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Response of benthic infauna and epifauna to ocean disposal of red clay dredged material in the New York Bight: A study using sediment-profile imaging, surface imaging and traditional methods

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Abstract

In 1997, approximately 1 million cubic yards of consolidated red clay was dredged from Newark Bay in New Jersey and deposited on the seafloor at an open-water dredged material disposal site located on the inner continental shelf of the New York Bight. To address concerns about the ability of benthic organisms to colonize the seafloor deposits of this compact, organic-poor red clay, monitoring surveys were conducted in 1998 (1 year after disposal) and 2002 (5 years after disposal). The surveys used a combination of sediment imaging and traditional grab sampling methods to characterize physical and biological conditions over the surface of the red clay deposits in comparison to nearby reference areas consisting of either naturally-occurring, sandy surface sediments or deposits of unconsolidated, muddy dredged material. Sediment-surface and sediment-profile images (SPI) collected in summer 2002 indicated that the surface of the red clay deposits had become much smoother and more heterogeneous in texture compared to images collected in 1998. The images also indicated that these deposits had become colonized to a much greater degree by relatively abundant and diverse infaunal and epifaunal communities compared to 1998. Taxonomic analysis of benthic grab samples confirmed the imaging results and indicated relatively high infaunal organism abundance and diversity over the red clay deposits in 2002 compared to the reference areas. However, the structure of the benthic community inhabiting the red clay was fundamentally different from the communities in the reference areas, due to the differences in sediment texture and composition. The combination of imaging and traditional taxonomic approaches used in this study provided much greater insight on the red clay colonization process than either approach by itself.

Keywords: Red clay; Dredged material disposal; Benthic colonization; Infauna; Epifauna; SPI; Sediment-profile imaging; New York Bight

1. Introduction

Prototype diver- and ship-deployed sediment-profile cameras for use in benthic studies were first introduced in the early 1970s (Rhoads and Young, 1970; Rhoads and Cande, 1971); this was later followed by the development of a formal theory of image interpretation (Rhoads and Germano, 1982, 1986). As camera hardware and image analysis software have continued to evolve and become more widely available, a variety of sediment-profile imaging (SPI) applications have been documented. These include evaluating effects of hypoxia/anoxia (Rosenberg and Diaz, 1993; Nilsson and Rosenberg, 1997, 2000; Rosenberg et al., 2001, 2002), mapping of organic enrichment gradients and benthic habitats (Grizzle and Penniman, 1991; Valente

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et al., 1992; Bonsdorff et al., 1996; Rosenberg et al., 2003a), documenting impacts of coastal fish-farming (O'Connor et al., 1989; Karakassis et al., 2002; Wildish et al., 2003), and assessing trawling disturbance (Smith et al., 2003; Rosenberg et al., 2003b; Nilsson and Rosenberg, 2003).

One of the most extensive applications of SPI, especially in the U.S., has been for routine monitoring of dredged material disposal impacts. For example, the U.S. Army Corps of Engineers' Disposal Area Monitoring System (DAMOS) program has developed a formal, tiered monitoring approach that relies heavily on collection of SPI data (Germano et al., 1994; Valente, 2004). As a result, DAMOS has collected tens of thousands of SPI images over the past 25 years as part of its continuous, routine monitoring at 10 open-water dredged material disposal sites located along the New England coastline (Fredette, 1998; U.S. Army Corps of Engineers, 2004).

SPI also has become an integral component of government-sponsored disposal site monitoring programs in New York, the Pacific Northwest and California, and it has been used successfully for monitoring of dredging- and disposal-related impacts in New Zealand and Hong Kong (Valente et al., 1998, 1999). Cost-efficiency is one of the main appeals of this technique for disposal monitoring: SPI is effective both for mapping the physical distribution and "weathering" of dredged material on the seafloor and for simultaneously evaluating benthic community response and recovery through time. Despite this extensive past use, dredged material-related applications of SPI have been documented mainly in the grey literature and non-mainstream publications (e.g., Germano and Rhoads, 1984; Germano et al., 1989; Revelas et al., 1987; Rhoads and Germano, 1990; Valente et al., 1999, 2001, 2004).

This paper therefore provides an example of the use of SPI, in combination with other techniques, for evaluating dredged material disposal impacts. Dredged material removed from channels and inner harbor areas typically consists of unconsolidated, fine-grained sediment (e.g., organic-rich mud or muddy sand) that must meet established testing criteria to be deemed suitable for unconfined, open-water disposal (U.S. Environmental Protection Agency, 1991). Numerous studies have demonstrated the ability of benthic organisms to recolonize, on varying timescales, seafloor areas where such "conventional" muddy dredged material has been disposed (Oliver et al., 1977; Van Dolah et al., 1984; Engler et al., 1991; Somerfield et al., 1995; Harvey et al., 1998; Valente et al., 1999). The present study was undertaken to evaluate benthic recolonization of a relatively unique, atypical dredged material consisting of highly-consolidated red clay.

During the summer of 1997, approximately 760,000 m^3 (10^6 yd^3) of this naturally-occurring, subsurface red clay was dredged from Newark Bay in New Jersey and dumped from scows onto the seafloor at the Mud Dump Site (MDS), located at a depth of 20 m in the open-ocean waters of the New York Bight (Fig. 1A). The red clay disposal was concentrated in three areas located in the northeast quadrant of the MDS (Fig. 1B). During the same time period, disposal of "conventional" organic-rich, muddy dredged material emanating from other dredging projects was occurring in areas located in the northwest quadrant of the MDS (Fig. 1B). Both the red clay and the conventional dredged material met all of the chemical and biological testing criteria for ocean disposal suitability, and based on the results of past monitoring at the MDS, the conventional dredged material was expected to become rapidly colonized by benthic infauna. However, due to the compactness and low total organic carbon content (<1%) of the red clay, concerns existed about its ability to provide habitat suitable for colonizing benthic organisms following disposal.

The objective of this study, therefore, was to evaluate benthic colonization of the red clay deposits through the combined use of SPI, sediment surface photographs and benthic grab sampling. To provide a basis for comparison, this combination of techniques also was used to sample the nearby area of the MDS where conventional, muddy dredged material had been placed at the same time as the red clay. Additional samples for comparative purposes were collected at the previously established South Reference Area, located 3.2 km to the southwest of the MDS in an area known to be unaffected by disposal (Fig. 1A).

