material chemically and visually in many cores, although the inability to do so for some cores raised the likelihood that the original assumptions were not generally applicable, possibly flawed due to the complex nature of dredging and disposal sequences. Although the processes are well-understood from numerous studies, they are not usually monitored on a routine basis. Two types of dredging are usually employed in the New England region, hydraulic dredging with a hopper barge and clamshell dredging with a bottom-dump barge.

During the hydraulic dredging process, the sediment texture is destroyed and the pore waters and sediments (with adsorbed contaminants) are well mixed. This fluidized material is redeposited into the barge or hopper where it begins to reconsolidate. The mass properties and distribution are established during the deposition and consolidation processes both in the barge and during descent to the sea floor (Bohlen, 1990). This type of dredged material disposal has usually been used for uncontaminated materials. Sediments deposited using this dredging method might meet the general assumptions that cap material should have relatively low (and uniform) contaminant loading and texture (cap at STNH-N) and be distinct from the mound materials, which would be expected to have relatively high (and variable) contaminant loading and texture.

During clamshell dredging of cohesive sediments, the bucket usually collects a coherent volume (5–14 m^3) of sediment, retaining the texture and mass properties of the original deposit (Bohlen, 1990). This mass is dumped into a barge with many other bucket loads, some of which collapse and some which continue to retain most of their structure. Due to the shape of the clamshell bucket (width and length greater than depth), many of the individual loads should retain the same orientation to the vertical axis as in the original deposit. The material in the barge consolidates during the journey to the dump site, melding the pieces into a relatively solid mass.

When the bottom of the barge is opened, this melange of material falls through the water column as a mass, entrains some water along its edges and usually hits the bottom more or less intact. If there is any stratification or variation in texture and contaminant loading within the original deposit, mounds and caps formed with this type of dredging would not be expected to meet the general assumption of uniform contaminant loading and texture (CS-2, cap at STNH-S, mound at STNH-N). If the original deposit is relatively uniform in texture or contaminant loading, the process of clamshell dredging may preserve this uniformity in mounds or caps (mound at STNH-S).

Application of this awareness of dredging processes to the data leads to a new set of hypotheses. With clamshell dredging, some of the stratification, texture and contaminant distribution from the original deposit may be preserved and observed in long cores taken from disposal mounds and caps. This assumption leads to the possibility that a characteristic of some types of dredged material is the variability in texture and contaminant loading in long vertical profiles (Fredette *et al.*, 1992). Based on results from a grab sampling study, Morton and Karp (1980) suggested that localized heterogeneity in contaminant loading might be diagnostic of dredged material.

The fact that both the cap and the mound are composed of dredged material reduces the certainty that the interface between the cap and the mound will be distinct and easily recognizable visually or chemically. There may be several interfaces between successive barge dumps. If the top of the mound happens to contain the low end of the range of contaminants (i.e. deeper or coarser dredged material) and the first barge load of cap material happens to have the high range for this material (i.e. surface or finer dredged material), the interface may appear to be blurred or mixed. Therefore, it may be impossible to distinguish inherent variability from variability due to mixing during the disposal process.

At STNH-N, the uniform texture and contaminant levels within the cap may be, in part, due to the use of a hopper dredge to collect and dispose of the coarse material from outer New Haven harbour. This mound was deliberately constructed with a coarse cap and the hopper dredge was used to produce an even coverage of material.

At STNH-S a very different disposal operation occurred. The mound was supposed to be covered with inner harbour silts from New Haven, but there were two rounds of disposal resulting in the following sequence of deposition:

Date	*Volume*	*Source*
4/79	76,000 m^3	Stamford silt
5/79	33,000 m^3	New Haven silt
10/79	6,000 m^3	Stamford silt
1/80–4/80	110,000 m^3	New Haven silt

Clearly some cores might not have any representation of the 6,000 m^3 of Stamford silt, while others might. Because of the large total volume of cap material, it is clear why many of the long cores might not have reached mound material.

Because the sampling intervals do not necessarily coincide with the bands of black and grey silt observed at STNH-S, it is not possible to correlate the variations in contaminant levels with the variation in visual texture. However, it seems likely that the contaminant variations reflect the interleaving of silts with high and low levels of organic material (and associated contaminants) obtained from the original dredging sites.

