Reports

Man-Made Radionuclides and Sedimentation in the Hudson River Estuary

Abstract. *Recently deposited fine-grained sediments in the Hudson River estuary contain radionuclides from global fallout produced by atmospheric bomb tests as well as from low-level releases of a local nuclear reactor. Accumulation rates of these nuclides are dependent on rates of sediment deposition and vary with location in the estuary by more than two orders of magnitude. Within the Hudson estuary, New York harbor is currently the zone of most rapid deposition of sediments containing radionuclides, some of which were released from a nuclear reactor about 60 kilometers upstream of the harbor.*

Many estuaries are sites of rapid sediment accumulation. Shoaling of estuarine harbors often requires extensive dredging operations to maintain adequate navigation depths. There is some general understanding of the processes which cause sediment deposition in estuaries, but patterns of accumulation are usually sufficiently complicated to defy simple prediction (*1*). Many chemically reactive wastes, such as metals from the electroplating industry and some types of radionuclides, are rapidly bound to particles when discharged to turbid estuarine waters. Patterns of accumulation of estuarine sediments are thus of importance both for management of reactive waste discharges and for maintenance of adequate navigation depths. We have exploited the presence of man-made radionuclides in sediments to provide information concerning patterns of recent sediment accumulation in the Hudson River estuary.

The Hudson River forms one of several major estuarine systems which dominate the coastal environment in the densely populated northeastern United States. The New York metropolitan region is dependent on the Hudson estuary for water transportation as well as for disposal of wastes, including treated and untreated domestic sewage and a wide range of industrial chemicals. We have collected sediment cores, most of which were between 0.5 and 1 m in length, at more than 50 localities in the Hudson estuary (Fig. 1). Gravity cores (~ 6 cm in diameter) from sites throughout the range of salinity within the estuary were sectioned into depth intervals (usually 5 cm), dried, and sealed into 100-cm^3 aluminum cans. Gamma-ray emissions were measured by using a lithium-drifted germanium [Ge(Li)] detector and a multichannel analyzer. Because of the good energy resolution of a Ge(Li) detector ($\leq$ 2 kev), a large number of clearly defined photopeaks whose energies are characteristic of individual radioactive nuclides can be observed in the gamma spectrum between 100 and 3000 kev. These peaks include those from naturally occurring radionuclides such as ^{40}K and daughters of ^{238}U and ^{232}Th, as well as from man-made nuclides such as ^{137}Cs (a fission product from bomb testing and nuclear reactor releases), ^{134}Cs (an activation product almost exclusively from nuclear reactor operations), and ^{60}Co (an activation product predominantly from nuclear reactor operations).

The distribution of ^{137}Cs, ^{134}Cs, and ^{60}Co in Hudson estuary sediment cores (Table 1) generally falls within one of three distinct types. The locations of cores representative of each type are shown in Fig. 1, and the distribution of ^{137}Cs with depth in the sediment for each of these three cores is shown in Fig. 2.

Cores from most areas of the estuary have relatively low activities of ^{137}Cs, generally confined to the upper 5 to 10 cm of sediment. Many cores from the sandy main navigation channel (water depth, 10 to 20 m) have an order of magnitude less ^{137}Cs than that in the lowest-activity example shown in Fig. 1 (labeled