2. Methods

2.1. Sampling design

Field surveys were conducted in October 1998 (roughly 1 year after disposal of the red clay and conventional dredged material) and July 2002 (5 years after disposal). In both years, sediment-profile and sediment-surface images were collected at a total of 70 stations located over the red clay deposits and 20 stations over the nearby deposits of conventional dredged material (Fig. 2), as well as at 10 stations in the South Reference Area. The South Reference Area had a depth of 20 m, similar to the MDS, but surface

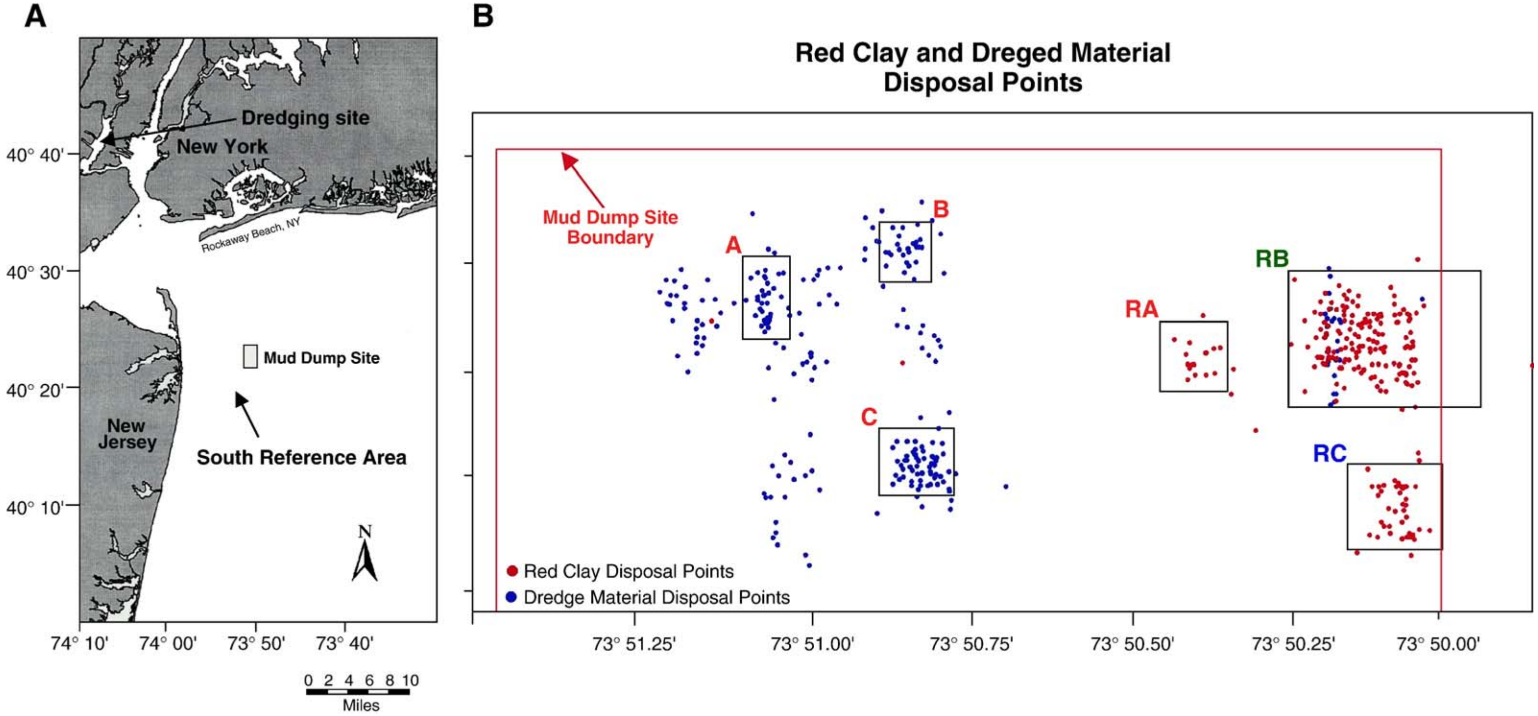

Fig. 1. A) Locations of the Mud Dump Site (MDS) and South Reference Area in the New York Bight and the dredging site in Newark Bay. B) Map of the northern part of the MDS showing locations where individual scow loads of conventional dredged material (areas A, B, and C) and red clay (areas RA, RB, and RC) were released.

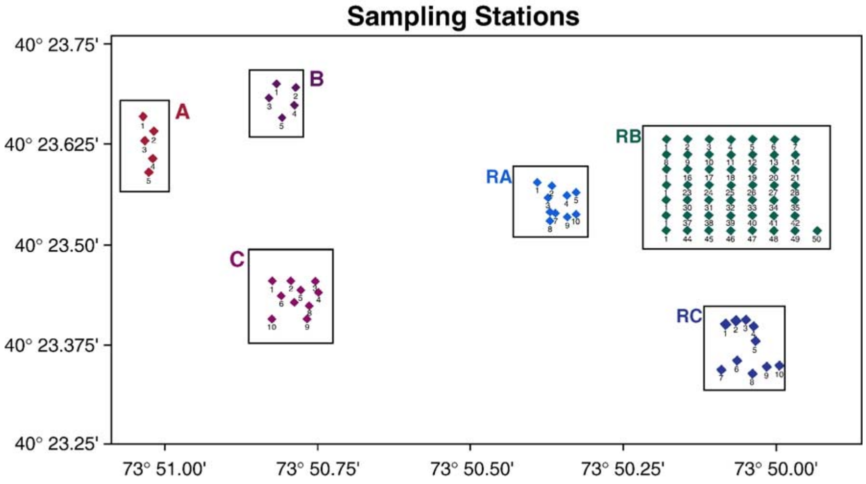

Fig. 2. Map of sampling stations corresponding to areas where either conventional dredged material (areas labeled as A, B, and C) or red clay (areas labeled as RA, RB, and RC) was placed. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

sediments consisted of clean, rippled fine sands representing the ambient, “pre-disposal” seafloor conditions that exist over large portions of the inner New York Bight. Stations in all three survey areas were arranged in loose grid patterns and spaced roughly 30 to 60 m apart (Fig. 2). During all sampling operations, positioning of the survey vessel to within ±5 m of each target station location was accomplished using a differential Global Positioning System (d-GPS).

2.2. Image acquisition and analysis

The photographs of the sediment surface were acquired with a downward-looking 35-mm underwater camera and strobe light system (PhotoSea® Model 1000a) that was attached to the frame of the sediment-profile camera (Benthos® Model 3731). A hang weight was used to trigger the downward-looking camera just before landing and penetration of the sediment-profile camera, providing a photograph of a 0.3 m^2 area of the undisturbed sediment surface corresponding to each sediment-profile image. Two replicate sediment-profile images and one corresponding sediment surface image from each station were analyzed to obtain the dataset for this study.

Computer-based analysis of each SPI image consisted of measuring a suite of standard physical and biological parameters (e.g., sediment type and grain size, penetration depth, depth of the apparent redox potential discontinuity, etc.), as described in Rhoads and Germano (1982, 1986). For brevity, only the results for sediment type, surface boundary roughness, and infaunal successional stage are presented here. Sediment type (e.g., mud, sand, dredged material, red clay, etc.) was determined visually based on the color and texture of the substrate in each image. Surface boundary roughness is a measure of the vertical relief of features at the sediment–water interface across the 14-cm width of each image; it was determined by measuring the vertical distance between the highest and lowest points of the sediment–water interface in contact with the camera window. This “small-scale” surface boundary roughness typically ranges from 0 to 5 cm on muddy bottoms, due to the presence of either physical structures (e.g., ripples, rip-up structures, mud clasts) or biogenic features (e.g., burrow openings, fecal mounds, foraging depressions).

