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Spatial and Temporal Distribution of Dredged Sediments Disposed at the Pensacola, Florida, Ocean Dredged Material Disposal Site Using Naturally Occurring Gamma Radiation

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The fate and effects of large volumes of dredged sediments disposed at offshore disposal sites are of particular interest to the federal and state agencies responsible for its management. During the period from Jan. to April 1990, 3.7 million m^3 of dredged sediments were disposed of at the Pensacola, FL, Ocean Dredged Material Disposal Site (ODMDS). From May 1990 to Oct. 1993, the dispersal of dredged sediments in the area surrounding the disposal site was studied using bathymetry, sediment particle size distribution, and the differential abundance of naturally occurring gamma radiation emitters in dredged sediments and native seafloor sediments. Gamma radiation measurements in the 0.4- to 3.0-MeV energy range, made in May 1990, showed that disposal activities at the Pensacola site resulted in the accumulation of fine (silts and clays) dredged sediments throughout the 91-km^2 survey area. The average proportion of fine-grained sediment particles (silts and clays) in surface sediments outside the boundaries of the designated disposal site more than doubled after disposal. By the end of the 3-yr study period in 1993, the bulk of the fine-grained dredged sediment had been transported away from the area surrounding the ODMDS. Gamma radiation measurements were able to detect the presence of dredged sediments in the disposal zone and in several areas outside the disposal site boundaries.

Ocean disposal is a commonly used method of disposal of uncontaminated dredged sediments from harbors and other coastal waterways in the United States. The disposal of large volumes of dredged sediments onto the seafloor may affect biological communities and other natural resources within and outside the boundaries of a designated disposal area. The greatest risk to resources outside the disposal site boundaries is due to the fine-grained sediments (silt and clay fractions <0.05-mm particle diameter) entrained in the water column in the disposal plume and the disposed benthic sediments that can be resuspended by wave action and storm-induced currents. Disposed sediments suspended in the water column can be transported and deposited over large distances by ocean currents. Dredged sediment disposal plumes may result in degraded water quality because of the release of nutrients and trace metals from anaerobic sediments (Blom et al., 1976; Chen et al., 1976). Disposal may also result in increased suspended sediment loads and water column turbidity (Windom, 1976; Morton, 1977). The transport and deposition of disposed sediments may affect benthic communities by altering habitat through changes in the sediment grain size distribution or, in severe cases, burial (Marszalek, 1981; Maurer et al., 1981a, 1981b, 1982; Engler et al., 1991; Harvey et al., 1998).

Rocks and sediments in the earth's crust contain trace radioactive elements, which emit gamma (electromagnetic) radiation as a result of the radioactive decay process. Measurements of naturally occurring gamma radiation are commonly used in offshore mineral exploration (Noakes et al., 1974; Grosz, 1992; De Meijer et al., 2000). Emery and Uchupi (1972) found that specific heavy mineral deposits on the seafloor are significantly higher in uranium and thorium content, and in the content of their decay daughter radioisotopes, than the surrounding natural seafloor sediments. The most common radioelements found in marine mineral deposits are potassium-40, thorium-232, and uranium-238, found in clayey sediments, placer minerals, and phosphorite minerals, respectively (Emery and Uchupi, 1972; Grosz, 1992; Kunzendorf, 1992). Submersible gamma radiation detectors have been used in seafloor mineral exploration since the late 1960s and early 1970s (Summerhayes et al., 1970; Miller et al., 1977).

In 1988, a series of studies were initiated at the Pensacola Ocean Dredged Material Disposal Site (ODMDS) designed to identify disposed dredged sediments on the seafloor and track changes in their spatial distribution during a 3-yr period (1990–93), after the disposal that occurred during the early part of 1990. The studies measured the differential abun-