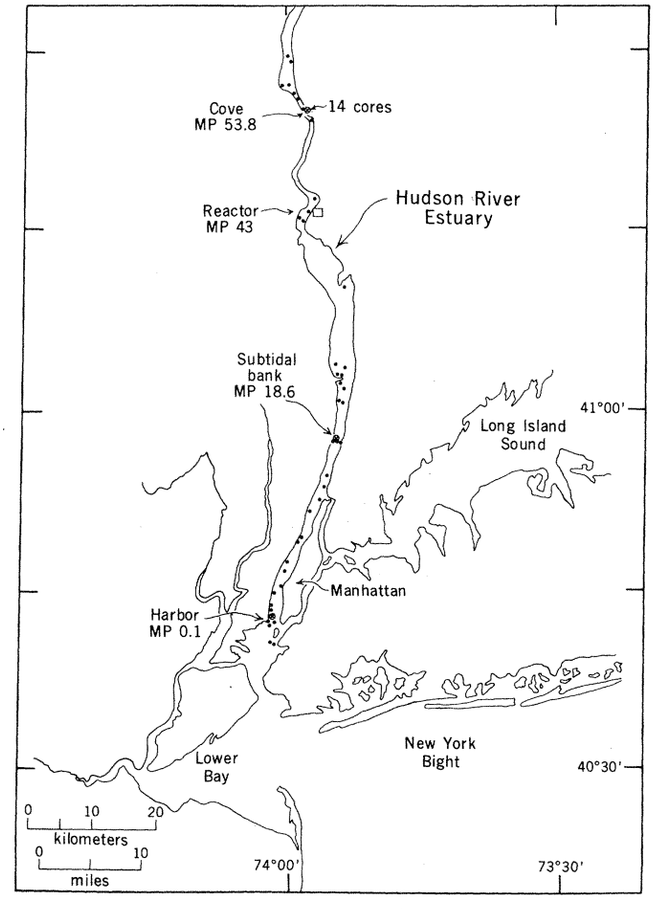

Fig. 1. Location map of analyzed cores from the Hudson estuary. Samples are designated in terms of the number of miles (MP = mile point) upstream from the southern tip of Manhattan. One representative core from each of three locations is indicated by ⊗. The harbor salinity south of Manhattan ranges between 18 and 26 per mil. Saline water ($\geq$ 0.1 per mil) intrudes upstream to ~ MP 15 during springtime high discharge of freshwater and to ~ MP 60 during average summertime conditions (*20*).

"subtidal bank"). The core at mile point (MP) 18.6 was taken on a shallow bank (≤ 8 m) which is more conducive to the deposition of fine-grained particles than the adjacent sandy navigation channel.

Marginal coves show a second type of profile having much more ^{137}Cs in the top 5 cm of sediment per gram (dry weight) and measurable activities usually to 10 to 15 cm although sometimes to 30 to 40 cm. This type of ^{137}Cs depth profile has been reported for the Hudson estuary by other authors and interpreted as indicative of high sedimentation rates in shallow protected environments (*2*). The core reported here (Fig. 1; MP 53.8) is one of more than a dozen cores we have collected from Foundry Cove, a small (0.5 km^2), shallow (1 to 2 m) embayment on the east side of the Hudson River near West Point.

The third type of ^{137}Cs profile is illustrated by a core collected in New York harbor at MP 0.1. It shows high ^{137}Cs activities from the surface to the bottom of the core at 40 cm (Fig. 2). We have measured comparable activities to 250 cm in another core from the harbor (*3*). Sediment cores which have high ^{137}Cs activities from the surface to depths below 30 cm are clear indicators of rapid sediment accumulation.

There are two significant potential sources of ^{137}Cs in Hudson sediments: (i) fallout from atmospheric testing of nuclear weapons and (ii) periodic low-level releases from a commercial nuclear power generating station at MP 43 (Fig. 1). The major peak of fallout from weapons testing was delivered to the Hudson in the years 1962 to 1965. Strontium-90 and ^{137}Cs, both of which have radioactive half-lives of about 30 years, are the fission products from the peak fallout years which are found in greatest abundance in soils and the surface ocean throughout the globe. Most of the fallout arrived at the earth's surface in rain and snow. As rainwater percolates into soils of continental areas, ^{90}Sr (*4*) and ^{137}Cs (*5*) are rapidly attached to particulates in the upper 10 to 20 cm of the soil. In the open ocean, fallout ^{90}Sr and ^{137}Cs are predominantly in solution (*6*) and are frequently used as tracers of water circulation because of the minor role of particulate phases in the transport of these nuclides in seawater.

In freshwater lakes such as Lake Michigan and Lake Ontario, most of the ^{90}Sr remains in solution, while a major fraction (> 90 percent) of fallout ^{137}Cs is now found attached to particulate phases in the sediments (*7*). In estuarine systems such as Chesapeake Bay, dissolved ^{137}Cs appears to be roughly proportional to salinity, with very low values typical of salinities less than a few parts per thousand (*8*). Higher values in more saline estuarine waters are usually attributed to dissolved potassium decreasing the removal onto particles of ^{137}Cs supplied by rain. Thus, there appears to be substantial variation in the behavior of fallout ^{137}Cs in natural water systems, dependent on the salinity of the water and the degree of contact with solid phases such as soil particles.