At CS-2 there was no clear evidence that placement of the coarse-grained cap disrupted the fine-grained sediments of the mound. However, the transition area within core 80NE could be interpreted as a result of limited mixing of materials between the cap and the mound during deposition. It seems more likely that the top of the mound around this core originally consisted of a mixture of sand and shell which was mistaken for cap material during visual analysis. The potential for incorporation of coarse, relatively clean material into the mound material during the dredging operation is relatively high, given the nature of clamshell dredging operations.

These results suggest that variation in contaminant levels within horizons[1] and

---

[1] Horizon in this context refers to the geological sense of a time plane, or a layer of sediment deposited during a distinct period of time (series of barge dumps) separated from other horizons by a period of time marked by erosion or no net deposition.

correlation of contaminants with sediment texture are not necessarily diagnostic criteria. Without further evidence to distinguish the processes, they could both result from mixing of cap and mound materials during disposal or from preservation of variability introduced during dredging. From a management standpoint, it is not important which process is responsible as long as the contaminants remain isolated beneath the cap.

In many cores which recovered cap and mound sediments, both sediment types were geochemically distinguishable and were consistent with original source characterizations (Fredette *et al.*, 1992). These results indicate that no chemical gradients of the measured contaminants existed throughout the entire cap from the mound to the sediment/water interface. A few cores recovered a finite interval of apparent mixing between cap and mound. However, the sampling resolution in this study did not allow distinction between the process of mixing of separate barge loads and contaminant mobilization. In addition, the documented heterogeneous nature of dredged sediments further confuses the situation; a "mixed" interval may actually be a remnant of two separate disposal episodes of naturally varying contaminant concentrations from the same source.

The criterion most likely to influence management decisions is the presence or absence of gradients of contaminants within the cap. Given the lack of sediment gradients, the only possible pathway for contaminant release to sea water is through the mechanism of pore water advection or diffusion. The possibility that an active pore water flux exists with no apparent effect on sediment contaminant concentration is unlikely. High-resolution pore water sampling could confirm or exclude the possibility of contaminant mobilization and the subsequent potential availability to the benthic ecosystem.