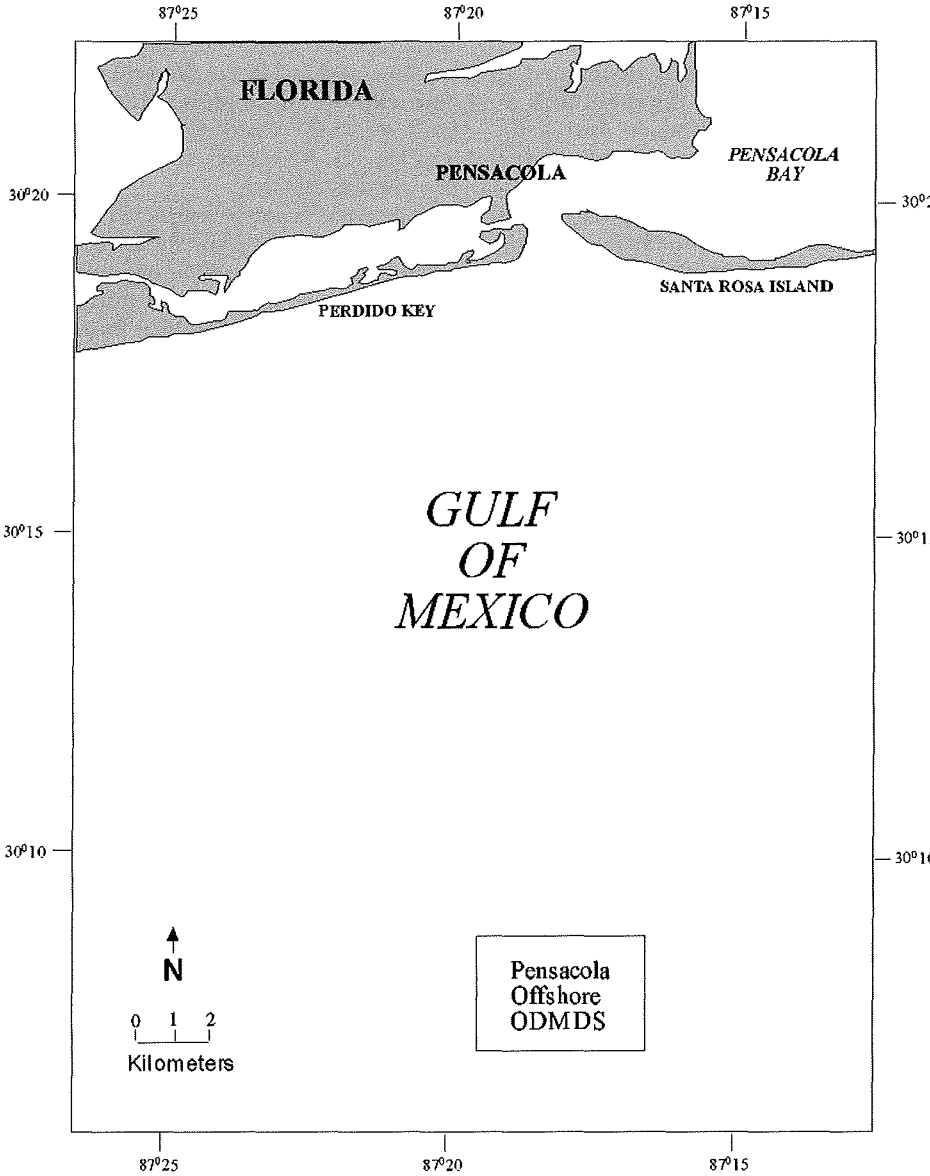

Fig. 1. Location of the Pensacola, FL, ODMS.

dance of gamma radiation emitters in dredged material and normal seafloor sediments as a qualitative indicator of dredged sediments. The studies also measured changes in the particle size distribution of benthic sediments and in the seafloor topography within the study area as a result of dredged sediment disposal.

Materials and Methods

Study area.—The Pensacola, FL, ODMDS is centered at coordinates 30°08.0′N 87°17.0′W and is located approximately 22 km south of the entrance to Pensacola Bay (Fig. 1). The disposal site measures approximately 3.2 km wide and 6.4 km long, comprising about 20.5 km^2 of seafloor. Water depths within the ODMDS ranged from approximately 18 to 24 m before dredged sediment disposal. Seafloor sediments off Pensacola comprised medium to course grain sands (mean = 96%), and benthic communities were found to consist of fauna typical of soft sediments (USEPA, 1988). Currents measured off Pensacola are mainly nontidal, wind-driven flows that move to the southeast or southwest (Pickett and Burns,

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1988). Nonstorm current speeds tend to be low, ranging from about 1 to 6 cm/sec.

The Pensacola ODMDS was designated in 1988 to accept a portion of the more than 10 million m^3 of sediments dredged during the construction of a turning basin and channel deepening for the U.S. Naval Air Station at Pensacola. During the 4-mo disposal period from Jan. to April 1990, approximately 4.0 million m^3 of dredged sediments were placed on the beach at Perdido Key, about 3.0 million m^3 were disposed of at a nearshore site off Perdido Key, and the remaining 3.7 million m^3 were placed within the eastern half of the ODMDS. The initial 2.7 million m^3 of dredged sediments was used by the USACOE to construct a U-shaped containment area or berm with the opening facing west. The berm was designed as a stable structure intended to contain the less-cohesive sediments dredged from the project area by preventing excessive seafloor spreading (USEPA, 1988). The berm sediment consisted mainly of medium- to course-grained sand and more cohesive clump-forming sediments. The remaining 1.0 million m^3, consisting of approximately 40% sand and 60% silts and clays, was placed in the center of the "U." Of the total volume of dredged sediments placed in the berm, about 300,000 m^3 (30%) consisted of noncohesive fine-grained sediments.

Seafloor gamma radiation detection.—The seafloor gamma radiation detection system was developed and operated by the Center for Applied Isotope Studies (CAIS) at the University of Georgia. The system consists of a ship-towed scintillation counter containing a thallium-activated sodium iodide crystal designed to measure four specific radiation energies. Potassium-40 (^{40}K) is measured at 1.46 million electron volts (MeV). Uranium is detected by measuring its decay daughter radioisotope, bismuth-214 (^{214}Bi), at 1.76 MeV, and thorium is detected by measuring thallium-208 (^{208}Tl) at 2.61 MeV. Total gamma energy, all radiation energies between 0.4 and 3.0 MeV, is also measured. Gamma radiation energies are measured in counts per second (cps), and the system was designed to detect gamma radiation to depths below the seafloor surface of up to 25 cm depending on the strength of the gamma emitter and sediment properties. The radiation detector was connected to a shipboard gamma spectrometer, a portable computer, a fathometer, and a Loran navigational unit (CAIS, 1995).

Survey.—The survey area included the ODMDS and a portion of the surrounding seafloor extending about 2.7 km beyond the northern and southern disposal site boundaries and 2.1 km beyond the eastern and western boundaries (Fig. 2). The total area surveyed was approximately 91 km^2.

Four surveys were conducted from 1988 to 1993. The Oct. 1988 survey was conducted before disposal to determine baseline gamma activity, sediment particle size distribution, and seafloor topography. The first postdisposal survey was conducted in May 1990, immediately after disposal of all project sediments, to document immediate changes resulting from the disposal activities. The second postdisposal survey was conducted in Oct. 1990 to detect short-term spatial changes. The last survey was conducted in Oct. 1993 to examine long-term changes in sediment structure and dredged sediment distribution.