Table 1. Anthropogenic radionuclides in Hudson estuary sediments: discrete samples. Sample locations are given as mile point (MP) upstream of the southern tip of Manhattan (Fig. 1). Uncertainties reported for sediment activities are based only on 1 standard deviation counting statistics for both the photopeak and background adjacent to the photopeak. The ^{60}Co data are averages from two photopeaks. Activities are reported in terms of the date of sample collection. Samples with negative net activities are reported for the counting date and no attempt was made to extrapolate to the date of collection.

Collection date	Location of sample	Depth interval in sediments (cm) or sample type	Activity (pc/kg)			
			^{137}Cs	^{134}Cs	^{60}Co	$^{239,240}Pu$
25 October 1973	MP 0.1	0–5	1260 ± 38	230 ± 33	190 ± 18	32.7 ± 2.4
		5–10	1795 ± 60	395 ± 56	300 ± 27	31.7 ± 3.2
		10–15	1995 ± 56	480 ± 58	245 ± 18	43.3 ± 3.0
		15–20	960 ± 44	135 ± 33	65 ± 20	45.8 ± 3.2
		20–25	1030 ± 40	175 ± 33	125 ± 19	26.4 ± 1.2
		25–30	570 ± 28	−1 ± 10	59 ± 16	38.5 ± 1.3
		30–35	925 ± 49	22 ± 33	100 ± 28	48.5 ± 1.6
		35–40	1190 ± 40	75 ± 24	152 ± 19	
20 June 1975	MP 18.6	0–1	580 ± 25	19 ± 10	67 ± 10	12.9 ± 0.9
		1–3	525 ± 45	22 ± 21	64 ± 21	12.4 ± 0.8
		3–4	410 ± 20	5 ± 8	44 ± 9	11.1 ± 0.8
		4–5	335 ± 25	35 ± 13	51 ± 16	
		5–10	−1 ± 15	−11 ± 10	−8 ± 13	
11 June 1975	MP 43	0–10	2700 ± 72	345 ± 42	400 ± 27	25.0 ± 1.6
29 August 1973	MP 53.8	0–5	2475 ± 63	98 ± 26	69 ± 19	69.2 ± 6.4
		5–10	1825 ± 68	17 ± 32	19 ± 20	52.1 ± 4.3
		10–15	210 ± 17	−8 ± 10	15 ± 11	5.7 ± 0.4
		15–20	26 ± 17	−15 ± 11	30 ± 15	
		20–25	35 ± 23	0 ± 12	7 ± 18	
		50–55	9 ± 14	7 ± 9	13 ± 15	
30 September 1975	MP 18	Suspended solids*	1260 ± 35	210 ± 25	145 ± 18	23.4 ± 1.0
20 April 1976	MP 24	Suspended solids*	1135 ± 35	101 ± 15	100 ± 12	18.9 ± 0.9

*Samples of suspended sediments were collected with a continuous-flow centrifuge and large settling tanks during two high-runoff episodes, one following a period of abnormally heavy rainfall and the other during the normal spring discharge peak.

Table 2. Average radionuclide ratios in Hudson sediments and reactor releases. Ratios are reported in terms of the activities during the year indicated, even if collected at an earlier date. Ratios for 1975 are reported to 1 November, using half-lives of 30.0 years (^{137}Cs), 2.1 years (^{134}Cs), and 5.2 years (^{60}Co).

Year of reporting	Location and number of samples	Depth interval in sediments (cm)	Source	$^{134}Cs/^{137}Cs$	$^{60}Co/^{137}Cs$
1975	MP 43 (1)	0–10	Reactor site; large composite surface sediment	0.13	0.15
1975	MP −1.6 to MP 6 (6)	0–10	New York harbor cores	0.07–0.11	0.07–0.15
1975	MP 53.5 to MP 54 (13)	0–5	Foundry Cove (upstream of reactor site) cores	0.02	0.02
1971	MP 35 to MP 49 (5)	0–10	Reactor region; surface sediment (*2*)	0.6–0.7	0.12–0.36
1971			Reported reactor releases for year of maximum discharge (*8*)	0.73	0.21
1975			Reactor releases (decay corrected 1971 to 1975)	0.22	0.14

The time history of ^{137}Cs release from the nuclear reactor at MP 43 cannot be defined quite as well as for fallout. The reactor began operating in 1962, but reported releases through 1964 were very low. Activities of specific nuclides in the releases have not been reported for the entire operating period, but estimates for earlier years can be made from the gross activity of all the nuclides in the releases, assuming a composition similar to the most recent data. The highest annual release of ^{137}Cs was in 1971, accounting for almost half of the total discharges of ^{137}Cs since 1962. During the period 1973 and 1974, very little ^{137}Cs activity was released (*9*).