The successional stage determination is based on the widely-accepted model of infaunal succession that indicates a predictable, sequential appearance of macrobenthic invertebrates belonging to specific functional groups with increasing time or distance following a natural or anthropogenic seafloor disturbance (McCall, 1977; Pearson and Rosenberg, 1978; Rhoads and Boyer, 1982; Rhoads and Germano, 1982, 1986). Assignment of an infaunal successional stage “number” (sensu McCall, 1977) to each SPI image was based on observing specific biological features relative to this model. Specifically, Stage I was assigned based on the observation of small, tube-dwelling, “pioneering” or opportunistic polychaetes, often in dense aggregations, at the sediment surface. Stage II represents a transitional stage and was assigned based on the observation of tubicolous amphipods (e.g., *Ampelisca* sp.) and/or shallow-dwelling tellinid bivalves. Stage III denotes the presence of larger-bodied, head-down-deposit-feeding, "equilibrium" taxa. Stage III organisms are rarely seen in images, but subsurface burrows or feeding voids that develop at depth near their head ends serve as visible evidence of their presence. Surface-dwelling Stage I or II taxa can occur at the same time and place as deeper-dwelling Stage III organisms, resulting in the assignment of "Stage I on III" or "Stage II on III" to SPI images.

Analysis of each sediment surface image consisted of qualitative descriptions of key physical and biological characteristics (e.g., sediment type, bedforms and biological features). Typical evidence of epifaunal and infaunal organisms included either the organisms themselves (e.g., fish, decapods, sea stars, hydrozoans) or biogenic structures (e.g., tubes, burrow openings, fecal mounds, tracks, etc.).

2.3. Benthic grab sampling and analysis

In addition to the images collected in the July 2002 survey, a single sediment grab sample was obtained for benthic community analysis at a randomly-selected subset of 15 of the 70 SPI stations over the red clay area, 5 of the 20 stations over the conventional dredged material deposits, and at 3 of the 10 stations in the South Reference Area. The sample was collected at each station using a 0.04 m^2 van Veen grab having a maximum penetration depth of 12 cm.

A small subsample of surface sediment was removed from each grab for subsequent grain size analysis by American Society for Testing and Materials (ASTM) Method D422, which involves the use of sieves and a hydrometer (ASTM, 2002). The remaining sediment was washed carefully through a sieve having a 0.5 mm mesh size, and the retained organisms preserved using a 6% buffered formalin solution with Rose Bengal stain. In the laboratory, macroinvertebrates were enumerated and identified to the Lowest Practicable Identification Level (LPIL), which was typically the species level.

Analysis of the benthic community data included both univariate and multivariate approaches to determine similarities and differences among the three *a priori* station groups (i.e., red clay stations, dredged material stations, and South Reference Area stations). After verifying that the data were distributed normally and variances homogenous, single-classification Analysis of Variance (ANOVA) was used to test for differences among the three station groups in mean abundance (number of individuals per m^2), number of taxa, Margalef's species richness, Shannon–Weiner diversity, and Pielou's evenness; this was followed by pair-wise comparisons of means by the GT-2 method (Sokal and Rohlf, 1981). Non-parametric, multivariate analyses using the PRIMER software package (Clarke and Warwick, 1994) included both hierarchical agglomerative clustering with group-average linking and non-metric multi-dimensional scaling (nMDS; Kruskal and Wish, 1978) to evaluate among-station similarity in overall community structure. Prior to both clustering and nMDS, the abundance values were square-root transformed and a matrix was constructed of Bray–Curtis similarity index values (Bray and Curtis, 1957) calculated between each possible pair of stations (Clarke, 1993). The ANOSIM (Analysis of Similarities) randomisation procedure within PRIMER (Clarke and Green, 1988; Clarke, 1993) also was used as a formal test for differences in overall benthic community structure among the three station groups.

3. Results

3.1. Surface and sediment-profile imaging, 1998

In the October 1998 survey, red clay was observed in the SPI and surface images at all 70 of the sampling stations located in areas RA, RB and RC. At 29% of these stations, scattered throughout the sampled areas, the SPI and surface images showed the red clay occurring in homogenous, cohesive clumps (Table 1 and Fig. 3A and C). Surface boundary roughness was relatively high (>5 cm) at such stations. At the remaining 71% of the stations, the red clay was homogenous in texture but appeared less consolidated, and there was either moderate (>2 to 5 cm) or low (<2 cm) boundary roughness measured across the SPI field-of-view (Table 1 and Fig. 3B).

At 30% of the red clay stations, mainly those having cohesive clumps, there was no visible evidence of benthic macroinvertebrates in the SPI images (Table 1 and Fig. 3A). At the remaining 70% of the stations, evidence of benthic infauna consisted solely of the tubes of small opportunistic polychaetes occurring at relatively low to moderate densities at the sediment–water interface, indicative of successional Stage I (Table 1 and Fig. 3B). These small tubes were observed in the images of the sediment surface taken by the downward-looking camera at only 40% of the red clay stations (Table 1), but they could easily have been missed in many of these lower-resolution images due to their diminutive size and low apparent densities. The surface images also indicated that larger mobile epifauna were active over the red clay deposits: burrow openings were observed in the images at 8% of the stations (e.g., Fig. 3C), organism tracks and/or furrows were observed at 43% of the

Table 1
Summary of the SPI and surface imaging results for the 70 red clay area, 20 dredged material area, and 10 South Reference Area stations in 1998 and 2002

	1998			2002		
	Red clay (%)	Dredged material (%)	South Reference (%)	Red clay (%)	Dredged material (%)	South Reference (%)
SPI characterization						
Sediment type:						
– Black, silty dredged material	0	100	0	4	100	0
– Red clay, clumps	29	0	0	0	0	0
– Red clay, unconsolidated	71	0	0	25	0	0
– Red clay, mud–sand mixed	0	0	0	70	0	0
– Fine sand	0	0	100	1	0	100
Boundary roughness:						
– Low (<2 cm)	27	75	80	96	100	100
– Moderate (2–5 cm)	44	20	20	4	0	0
– High (>5 cm)	29	5	0	0	0	0
Successional stage:						
– No visible macrofauna	30	0	0	0	0	0
– Stage I	70	80	100	28	50	100
– Stage II	0	0	0	36	17	0
– Stage III (or I on III)	0	20	0	36	33	0
Surface imaging characterization						
Biological activity:						
– Small worm tubes	40	80	100	80	83	40
– Burrow openings	8	0	20	2	0	0
– Tracks/furrows	43	0	40	9	0	0
– Crabs, sea stars, shrimp	13	15	10	14	0	30
– Hydrozoans	0	0	0	41	0	0

Values are the percentage of stations in each area displaying each characteristic.

stations, and the organisms themselves (including crabs, burrowing shrimp, or sea stars; Fig. 3C) were present at 13% of the stations (Table 1).

