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BENTHIC CONTAMINANT ACCUMULATION AND MIXING RATE STUDIES IN THE HUDSON RIVER ESTUARY

J. Kirk Cochran
David J. Hirschberg
Marine Sciences Research Center
State University of New York
Stony Brook, NY 11794-5000

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INTRODUCTION

This is a final report on Hudson River Foundation grant 005/91A "Benthic Contaminant Accumulation and Mixing Rate Studies in the Hudson River Estuary", J.K. Cochran and D.J. Hirschberg, principal investigators. This report consists of three sections. The first section comprises the bulk of the report and is a manuscript entitled "Dynamics of sediment and contaminant transport in the Hudson River Estuary: evidence from naturally occurring radionuclides" by D. Hirschberg, P. Chin, H. Feng and J.K. Cochran. This manuscript has been previously submitted to Dennis Suszkowski at the Hudson River Foundation in his capacity as editor of the special volume in Estuaries devoted to the Hudson River Estuary. It contains a detailed description of the sampling and analytical procedures employed and a comprehensive discussion of the major results of this project. The second section contains tables of data described in the Estuaries paper but not included there because of space limitations. The third section of this report contains tables, figures and a brief discussion of additional data obtained during the course of this study but not included in the Estuaries paper. Included with the original copy of this report is a disk containing ASCII format files of the data tables.

SECTION I

Dynamics of sediment and contaminant transport in the Hudson River Estuary: evidence from sediment distributions of naturally occurring radionuclides

D.J. Hirschberg
P. Chin
H. Feng
J.K. Cochran*

Marine Sciences Research Center

State University of New York

Stony Brook, NY 11794-5000

516-632-8744

516-632-8820 - FAX

*516-632-8733 KCOCHRAN@ccmail.sunysb.edu

Submitted to Estuaries

ABSTRACT

Seasonal variation in near surface sediment distributions of ^{234}Th at five locations along the axis of the Hudson Estuary shows large variability caused by sediment accumulation and physical and biological sediment mixing acting on the decreasing upriver gradient in ^{234}Th production from the water column. Sediment deposited throughout the estuary after the spring riverflow freshet is redistributed by hydrodynamic forces during the remainder of the year. Lead-210 in gravity cores indicates little long term sediment accumulation below Haverstraw Bay, except for the upper bay.

Pb,Cu, and Zn distributions in sediment are controlled by similar processes and show no evidence of a uniquely urban source in the lower estuary. Cd has a different distribution, reflecting its different marine geochemistry. Silver distributions in sediment indicate a source of silver from New York City, probably related to sewage inputs.

INTRODUCTION

The transport and deposition of particle associated contaminants in a river estuary are controlled by a number of factors including the distribution of sources, seasonal variation in river flow and particle transport and spatial patterns in sediment deposition and mixing by infaunal organisms. Naturally occurring radionuclides that associate strongly with particles are useful tracers for the fate of particle-reactive contaminants because their sources are well characterized and differences in half-life can be used to study transport and deposition processes on different time scales. The radionuclides ^{234}Th (half-life = 24 d) and ^{210}Pb (half-life = 22 y), both members of the ^{238}U decay series, are useful tracers on seasonal (~3 months) and decadal time scales. ^{234}Th is produced in situ from decay of dissolved ^{238}U and ^{210}Pb is added to the estuary principally from the atmosphere where it is produced from decay of ^{222}Rn and from watershed sources.

The Hudson River Estuary (Fig. 1) is a partially mixed estuary showing strong seasonal variations in flow. Olsen et al. (1981) have used impulse tracers such as the anthropogenic radionuclide ^{137}Cs to map the variability in sediment and contaminant accumulation in the Hudson estuary on the decadal time scale. More recently, Olsen et al. (1993) have suggested that spatial variability in contaminant accumulation can be explained by the concept of an "equilibrium sediment surface", whose characteristics are

determined by a delicate adjustment to the spatial variation in hydrodynamic forces. Bottom areas of the estuary that lie significantly below the equilibrium surface constitute important sinks for contaminants.

In this paper, we seek to understand the mechanisms by which the adjustment of sediment characteristics and contaminant accumulation to hydrodynamic forces occurs in the Hudson and the implications of this process for transport of particle associated contaminants through the system. To do this, we compare seasonal variations in ^{234}Th at five stations with the longer term record indicated by ^{210}Pb and anthropogenic trace metals at the same stations.

METHODS

Coring - Sediment cores were taken at five sites (Table 1, Fig. 1), chosen to include a range of depositional conditions as indicated by sediment accumulation rate (Olsen et al., 1983), suspended sediment concentrations and salinities (Hirschberg and Bokuniewicz, 1993), and tidal current velocities (NOAA Tidal Current Charts). Conditions at each station are summarized in Table 1. The upstream stations Piermont (P) and Haverstraw Bay (H) have moderate sediment accumulation rates (<1 cm/y), moderate tidal current velocity, moderate suspended solids concentrations, and low salinity (< 12 ppt). The stations off 79th Street, Manhattan (79W and 79M), have low sediment accumulation rate, high tidal current velocity, high suspended sediment concentrations, and intermediate salinity. The seaward

station off Governors Island (GI), has a high sediment accumulation rate (several cm/y), high tidal current velocity, high salinity, and moderate suspended sediment concentration.