In addition to ^{137}Cs, reactor releases of gamma-emitting nuclides to the Hudson have included ^{134}Cs (half-life = 2.1 years) and ^{60}Co (half-life = 5.2 years). Since ^{60}Co also becomes bound to particles in the Hudson, the proportions of ^{134}Cs and ^{60}Co relative to ^{137}Cs in Hudson sediments can be used in conjunction with the time history of release data to estimate the relative importance of fallout and reactor releases as a source of ^{137}Cs in the sediments.

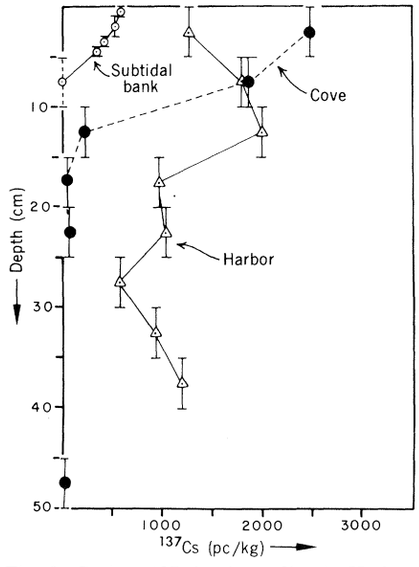

Fig. 2. Cesium-137 depth profiles in Hudson estuary sediments. All data were normalized to National Bureau of Standards environmental radioactivity standard 4350 and are expressed as activity per dry weight (1 pc = 10^{-12} curie). Activities at the core tops vary over a large range, presumably because of variations in sediment grain size, organic content, and percentage of fine-grained particulates which have been exposed to water with a relatively high ^{137}Cs activity over the past decade or so. The profile shown for the subtidal bank site is a composite of four points (0 to 5 cm) from a large grab sample sectioned at 1- to 2-cm intervals and one point (5 to 10 cm) from a core taken at the same site. The core from the harbor shown here has significant ^{137}Cs activity to the bottom of the sample (40 cm). Other harbor cores within a kilometer of this site have similar activities to 250 cm, while others reach background levels between 50 and 60 cm.

Table 3. Summary of budget estimates for ^{137}Cs and $^{239,240}Pu$ in the Hudson estuary. Values in parentheses have the largest uncertainties.

Source	Activity (curies)	
	^{137}Cs	$^{239,240}Pu$
Sediment burden		
High sedimentation areas (~ 10 percent of estuary)	~ 5	~ 0.1
Low sedimentation areas (~ 90 percent of estuary)	~ 5	~ 0.1
Direct inputs to estuary		
Fallout on water surface (rain and snow)	~ 25	~ 0.5
Reactor discharge to water	~ 35	?
Other inputs to estuary		
Soil erosion from drainage basin	(~ 10)	(~ 0.2)
Dissolved runoff from drainage basin	(~ 50)	(~ 0.3)
Removal from estuary		
Dredging	~ 20	~ 0.4
Outflow (by difference)	(~ 90)	(~ 0.4)

Nearly all of the sediment samples from the Hudson near the reactor site or downstream to New York harbor in which we have measured ^{137}Cs activity also contain ^{134}Cs and ^{60}Co, in proportions roughly similar to those in surface sediment samples collected near the reactor site (see Table 2; $^{134}Cs/^{137}Cs$ and $^{60}Co/^{137}Cs$ ~ 0.1). The cove site approximately 15 km upstream from the release area has relatively low $^{134}Cs/^{137}Cs$ and $^{60}Co/^{137}Cs$ (~ 0.02), indicating that a smaller proportion of the ^{137}Cs in this sediment is derived from the reactor than in the sediments of New York harbor.

On the basis of the nuclide ratios reported in Table 2, which include data from many more of our cores than the few itemized in the table plus data for sediments at several localities collected within about 12 km of the reactor site during 1971 by other authors (*2*), we conclude that a substantial fraction of the ^{137}Cs now found in New York harbor sediments was derived from reactor releases, primarily from the period of peak discharge about 5 years ago (*10*).