As expected, the SPI images showed that the surface sediment at all of the stations in areas A, B and C consisted primarily of organic-rich, black (i.e., sulfidic), unconsolidated dredged material (Table 1 and Fig. 3D). At many stations, this black fine-grained dredged material was covered with a relatively thin (i.e., 2 to 5 cm) surface depositional layer of high-reflectance, ambient fine sand (Fig. 3D). This type of stratigraphy is commonly observed in SPI images at the Mud Dump Site as a result of the clean fine sand that is native to the surrounding seafloor being transported by bottom currents over deposited black dredged material. Stage I, consisting of surface-dwelling opportunistic polychaetes, was observed in both the SPI and surface images at 18 of the 20 dredged material stations (Table 1). The SPI images at the other two dredged material stations had both Stage I surface tubes and subsurface feeding voids, evidence of Stage III deposit-feeding infauna. These two stations therefore were assigned a Stage I on III successional stage (Table 1). Crabs or sea stars were observed in the surface images at 15% of the stations, but there were no visible burrow openings or tracks (Table 1).

At the South Reference Area, the SPI and surface images showed that the native sediment consisted of clean, rippled fine sand that had small, opportunistic, Stage I polychaetes visible at the sediment–water interface at all 20 stations (Table 1 and Fig. 3E). The surface images further revealed the presence of burrow openings, tracks or furrows, and mobile epifauna at 10% to 40% of the reference area stations (Table 1).

3.2. Surface and sediment-profile imaging, 2002

In the 5 year post-disposal survey of July 2002, the surface of the red clay deposit in the SPI and surface images appeared to be both smoother and more variable in texture compared to the 1998 survey. The cohesive clumps of red clay that had imparted relatively high relief to the sediment–water interface in 1998 (Fig. 3A and C) were not observed at any of the 70 red clay stations in 2002. As a result, the measured boundary roughness values were low (<2 cm) at 96% of these

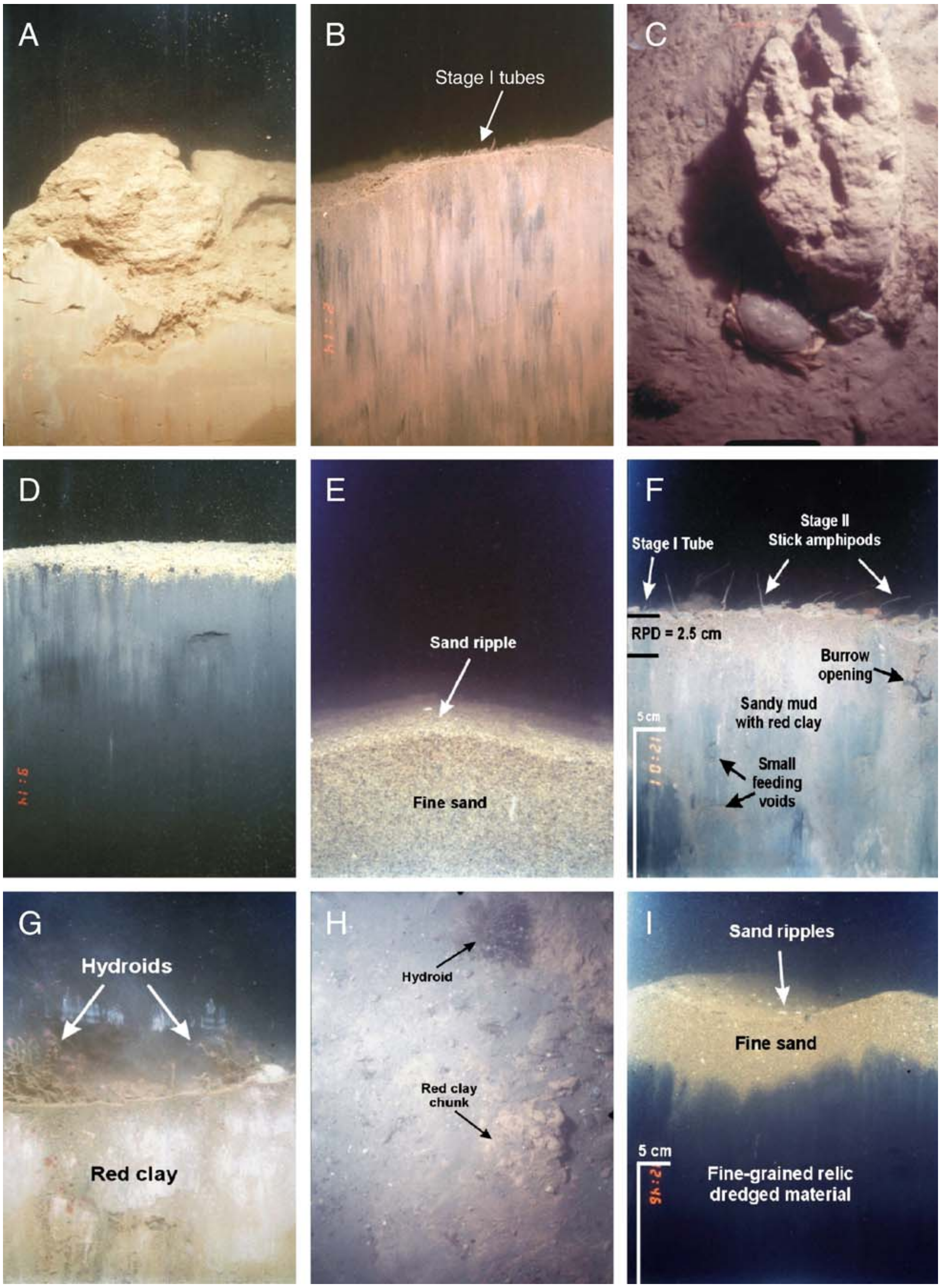

Fig. 3. Representative sediment-profile and surface images from the 1998 and 2002 surveys. Field-of-view is 14 × 21 cm in sediment-profile images and 40 × 60 cm in surface images. (A) Profile image from 1998 showing a cohesive clump of homogenous red clay with high small-scale vertical relief and lacking any visible benthic infauna. (B) Profile image from 1998 showing loosely-consolidated red clay with moderate relief and tubes of surface-dwelling, Stage I polychaetes. (C) Surface image from 1998 showing cohesive clay clump with numerous larger burrow openings and crab. (D) Profile image from 1998 showing unconsolidated, organic-rich conventional dredged material with thin depositional layer of light-colored fine sand. (E) Profile image from 1998 showing clean rippled fine sand at the South Reference Area. (F) Profile image from 2002 showing sandy mud mixed with red clay and numerous biogenic features; the surface of the red clay has only minor vertical relief across the field-of-view. (G) Profile image from 2002 showing minor vertical surface relief, sand mixed with red clay, and attached hydrozoans. (H) Surface image of the red clay from 2002 showing a hydrozoan, small clay clump and surface depositional layer of fine-grained sediment. (I) SPI image from 2002 showing distinct surface depositional layer of rippled fine sand over conventional dredged material. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

stations, and no stations exhibited boundary roughness >5 cm (Table 1). At the majority (70%) of the 2002 stations, the red clay that had previously exhibited homogenous texture in 1998 (in both its clumped and unconsolidated forms) appeared to be mixed with greater amounts of silty sand, mud and/or a surface depositional layer of muddy, organic detritus (Table 1 and Fig. 3F and G).