Gravity cores were taken using a 6.7 cm ID plastic core barrel. The cores were sealed and returned to the laboratory for prompt (<2 days) sectioning at 5 cm increments. Box cores, typically 20-30 cm long, were taken with a 30 cm x 30 cm spade type box corer. The box cores were subcored using 30 cm x 15 cm plexiglass boxes and sectioned at 1 cm increments on shipboard, immediately after sampling. Separate thin subcores, 1 cm x 10 cm, were taken for x-radiography. Water content and bulk density were determined as part of the sediment preparation procedure.

Radionuclides - Thorium-234 was determined in the box cores by low level beta counting of the ingrown ^{234}Pa daughter following radiochemical purification of strong acid leachates of dried sediment aliquots (Aller and Cochran, 1976). The chemical yield of this procedure was determined by alpha spectrometry of added ^{228}Th, which also provided ^{232}Th and ^{238}U results. Lead-210 in the gravity cores was measured by direct gamma spectrometry of sediment aliquots using an intrinsic germanium detector. The detector was calibrated by comparison to standards prepared in the same geometry and density as the samples from calibrated ^{210}Pb (+/- 5%) solution. The reported uncertainties in the

radionuclide data are the propagated uncertainty from the counting statistics, calibration uncertainty, and the background and blank for each isotope.

Trace Metals - Trace metals in the gravity cores were determined by atomic absorption spectrometry on totally dissolved sediment aliquots using HF, HCl, and HNO_3. Silver and cadmium were determined using graphite furnace ionization, while Fe, Mn, Cu, Zn and Pb were determined using flame ionization. Precision of the metal analyses, determined from the standard deviation of five replicate analyses for each sample run, averaged ± 5%. Accuracy of the metal analyses were evaluated by comparison to U.S. and Canadian sediment reference materials and was ± 5%. In all cases satisfactory agreement with standard values were obtained (Willie and Berman, 1993).

X-radiography - The x-radiographs were made with a portable x-ray unit on the thin x-ray subcores of the boxcores in the laboratory, immediately on return from the field (<2 days).

RESULTS

X-radiographs and Physical Properties - X-radiographs were obtained from every box core. Representative positive prints of x-radiographs from the five stations are shown in Fig 2a-e. Features of particular samplings not illustrated in Fig. 2 are noted in the text.

Governors Island Station (GI) - All x-radiographs show a surface uniform layer about 5 cm. thick containing shells and worm tubes. In May 1993, the uniform layer was 10 cm thick. Beneath the uniform layer the sediments are laminated at 1-3 cm increments.

79th Street Midchannel Station (79M) - The sediment surface at this site is partly covered by anthropogenic debris consisting of 10-20 cm long pieces of brick, concrete, and metal fragments. This caused coring at this location to be difficult and subcores for x-radiography were not recovered in May 1992. X-radiographs generally show a sediment-water interface veneered with rubble and dense mottled sediment with many x-ray opaque objects of irregular shape. However, in May 1993, x-radiographs indicated a texturally uniform sediment to 8 cm.

79th Street West Station (79W) - Compared to station 79M, located 300 m east, sediments here are highly liquid and uniform. X-radiographs consistently show sharply defined laminations on a 1 cm scale. Small (<1 cm) Laminaria sp. burrows are sometimes truncated at the upper edges of the laminations which are alternately concave or convex upwards, suggesting episodic sediment deposition and erosion.

Piermont Station (P) - Radiography shows a surface laminated deposit, about 5 cm thick, underlain by homogeneous sediment. Worm tubes penetrate both the laminated and homogeneous sediment.

Haverstraw Bay Station (H) - X-radiographs show mottled texture, worm tubes, and some small shells. Discontinuous laminations are present near the surface and occasionally at depth, interrupted by mottling in the horizontal.

Thorium-234 - Thorium-234 was measured in box cores taken at the five stations on 12/9/91, 5/18/92, 9/22/92, and 5/12/93 (Fig. 3). The Piermont and Haverstraw stations were not sampled in December 1991. Uranium analyses were not made on every sample. Moreover, the leaching procedure used to release the ^{234}Th and ^{238}U to solution resulted in ^{234}Th activities greater than ^{238}U at depth in the cores where equilibria between those nuclides should exist (> 10 cm). This was likely due to preferential leaching of ^{234}Th relative to ^{238}U. In order to better evaluate the excess ^{234}Th (that not supported by ^{238}U) in the sediments, we took the average $^{234}Th/^{232}Th$ activity ratio at depth in the cores as representative of the $^{238}U/^{232}Th$ activity ratio. Excess ^{234}Th in each depth interval i was thus calculated as:

$$^{234}Th^{i}_{xs} = {}^{234}Th^{i}_{tot} - \left(\frac{^{234}Th}{^{232}Th}\right) \bullet {}^{232}Th^{i}$$

where

$^{234}Th^{i}_{xs,tot}$ = Excess and total ^{234}Th in depth interval i

$^{232}Th^{i}$ = ^{232}Th activity in depth interval i

$\left(\frac{^{234}Th}{^{232}Th}\right)$ = average $^{234}Th/^{232}Th$ activity ratio at depth in core.