We can compare the ^{137}Cs activities in Hudson estuary sediments with the magnitudes of several source terms, some of which have reasonably small uncertainties, while others can only be roughly approximated from indirect evidence (Table 3). We estimate the present sediment ^{137}Cs burden between MP 60 and New York harbor to be ~ 10 curies (1 curie = 2.2×10^{12} disintegrations per minute), with approximately half of the total in zones of rapid sedimentation which cover ~ 10 percent of the total surface area.

The delivery of fallout ^{137}Cs to the water surface of the Hudson can be estimated more accurately than any of the other budget terms. The total deposition rate corrected for radioactive decay to 1975 has been about 120 mc/km^2 (*11*, *12*). Using an area of water surface for the Hudson between MP 60 and MP 0 of 200 km^2, the total direct fallout deposition of ^{137}Cs to the estuary surface is ~ 25 curies.

The total supply of ^{137}Cs from the reactor since 1967 has been ~ 35 curies with ~ 20 curies released in 1971. Thus, direct fallout and reactor releases have supplied comparable amounts of ^{137}Cs to the Hudson estuary.

There is a very large reservoir of fallout ^{137}Cs in the soils of the Hudson drainage basin (~ 4×10^3 curies for the total drainage basin of ~ 3.5×10^4 km^2). Some of the ^{137}Cs from this soil reservoir has undoubtedly reached the Hudson estuary, but the magnitude of this source is not simple to establish. We have estimated the input from the drainage basin to be ~ 60 curies, but this number has a large uncertainty (*13*).

The rate of removal of ^{137}Cs from the Hudson estuary is also difficult to establish. Dredging of New York harbor is nearly continuous at a few extremely rapid shoaling areas, and occurs at least every few years at many other sites (*14*). During the past 15 years, the average annual removal of sediments has been ~ 4×10^6 tons (dry weight) (*15*). Assuming that 50 percent of this amount is taken

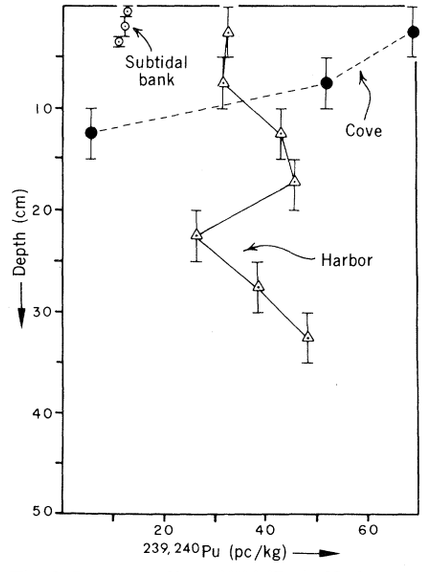

Fig. 3. Depth profiles of $^{239,240}Pu$ in Hudson estuary sediments, expressed as activity per dry weight. The distribution of $^{239,240}Pu$ in these cores is similar to that of ^{137}Cs (Fig. 2).

from shoaling areas with fine-grained sediments having a mean ^{137}Cs activity of 1 pc/g, then the total removed over 10 years has been ~ 20 curies. We have no direct means for estimating loss of ^{137}Cs in solution and on suspended particulates. Assuming our other budget estimates are correct, the total outflow loss has been ~ 90 curies.

We have also analyzed a number of Hudson sediment samples for $^{239,240}Pu$ (*16*). Concentration profiles of $^{239,240}Pu$ in the three sediment cores discussed earlier are shown in Fig. 3. Variations in the activity of $^{239,240}Pu$ with depth are not identical to those for ^{137}Cs in the harbor core, but the general similarity in the distribution of both radioactive elements within each of the three cores is obvious. This would be expected if transport and accumulation on particulates were important for both $^{239,240}Pu$ and ^{137}Cs. Covariance of fallout ^{137}Cs and $^{239,240}Pu$ in sediments of freshwater lakes has also been observed in the Great Lakes (*7*) and in soil profiles (*5*). In the ocean, $^{239,240}Pu$ is much more rapidly and completely associated with particulate phases than is ^{137}Cs (*17*).