The red clay SPI images also exhibited a greater variety and number of biogenic features in 2002 compared to 1998. Small tubes of surface-dwelling Stage I polychaetes and thin stalks created by Stage II amphipods (i.e., "stick amphipods" presumed to be of the Family Podoceridae) were ubiquitous across the surface of the red clay (Fig. 3F). Evidence of larger-bodied Stage III infauna also was observed, including subsurface feeding voids and burrows (Fig. 3F). For the red clay stations as a whole, 28% had Stage I (only surface polychaete tubes observed), 36% had Stage II (mix of polychaete tubes and amphipod stalks), and 36% had Stage III (subsurface feeding voids or burrows, with or without surface tubes or amphipod stalks) as the highest observed successional stage in the July 2002 survey (Table 1).

Epifauna and evidence of epifaunal activity were visible in both the SPI and surface images obtained at the red clay stations in 2002. Sea stars, infaunal burrows, tracks and furrows, polychaete tubes, amphipod stalks, hydrozoans, and crabs were some of the organisms and/or biological features that were readily observed at the surface of the red clay (Fig. 3F, G and H). Small polychaete tubes were observed at 80% of the stations, tracks or burrows at 2%, hydrozoans at 41%, and crabs or sea star at 14% (Table 1).

All of the 2002 SPI images from the dredged material stations continued to exhibit a distinct stratigraphy consisting of sand overlying black dredged material (Fig. 3I). The highest observed successional stage was Stage I at 50% of the dredged material stations, Stage II at 17% of the stations and Stage III at 33% of the stations. Native clean, fine sand dominated by a Stage I community continued to be observed in the images at all of the South Reference Area stations in 2002. Small worm tubes were the primary infauna observed in the surface images at the dredged material and South Reference Area stations (Table 1).

3.3. Benthic grab sampling, 2002

Grain size analysis of the subsamples taken from each benthic grab in 2002 showed that rather than being homogenous, as might be expected based on the 1998 imaging results, the surface of the red clay deposit was comprised of sediment having variable texture (Table 2). On average, the grain size distribution at the red clay stations consisted of roughly equal proportions of fine sand (42%) and silt-clay (41%), with minor amounts of medium sand (10%) and coarse sand/gravel (7%; Table 2). The silt-clay and fine sand fractions generally were inversely proportional at most stations. Similar results were obtained at the dredged material stations, which on average had roughly equal proportions of fine sand (48%) and silt-clay (47%), with relatively insignificant amounts of medium/coarse sand and gravel (Table 2). Fine sand was the dominant sediment type at the South Reference Area stations, with one station exhibiting a considerable fraction of medium sand (Table 2).

For the benthic univariate statistics, the ANOVA indicated significant differences among the three station groups in average abundance, Shannon–Weiner diversity and Pielou's evenness at the $P < 0.05$ level,

Table 2
Results of grain size analysis for subsamples taken from each benthic grab sample

	% Coarse sand and gravel	% Medium sand	% Fine sand	% Silt-clay
Red clay stations				
24	1.9	10.5	60.0	28.1
26	3.9	15.2	52.3	28.7
34	5.1	5.5	64.1	25.3
39	4.2	18.9	42.6	34.3
43	8.6	16.0	24.3	51.1
44	11.4	7.1	20.5	61.0
50	5.8	11.4	18.2	64.6
51	1.7	6.5	51.1	40.7
55	1.1	1.8	5.6	91.5
57	2.6	10.3	54.6	32.4
64	10.8	11.2	40.2	37.8
66	6.5	4.2	64.5	24.8
74	2.7	6.9	52.7	37.6
78	15.1	15.4	36.7	32.9
85	25.0	12.2	41.3	21.6
Average	7.1	10.2	41.9	40.8
Dredged material stations				
2	3.3	8.0	40.2	48.5
3	0.1	1.3	31.6	67.0
14	0.9	2.7	62.2	34.2
15	2.5	3.8	62.4	31.3
16	0.3	2.3	41.4	56.0
Average	1.4	3.6	47.6	47.4
South Reference stations				
S-4	0.8	50.2	46.4	2.7
S-8	0.2	19.7	75.7	4.4
S-14	0.0	9.5	88.8	1.7
Average	0.3	26.5	70.3	2.9

but no significant differences among means for average number of taxa per station or Margelef's species richness (Table 3). The average abundance of 19,635 individuals/m^2 at the dredged material stations was higher than the averages for both the red clay and South Reference Area stations, but the difference was statistically significant only between the dredged material and South Reference Area values (Table 3). The elevated average abundance at the dredged material stations was due to disproportionately high numbers of the bivalve *Nucula proxima* (nut clam). The dominance of this single species also resulted in the dredged material stations exhibiting significantly lower Shannon–Weiner diversity and Pielou's evenness compared to both the red clay and South Reference area stations (Table 3). *N. proxima* also was relatively abundant at, but distributed unevenly among, the red clay stations.

In the cluster analysis dendrogram, four distinct groups of stations occur at the 42% Bray–Curtis similarity level: Group 1 consisting of all the red clay stations except station 55, Group 2 consisting of all the dredged material stations, Group 3 consisting of red clay station 55, and Group 4 consisting of the three South Reference Area stations (Fig. 4). The 2-dimensional nMDS plot shows the same station grouping (Fig. 5). Both representations indicate that the three different areas (red clay, dredged material, and South Reference) were inhabited by characteristic and unique benthic communities. Station 55 was an obvious outlier: its silt-clay content was more than double that at any other red clay station, and it exhibited a benthic community that was extremely depauperate (in terms of both numbers of taxa and organism density) compared to all the other stations.

