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Comparative ^{210}Pb, ^{137}Cs, and Pollen Geochronologies of Sediments from Lakes Ontario and Erie

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The distribution of ^{210}Pb, ^{137}Cs, and *Ambrosia* (ragweed) pollen in two sediment cores from Lake Ontario and in three cores from Lake Erie provides independent estimates of sediment accumulation rates. Geochronology with ^{210}Pb is based on radioactive decay of the isotope following burial in sediments. The method can reveal with precision changes in sedimentation occurring over the past 100 yr or so. Geochronologies with ^{137}Cs and *Ambrosia* are based on the occurrence of a horizon corresponding, respectively, to the onset of nuclear testing 25 yr ago and to regional forest clearance in the middle 1800s. These methods provide estimates of long-term average sediment accumulation rates. In all but one core, the distributions of ^{137}Cs and ^{210}Pb indicate no physical mixing of near-surface sediments. In two cores, including one from central Lake Erie collected by diver, all three estimates of sedimentation rates are in excellent agreement. In two other cores, rates based on ^{210}Pb are significantly higher than those inferred from *Ambrosia* pollen profiles. Lower average rates appear to result from occasional massive losses of sediments. Such events, apparent in the distribution of ^{210}Pb but not in pollen records, correlate with the occurrence of major storm surges on the lakes during this century. In one core from western Lake Erie, exponential distributions of both ^{210}Pb and *Ambrosia* appear to be artifacts which may result from extensive biological or physical reworking of sediments in shallow water (11 m). Previous indications of increased sedimentation in Lake Erie since about 1935 based on *Castanea* (chestnut) pollen data are not substantiated.

INTRODUCTION

Both palynological and radiometric methods have been used to determine modern sedimentation rates in the Great Lakes. The intensive regional forest clearance occurring about 130 years ago resulted in a marked increase in the abundance of *Ambrosia* (ragweed) and in the flux of its pollen to lake sediments. The rise in concentration of *Ambrosia* toward the sediment surface (horizon) provides a time marker for estimating the average rate of accumulation of sediment if a time can be correctly associated with the horizon. The varved sediments of Crawford Lake, situated just north of Lake Ontario, provided Boyko (1973) with an independent chronology indicating that the *Ambrosia* horizon occurs around 1850. Anderson (1974), Kemp *et al.* (1974), and Harper *et al.* (1976) have estimated modern sedimentation rates in Lakes Erie and Ontario from analysis of *Ambrosia* profiles assuming that the 1850 data found

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by Boyko apply to unvarved sediment cores from the Great Lakes as well.

More recently Robbins and Edgington (1972, 1975) have shown that measurements of ^{137}Cs and ^{210}Pb provide independent methods of establishing a time scale within the sediment column. ^{137}Cs in sediments has originated from the testing of nuclear devices in the atmosphere since the 1950s. Thus a sedimentation rate calculated from a ^{137}Cs profile, like that of pollen, is based on the occurrence of a horizon and is an estimate of the average rate of accumulation of material over the past 25 yr. Geochronology with ^{210}Pb is based on a different principle. This naturally occurring member of the ^{238}U series is a decay product of radon present in the atmosphere and is added to sediments of the Great Lakes at a practically constant rate. The determination of a sedimentation rate in this case does not involve the identification of a horizon, but is based on the continuing decay of the isotope ($t_{1/2} = 22.3$ yr) after burial (Robbins, 1978). This method is in principle able to reveal much more detail about the sedimentation process than methods involving discreet time markers. The radiometric methods have been employed primarily in Lake Michigan (Robbins and Edgington, 1975; Edgington and Robbins, 1976a) and more recently in Lake Huron (Robbins *et al.*, 1977; Robbins, 1977). Thus there has been very little overlap in the application of radiometric and palynological methods to studies of sedimentation in the Great Lakes. Furthermore there have been very limited comparisons of the methods. Bruland *et al.* (1975) showed that values of the sedimentation rates were in serious disagreement for two cores from Lake Superior. Because background values of *Ambrosia* and ^{210}Pb occurred very close to the sediment–water interface (~2.5 cm), the discrepancies in sedimentation rates could easily arise from disturbance of surface sediments. On the other hand, Robbins and Edgington (1975) found that the pollen (*Ambrosia*) and ^{210}Pb rates were consistent in two cores taken at approximately the same location in southern Lake Michigan. Bortleson and Lee (1972) and Koide *et al.* (1972, 1973) showed that these same two methods gave comparable estimates of sedimentation rates for cores from Lake Mendota, Wisconsin. In this paper we will critically compare the palynological and radiometric methods applied to replicate sediment cores.