We cannot establish budget terms for $^{239,240}Pu$ in the Hudson as well as for ^{137}Cs at the present time. The activities of $^{239,240}Pu$ present in global fallout are 1 to 2 percent of that of ^{137}Cs. The ratio of $^{239,240}Pu$ to ^{137}Cs in Hudson sediments reported here ranges between 1 and 7 percent, with most samples in the range 2 to 3 percent. By analogy to the ^{137}Cs budget for the Hudson, the sediment burden is ~ 0.2 curie (Table 3), while the direct input from fallout is ~ 0.5 curie and the loss by dredging is ~ 0.4 curie. We estimate the contribution of $^{239,240}Pu$ from the soils of the drainage basin to be ~ 0.5 curie (*18*), a smaller proportion of the input than was true for ^{137}Cs. Again, this input is not well determined. We do not have any direct estimate of $^{239,240}Pu$ which might be derived from the reactor at MP 43. If such releases have occurred, they do not appear to have been large compared with the fallout source.

Our primary conclusions follow.

1) Cesium-137 can be a valuable tracer for recent (last 10 to 15 years) accumulation of fine-grained sediment in estuaries (*19*).

2) Particulate phases play a significant role in the transport processes for both ^{137}Cs and $^{239,240}Pu$ in turbid estuarine waters.

3) Sedimentation in the Hudson estuary occurs primarily in the harbor adjacent to New York City and in freshwater or low-salinity shallow marginal coves. Accumulation rates of sediment in the harbor approach 5 to 10 cm/year over large areas, which is more than an order of magnitude greater than the long-term (last 10^4 years) average for the Hudson. Recent sediments within the harbor contain readily measurable activities of gamma-emitting nuclides derived from a nuclear reactor and released more than 60 km upstream of New York harbor. The activities of reactor nuclides in Hudson sediments are comparable to those of fallout nuclides found in surface soils on a global basis and do not currently appear to present a biological hazard to humans. The present distribution of nuclides derived from low-level releases of a reactor which has been in operation for more than a decade can provide valuable information as to the likely transport pathways of radionuclides in the event of a major release to the Hudson estuary.

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3. A few harbor cores collected in deep channels show low or undetectable ^{137}Cs activities. Boundaries between zones of high activity and zones of background activity within a core are often quite sharp. In one core in the harbor, a 15-cm-thick sandy layer with background activities of ^{137}Cs was observed between layers of fine-grained sediment with high activities.
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10. Although we have observed sharp peaks of ^{137}Cs activity corresponding to the year of maximum reactor release in some harbor cores not reported here, such a peak does not always occur. Several processes may act to obliterate this curve, including mixing of the sediments by organisms and gas bubbles formed within the sediments, and local resuspension and deposition of sediments during dredging operations. Also, it appears likely that a substantial fraction of the releases become bound to particles within a few kilometers of the point of discharge and are then transported downstream in the suspended load. Suspended particles from near the water surface of the Hudson collected about halfway between the reactor and New York harbor during 1975 and 1976 have man-made nuclide activities similar to those in surface sediments near the reactor and in sediments which have accumulated in New York harbor over the past several years (Table 1). Those suspended particles do not have nuclide ratios typical of fresh reactor releases (< 1 year since discharge) and probably include some fraction of particulates which have been deposited and resuspended many times as they pass down the estuary. Such a process would produce a complicated depth profile of radionuclides in sediments of a downstream zone of accumulation which may not be simply related to the time history of releases.
11. Annual fallout ^{137}Cs delivery to the Hudson was computed from ^{90}Sr data for New York City (*12*), assuming a $^{137}Cs/^{90}Sr$ ratio of 1.5.
12. *USERDA Rep. HASL-294* (1975), appendix.
13. We estimated the drainage basin supply of ^{137}Cs as two components: particulate and dissolved. Assuming that all of the suspended solids in the Hudson River are soil particles with an average ^{137}Cs activity of 1 pc/g, which is approximately equal to that found in the upper 5 cm of soil from a well-studied site on Long Island (*5*), the supply of ^{137}Cs in 10 years is ~ 10 curies for an average river flow of 500 m^3/sec and a suspended solids load of 60 parts per million. Three lines of evidence indicate that the supply of dissolved ^{137}Cs from the drainage basin is a very small fraction (~ 1 percent) of the total fallout delivered to the soil. New York City drinking water is derived primarily from tributary streams to the Hudson and Delaware rivers. Data on ^{90}Sr and ^{137}Cs from both rainwater and New York City tap water (*12*) indicate that approximately 1 percent of the total fallout ^{137}Cs has been removed in solution from the soil zone. This estimate is based on the assumptions that tap water is representative of Hudson tributaries and that negligible losses of ^{137}Cs occur in reservoir storage and water treatment. A second line of evidence is provided by published data on the annual average ^{137}Cs activity in the Hudson near the reactor site at MP 43. Activities declined from 1 to 2 pc/liter to 0.01 to 0.1 pc/liter between 1964 and 1968 (*2*), approximately following the trend in ^{137}Cs levels in precipitation (*11, 12*) with absolute concentrations averaging a few percent of the precipitation values. A third line of evidence is provided by published data for dissolved ^{137}Cs in Chesapeake Bay during 1970 to 1972 (*8*), where freshwater and low-salinity (≤ 2 per mil) samples had activities (≤ 0.02 pc/liter) less than one-third of those of New York City tap water for the same years. Using reported data for the Hudson for 1964 to 1968 (*2*) and extrapolations from years before 1964 and after 1968 we estimated the total drainage basin input of soluble ^{137}Cs to the Hudson estuary to be ~ 50 curies.
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16. Samples were prepared by chemical procedures similar to those of K. M. Wong [*Anal. Chim. Acta* **56**, 355 (1971)], using ^{236}Pu and ^{242}Pu as yield tracers and counted with an alpha-particle spectrometer. The peaks in the alpha-particle energy spectrum for ^{239}Pu and ^{240}Pu are not resolved, so data obtained by alpha spectrometry are reported as the sum for these two nuclides, $^{239,240}Pu$.
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18. At present our only line of evidence to estimate soluble $^{239,240}Pu$ released from soils is from analysis of New York City tap water for 1973 to 1975. The ratio of $^{239,240}Pu$ to ^{137}Cs in tap water averaged ~ 0.3 times the fallout ratio [B. G. Bennett, *USAEC Rep. HASL-306* (1976)]. Assuming