During each survey (May 1990 sediment data were not obtained), sediment samples were collected by box core from predetermined locations within and outside the disposal site boundaries (Fig. 2). The upper 7.5 cm of each core sample was collected and refrigerated at 4 C for storage and transport to a U.S. Environmental Protection Agency laboratory (Athens, GA) for processing. Particle size distribution was determined by wet sieving.

Before deployment of the gamma sled, the spectrometer was calibrated to a radioactive reference sample, and the positioning system and fathometer were calibrated to the support vessels' systems. The sled was towed in contact with the seafloor within the surveyed area along predetermined transects running north to south at a speed of 4.6–5.5 km/hr (Fig. 2). Transects were spaced approximately 0.42 km apart during the 1988 predisposal survey. Postdisposal survey transects were spaced approximately 0.24 km apart. Positioning, bathymetry, and radiometric data were collected at intervals of 60 sec (120 sec for the May 1990 survey) of sled travel throughout each survey. The total number of samples of each data type collected during each survey depended on the transect spacing and data collection intervals, which resulted in a range of approximately 400–1,700 separate sampling events per survey. Parameters measured included total gamma radiation, ^{214}Bi, ^{208}Tl, and ^{40}K gamma activity, and the depth and position (latitude/longitude) of the sled. The results of the total gamma radiation (0.4–3.0 MeV) measurements are presented in this study.

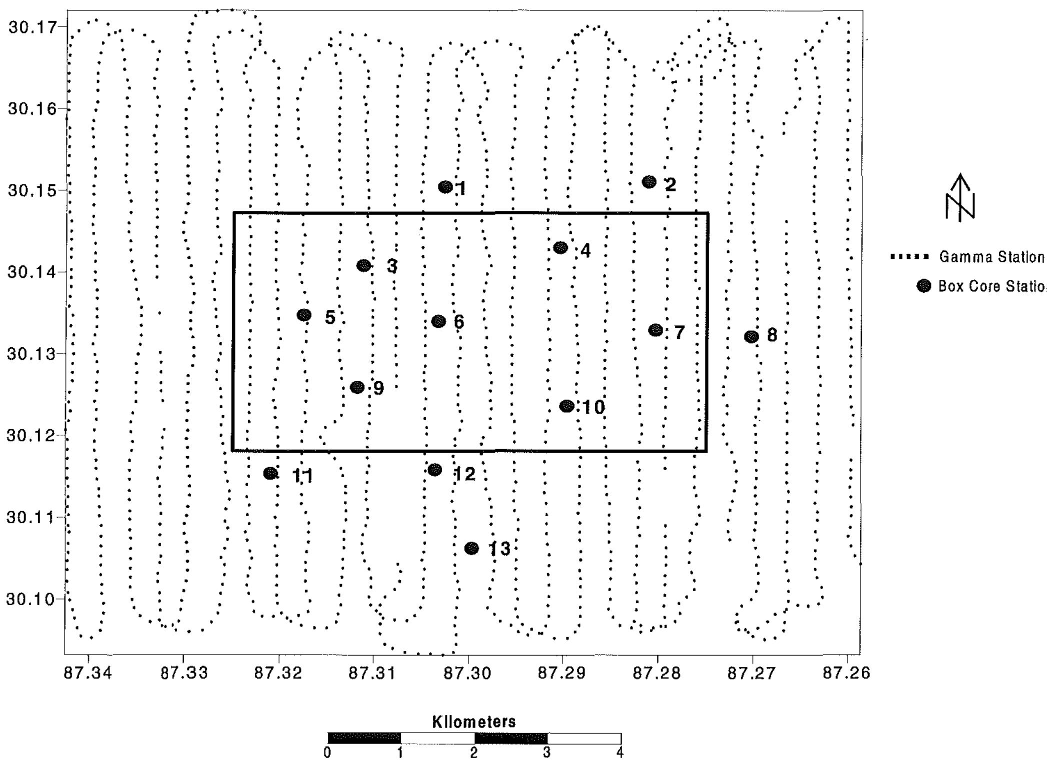

Fig. 2. Pensacola ODMDS survey area, gamma sled path, gamma and box core sample stations from the Oct. 1990 survey.

Results

Predisposal: Oct. 1988 survey.—Predisposal bathymetric data show that the survey area generally slopes seaward from the northwest to the southeast (Fig. 3). The southwest corner of the survey area slopes rapidly to a maximum depth of about 33 m, forming a trenchlike depression oriented from the northwest to the southeast. The area within the ODMDS boundaries follows the general survey area trend, with the shallowest portion (17-m depth) in the northwest corner and the deepest portion (24 m) in the southwest part of the site. The planned disposal zone was relatively flat and featureless.

The predisposal total gamma intensity of the natural seafloor sediments within the surveyed area ranged from 730 to 1,950 cps and averaged 918 cps (Table 1). The area of highest total gamma intensity corresponds to the valleylike depression in the southwest corner of the survey area (Fig. 4). Gamma count rates in this area exceeded 1,900 cps and averaged about 1,000 cps higher than the rest of the survey area. The remaining area outside the ODMDS boundaries was in the 700- to 1,000-cps range with a few isolated areas of higher intensity, mainly in the eastern portion of the survey area. Gamma intensity within the ODMDS was fairly uniform throughout, averaging 856 cps.

Overall, the silt-sized (0.05–0.002 mm) and clay-sized (<0.002 mm) particles accounted for less than 1.0% (by weight) of the surface sediments in the survey area (Table 2). The silt fraction was fairly uniform among stations (range = 0.1–0.2%). The clay fraction displayed more between-station variability with a range from 0.2% to 1.2%.