METHODS

Sediment samples were obtained at the five locations in Lakes Ontario and Erie shown in Fig. 1. The coordinates, collection date, and sediment characteristics are given in Table 1. These particular cores were selected by one of us (A.L.W.K.) for radiometric analysis because either the position of the *Ambrosia* horizon was not well defined or the derived sedimentation rates were inconsistent with other information.

The samples at stations U42, M32, WB, and KB were obtained with a modified Benthos gravity triple corer (Kemp *et al.*, 1971). Cores were collected by diver at station G16. In each case two cores were immediately subsampled at 1-, 2-, or 5-cm intervals and the sediment was freeze-dried on shipboard. Water content (Kemp et al., 1972), ^{210}Pb and ^{137}Cs (Robbins and Edgington, 1975) were determined on all available samples. The third core was stored at 4°C and subsampled later for pollen analysis. Absolute concentrations (grains/gram) of *Ambrosia*, *Pinus* (pine), and *Castanea* (chestnut) pollen were made using standard methods (Anderson, 1974; Kemp *et al.*, 1974).

RESULTS AND TREATMENT OF DATA

The experimental data for ^{210}Pb, ^{137}Cs, *Ambrosia*, *Pinus* (pine), and *Castanea* (chestnut) pollens, water content (porosity), and cumulative weight of sediment at each depth interval are given for each core in Tables 2–6. The data for ^{210}Pb, ^{137}Cs, and *Ambrosia* pollen are also shown in Figs.

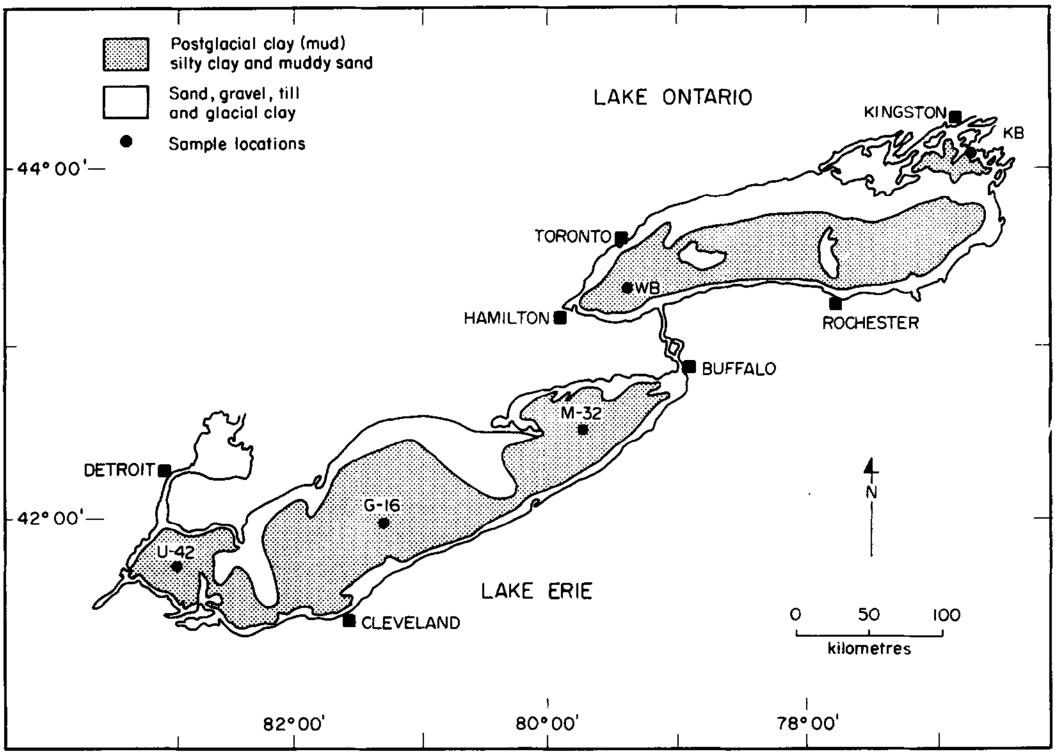

FIG. 1. Location of coring sites in Lakes Erie and Ontario.

2-6. Experimental uncertainties in the activities of total ^{210}Pb are generally 10% or less, while for ^{137}Cs uncertainties are $\leq$ 15% except as indicated in Tables 2-6. Typically the precision of the pollen counts is about ±2%. However, the reproducibility when core samples were split into three parts, extracted, and analyzed separately, was of the order of ±3000 grains/g for counts of 0-10,000 grains/g and ±5000 grains/g for counts of 10-20,000 grains/g.