All ^{234}Th data were corrected for decay to the time of sample collection.

There is a large and complicated temporal variability in the vertical profiles of excess ^{234}Th at each station (Fig. 3). The data indicate a general decrease in the surficial sediment specific activity of excess ^{234}Th up river or up estuary, consistent with decreasing ^{234}Th production under low salinity (^{238}U) conditions. The most landward stations, Piermont and Haverstraw, have only four significant excess ^{234}Th values, three of which occur in Sept. 1992.

The Governors Island Station shows excess ^{234}Th profiles most like those obtained in other nearshore studies (e.g. Aller and Cochran, 1976; Cochran and Aller, 1979). Specific activities are high at the sediment-water interface and decrease nearly monotonically to supported levels by ~3 cm. In contrast, the 79th Street stations have highly irregular profiles, with subsurface maxima common. Despite the proximity of the two stations, considerable variability is evident. The 79 west station consistently shows penetration of ^{234}Th to >5 cm at most times and to 8 cm in May 1993. The 79th St. midchannel station is characterized by excess ^{234}Th to <3 cm at most times, but in May, 1993, it is present to 10 cm. Both the Piermont and Haverstraw stations display low excess ^{234}Th activities with no consistent vertical trend. However, in May 1992,

significant excess ^{234}Th was present in the upper 2 cm at Haverstraw.

Inventories of excess ^{234}Th are calculated from:

$$\Sigma A_{xs} = \sum_{i} (\rho_i A_i \Delta x_i)$$

where ΣA_{xs} = inventory of excess ^{234}Th (dpm/cm^2)

A_i = excess ^{234}Th in depth interval i (dpm/g)

Δx_i = thickness of interval i (cm)

ρ_i = dry bulk density (g dry/cm^3 wet sediment)

Dry bulk densities were determined using the measured water content and a sediment grain density of 2.5 g/cm. Care was taken to analyze a continuous depth record of samples in a core. Occasionally samples were lost due to spillage or low yield. In such cases, if the ^{234}Th profiles indicated consistent vertical trends, such as at Governors Island station, interpolation was used to accommodate missing data and calculate inventories. Where the vertical profiles indicate no consistent vertical trend, such as at 79M, no interpolation was attempted if analyses were missing, and the resultant calculated inventories are therefore minima.

Inventories of excess ^{234}Th are quite variable at a given station over time (Table 3) but generally decrease up estuary, reflecting the decreasing production from ^{238}U.

Lead-210

The gravity cores show gradients in excess ^{210}Pb in the upper 10-45 cm (Figs. 4-8). ^{226}Ra, the precursor of ^{210}Pb, was not measured on the samples, and excess ^{210}Pb was calculated by subtracting the constant ^{210}Pb activity at depth in each core (except that at Governors Island). These values ranged from 1.7 to 2.2 dpm/g (Table 3) and the overall average 2 dpm/g was used to calculate excess ^{210}Pb for the Governors Island samples.

The Governors Island core shows only a slight decrease in ^{210}Pb activity with depth, with significant excess present throughout the core. In contrast, the other stations show gradients confined to the upper 10-20 cm.

Inventories of excess ^{210}Pb are calculated in a fashion similar to that for ^{234}Th (Table 4). There is significant variation among the stations, with the greatest inventory in the Governors Island core.

Trace metals - The gravity cores also were analyzed for Ag, Cd, Cu, Fe, Mn, Pb, and Zn. With the exception of Fe and Mn, and all the metals at Station GI, the trace metals generally decrease in concentration with depth (Figs. 4-8). At Governors Island, concentrations increase with depth. With the exception of Fe and Mn, the shape of the metals profiles among the metals at a given station are generally similar. There is no consistent geographical variation in trace metal concentrations among these stations. The highest trace metal concentrations occur at station GI and

the lowest at 79M. The concentration of metals at depths in the cores, with the exception of station GI, varies only slightly among the stations. Of the metals with significant anthropogenic sources examined here Zn is generally present in surficial sediment at the highest concentrations followed by in order of decreasing concentration Pb, Cu, Ag, and Cd.

As observed in other estuaries (e.g. Turekian et al. 1980) there is a general similarity in the Hudson in the depth of penetration and inventories of excess ^{210}Pb and "excess" or anthropogenic trace metals. This is consistent with the observations made by Williams et al. (1978) and Bopp and Simpson (1989) regarding contaminant distributions in Hudson sediments and reflects the fact that anthropogenic inputs of contaminants have increased over the past ~100 years, the length of time representing in 5 half-lives or the useful range of excess ^{210}Pb.

DISCUSSION

Spatial and temporal variation in excess ^{234}Th: The short-term sedimentary record.