The ANOSIM test indicated that the differences in benthic community structure among the three station groups suggested by the dendrogram and nMDS plot were statistically significant at the 0.1% level (Table 4). The strongest differences existed between the South Reference Area stations and each of the other two station groups, as indicated by *R*-statistics of 0.96 and 1.0 in Table 4 and the distances between the groups in Fig. 5. Both the red clay and dredged material stations

Table 3
Comparison of benthic community parameters for the dredged material, red clay, and South Reference Area stations

	Dredged material	Red clay	South Reference
Number of stations (samples)	5	15	3
Avg. no. of individuals/m^2 per station (±1 S.D.)	19,635* (±7984)	10,592 (±8994)	3850 (±1637)
Avg. no. taxa per station (±1 S.D.)	36 (±12)	35 (±11)	32 (±5)
Avg. Shannon–Weiner diversity (±1 S.D.)	1.60**±0.62)	2.55 (±0.32)	2.9 (±0.4)
Avg. Pielou's evenness (±1 S.D.)	0.44** (±0.14)	0.73 (±0.10)	0.84 (±0.07)
Avg. Margelef's species richness (±1 S.D.)	3.58 (±1.16)	3.80 (±0.98)	3.80 (±0.70)
Fifteen most abundant taxa for all stations combined (percent of total abundance in parentheses)	*Nucula proxima* (57%)	*Nucula proxima* (28%)	Tubificidae (LPIL) (16%)
	Cirratulidae (LPIL) (7%)	*Levinsenia gracilis*(14%)	*Exogone hebes* (10%)
	Tharyx acutus (5%)	Cirratulidae (LPIL) (11%)	Polygordius (LPIL) (8%)
	Tellina agilis (5%)	*Scoletoma* sp. AA (6%)	Pellucistoma (LPIL) (8%)
	Mediomastus (LPIL) (4%)	*Scoletoma verrilli* (5%)	*Nepthys picta* (6%)
	Pitar morrhuanus (4%)	*Pitar morrhuanus* (4%)	*Mancocuma stellifera* (4%)
	Polygordius (LPIL) (4%)	Scoletoma (LPIL) (4%)	Caulleriella sp. J (4%)
	Levinsenia gracilis (3%)	*Cossura soyeri* (3%)	*Aricidea catherinae* (3%)
	Tubificidae (LPIL) (1%)	*Cerastoderma pinnulatum* (2%)	*Rhepoxynius epistomus* (3%)
	Mediomastus ambiseta (1%)	*Nephtys incisa* (2%)	Rhynchocoela (LPIL) (2%)
	Pellucistoma (LPIL) (1%)	*Eusarsiella zostericola* (2%)	*Tanaissus psammophilus* (2%)
	Aricidea (LPIL) (1%)	*Pherusa affinis* (1%)	*Monticellina dorsobranchialis* (2%)
	Spiophanes bombyx (1%)	Polygordius (LPIL) (1%)	*Nucula proxima* (2%)
	Aricidea catherinae (1%)	Mediomastus (LPIL) (1%)	Unciola (LPIL) (2%)
	Apoprionospio pygmaea (<1%)	*Ninoe nigripes* (1%)	*Chiridotea tuftsi* (2%)

LPIL = lowest practical identification level.

* Average value significantly higher than South Reference at $P<0.05$ by the GT-2 method; all other pairwise comparisons for this parameter indicated no significant differences.

** Average value significantly lower than each of the other two means at $P<0.01$ by the GT-2 method; all other pairwise comparisons for this parameter indicated no significant differences.

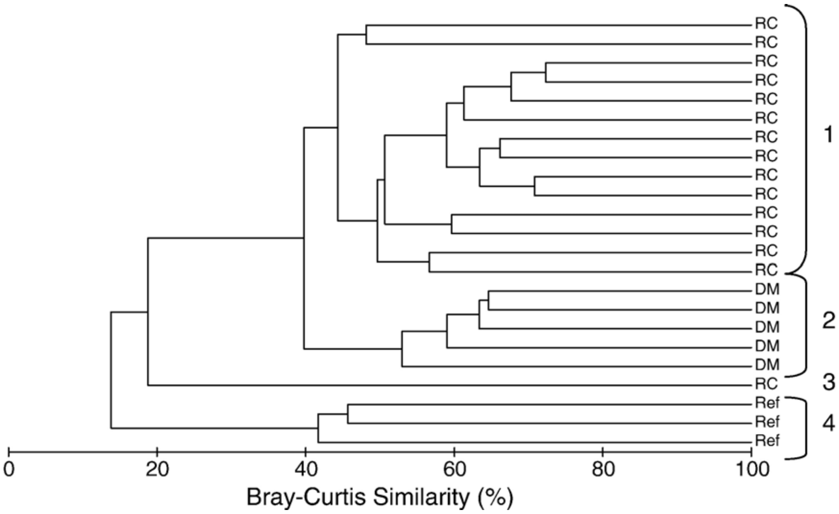

Fig. 4. Dendrogram showing hierarchical clustering of the red clay (RC), dredged material (DM) and South Reference Area (REF) stations based on Bray–Curtis similarity in benthic community structure.

had high densities of the nut clam *N. proxima* and several polychaetes (e.g., *Cirratulidae*, *Tharyx acutus*, *Mediomastus*, *Levinsenia gracilis*, *Scoletoma* sp.) that were either not present or present at comparatively low densities at the South Reference Area stations (Table 3).

The dredged material and red clay stations also had significantly different benthic community structure, although the *R*-statistic of 0.53 in Table 4 and the distance between these two groups in Fig. 5 both indicate a moderate degree of overlap. The difference was primarily due to the following: 1) the average abundance of *N. proxima* was much higher at the dredged material stations (11,215 individuals/m^2) compared to the red clay stations (3010 individuals/m^2), 2) the polychaetes *L. gracilis*, *Scoletoma* sp., and *C. soyeri* were much more abundant at the red clay stations, and 3) several taxa (e.g., *T. acutus*, *Mediomastus*, *Tellina agilis*, *Polygordius*, *Pitar morrhuanus*,

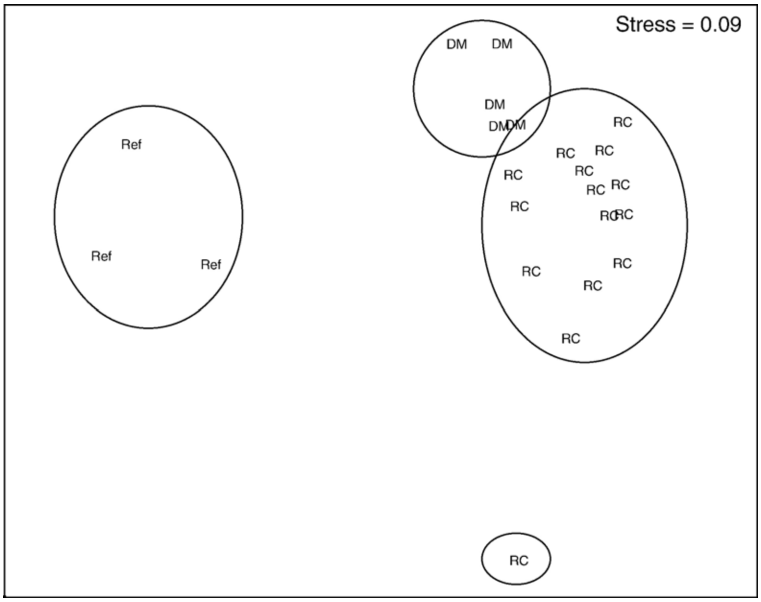

Fig. 5. Two-dimensional nMDS plot of the red clay (RC), dredged material (DM) and South Reference Area (REF) stations based on Bray–Curtis similarity in benthic community structure; the four station groups from the cluster analysis (Fig. 4) are circled.