Postdisposal: May 1990 survey.—The May 1990 postdisposal bathymetry plot (Fig. 3) shows the presence of several distinct mounds of dredged sediments located just east of the center of the ODMDS. The sediments form a low-relief U-shaped berm, oriented with the opening facing west, constructed with the initial 2.7 million m^3 of coarse sand and cohesive sediments. A higher relief mound of unconsolidated sediments was placed within the berm. A vertical cross-section of the disposal mound was produced from a profile line running from

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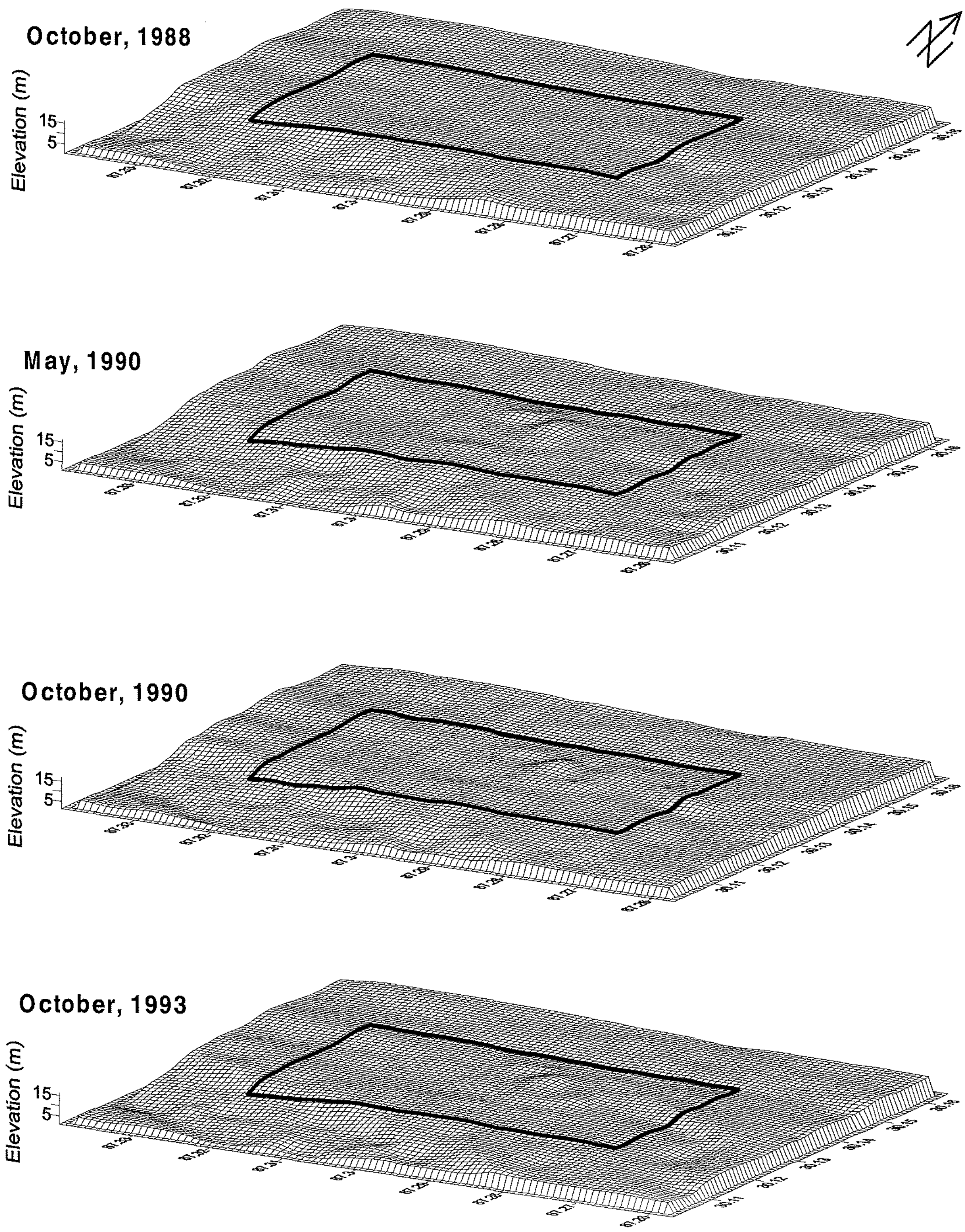

Fig. 3. Pensacola ODMDS survey area bathymetry for Oct. 1988, May 1990, Oct. 1990, and Oct. 1993. The ODMDS boundary is shown by the rectangle within the survey plots.

the northern and southern boundaries of the ODMDS through the highest point of unconsolidated spoil mound and a portion of the berm (Fig. 5). The cross-section shows that the elevation of the spoil mound reached about 4.5 m above the surrounding seafloor at its highest point and about 3.6 m above the berm. Other topographic changes in the ODMDS and the remainder of the survey area appeared to be relatively minor.

Total gamma radiation measured during the May 1990 postdisposal survey ranged from

TABLE 1. Count rates (means and ranges) for total gamma radiation measured at all surveys conducted at the Pensacola, FL, ODMDS.

	Predisposal 10/1988	Postdisposal 5/1990	Postdisposal 10/1990	Postdisposal 10/1993
Survey area				
Mean ± SD	917.8 ± 181.8	2,289.5 ± 447.1	2,208.9 ± 404.8	1,393.2 ± 343.6
Range	730–1,950	1,699–6,658	1,826–6,090	960–3,307
In ODMDS[a]				
Mean ± SD	856.1 ± 42.1	2,467.1 ± 762.0	2,343.5 ± 665.7	1,385.2 ± 412.5
Range	760–1,110	1,784–6,658	1,892–6,090	989–3,307
Out ODMDS[b]				
Mean ± SD	932.8 ± 198.8	2,248.1 ± 274.2	2,169.8 ± 275.8	1,395.9 ± 315.9
Range	730–1,950	1,699–3,554	1,826–3,836	960–2,755

[a] Inside the boundaries of ODMDS.
[b] Outside the boundaries of ODMDS.