Sediment profiles of excess ^{234}Th reflect the action of physical and biological sediment mixing and accumulation on the flux of excess ^{234}Th to the sediment-water interface. The short half-life of ^{234}Th (24 d) makes this radionuclide particularly useful to examine short timescale changes in depositional conditions in the near surface (<5 cm) sediment. Because the dissolved ^{238}U activity varies in proportion to salinity in most estuaries (Cochran, 1992)

^{234}Th production varies with time in response to seasonal changes in river discharge and spatially with the estuarine axial salinity gradient. River sediment discharge is also largely controlled by riverflow. Hudson River discharge measured at the Green Island Dam (near Albany, NY) during the period of this study is shown in Fig. 9, which also indicates the dates box cores were taken. Discharge data for the period October 1991 through October 1992 were obtained from the USGS Water Resources Division, Albany, NY. After October 1992, USGS discharge data are unavailable, and the data for this period are based on a correlation of Mohawk River and Hudson River discharge (S. Findley, Inst. for Ecosystem Studies, Cornell Univ., pers. comm.). The data indicate that the freshet discharge in May 1992 is about half that obtained in May 1993, there is a secondary high discharge period in Dec-Jan 1991 and 1992, and the summer period in both years had low discharge. The long term riverflow data indicate that the freshet of 1993 is more typical of spring conditions and that the freshet in May 1992 was unusually small.

Only one station, Governors Island, shows quasi-exponential decreases in excess ^{234}Th that typically occur as a result of near-surface mixing of sediment by infauna (Fig. 3). X-radiographic images show burrows and shells in an upper mixed layer, underlain by laminated sediment. In May 1993, the $^{234}Th_{xs}$ profile shows a subsurface maximum (~7 cm) at this site and x-radiographs show an increased

thickness of the mixed layer. Such an increase is possibly significant in relation to the larger riverflow freshet in 1993. Indeed, this area of the inner New York Harbor is one where sediments are accumulating rapidly (Olsen et al. 1981 and our ^{210}Pb results, see below), and it is likely that both mixing and accumulation affect the $^{234}Th_{xs}$ profiles at this site. We interpret the $^{234}Th_{xs}$ profiles at this site to represent particle mixing of 5-10 cm of rapidly deposited river sediment supplied annually.

In contrast, the 79th St. Stations display little net long term accumulation but short term storage of sediment and excess ^{234}Th. The midchannel station (79M) is subject to the most rapid tidal current velocities of all the stations and excess ^{234}Th is generally present only in the upper few centimeters. Inventories $^{234}Th_{xs}$ are also generally low. An exception to this pattern is the May, 1993, core, which was characterized in x-radiographs by a surficial 8 cm thick homogeneous layer and significant excess ^{234}Th in the upper 10 cm. The high degree of spatial variability on the bottom at this site observed in repeated coring attempts makes it difficult to separate spatial from temporal variability in the deposition of sediment, but we conclude that little net sediment accumulates at this station except possibly immediately after the spring riverflow freshet when large quantities of sediment are transported through the estuary and can accumulate in small

depressions between the debris (rocks, bricks, etc.) covering the bottom.

The sediment characteristics at the nearby 79W station are markedly different from those at 79M. X-radiographs consistently show sharply defined laminations on a 1 cm scale with minimal mixing by infauna. Small Laminaria sp. burrows are truncated indicating erosional events. The ^{210}Pb profile at this site shows no excess ^{210}Pb below ~15 cm (Fig. 6; see below) indicating little long term deposition, yet $^{234}Th_{XS}$ is present to ~ 5 cm. As at 79M, $^{234}Th_{XS}$ is present to ~10 cm in May 1993 after the spring freshet. These results indicate rapid sediment deposition on seasonal time scales but little long-term accumulation.

Both the Piermont and Haverstraw stations show low $^{234}Th_{XS}$ activities and inventories, except during September 1992. This is consistent with the relatively low salinity and consequently low production from ^{238}U at those stations. Although the salinity is higher at Piermont and Haverstraw Bay during the low river flow conditions typical of September, 1992, the relatively high value of excess ^{234}Th at the upper 1 cm of sediment at Haverstraw Bay at that time may reflect up estuary transport of particles in association with the estuarine circulation.

Comparison of sediment inventories of excess ^{234}Th to local water column production is useful in highlighting the time scales of transport of sediments and associated ^{234}Th through the estuary. Production of ^{234}Th in the overlying

water column at each site was calculated from the integrated ^{238}U activity. The latter was estimated from salinity data assuming conservative chemical behavior of U in the estuary (^{238}U = (dpm/l) = 0.686 S; Chen et al. 1986). Monthly vertical averages of salinity from nearby stations sampled by the NY City Dept. of Environmental Protection were used (NYDEP, 1982; R. Ranheim, pers. comm.). Because the water column salinity structure changes with river flow, data from three months (~4 half-lives of ^{234}Th) prior to sampling were weighted by the ^{234}Th decay factor appropriate to each time period and used to calculate production.

Over time periods corresponding to several half-lives of ^{234}Th (3 months), sediment inventories are unequal to local production at all stations (Fig. 10). The Governors Island station shows the clearest temporal pattern: following periods of low river flow (12/91, 9/92) ^{234}Th inventories are deficient relative to production (~0.5) and following periods of high flow (5/92,93) surpluses of about a factor of 2 are observed (Fig. 10). At 79th St., deficiencies are observed except following the 1993 freshet, when the cores collected indicate short term storage of ^{234}Th is evident at these stations.