^{210}Pb

The ^{210}Pb profiles for the present set of cores (Figs. 2-6) do not show evidence of surficial mixing of sediments as the excess ^{210}Pb activity decreases exponentially from

TABLE 1

SAMPLE LOCATIONS, WATER DEPTH, AND SEDIMENT PARTICLE SIZE DISTRIBUTION

Sample number	Year collected	Sample location		Water depth (m)	Particle size distribution by class in top 5 cm of sediment		
		Lat. N	Long. W		Sand (%)	Silt (%)	Clay (%)
KB	1973	44°04.71′	76°24.72′	26	1.1	49.3	49.6
WB	1970	43°24.10′	79°26.66′	101	0.6	28.7	71.6
M32	1971	42°32.19′	79°39.63′	58	0.7	31.0	68.0
G16	1973	42°0.2′	81°36.2′	24	0.0	24.1	76.1
U42	1975	41°45.71′	82°59.2′	11	0.4	40.3	59.3

TABLE 2

SUMMARY OF ^{210}Pb, ^{137}Cs, AND POLLEN ANALYSES AND ASSOCIATED DATA FOR STATION KB, LAKE ONTARIO

Sediment depth	^{210}Pb[a]	^{137}Cs	*Ambrosia*	*Pinus*	*Castanea*	H_2O Content[b]	Cumulative weight of sediment[b]
(cm)	(pCi/g)		(10^3 grains/g of dry sediment)			(wt%)	(g/cm^2)
0–1	14.9	12.1	46.6	—	0	88.6	0.11
1–2	14.4	15.1	31.9	—	0	85.2	0.27
2–4	12.8	12.1	37.5	—	0	82.9	0.65
4–6	16.0	9.76	30.0	—	0	81.7	1.06
6–8	8.27	5.70	34.4	—	0	81.8	1.46
8–10	7.33	0.0	12.9	—	0.75	75.1	2.04
10–12	5.66	0.0	30.3	—	0	74.4	2.64
12–14	4.42		24.3	—	0	74.4	3.24
14–16	2.66		20.4	16.7	0	73.7	3.86
16–18	2.43		17.4	16.3	0.92	72.9	4.50
18–20	0.99		27.0	34.7	—	72.9	5.14
20–22	1.68		24.0	38.1	1.80	72.1	5.80
22–24	—		12.9	34.8	7.59	72.1	6.46
24–26	—		14.4	25.8	—	72.1	7.12
26–28	—		11.4	44.4	1.50	72.1	7.78
28–30	—		6.00	44.2	3.35	72.1	8.44
30–34	0.93		—	—	—	(69.3)	(10.08)
34–36	—		6.36	48.3	2.42	69.3	10.90
40–45	—		2.13	86.3	3.20	69.7	14.27
45–50	—		2.63	78.4	5.25	69.7	16.12
50–55	—		1.26	—	2.52	67.3	18.12
55–60	0.83		2.03	—	2.03	67.3	20.12
60–65	0.87		4.92	—	5.74	67.3	22.12
65–70	—		1.17	—	4.69	67.3	24.12
70–75	0.84 [0.73]		—	—	—	(67.3)	(26.12)
80–85	0.84 [0.76]		—	—	—	(67.3)	(28.12)

[a] Activity of ^{226}Ra (pCi/g) in brackets.

[b] Interpolated values in parentheses.

the sediment–water interface. This behavior is in marked contrast to that observed in many cores from Lakes Michigan (Robbins and Edgington, 1975; Edgington and Robbins, 1976a) and Huron (Robbins *et al.*, 1977a) where there is a zone of constant activity immediately below the sediment–water interface. However, other cores from Lake Erie have ^{210}Pb profiles indicating surficial mixing (unpublished data). For the present analysis a simpler mathematical treatment is used than that previously described (Robbins and Edgington, 1975). Provided that the sedimentation rate, r (g/cm^2/yr) and activity of excess ^{210}Pb added to surface sediments, A_0 (pCi/g) are constant in time the distribution of excess ^{210}Pb in undisturbed sediments is given by

$$A = A_{\text{obs}} - A_f = A_0 e^{-\lambda m/r} \qquad (1)$$

where A_{obs} is the measured (total) activity of ^{210}Pb at a given depth, A_f is the activity of ^{210}Pb supported by decay of ^{226}Ra, m is the cumulative weight of sediment (g/cm^2), and λ is the radioactive decay constant for ^{210}Pb (0.693/22.26 yr^{-1}). A significant degree of compaction characterizes some cores. For example, the percent solids in the core at Station G16 increases by more than a factor of four from surface to a depth of 30 cm. For this reason the sedimentation rate in centimeters per year is not uniquely defined even