that only ~ 1 percent of the fallout ^{137}Cs has left the soil in solution (*13*), then ~ 0.3 curie of $^{239,240}Pu$ would have reached the Hudson in solution from the drainage basin soils.
19. A similar conclusion was reached in a recent study of low-level releases of radioactive wastes into Bombay harbor [B. Patel, C. D. Mulay, A. K. Ganguly, *Estuarine Coastal Mar. Sci.* **3**, 13 (1975)].
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21. We thank J. Kelly of Consolidated Edison of New York, Inc., for providing copies of operating reports for Indian Point, N. Chu of the Health and Safety Laboratory of the Energy Research and Development Administration for advice on plutonium chemistry and for supplying ^{236}Pu and ^{242}Pu spikes, and G. Mathieu and P. Breland for help in the coring operations. Financial support was provided by ERDA contract E (11-1) 2529. Contribution No. 2390 from Lamont-Doherty Geological Observatory of Columbia University.

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Histologic Structures Preserved for 21,300 Years

Abstract. *Histologic examination of rehydrated tissue samples from late Pleistocene (Alaskan) mammal mummies demonstrates that the preservative effect of freezing and drying extends to remains 15,000 to 25,000 years old. Some muscle and liver tissue retained identifiable histologic structures. Most tissues were completely disintegrated and partly replaced by masses of bacteria, an indication of considerable postmortem decay before the remains were entombed beneath the permafrost zone.*

The frozen, mummified bodies of a variety of late Pleistocene mammals have been discovered in Alaska in the course of gold mining operations. Geological studies in Alaska (*1*) have indicated that mummified remains are present only in the latest Pleistocene fauna, which radiocarbon dating suggests lived from 15,000 to nearly 25,000 years before the present. Frozen mammoths have been found in Siberia (*2*, *3*) and mummified seals in Antarctica (*4*). Autolyzed marrow tissue has been reported in older remains from northeastern Siberia (*5*) and Alaska (as is reported below), but the mummified remains from Siberia also seem to be restricted to the late Pleistocene fauna.

While there have been many examinations of human mummies (*6*), only a few frozen human mummies have been examined grossly or microscopically. These have included 2000-year-old Scythian bodies from Siberia (*7*), an Inca child dated to about 1300 years ago (*8*), and an Eskimo woman frozen for 1600 years (*9*). The preservation of histologic detail in the Eskimo body encouraged one of us (M.R.Z.) to examine the mummified remains of several late Pleistocene Alaskan mammals in the collection of the American Museum of Natural History. Previous microscopic study of such material has been limited to an examination of bone from an Alaskan Pleistocene mammoth, showing structure comparable to modern elephants (*10*). Our study is directed toward obtaining information on the preservation of microscopic structure by freezing and subsequent desiccation, and on the antiquity of any disease process that might be discovered.