Piermont shows low inventories relative to production at all times, and both at this station and Haverstraw, the highest values are evident following periods of low river flow. Indeed, the $^{234}Th_{XS}$ inventory at Haverstraw in September, 1992 substantially exceeds the local production

and likely reflects the up-estuary transport of particles and ^{234}Th by the estuarine circulation. Such transport is more effective during conditions of low river flow. Thus at most of the sampling times, excess ^{234}Th is not stored effectively in the riverine portion of the Hudson Estuary (e.g. Piermont, Haverstraw) but can be stored in the more saline portions of the estuary (79th St.). The Upper Bay (Governors Island) receives pulses of ^{234}Th during conditions of high flow and the riverine portion of the system can receive up-estuary transport of particles during low flow.

Spatial Variation in excess ^{210}Pb: The long-term record

The longer half-life of ^{210}Pb (22 y) relative to ^{234}Th ensures that its distribution is dominated by transport and deposition of sediment over longer time scales (~100 years). In gravity cores collected from all the stations, excess ^{210}Pb is generally present only in the upper 5-20 cm (Figs. 4-8). The exception to this pattern is seen at Governors Island, where excess ^{210}Pb is present to $\geq$ 45 cm (Fig. 4). X-radiographic data suggest that this site receives periodic inputs of sediment from the river and is likely characterized by a high sediment accumulation rate (Olsen et al. 1981). The likelihood of particle mixing by infauna, suggested by x-radiographic and ^{234}Th data makes it difficult to calculate a rate from the ^{210}Pb data, but it is probably several cm/y. A high accumulation rate in this area may result from sedimentological disequilibrium caused

by dredging, and is consistent with the ^{137}Cs and ^{7}Be results of Olsen et al. (1981) and Bopp and Simpson (1989).

As with ^{234}Th, it is useful to compare sediment inventories of excess ^{210}Pb with inputs. Because of the relatively shallow depth of the estuary, in situ production of ^{210}Pb from ^{226}Ra decay (Li and Chan, 1979) is small, and the minimum input of ^{210}Pb to the estuary is that estimated from direct atmospheric deposition. The direct atmospheric flux to the estuary can be estimated from measurements in New Haven, CT to be 1±0.2 dpm/cm^2/y (Turekian et al. 1983) and from soil profiles in the eastern US to be 0.8±0.1 dpm/cm^2/y (Graustein and Turekian, 1983). These fluxes support a steady state inventory of ~29 dpm/cm^2. Additional ^{210}Pb input to the Hudson estuary may occur as soil particles are transported from the watershed.

The Haverstraw and 79th St. stations are markedly deficient in excess ^{210}Pb inventory (<10 dpm/cm^2), while Piermont shows about the atmospheric flux and Governors Island shows a surplus of about a factor of 2-3 (Fig. 11). This pattern is consistent with the transport of sediment and particle associated nuclides such as ^{210}Pb into the upper Bay and suggests that on the long term there is relatively little storage of this nuclide in the estuary. It is important to keep in mind that a part of the export of ^{210}Pb from the estuary could be due to dredging activities and that a more detailed ^{210}Pb balance may show removal of ^{210}Pb from the estuary and harbor by this activity.

Spatial variation in trace metal deposition

Introduction of anthropogenic contaminants into urban estuaries has generally followed industrial development. In the northeastern US, contaminant inputs from both point and nonpoint sources have increased within the past 100-150 years. This is the effective time scale over which ^{210}Pb distributions integrate, and because the source of ^{210}Pb is relatively well constrained, it is possible to eliminate some of the physical causes of variation in excess metal inventories (e.g. sediment grain-size deposition rate or mixing rate) by normalizing them to ^{210}Pb inventories. Although profiles of excess metals and ^{210}Pb are generally similar at all the stations, there is considerable variation in the ratios of inventories of excess metals (Ag, Cu, Zn, Pb, Cd) to excess ^{210}Pb (Fig. 12). The trace metals have both point and non-point sources to the estuary, and the normalized inventories in Fig. 12 show three distinct groupings. Cu, Pb and Zn show similar patterns to one another, indicating that to a first approximation these trace metals have comparable sources and chemical behavior in the estuary. Cd displays a pattern distinctly different from Cu, Pb and Zn consistent with its different chemistry (Windom et al. 1989). The normalized Ag inventories display maximum values adjacent to Manhattan. Of all the trace metals studied here, Ag has the strongest correlation with sewage inputs (Sanudo-Wilhelmy and Flegal, 1992). The relatively high normalized Ag inventories off Manhattan are

consistent with inputs from sewage treatment facilities in this area. However, the stations sampled are too few to determine the spatial extent and significance of this pattern.

SUMMARY AND CONCLUSIONS

Thorium-234 and ^{210}Pb distributions in sediments from the Hudson Estuary show that little permanent sediment accumulation occurs between the Battery and Haverstraw Bay. Some temporary sediment accumulation does occur adjacent to Manhattan, especially in the period immediately following the spring freshet. This material is then redistributed by tidal and estuarine circulatory processes and mostly is deposited in the upper bay, the location of most long term sediment accumulation. The turbidity maximum zone that occurs roughly between the George Washington Bridge and 79th Street is not an area of long term sediment accumulation. Distributions of ^{234}Th in sediment indicate that except for the Governors Island Station, vertical distributions of sediment associated nuclides in the upper few centimeters of sediment are controlled by physical redistribution of sediment not mixing by infauna.