TABLE 3

SUMMARY OF ^{210}Pb, ^{137}Cs, AND POLLEN ANALYSES AND ASSOCIATED DATA FOR STATION WB, LAKE ONTARIO

Sediment depth	^{210}Pb[a]	^{137}Cs	*Ambrosia*	*Pinus*	*Castanea*	H_2O Content	Cumulative weight of sediment
(cm)	(pCi/g)		(10^3 grains/g of dry sediment)			(wt%)	(g/cm^2)
0–1	13.2	19.4	12.5	8.36	1.44	88.8	0.11
1–2	—	21.3	11.4	7.90	—	87.3	0.25
2–3	10.4	5.92	10.0	3.35	1.59	83.8	0.42
3–4	—	1.37	8.71	2.49	0.23	80.8	0.63
4–5	8.53	0.0	6.01	2.86	0.85	77.7	0.88
5–6	—	0.0	8.02	1.78	0.42	76.6	1.14
6–7	7.66	0.0	2.90	2.90	1.27	75.1	1.43
7–8	—		8.86	5.64	0	74.4	1.73
8–9	6.92		6.39	1.16	1.61	75.9	2.01
9–10	—		10.60	3.18	0	75.9	2.29
10–11	5.53		2.90	2.51	1.01	73.7	2.59
11–12	—		3.65	6.70	—	73.7	2.89
12–13	2.48[1.54]		1.35	4.06	—	73.7	3.19
13–14	—		0	12.5	4.51	73.7	3.49
14–15	1.89[1.50]		0	29.8	—	73.7	3.79
15–16	—		0	31.4	10.80	71.2	4.41
16–17	—		0	43.1	—	71.2	4.49
17–18	1.33[1.41]		0	38.5	—	71.2	4.84
18–19	1.26[1.39]		0	39.1	1.24	71.2	5.19

[a] Activity of ^{226}Ra (pCi/g) in brackets.

when the mass sedimentation rate r is constant. By expressing the distribution of excess ^{210}Pb (Eq. (1)) in terms of the cumulative weight (m), the effects of compaction are taken into account automatically. However, in Figs. 2–6 the excess ^{210}Pb values are plotted against depth (centimeters). Thus in some cases there is a slight departure of the observed and calculated profiles from exponential form near the sediment–water interface which results from compaction.

The mass sedimentation rates were determined using a weighted linear least

TABLE 4

SUMMARY OF ^{210}Pb, ^{137}Cs, AND POLLEN ANALYSES AND ASSOCIATED DATA FOR STATION M32, LAKE ERIE

Sediment depth	^{210}Pb[a]	^{137}Cs	*Ambrosia*	*Pinus*	*Castanea*	H_2O Content[b]	Cumulative weight of sediment[b]
(cm)	(pCi/g)		(10^3 grains/g of dry sediment)			(wt%)	(g/cm^2)
0–1	7.96	8.17	32.5	—	1.38	84.1	0.17
1–2	—	7.92	—	—	—	(80.7)	(.44)
2–3	6.71	5.63	—	—	—	(77.9)	(.71)
3–4	—	11.0	—	—	—	(75.8)	(.97)
4–5	7.38	9.69	—	—	—	(76.1)	(1.24)
5–6	—	10.7	33.8	—	—	72.9	1.51
6–7	6.47	8.54	—	—	—	(72.7)	(1.85)
7–8	—	10.6	—	—	—	(72.3)	(2.20)