1,699 to 6,658 cps throughout the survey area, with an overall average intensity of 2,298 cps (Table 1). The average gamma intensity within the ODMDS was significantly greater than the values outside the ODMDS boundaries. The spatial distribution pattern of total gamma activity measured during the May 1990 survey showed a marked change from predisposal conditions (Fig. 4). A distinct area of high gamma intensity (>6,000 cps) occurred in the eastern half of the ODMDS, corresponding to the dredged sediment spoil mounds. Total gamma activity in the southwest depression also increased significantly, both in intensity and in spatial distribution, with count rates ranging from about 2,500 to 4,000 cps. Gamma intensity throughout the remainder of the survey area was uniformly higher, with count rates ranging between 2,000 and 2,500 cps. Several areas of reduced gamma intensity (1,500–2,000 cps) occurred in the northwest portion of the survey area (Fig. 4).

Short-term postdisposal changes: Oct. 1990 survey.—Bathymetry measurements made in Oct. 1990 show that the area dimensions and position of the berm and spoil mound did not appear to change during the 5 mo following the May 1990 survey (Fig. 3). The spoil mound elevation decreased by approximately 18% to a maximum height of 3.7 m above the surrounding seafloor, whereas the berm elevation decreased by about 33% to a height of 0.6 m (Fig. 5).

Total gamma activity measured during the Oct. 1990 survey was similar to that measured during May 1990, with a range of 1,826–6,090 cps and an average of 2,209 cps within the survey area (Table 1). The disposal site remained the area of highest gamma intensity, although some spreading of the disposal mounds in the north-south direction was evident (Fig. 4). Gamma activity in the sediments in the southwest depression remained in the 2,500- to 4,000-cps range. Areas of reduced gamma intensity in the remainder of the survey area increased in both number and surface area, particularly in the northwest portion of the survey area (Fig. 4).

Results from the Oct. 1990 box core analysis (Table 2) show that the proportions of silt- and clay-sized particles in surface sediments both within and around the disposal site increased considerably compared with predisposal conditions. The proportion of silt-sized (1.46% by weight) and clay-sized (1.32% by weight) particles in postdisposal sediments increased by a factor of 10.6 and 1.8, respectively. The largest increases in the proportion of fine sediments occurred within the spoil mound at stations 3 and 4, to the west of the spoil mound at station 7, and at station 11 on the slope of the southwest depression.

Long-term changes: Oct. 1993 survey.—The Oct. 1993 bathymetry survey did not reveal any significant changes in overall seafloor topography during the 3-yr period starting from the Oct. 1990 survey (Fig. 3). The vertical cross-section of the 1993 spoil mound, however, showed an additional reduction in elevation of about 0.8 m (22%), with a final mound height of about 2.9 m (Fig. 5). Berm elevation was reduced by just less than 0.2 m, an additional reduction of about 33%.

Total gamma intensity measured in Oct. 1993 ranged from 960 to 3,307 cps with an area-wide average of 1,393 cps, an overall area-

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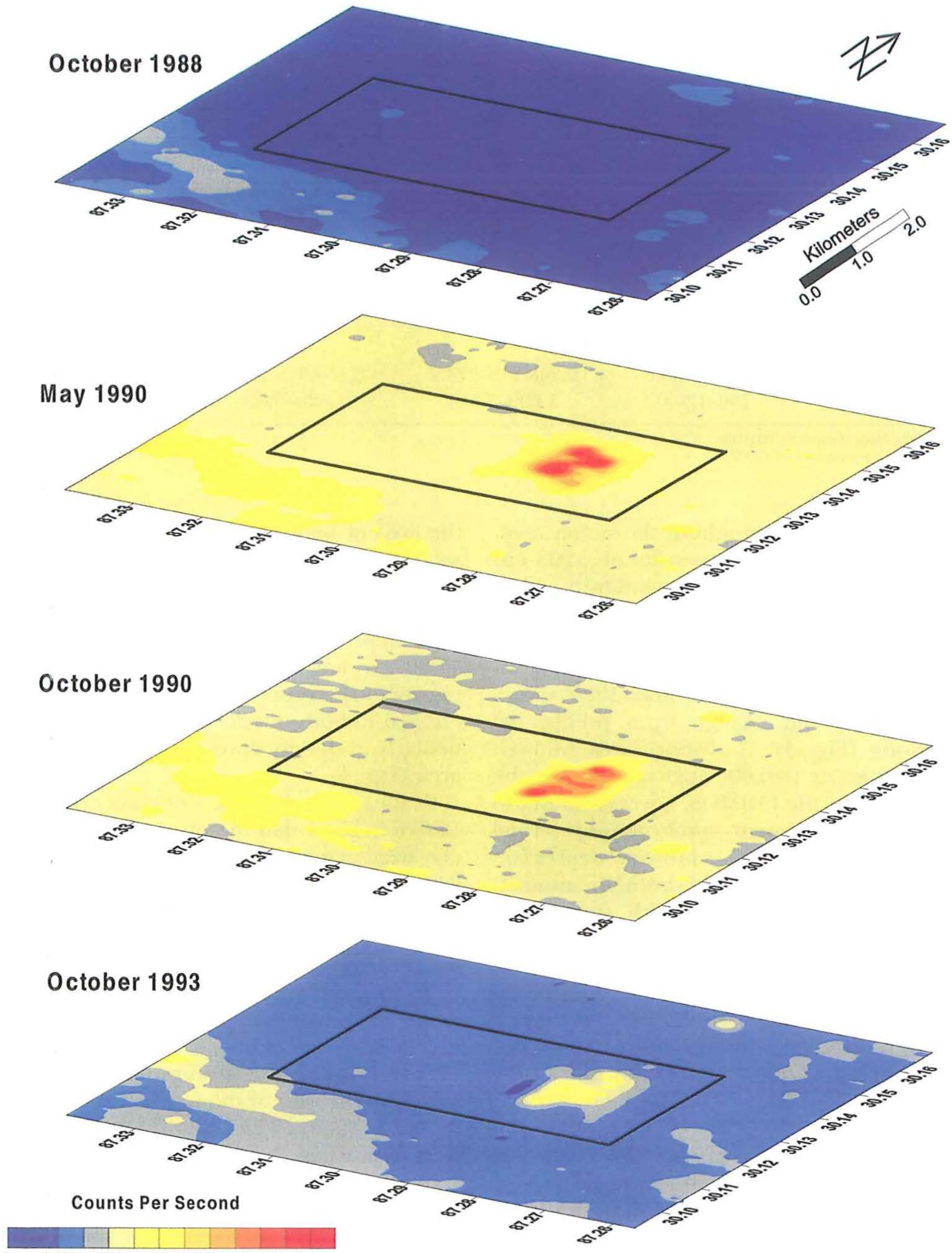