In the lower Hudson, Pb, Cu, and Zn distributions in sediment are controlled by similar processes, as indicated by the ratios of these elements to ^{210}Pb. The data obtained from this study cannot resolve a strong urban source for these metals to New York Harbor. Cadmium deposition in sediment responds to different geochemical processes than

Pb, Cu, and Zn, possibly because of its different marine chemistry. Silver is different from the other metals examined here also, probably because of a strong sewage related silver source from New York City.

LITERATURE CITED

Aller, R. C. and J. K. Cochran. 1976. $^{234}Th/^{238}U$ disequilibrium in near shore sediment: Particle reworking and diagenetic time scales. Earth and Planetary Science Letters, 29:37-50.

Bopp, R. F. and H. J. Simpson. 1989. Contamination of the Hudson River - The sediment record. In: Contaminated Marine Sediments Assessment and Remeadiation. National Research Council, National Academy Press, Washington, D.C. pp. 401-416.

Cochran, J. K. and R. C. Aller. 1979. Particle reworking in sediments from the NY Bight Apex: Evidence from $^{234}Th/^{238}U$ disequilibrium. Estuarine and Coastal Marine Science, 9:739-747.

Cochran, J. K. 1992. The oceanic chemistry of the uranium and thorium series nuclides. In: Uranium Series Disequilibrium: Application to Earth, Marine and Environmental Sciences (M. Ivanovich and R. Harmon, editors) 2nd edition, Oxford University Press, pp. 334-395.

Graustein, W. C. and K. K. Turekian. 1986. ^{210}Pb and ^{137}Cs in air and soils measure the rate and vertical profile of aerosol scavenging. Journal of Geophysical Research, 91:14355-14366.

Hirschberg, D. J. and H. J. Bokuniewicz. 1991. Measurements of water temperature, salinity, and suspended sediment concentrations along the axis of the Hudson River Estuary 1980-1981. Special Data Report#11. Marine Sciences Research Center, State University of New York at Stony Brook, Stony Brook, N.Y. 11794-5000.

Li, Y. H. and L. Chan. 1979 Desorbtion of Ba and ^{226}Ra from river borne sediment in the Hudson Estuary. Earth Planetary Science Letters, 43:343-350.

NOAA. 1992 Tidal Current Charts, New York Harbor.

NYDEP. 1992. New York Harbor Water Quality Survey 1991-1992.

Marine Sciences Section, Division of Scientific Services, Bureau of Clean Water, Wards Island N.Y. 10035

Olsen, C. R., H. J. Simpson, and R. M. Trier. 1981. Plutonium, radiocesium, and radiocobalt in sediments of the Hudson River Estuary. Earth and Planetary Science Letters, 55:377-392.

Olsen, C. R. and H. J. Simpson. 1981. Suspended particle concentrations, compositions, and fluxes in the Hudson River Estuary. Estuaries 4:291-307.

Olsen, C. R., H. J. Simpson, T. H. Peng, R. F. Bopp, and R.M. Trier. 1981. Sediment mixing and accumulation rate effects on radionuclide depth profiles in Hudson Estuary sediments. Journal of Geophysical Research, 86:11020-11028.

Olsen, C. R., I. L. Larsen, P. J. Mulholland, K. L. Von Damm, J. M. Grebmeier, L. C. Schnaffner, R. J. Diaz, and M. M. Nichols. 1993. The concept of an equilibrium surface applied to particle sources and contaminant distributions in estuarine sediments. Estuaries 16:683-696.

Sanudo-Wilhelmy, S. and A. R. Flegal. 1992. Anthropogenic Silver in the southern California Bight: A new tracer of sewage in coastal waters. Environmental Science Technology, 26:2147-2151.

Turekian, K. K., J. K. Cochran, L. K. Benninger and R. C. Aller. 1980. The sources and sinks of nuclides in Long Island Sound. In: Estauarine Physics and Chemistry: Studies in Long Island Sound. B.Saltzman (ed.), Advances in Geophysics, 22:129-164, Academic Press, N.Y.

Turekian, K. K., L. K. Benninger, and E. P. Dion. 1983. ^{7}Be and ^{210}Pb total deposition fluxes at New Haven Ct., and at Bermuda. J. Geophys. Res. 88:5411-5415.

Williams, S. C., H. J. Simpson, C. R. Olsen, and R. F. Bopp. 1978. Sources of heavy metals in sediments of the Hudson River Estuary. Marine Chemistry 6:195-213.

Willie, S. and S. Berman. 1993. NOAA seventh round intercomparison for trace metals in marine sediments and biological tissues. Ocean Assessments Division, NOAA 48pp.

Windom, H. L., S. J. Scropp, F. D. Calder, J. D. Ryan, R. J. Smith, L. C. Burney, F. G. Lewis, and C. H. Rawlinson. 1989. Natural trace metal concentrations in estuarine and coastal marine sediment of the southeastern United States. Environmental Science Technology, 23:314-320.

Table 1. Characteristics of sediment coring stations.