TABLE 4—*Continued*

Sediment depth	^{210}Pb[a]	^{137}Cs	*Ambrosia*	*Pinus*	*Castanea*	H_2O Content[b]	Cumulative weight of sediment[b]
(cm)	(pCi/g)		(10^3 grains/g of dry sediment)			(wt%)	(g/cm^2)
8-9	6.95	14.2	—	—	—	(71.3)	(2.89)
9-10	—	13.9	—	—	—	(71.3)	(3.06)
10-11	6.71	—	39.0	—	0.86	71.2	(3.23)
11-12	—	12.7	—	—	—	(71.2)	(3.57)
12-13	6.49	6.99	—	—	—	(71.2)	(3.93)
13-14	—	6.91	—	—	—	(71.2)	(4.30)
14-15	5.62	2.62	—	—	—	(71.2)	(4.65)
15-16	3.62	—	46.0	—	—	68.9	5.01
16-17	—	4.36	—	—	—	(68.9)	(5.39)
17-18	3.72	—	—	—	—	(68.9)	(5.76)
18-19	—	1.53	—	—	—	(68.9)	(6.14)
19-20	3.98	—	—	—	—	(68.9)	(6.51)
20-21	—	1.82	39.3	—	0.40	70.1	6.89
21-22	3.20	0.0	—	—	—	(70.1)	(7.25)
22-23	3.52	0.0	—	—	—	(70.1)	(7.61)
24-25	3.67		—	—	—	(70.1)	(8.33)
25-26	—		35.9	—	—	70.1	8.69
30-31	3.11		46.0	—	0.33	66.4	10.55
31-32	2.65		—	—	—	(66.4)	(10.97)
33-34	3.30		—	—	—	(66.4)	(11.81)
35-36	2.88		27.6	—	—	(66.4)	12.65
40-41	2.46		34.4	—	0.44	65.5	14.77
41-42	—		—	2.27	0.32	65.5	15.19
42-43	2.39		—	—	—	(65.5)	(15.61)
43-44	2.58		—	—	0.71	65.5	16.03
44-45	2.40		—	2.29	0.19	65.5	16.45
50-51	1.77		30.1	—	1.68	64.5	19.19
52-53	1.93		—	—	2.97	64.5	20.11
54-55	—		—	—	1.53	64.5	21.03
55-56	1.48		33.0	—	0.95	64.5	21.49
57-58	1.82		—	—	—	(64.5)	(22.42)
58-59	—		—	—	1.92	64.5	22.88
60-61	1.71		40.8	—	2.84	63.4	23.81
62-63	—		33.6	3.47	3.19	63.4	24.77
64-65	1.55		—	—	—	(63.4)	(25.73)
65-66	—		28.5	7.06	2.14	63.4	26.21
70-71	1.32		20.7	5.85	—	61.9	28.62
75-76	—		18.3	7.37	1.05	61.9	31.15
77-78	—		7.6	6.04	—	61.9	32.17
78-79	—		3.0	4.35	—	61.9	32.60
80-81	1.20		5.19	5.99	1.38	60.4	33.56
85-86	—		5.39	4.80	—	60.4	35.68
90-91	1.05[0.81]		2.54	7.24	2.48	60.4	38.86
95-96	—		2.85	15.6	—	60.4	41.51
100-101	1.06		1.88	15.7	6.05	60.4	44.16
105-106	—		0.93	8.57	1.71	60.4	46.81
110-111	0.90[0.69]		0.33	10.1	1.63	60.4	49.46
115-116	—		1.03	17.0	1.55	60.4	52.11
120-121	0.88		0	5.91	1.89	58.9	54.78

[a] Activity of ^{226}Ra (pCi/g) in brackets.

[b] Interpolated values in parentheses.

squares fit to the log of the excess ^{210}Pb activity with weights inversely proportional to the square of the estimated uncertainty in individual data points. For the value of unsupported ^{210}Pb we used the average value of the measured activities of ^{226}Ra in each core. These values are presented in Tables 2–6 within brackets adjacent to reported ^{210}Pb activities. Activities of ^{226}Ra are generally 10–30% lower than activities of ^{210}Pb at depths in the cores where these decay products should be essentially in secular equilibrium. This difference could be due to small intercalibration errors, to real departures from secular equilibrium, or to differences in the leachability of ^{226}Ra and ^{210}Pb from sediments by strong acids. Thomson *et al.* (1975) reported similar differences in a sediment core from Long Island Sound and suggested that this is due to the escape of ^{222}Rn and subsequent formation of ^{210}Pb outside of mineral lattice sites.

In most cases the determination of sedimentation rates is insensitive to the value of A_f. In fact the variation of 10% in the value of A_f will introduce an uncertainty of 3% in the value of r calculated from least squares analysis (G16). The values of the mass sedimentation rates along with estimated uncertainties are given in Table 7. The uncertainties reflect the combined er-

TABLE 5

SUMMARY OF ^{210}Pb, ^{137}Cs, AND POLLEN ANALYSES AND ASSOCIATED DATA FOR STATION G16, LAKE ERIE

Sediment depth (cm)	$^{210}Pb^a$	^{137}Cs	*Ambrosia*	*Pinus*	*Castanea*	H_2O Content^b (wt%)	Cumulative weight of sediment^b (g/cm^2)
	(pCi/g)		(10^3 grains/g of dry sediment)				
0–1	12.3	—	67.5	10.4	0	91.9	0.08
1–2	—	12.6	—	—	—	(88.7)	(0.28)
2–3	11.1	12.8	—	—	—	(87.9)	(0.42)
3–4	—	19.6	—	—	—	(85.3)	(0.56)
4–5	9.58	13.3	—	—	—	(83.9)	(0.70)
5–6	—	10.7	53.2	10.1	0	82.2	0.84
6–7	8.02	4.26	—	—	—	(79.5)	(1.08)
7–8	—	5.16	—	—	—	(79.0)	(1.32)
8–9	8.08	1.88	—	—	—	(78.6)	(1.56)
9–10	—	0.88	—	—	—	(78.6)	(1.80)
10–11	5.75	0.0	47.6	5.46	0.39	75.2	2.04
12–13	4.57	0.0	45.8	4.62	0	75.2	2.62
14–15	4.59	0.0	—	—	—	(75.2)	(3.20)
15–16	—		54.9	5.40	0.32	74.9	3.49
16–17	—		30.9	4.27	0.50	74.9	3.78
17–18	3.57		39.4	5.28	0.62	74.9	4.07
18–19	—		40.6	6.19	1.03	74.9	4.36
19–20	—		37.4	7.22	0.98	74.9	4.65
20–21	2.95		30.1	5.83	0.68	71.4	5.00
22–23	—		31.9	3.54	1.42	71.4	5.70
23–24	2.29		—	—	—	(71.4)	(6.05)
25–26	—		27.5	7.40	0.62	71.4	6.75
26–27	2.14		—	—	—	(71.4)	(7.11)
28–29	1.90[1.28]		—	—	—	(71.4)	(7.84)
29–30	1.73[1.04]		—	—	—	(71.4)	(8.21)
30–31	2.03		17.9	11.3	1.41	66.1	8.57
31–32	1.95		15.8	12.1	1.29	66.1	8.99