The specimens examined were all collected in the Fairbanks district of Alaska under the auspices of Childs Frick (Frick Collection, Department of Vertebrate Paleontology, American Museum of Natural History). They include the face and right forefoot of an immature woolly mammoth (*Mammuthus primigenius*, F:AM 99927), nearly complete remains of a rabbit (*Lepus* sp., F:AM 99926), a lynx (*Lynx* sp., F:AM 99925), a lemming or vole (F:AM 99928), and marrow from a horse canon bone (*Equus* sp., F:AM 99929). Carbon-14 dating of the mammoth indicated an age of 21,300 ± 1,300 years (Lamont Geological Observatory L-601, 1960) (*3*); and the lynx, rabbit, and rodent probably fall within the range of 15,000 to 25,000 years on the basis of stratigraphic evidence. The horse marrow was taken from a specimen from the Gold Hill site now known to be pre-Wisconsinan (?Illinoian) in age (*1*).

The animals were dry and leatherlike, with skin and hair well preserved. Dissection of the mammoth head revealed preservation of the eyes as globoid structures filled with soft, white, cheesy material. The viscera of the rabbit were easily identifiable and appeared to be well preserved. The viscera of the lynx were totally autolyzed, and the marrow of the horse bone was reduced to a small amount of greasy yellow material.

Representative specimens of the various structures were selected for rehydration, which was based on the technique developed by Ruffer (*11*) for mummified human tissue. The specimens were immersed in a solution of distilled water, alcohol, and sodium carbonate until fully rehydrated to visual inspection, overnight immersion being sufficient. Of interest was the failure of the rehydration solution to turn dark brown, a change usually seen in the rehydration of human tissues. The lemming (or vole) was rehydrated in toto for a 1-week period, in an effort to facilitate identification.

After rehydration, the specimens were fixed in absolute alcohol and processed as would be fresh tissue. The sections were stained with hematoxylin and eosin, Masson trichrome, phosphotungstic acid hematoxylin (PTAH), and the Fontana stain for melanin, according to described techniques (*12*).

Histologic structure was found to be preserved in several of the specimens. The mammoth eye showed preservation of the extraorbital skeletal muscles, which retained their affinity for the Masson trichrome. The PTAH stain revealed preservation of the cross striations characteristic of skeletal muscle (Fig. 1). The melanin of the retina was not preserved, and no other structures could be identified.

The general architecture of the rabbit liver was preserved, the fibrous tissue of the portal areas being clearly visible (Fig. 2). The hepatocytes had completely disintegrated, being replaced by masses of bacteria. The wall of the rabbit bowel remained as strands of tissue, and the vegetable intestinal contents were well

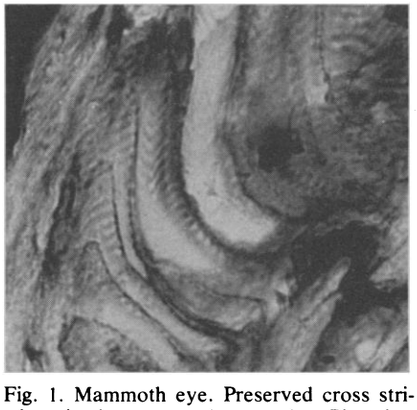

Fig. 1. Mammoth eye. Preserved cross striations in the extraocular muscles. Phosphotungstic acid hematoxylin stain (× 950).

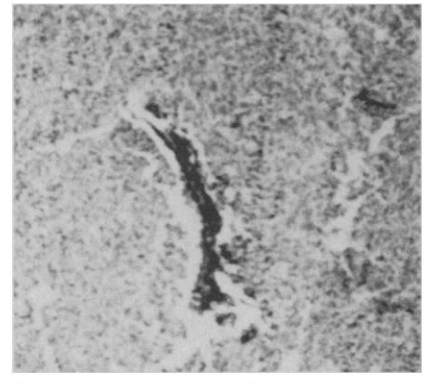

Fig. 2. Rabbit liver. The fibrous tissue of the portal area is preserved, although the hepatocytes have completely decomposed. Hematoxylin and eosin stain (× 95).