Table 4
Results of the ANOSIM test of the null hypothesis: no significant difference in benthic community structure between the station groups

Test	*R*-statistic	Significance level (%)	Conclusion
Global test	0.71	0.1	s
Pairwise comparisons:			
Reference stations versus red clay stations	0.96	0.1	s
Reference stations versus dredged material stations	1.0	1.8	s
Red clay versus dredged material stations	0.53	0.2	s

The letter "s" indicates a significant difference between groups and rejection of the null hypothesis. An R statistic of >0.75 indicates a strong separation or large difference in overall benthic community structure between groups, while $0.75>R>0.25$ indicates varying degrees of overlap but generally different community structure between groups.

and *Tubificidae*) were much more abundant at the dredged material stations (Table 3).

4. Discussion

4.1. Changes in physical characteristics of the red clay

In the October 1998 survey undertaken 1 year after disposal, both the SPI and surface images revealed the presence of intact clumps of cohesive red clay at a considerable number of stations, imparting elevated small-scale relief (i.e., boundary roughness) to the sediment–water interface. The images further demonstrated that the surface of the red clay deposit 1 year following disposal was proving particularly attractive to a variety of burrowing and mobile megafauna. The clay's cohesiveness, which facilitated the creation of semi-permanent burrows/tunnels, and the greater structural complexity imparted to the sediment–water interface by the clumps, are both factors that probably contributed strongly to this attraction. In contrast, neither cohesive clumps nor high boundary roughness were observed in the images collected in July 2002, suggesting that the surface of the red clay deposits became considerably smoother since 1998. It is hypothesized that the burrowing and tunnelling activities of the organisms, combined with the continuous washing action of bottom currents, are the key factors acting to break down the original angular clay clumps into smaller and gradually smoother pieces between the 1998 and 2002 surveys.

In 1998, the freshly-deposited red clay also appeared to have a very homogeneous composition in both the SPI and surface images. In contrast, the images from the July 2002 survey showed considerable amounts of silty sand and organic detritus occurring in thin, discrete layers at the sediment–water interface and/or mixed within the surface layer of red clay. These observations are consistent with the grain size analyses showing the presence of fine and medium sand mixed with the red clay at the time of the July 2002 survey. The discharge of the Hudson River and the on-going disposal of large volumes of fine-grained dredged material both represent important, continuous sources of suspended sediment and particulate organic matter to the New York Bight (Mayer, 1982; Caracciolo and Steimle, 1983). Furthermore, waves and bottom currents are sufficiently strong during periodic storm events to resuspend muddy and sandy surface sediments within this dynamic inner continental shelf environment (Harris et al., 2003). The observed fine sand, silt and organic matter, therefore, presumably either settled out of the overlying water column or were transported laterally by bottom currents from surrounding seafloor areas onto the surface of the red clay deposit.

The same lateral-transport process serves to explain the thin surface depositional layer of sand over black dredged material (e.g., Fig. 3D and I) that was observed in this and numerous previous SPI monitoring surveys in and around the Mud Dump Site (SAIC, 1996, 1998, 2002). This unique stratigraphy results when clean fine sand, the native sediment throughout much of the inner New York Bight surrounding the disposal site, is resuspended by bottom currents and deposited on top of reduced, fine-grained dredged material.

It is reasonable to assume, therefore, that silt, sand and organic matter became entrapped and accumulated gradually over time in the interstitial spaces among the cohesive clay clumps. The gradual in-filling of these interstitial spaces, combined with the weathering of the clumps by current action and biological reworking, would all result in the observed smoothing of the red clay's surface. In a study of terrigenous clay experimentally deposited on an estuarine sandflat, Gibbs et al. (2001) observed that repeated drying cycles left cracks in the clay surface that similarly facilitated entrapment of natural sediments and food. They also found that burrowing activity by crabs enhanced both erosion of the clay surface and blending of the clay with underlying sediments. In the present study, the net effect of physical and biological weathering processes was to change both the form and composition of the red clay's surface, as it became both smoother and more heterogeneous in texture over the 5 year post-disposal period.

4.2. Benthic recolonization of the red clay and conventional dredged material

Because disposal of organic-rich, muddy sediment dredged from New York City waterways has been occurring in and around the Mud Dump Site for decades, "Stage III" communities dominated by larger-bodied, deposit-feeding infauna have become well-established in areas of the inner New York Bight where the seafloor is comprised of the disposed material. These communities in turn provide a local supply of adults and larvae to colonize new deposits of fine-grained dredged material. Long-term dominants of these communities include the burrowing anemone *Ceriantheopsis americanus*, the polychaetes *Nephtys incisa*, *T. acutus*, *Capitella capitata*, *Prionospio steenstrupi*, *Mediomastus ambiseta*, and the bivalves *P. morrhuanus*, *T. agilis* and *N. proxima*, while the natural macrofaunal assemblages on the silty-sand and sand bottoms of the wider surrounding region commonly include the sand dollar *Echinarachnius parma* and the amphipods *Byblis serrata*, *Corophium crassicorne*, *Rhepoxinius hudsoni*, *Unciola irrorata* (Caracciolo and Steimle, 1983; Chang et al., 1992). The deposits of fine-grained dredged material, therefore, function much like the soft-bottom equivalent of an artificial reef, providing organic-rich muddy habitat in a region where the natural bottom consists predominantly of more-compact, organic-poor silts and clean sands.

Past SPI monitoring surveys in and around the Mud Dump Site serve to demonstrate that colonization of organic-rich, fine-grained dredged material by the existing Stage III "climax" community of larger-bodied deposit-feeders tends to be rapid, typically occurring within 1 or 2 years (SAIC, 1996, 1998, 2002). In the 1998 SPI survey conducted roughly 1 year after disposal of the red clay, however, colonization of both the red clay deposits and nearby conventional dredged material deposits by larger-bodied benthic infauna appeared to be very limited. The majority of images either lacked any visible organisms or revealed a community comprised solely of low to moderate numbers of small, tubiculous "Stage I" polychaetes known to feed on labile detritus located at or near the sediment surface.

The occurrence of these organisms as the presumed initial colonizers is consistent with both the generalized model of infaunal succession in response to physical disturbance of the seafloor (McCall, 1977; Pearson and Rosenberg, 1978; Rhoads et al., 1978; Rhoads and Boyer, 1982; Rhoads and Germano, 1986) and observations from numerous other dredged material-specific studies (see recent review by Bolam and Rees, 2003). However, the relatively limited degree of colonization was not consistent with expectations: past experience at this site and studies in similarly shallow, energetic, nearshore environments indicate that benthic communities generally tend to recover to a much greater degree (i.e., approaching pre-disturbance or nearby reference area conditions) within 1 year of disposal (Oliver et al., 1977; Rhoads et al., 1978; Van Dolah et al., 1984; Ray and Clarke, 1999; Bolam and Rees, 2003).

At the dredged material stations, the unexpected results are attributed to the presence of the relatively thin (2 to 5 cm) layer of fine sand that was observed in the images to be completely covering the surface of the black, conventional dredged material. It is hypothesized that this surface sand layer acted as a cap that effectively isolated the underlying organic-rich dredged material from migrating adults and settling larvae of Stage III organisms, thereby greatly inhibiting the expected rapid establishment of a community dominated by larger-bodied deposit-feeders.