[a] Activity of ^{226}Ra (pCi/g) in brackets.

[b] Interpolated values in parentheses.

TABLE 6

SUMMARY OF ^{210}Pb, ^{137}Cs, AND POLLEN ANALYSES AND ASSOCIATED DATA FOR STATION U42, LAKE ERIE

Sediment depth (cm)	^{210}Pb[a] (pCi/g)	^{137}Cs (pCi/g)	*Ambrosia* (10^3 grains/g of dry sediment)	*Pinus* (10^3 grains/g of dry sediment)	*Castanea* (10^3 grains/g of dry sediment)	H_2O Content[b] (wt%)	Cumulative weight of sediment[b] (g/cm^2)
0–2	4.41	3.79	33.8	17.8	0.15	74.82	0.60
2–4	3.78	2.31	—	—	—	(66.8)	(1.53)
4–6	2.51	—	16.0	12.8	0.31	59.47	2.46
6–8	2.02	0.0	—	—	—	(59.5)	(3.66)
8–10	1.62	0.0	13.0	22.4	0.15	56.90	4.86
10–12	1.57	0.0	9.12	25.9	0.25	56.20	6.06
12–14	—	0.0	7.14	42.8	0.19	53.73	7.36
14–16	1.07		2.21	46.2	0.18	51.74	8.74
16–18	—		4.26	52.6	0.53	51.52	10.12
18–20	1.01		4.44	55.4	0.30	50.66	11.54
20–22	0.86[0.64]		2.73	43.7	0.40	51.20	12.94
22–24	0.81		2.17	42.5	0.43	46.68	14.34
24–26	0.76[0.61]		3.65	40.1	0.66	47.23	15.90
26–28	—		2.69	34.2	0.21	49.91	17.36
28–30	0.89[0.70]		1.55	34.8	0	50.60	18.78
30–32			1.77	26.9	0.39	50.50	20.20
36–38			1.68	29.7	0.28	45.38	24.76
40–42			2.47	31.0	0.38	47.55	27.88
50–52			0.78	28.0	0.26	45.44	35.94

[a] Activity of ^{226}Ra (pCi/g) in brackets.

[b] Interpolated values in parentheses.

rors in estimate of r from least squares analysis of the excess ^{210}Pb profile and the error in the estimate of A_f. Sedimentation rates $\bar{\omega}$ expressed in centimeters per year given in Table 8 represent averages for the upper 10 cm of sediment. That is, $\bar{\omega} = 10/\Delta T$ where ΔT = (cumulative grams per square centimeter at 10 cm)/r(g/cm^2/yr). These values are included to provide a feeling for linear rates but are not used in the discussion of individual cores which follows below.

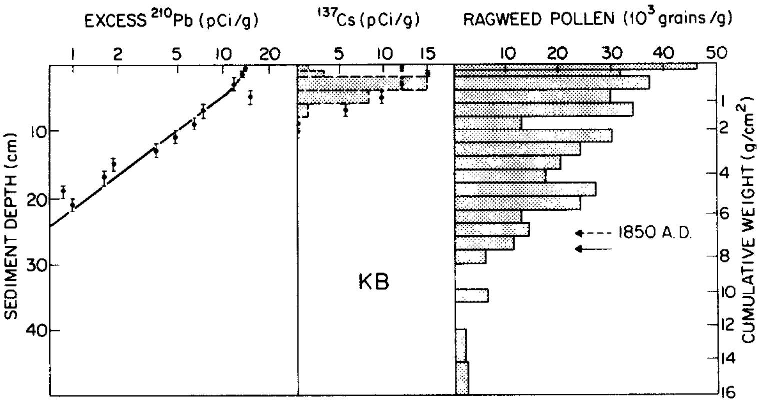

FIG. 2. Distribution of excess ^{210}Pb, ^{137}Cs, and ragweed (*Ambrosia*) pollen in cores from site KB (Lake Ontario). Independent analysis of each profile yields consistent sedimentation rates, about 0.06 g/cm^2/yr (0.2 cm/yr).