Station	Coordinates	Dates Sampled	Accumulation Rate	Mean Salinity	Mean Suspended Sediment	Average Maximum Current Velocity
Governors Island (6I)	40 40.87 N 74 01.67 W	12/09/91 05/18/92 09/22/92 05/12/93	> 2 cm/y[1]	23°/oo	15 mg/l	200 cm/sec
79th Street Midchannel (79M)	40 47.01 N 73 59.40 W	12/09/91 05/18/92 09/22/92 05/12/93	negligible(1)	19°/oo	30 mg/l	250 cm/sec
79th Street West (79W)	40 47.00 N 73 60.01 W	12/09/91 05/18/92 09/22/92 05/12/93	5 cm/y[1]	19°/oo	40 mg/l	200 cm/sec
Piermont (P)	41 02.00 N 73 53.01 W	05/18/92 09/22/92	0.1-0.3 cm/y[1]	12°/oo	20 mg/l	150 cm/sec
Haverstraw (H)	41 11.07 N 73 50.06 W	05/18/92 09/22/92	0.1-0.3 cm/y[1]	8°/oo	20 mg/l	150 cm/sec

(1) Olsen et al. 1978, 1984

Table 2. Thorium-234 Inventories and Production

Station	Sampling Date	^{234}Th Production	$\Sigma^{234}Th$ Deposition
6I	12/91	1.90	1.3 ± .4
	5/92	1.59	3.8 ± .19
	9/92	2.09	1.2 ± .4
	5/93	1.56	>3.0 ± .3
79M	12/91	1.53	1.1 ±0.2
	5/92	1.40	0 ± .48
	9/92	2.00	0 ± .45
	5/93	1.34	>3.6 ± .3
79W	12/91	1.17	0.76 ± .28
	5/92	1.06	0.83 ± .32
	9/92	1.52	0 ± .26
	5/93	1.02	2.9 ±0.5
P	12/91	0.26	ND
	5/92	0.23	0 ±0.52
	9/92	0.34	0.26 ± .88
	5/93	0.23	0.13 ± .14
H	12/91		ND
	5/92		0 ±0.29
	9/92		1.1 ±0.4
	5/93		ND

Table 3. Background level of trace metals in the Hudson sediments.

Ag (ppm)	Cd (ppm)	Cu (ppm)	Fe (%)	Mn (ppm)	Pb (ppm)	Zn (ppm)	^{210}Pb (dpm/g)
Haverstraw Bay							
0.29±0.03	0.11±0.02	15.0±0.8	3.59±0.22	831±87	15.2±1.6	83±3	1.88±0.16
Piermont							
0.33±0.12	0.12±0.11	15.6±1.4	3.56±0.18	1127±197	15.0±2.1	80±4	2.18±0.21
79th Street (west)							
0.08±0.00	0.10±0.01	14.4±1.2	3.76±0.18	743±45	18.7±5.1	87±4	1.86±0.30
79th Street (midchannel)							
0.28±0.02	0.09±0.02	12.6±1.2	3.40±0.21	866±61	12.5±1.3	75±5	1.68±0.45
Overall							
0.25±0.11	0.11±0.01	14.4±1.3	3.58±0.15	813±63	15.4±2.5	81±5	1.90±0.21
Hudson Estuary (William et. al. 1978)							
--	--	20	--	--	25	80	
Rock (Martin & Whitfield 1983)							
0.08	0.20	32	3.59	720	16	127	
Soil (Martin & Whitfield)							
0.05	0.35	30	4.0	1000	35	90	

Table 4a. Excess trace metal and ^{210}Pb inventories in the Hudson River estuary. Inventories in Governors Island are minimum values.

Station I.D.	Ag ($\mu g/cm^2$)	Cd ($\mu g/cm^2$)	Cu (mg/cm^2)	Pb (mg/cm^2)	Zn (mg/cm^2)	$^{210}Pb_{xs}$ (dpm/cm^2)
H	6.00±0.13	5.56±0.11	0.68±0.01	0.79±0.01	1.28±0.02	9.0±0.8
P	26.4±0.6	4.24±0.08	0.59±0.01	0.56±0.02	0.88±0.02	28.5±0.8
79W	12.7±0.1	1.66±0.05	0.28±0.01	0.74±0.02	0.71±0.02	5.4±1.5
79M	5.28±0.00	1.58±0.00	0.12±0.00	0.11±0.02	0.13±0.03	4.1±0.2
GI	55.1±0.5	66.5±0.6	4.19±0.02	6.34±0.05	5.07±0.03	77.4±0.8

Table 4b. Inventory ratios of excess trace metals to excess ^{210}Pb in the Hudson River estuary.

Station I.D.	Ag/^{210}Pb ($\mu g/dpm$)	Cd/^{210}Pb ($\mu g/dpm$)	Cu/^{210}Pb ($\mu g/dpm$)	Pb/^{210}Pb ($\mu g/dpm$)	Zn/^{210}Pb ($\mu g/dpm$)
H	0.67±0.06	0.62±0.06	75.6±7.0	87.8±8.2	142±13
P	0.92±0.03	0.15±0.01	20.7±0.7	19.6±0.8	30.9±1.1
79W	2.35±0.67	0.31±0.09	51.9±14.8	137±39	131±38
79M	1.29±0.07	0.39±0.02	29.3±1.7	26.8±5.1	31.7±6.6
GI	0.71±0.01	0.86±0.01	54.2±0.6	81.9±1.0	65.5±0.7

FIGURE LEGENDS

Fig. 1. Map of the study area showing coring locations.