Fig. 4. Stacked gamma radiation contour plots of the Oct. 1988, May and Oct. 1990, and Oct. 1993 Pensacola ODMDS surveys.

wide decrease of 56.8% from Oct. 1990 (Table 1). The spoil mound area and southwest depression remained the areas of highest gamma activity in the survey area. The peak total gamma intensity at the spoil mound was reduced from 6,090 cps in Oct. 1990 to 3,307 cps in Oct. 1993, a decrease of 54%. Total gamma radiation emissions from the southwest depression were reduced to 1,500–3,000 cps, an overall reduction of about 30%. The 1993 gamma distribution plot (Fig. 4) shows the relative reduction in gamma intensity throughout the survey area during the 3-yr period. A few isolated patches of slightly elevated gamma inten-

TABLE 2. Proportion of the silt-sized (0.05–0.002 mm) and clay-sized (<0.002 mm) particles in sediments collected within the area surveyed around the Pensacola, FL, ODMDS before and after the disposal of dredged sediments. Data are given in percent by weight.

	Silt			Clay		
	Predisposal	Postdisposal		Predisposal	Postdisposal	
Station	10/1988	10/1990	10/1993	10/1988	10/1990	10/1993
1	0.1	0.1	0.1	0.8	1.4	0.3
2	0.2	0.3	0.1	0.8	1.2	0.6
3	0.2	2.9	0.1	0.9	0.9	0.7
4	0.1	3.4	0.6	1.2	1.7	0.6
5	—	0.1	0.1	—	2.3	0.9
6	0.1	0.5	0.1	0.2	1.3	0.6
7	0.1	4.5	0.8	1.0	1.5	0.4
8	0.1	0.4	0.1	1.0	1.5	0.8
9	0.1	0.2	0.9	1.0	1.2	0.9
10	0.2	1.6	3.2	0.7	1.5	0.8
11	0.1	2.8	0.1	1.2	1.5	0.5
12	0.2	0.5	0.1	0.8	1.1	0.4
13	0.2	0.3	0.2	0.8	1.0	0.7
Mean	0.14 ± 0.05	1.35 ± 1.52	0.5 ± 0.82	0.87 ± 0.26	1.39 ± 0.36	0.63 ± 0.19
Range	0.1–0.2	0.1–4.5	0.1–3.2	0.2–1.2	0.9–2.3	0.3–0.9

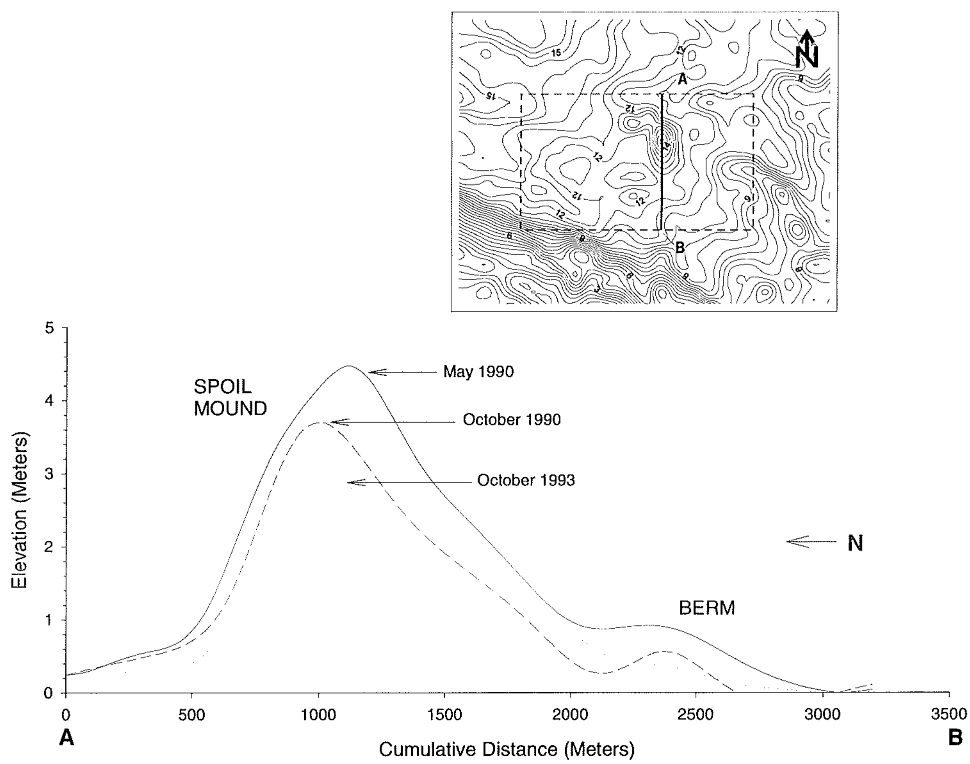

Fig. 5. Position of north–south profile line through the ODMDS (inset) and vertical cross-sections showing spoil mound and berm elevation for May and Oct. 1990 and Oct. 1993.