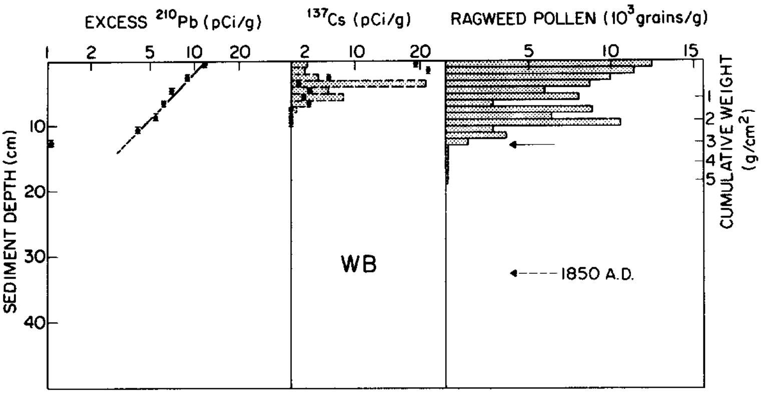

FIG. 3. Distribution of excess ^{210}Pb, ^{137}Cs, and ragweed (*Ambrosia*) pollen in cores from site WB (Lake Ontario). Sedimentation rates derived from radiometric data are consistent, about 0.078 g/cm²/yr (~0.3 cm/yr). An appreciably lower rate (0.03 g/cm²/yr) implied by the pollen distribution appears to result from loss of sediments at around 12 cm.

^{137}Cs

The effect of mixing of surface sediments seen in profiles of ^{210}Pb are reflected in corresponding profiles of ^{137}Cs in cores from Lakes Michigan (Robbins and Edgington, 1975) and Huron (Robbins *et al.*, 1977; Johansen and Robbins, 1977). Because there is no evidence of a well-defined zone of mixing in the present case, the following method of estimating a sedimentation rate from each ^{137}Cs profile has been adopted. The horizon corresponding to the initial input of ^{137}Cs into the atmosphere, 1952 ± 2 AD (Health and Safety Laboratory, 1972) is taken as the midpoint of the deepest interval which has measurable ^{137}Cs activity. Uncertainties in the position of the horizon are taken as the half-width of this interval. The expected distribution of ^{137}Cs discussed previously by Robbins and Edgington (1975) is based on the known time dependence of the input to the lakes from the nationwide monitoring of fallout (Health and Safety Laboratory, 1972). The histograms presented in Figs. 2–6 (arbitrarily normalized to the data) represent the expected distribution of ^{137}Cs in these cores on the basis of the mass sedimentation rate derived from the ^{210}Pb measurements and the assumption that the transfer of ^{137}Cs from the atmosphere to the sediments is immediate. In view of the fact that the residence time of ^{137}Cs in the upper Great Lakes is known to be on the order of 1–2 yr (Wahlgren and Nelson, 1974; Berry, 1973), this latter assumption is probably reasonable. Mass sedimentation rates derived from the ^{137}Cs profiles are given in Table 7. Uncertainties in the estimate of the rates result from the combined uncertainties in location of the horizon and the assignment of a date of introduction of the radionuclide into the environment. Average linear sedimentation rates (Table 8) are computed by the method described above.

Pollen

The concentrations of *Ambrosia* pollen in sediments increases from background levels of 0–8000 grains/g to a maximum of 46,000 grains/g dry weight. The ragweed pollen concentrations are variable in all cores, usually being at a maximum toward the sediment water interface. A complementary behavior would be expected in the concentration of *Pinus* pollen grains due to the clearing of the forests. The data presented in Tables 2–6 confirm this expectation. Pine pollen counts decrease from high values well below the ragweed horizon to low values well above the horizon. Pine and ragweed pollen constitute 34–46% of