Fig. 2. Representative x-radiographs of box cores from the stations.

Fig. 3. Depth profiles of excess ^{234}Th in the box cores.

Figs. 4-8. Depth profiles of Cu, Cd, Zn, Pb, Ag, Fe, Mn, and ^{210}Pb in the gravity cores. The vertical line in each figure is the basal value of ^{210}Pb.

Fig. 9a,b. Hudson River discharge at Albany for the period of this study.

Fig. 10. Ratio of ^{234}Th inventories in the box cores to ^{234}Th production in the overlying water at the stations.

Fig. 11. Inventories of ^{210}Pb in the gravity cores.

Fig. 12. Ratio of integrated metals to integrated excess ^{210}Pb in the gravity cores.

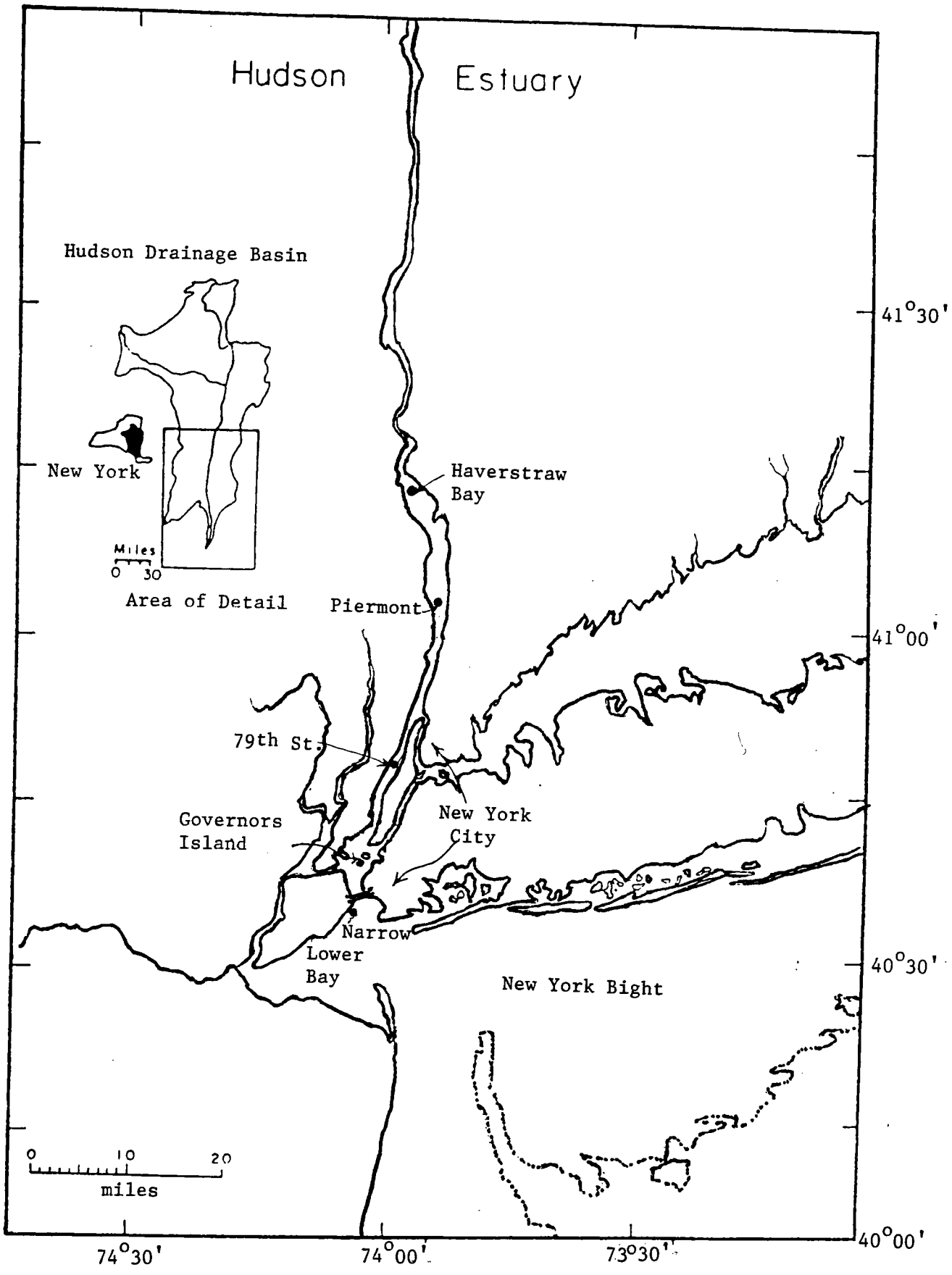
Hudson Estuary
Hudson Drainage Basin
New York
Miles
0 30
Area of Detail
Haverstraw Bay
Piermont
79th St.
Governors Island
New York City
Narrow
Lower Bay
New York Bight
0 10 20
miles
41°30'
41°00'
40°30'
40°00'
74°30'
74°00'
73°30'

Fig. 1