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sity occurred in the eastern portion of the survey area; however, the majority of the remaining area was in the 500- to 2,000-cps range.

Sediment grain size distribution data from the Oct. 1993 survey shows that the proportion of silts and clays in surface sediments changed significantly (Table 2). The average proportion of silt-sized particles in surface sediments was reduced by 63% and that of clay-sized particles by 56% from the Oct. 1990 values.

Discussion

The physical processes involved in the surface disposal of dredged sediments onto the seafloor have been described (Truitt, 1988). Early work by Gordon (1974) described the behavior of an instantaneous dredged sediment discharge as a three-part sequential process: 1) convective descent through the water column, 2) impact with the seafloor, and 3) lateral spread due to horizontal momentum of the sediment plume and redistribution of the spoil through passive dispersion. On release into the water column, the denser sediment forms the solid bulk phase and slurry phase of the discharge as it travels to the bottom (Bastian, 1974). The plume phase forms as turbulent eddies shear particulates from the falling slurry and begin dispersal in the water column (Bastian, 1974; Rhoads, 1994). Horizontal spreading occurs during the dynamic collapse phase, when the slurry impacts the seafloor, resulting in rebound and resuspension of sediments (Bastian, 1974; Johnson et al., 1992). Long-term transport of the discharged sediments occurs as wave action and ambient currents resuspend and disperse the material (Johnson et al., 1993).

Bathymetry data collected during the 3-yr postdisposal survey period indicate that the constructed berm and spoil mound remained in their original position and in their approximate aerial dimensions on the seafloor. The stable position of the contained spoil mound suggests that the more cohesive and heavier sediments used to construct the berm were effective in limiting the spread of the bulk of unconsolidated spoil sediments across the adjacent seafloor. Because of placement of the unconsolidated sediments within a relatively confined area, the elevation of the spoil mound exceeded that of the surrounding berm. This difference in height may have limited the berm's ability to control spoil mound erosion. The highest rate of decrease in spoil mound elevation (18%) occurred within about 6 mo of the conclusion of disposal activities. The spoil mound height continued to decrease, however, at a slower average annual rate (7.3%) during the 3-yr period from 1990 to 1993. The berm also subsided at a faster initial rate and more slowly during the subsequent 3-yr period. Compared with the spoil mound, the decrease in berm elevation was slower, reaching a total of 0.5 m by 1993 compared with a 1.6-m overall reduction in spoil mound height. In studies of dredged sediments in Long Island Sound, Bokuniewicz et al. (1980, unpubl., summarized in Tavolaro, 1983) observed disposal mound volume reduction of 33%, most of which occurred within the first month after disposal and the remainder within the first year. Open water disposal mounds in Chesapeake Bay and Delaware Channel reduced an average of 44% in volume within the first 6 mo after deposition, 54% after 1 yr, and 70% after 2 yr (Panageotou and Halka, 1989, 1990; Halka, et al., 1994).

Disposal mound reduction is usually due to a combination of both consolidation (dewatering and settling) of the disposed sediments and erosion processes. Tavolaro (1983, 1984) reported a spoil mound volume reduction of 41% at the New York Mud Dump Site, mostly attributed to consolidation. Panageotou and Halka (1989, 1990) and Halka et al. (1994) showed that consolidation accounted for roughly 33–50% of the total volume reduction of fine-grained disposal mounds, whereas 50–66% was due to erosion. Several factors may account for the greater overall reduction in spoil mound height compared with the berm. The higher percentage of unconsolidated fine sediment in the spoil material would likely result in a faster rate of erosion than the denser, more consolidated berm material. The higher spoil mound elevation may also have resulted in a localized increase in current speed, contributing to a higher erosion rate.

Before disposal, the average total gamma radiation intensity was higher in the portion of the survey area outside the boundaries of the ODMDS (Table 1). This was mainly due to the higher gamma values (>1,900 cps) that occurred in the depression in the southwest portion of the site. A possible explanation for the high gamma intensity in this area is that the depression may have formed an area of reduced wave effects and lower current speeds, resulting in greater accumulation of fine sediments in the depression relative to the rest of the area. Work conducted on the inner shelf of the western Atlantic showed that gamma intensity tends to increase with decreasing sediment particle size (Jaffe and Hughes, 1953;

Grosz and Escowitz, 1983; Grosz, 1987; Grosz et al., 1989; Grosz et al., 1990). An increase in fine-grained sediment accumulation in the depression would account for the relatively higher gamma intensities measured in that area.

Immediately after the disposal of dredged sediments, gamma radiation intensity increased significantly throughout the survey area, with the highest intensities measured at the location corresponding to the disposal zone (berm and spoil mound) and at the southwest depression (Fig 5). Disposal zone gamma intensities decreased steadily during the following 3-yr monitoring period. It is known from previous work that thorium and uranium and their decay daughter products are abundant in specific mineral deposits found in the marine environment, particularly heavy (specific gravity >3.0) minerals, whereas ^{40}K tends to be more abundant in clayey minerals with a specific gravity <3.0 (Emery and Uchupi, 1972). The high initial gamma intensities on the spoil mound and berm indicate that sediments dredged from Pensacola Bay contained minerals bearing thorium, potassium, uranium, and associated decay daughter radioisotopes and were highly concentrated at the disposal zone. The steady decreases in gamma intensity around the disposal zone with time, plus decreases in spoil mound and berm elevation, suggest that the gamma-emitting sediments within the instrument's sensitivity range (about 25 cm below the seafloor surface) were being transported away from the disposal area. The slower rate of gamma reduction that occurred in the southwest depression suggests that the dredged sediments that settled and accumulated in that area immediately after disposal were transported away more slowly.