Stage I surface-dwellers likewise were the only infauna observed at the red clay stations in the initial SPI survey that took place roughly 1 year following disposal. The red clay's stiffness and low organic carbon content likely inhibited extensive burrowing and sub-surface deposit feeding by the local Stage III taxa. However, by the time of the July 2002 survey (5 years following disposal), both the SPI and surface images indicated that the surface of the red clay had weathered considerably, becoming both smoother and draped to a much greater extent with deposits of silty sand and organic detritus. These images further revealed that the surface of the red clay had become populated by a more abundant and diverse community of infaunal and epifaunal organisms compared to the 1998 survey. Distinctive thin stalks, constructed by Podocerid amphipods to facilitate suspension-feeding above the seafloor, were observed frequently in the SPI images. Furthermore, both surface polychaete tubes (Stage I) and, to a lesser extent, subsurface feeding voids and burrows (Stage III), were visible in the SPI images obtained at the red clay stations. These observations suggest that after an initial delay in recolonization, as detected in the 1998 survey, a much more abundant and diverse community had become established over the red clay deposits by the time of the 2002 survey, 5 years after disposal. The breakdown of the red clay clumps and the incorporation of silts, sand and organic matter into the sediment matrix are the key physical changes observed between the 1998 and 2002 surveys; it is reasonable to assume that these greatly facilitated colonization by larger numbers and varieties of organisms.

While colonization of the red clay by infauna appeared to be delayed at the time of the 1998 survey, the images of the sediment surface revealed that larger mobile epifauna were active over the red clay 1 year after its disposal. This was evidenced by abundant burrow openings, tracks and furrows, and the presence of crabs, shrimp and sea stars. The extensive burrowing and foraging activities of these organisms likely helped to break down the larger cohesive clumps of clay and increased the mixing of organic matter into the substrate over time. The 2002 surface images showed that mobile predators like crabs and sea stars continued to be present, but numerous colonial hydroids not observed previously in October 1998 had become widespread over the surface of the red clay. Exposed patches of the cohesive clay, as well as small rocks and pebbles mixed with the clay, appeared to be providing hard surfaces that served as attachment points for these hydroids.

The benthic grab sampling generally serves to support the 2002 imaging results in showing that a relatively abundant and diverse community had developed over the red clay deposits. The 15 most-abundant taxa at the red clay stations included a variety of both Stage I and Stage III polychaetes (e.g., *Cirratulidae*, *T. acutus*, *Mediomastus*, *L. gracilis*, *Scoletoma*, *N. incisa*), as well as the bivalves *P. morrhuanus* and, most notably, the nut clam *N. proxima*. All of these taxa are common in the New York Bight, and most are considered to be relatively insensitive to contaminants and/or associated with areas where organic-rich, fine-grained dredged material has been disposed in the past (Caracciolo and Steimle, 1983; Chang et al., 1992).

At the dredged material stations, the benthic grab sampling results also support the SPI interpretation in showing a dominance of opportunistic and/or stress-tolerant taxa, including *N. proxima* as the overwhelming numerical dominant but also high relative numbers of the Stage I polychaetes Cerratulidae (LPIL), *T. acutus*, *M. ambiseta*, *Polygordius* sp., *Spiophanes bombyx*, the bivalve *T. agilis*, and tubificid oligochaetes. The occurrence of only two Stage III polychaetes (*Aricidea catherinae* and *L. gracilis*) among the numerical dominants at the dredged material stations in 2002 lends support to the earlier suggestion that the normal pattern of succession was greatly inhibited by natural capping of the dredged material by migrating sand.

Due to disproportionately high numbers of *N. proxima*, the dredged material stations had significantly higher average organism density than the South Reference Area stations and significantly lower diversity and evenness than both of the other areas. There were no significant differences among the three areas in average numbers of taxa or species richness. In terms of the original survey objective to address concerns about the red clay's suitability as habitat, it is possible to conclude that as of summer 2002, the red clay deposits had become recolonized by a benthic infaunal community whose average abundance, diversity, evenness and species richness were either not significantly different from or significantly greater than those in nearby seafloor areas. This includes both natural sandy bottom areas (South Reference) and deposits of conventional, unconsolidated dredged material.

The multivariate analyses indicated that the overall structure of the benthic community in the red clay area was fundamentally different from that observed in the nearby dredged material and South Reference areas. The significant differences in community structure among the three areas are most readily attributed to the differences in substrate types (i.e., organic-rich, muddy dredged material versus organic-poor, cohesive red clay versus clean fine sand), as well as differences in the timing of key physical processes (e.g., weathering of the red clay and sand capping of the dredged material) that appeared to have a strong influence on the successional dynamics. Such processes undoubtedly have continued to influence the physical and biological characteristics of surface sediments in the three areas, such that the benthic communities observed in 2002 may or may not be stable in the long-term. Additional surveys using the same techniques and stations are necessary to address the interesting questions surrounding longer-term successional patterns.

In general, placement of both conventional dredged material and, to a lesser extent, sewage sludge, at designated disposal sites in coastal environments is a worldwide practice, and the response of benthic communities is fairly well-documented in an extensive grey literature and journal articles (e.g., Watling et al., 1974; Caspers, 1987; Reid et al., 1995; Bolam and Rees, 2003; Kress et al., 2004). Only a few published studies could be found that report on benthic response to other, less-common materials, such as china clay waste (Probert, 1975), mine tailings (Kline and Stekoll, 1999), and a "muddy-maerl matrix" (De Grave and Whitaker, 1999). Several monitoring surveys conducted under the previously mentioned DAMOS program in New England have utilized SPI to document the gradual break down and successful recolonization of highly consolidated dredged material over the course of several years. Notable examples include blue clay dredged from Boston Harbor and placed at a disposal site in

Massachusetts Bay, and grey clay used for capping contaminated dredged material at the New London Disposal Site in eastern Long Island Sound (U.S. Army Corps of Engineers, 2002; Valente and Fredette, 2002).

This study therefore is among the first to demonstrate the concerted use of imaging and traditional grab sampling approaches to evaluate recolonization of an atypical dredged material (stiff red clay) over an extended timescale. Either approach by itself would probably have been sufficient to meet the broad study objective of determining whether or not the red clay eventually became colonized. However, the sediment images provided considerable insights on the physical conditions and changes over time experienced at the surface of the red clay deposits, and allowed *in-situ* viewing of the response of different types of benthic organisms to these conditions. In particular, the role of mobile epifauna in recolonizing and breaking down the red clay, as well as the presence of fragile amphipod stalks and attached hydroids in 2002, would likely have been missed or considerably underestimated if only benthic grab sampling had been conducted. The benthic grab sampling was valuable in providing data on the taxonomic composition of the infaunal communities observed in the images over both the red clay and nearby comparative areas. The combination of imaging and traditional techniques made for a much more definitive and conclusive study than either approach by itself.

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