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APPENDIX A
PCA VARIABLE AND REGRESSION CALCULATIONS

Example: STNHS 60NE

I. PCA VARIABLES AND AXIS CALCULATIONS

```
-----------------------------------------------------
TABLE 1. CORRELATION MATRIX

              Cd          Cu          Zn         TRPH

Cd          1.0000      0.9892      0.9547      0.9535
Cu          0.9892      1.0000      0.9843      0.9769
Zn          0.9547      0.9843      1.0000      0.9955
TRPH        0.9535      0.9769      0.9955      1.0000
-----------------------------------------------------
```

```
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TABLE 2. FACTOR PATTERN

            AXIS1

Cd          0.98330
Cu          0.99673
Zn          0.99275
TRPH        0.99058
-----------------------
```
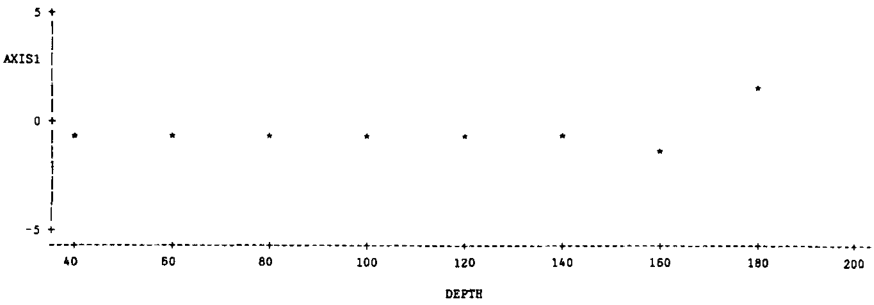

```
---------------------------------------------------------------------
TABLE 3. VARIABLES AND AXIS SCORES

CORE    LAYER    DEPTH   Cd      Cu      Zn      TRPH      AXIS1

60NE      2        40    5.7    120     200      260     -0.83095
60NE      3        60    5.8     99     180       25     -0.91245
60NE      4        80    6.9    110     194      180     -0.80978
60NE      5       100    5.8    110     200       25     -0.86678
60NE      6       120    7.2     79     148       16     -0.92717
60NE      7       140    6.3     94     170       16     -0.91266
60NE      8       160    5.9     30      83       87     -1.15040
60NE      9       180   15.0    410     760     8400      1.63571
60NE     10       200   39.0    940    1200    14000      4.77448
---------------------------------------------------------------------
```



```
 N = 9     Regression Models for Dependent Variable: D6


Number in      R-square          C(p)   Variables in Model
 Model

     1     0.27067486       1.32746   AXIS1
     1     0.03774374       3.34831   AXIS2
-------------------------------------------------
     2     0.30841861       3.00000   AXIS1 AXIS2
----------------------------------------------------------

 N = 9     Regression Models for Dependent Variable: D7


Number in      R-square          C(p)   Variables in Model
 Model

     1     0.44028859       1.85519   AXIS1
     1     0.06982407       6.39253   AXIS2
-------------------------------------------------
     2     0.51011266       3.00000   AXIS1 AXIS2
----------------------------------------------------------

 N = 9     Regression Models for Dependent Variable: D8


Number in      R-square          C(p)   Variables in Model
 Model

     1     0.84079001      99.30506   AXIS1
     1     0.15005166     551.83634   AXIS2
-------------------------------------------------
     2     0.99084167       3.00000   AXIS1 AXIS2
----------------------------------------------------------

 N = 9     Regression Models for Dependent Variable: D9


Number in      R-square          C(p)   Variables in Model
 Model

     1     0.81627259     224.05757   AXIS1
     1     0.17891480          1019   AXIS2
-------------------------------------------------
     2     0.99178249       3.00000   AXIS1 AXIS2
----------------------------------------------------------
```

```
II.      REGRESSION ANALYSES: BOUNDARY VARIABLES

OBS     CORE   LAYER   DEPTH     D1   D2   D3   D4   D5   D6   D7   D8   D9

 1      60NE     2       40       1    0    0    0    0    0    0    0    0
 2      60NE     3       60       1    1    0    0    0    0    0    0    0
 3      60NE     4       80       1    1    1    0    0    0    0    0    0
 4      60NE     5      100       1    1    1    1    0    0    0    0    0
 5      60NE     6      120       1    1    1    1    1    0    0    0    0
 6      60NE     7      140       1    1    1    1    1    1    0    0    0
 7      60NE     8      160       1    1    1    1    1    1    1    0    0
 8      60NE     9      180       1    1    1    1    1    1    1    1    0
 9      60NE    10      200       1    1    1    1    1    1    1    1    1


III.  REGRESSION ANALYSES: REGRESSION MODELS

  N = 9     Regression Models for Dependent Variable: D2


Number in      R-square         C(p)    Variables in Model
  Model

     1      0.02472477      1.00354    AXIS1
     1      0.00057488      1.15220    AXIS2
 -------------------------------------------
     2      0.02529965      3.00000    AXIS1 AXIS2
 -------------------------------------------------

  N = 9     Regression Models for Dependent Variable: D3


Number in      R-square         C(p)    Variables in Model
  Model

     1      0.06219233      1.00008    AXIS1
     1      0.00001293      1.39791    AXIS2
 -------------------------------------------
     2      0.06220526      3.00000    AXIS1 AXIS2
 -------------------------------------------------

  N = 9     Regression Models for Dependent Variable: D4


Number in      R-square         C(p)    Variables in Model
  Model

     1      0.10374338      1.03291    AXIS1
     1      0.00488950      1.69832    AXIS2
 -------------------------------------------
     2      0.10863288      3.00000    AXIS1 AXIS2
 -------------------------------------------------

  N = 9     Regression Models for Dependent Variable: D5


Number in      R-square         C(p)    Variables in Model
  Model

     1      0.16752643      1.03625    AXIS1
     1      0.00499914      2.21473    AXIS2
 -------------------------------------------
     2      0.17252557      3.00000    AXIS1 AXIS2
 -------------------------------------------------
```