The elevated gamma intensities measured throughout the rest of the survey area, both within and outside the ODMDS boundaries, in the first year after disposal, suggest that although the disposal of dredged sediments was confined to a relatively small zone in the ODMDS, dredged silts and clays were transported far beyond the disposal area. Sediment grain size distribution data from box cores taken during pre- and postdisposal surveys support this conclusion (Table 2). The average proportion of silts in surface sediments increased by a factor of more than 10, and the proportion of clays nearly doubled after disposal. As expected, the highest increases occurred in samples collected within the ODMDS near the disposal zone; however, the proportion of fine-grained sediment increased at all sample locations. Increases in fine sediments outside the ODMDS boundaries after disposal may be the result of downfield transport, settling, and accumulation of dredged sediments from the resulting disposal plumes as well as erosion of deposited dredged sediments. The results from a Disposal From and Instantaneous Dump (DIFID) model simulation, run before site designation, predicted that for a period of 180 min after disposal, nearly 50% of the noncohesive fine sediments disposed at the water's surface would remain in the water column to settle downfield of the spoil mound (USACOE, 1988). Of the 1.0 million m^3 of dredged sediments designated for confined disposal within the berm, 60% or 600,000 m^3 was composed of silt-and clay-sized particles. The DIFID model simulation predicted that as much as 200,000 m^3 (33% of the fines and 20% of the total disposed volume) of the fine fraction could have been retained in disposal plumes and made available for transport away from the disposal zone.

Various investigators have estimated the amounts of dredged sediment lost due to disposal plumes. Gordon (1974) reported water column loss of disposed dredged sediment in Long Island Sound of less than 5%. This was supported in studies of disposal operations at several sites by Bokuniewicz et al. (1978), who found that more than 95% of the sediment fell within a few hundred meters of the disposal zone. Plume dispersal studies in Chesapeake Bay indicated that 10% of dredged sediments were lost during the plume phase (Nichols et al., 1990). Rhoads (1994) determined that the loss of mass from the disposal sites in the Long Island Sound was approximately 6% owing to plume loss. Work by other researchers show that plumes account for much larger dredged sediment losses. Dayal et al. (1983) in studies conducted at the Pearl Harbor Dump Site suggest that plume dispersal was responsible for the loss of the majority of dredged sediment disposed of in 1977. Studies of the Cape Canaveral, FL, Dump Site concluded that plume dispersion was the principal factor in the overall dispersion of dredged sediments on the shelf (Vann, 1995). The actual volumes of dredged sediment transported in disposal plumes, transport distances, and the deposition patterns on the seafloor will be affected by a number of variables, including, but not limited to, the proportion of fine-grain particle sizes, the densities of both the particulate matter and the water column, horizontal and vertical current velocities, and turbulence.

Episodic high-weather events may also contribute to the erosion of disposed dredged sediments and their redistribution on the seafloor. Rhoads (1994) studied mass loss from erosional processes at disposal sites in the Long Island Sound. He found that approximately 16% of dredged sediment loss was due to hurricanes and 0.06% was due to fair-weather mound erosion. In 1990, a tropical storm traveled northward up the western Florida coast, and in 1992, hurricane Andrew passed to the south, each coming within about 230 nmi of the ODMDS. High winds generated from large storms increase wave height and period, which, in turn, increase the amounts of fine sediment particles suspended in the water column. The combination of large waves and currents contribute to both suspension and transport of seafloor sediments (Soulsby, 1997). Dispersal of deposited dredged sediments from the Pensacola disposal site during the 1990–93 study period was likely the result of a combination of infrequent high-intensity storms, occasional localized storm activity, and fair-weather currents characteristic of that part of the Gulf.

The distribution of gamma activity measured over the survey area in 1993 shows that gamma intensity was approaching predisposal levels throughout most of the survey area, suggesting a significant reduction in the amount of source material available for transport and deposition. Additional evidence is provided by a significant reduction in the proportions of silt- and clay-sized particles taken from sediment cores since 1990. The change in the amounts of gamma-emitting fine sediments throughout the survey area corresponds to the reduction in disposal zone gamma intensity (about 50% of the 1990 values) and the decreased elevation of the spoil mound and berm. These data suggest that by 1993, much of the plume-derived dredged sediment had been transported out of the survey area and the spoil mound and berm contained reduced amounts of fine sediments available for resuspension and transport.

Total gamma radiation measurements provided a reliable and cost-effective method for determining the spatial and temporal distribution of disposed dredged sediment on the seafloor relative to the designated ODMDS boundaries and disposal zone. The postdisposal gamma intensity distribution shows that dredged sediments were dispersed throughout the 91-km^2 survey area and some undetermined distance beyond. The gamma radiation data obtained in this study were used as a fingerprint of disposed dredged sediments and were not intended to provide a quantitative assessment of the volumes of dredged sediment placed within or dispersed beyond the disposal zone. These data do suggest, however, that sediment disposal plumes and postdisposal erosion of the spoil mound may have resulted in the transport of potentially large quantities of dredged sediments outside the ODMDS boundaries. The data also show that dredged sediments were present outside the ODMDS boundaries for up to 4 yr after disposal activities.

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