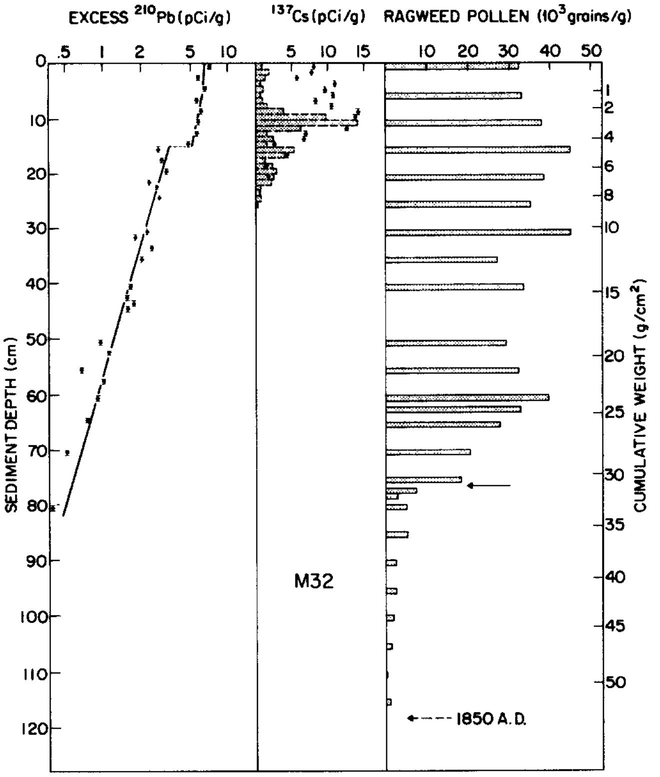

FIG. 4. Distribution of excess ^{210}Pb, ^{137}Cs, and ragweed (*Ambrosia*) pollen in cores form site M32 (Lake Erie). The ^{210}Pb profile reveals a major discontinuity at about 15 cm. Within experimental uncertainties sedimentation rates derived for each section separately are consistent, with an adopted value of 0.44 g/cm²/yr (~1 cm/yr). The significantly lower rate obtained from the pollen profile (0.26 g/cm²/yr) appears to result at least in part from loss of sediment at about 15-cm depth. As measurable ^{137}Cs activity occurs below as well as above this depth, the sedimentation rate based on this profile is a lower limit (>0.35 g/cm²/yr).

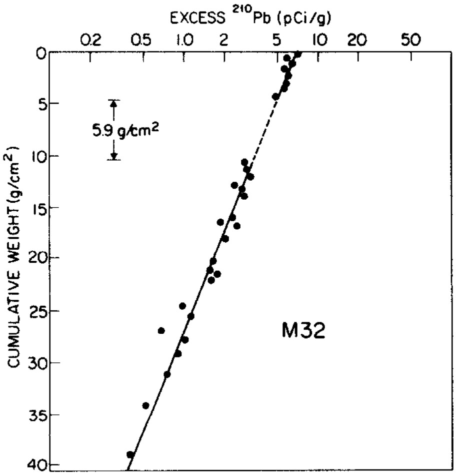

FIG. 5. Distribution of excess ^{210}Pb as it might have appeared without sediment loss. Requirement of an exponential distribution for the reconstructed profile implies a loss of 5.9 g/cm² of sediment.

the total arboreal and herb pollen species in Lake Ontario surface sediments (McAndrews and Powers, 1973).

Earlier, Kemp *et al.* (1974) had assigned sedimentation rates on the basis of a decline in chestnut pollen due to a blight in the early 1930s as observed by Anderson (1974). In the present study the counts were too low (Tables 2–6) to make any positive interpretation of a decline. Pollen counts of less than 1000 grains/g dry weight of sediment result in 5–10 grains per 12 traverses of a standard microscope slide. In this study, in 30–40 traverses generally less than 5 grains were found. This result is not unexpected since McAndrews and Powers (1973) found that *Castanea* pollen averaged 1% of the total arboreal pollen in the surface sedi-

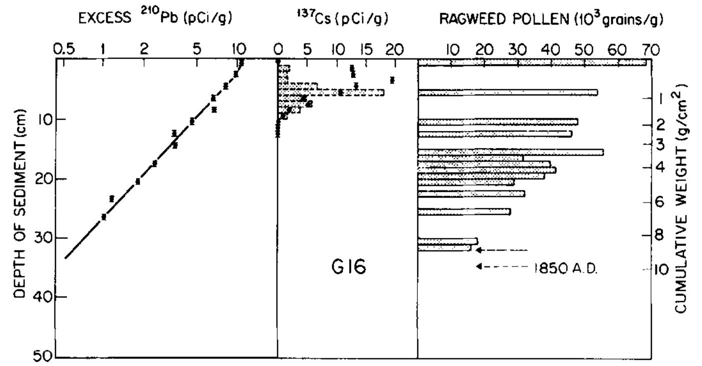

FIG. 6. Distribution of excess ^{210}Pb, ^{137}Cs, and ragweed (*Ambrosia*) pollen in cores from site G16 (Lake Erie). Independent analysis of each profile yields consistent sedimentation rates, about 0.08 g/cm^2/yr.

ments of Lake Ontario. In a recent study of Lake Ontario sediments, Kemp and Harper (1976) found that the concentration of chestnut pollen grains was too low for an interpretation of their profiles in 37 out of 39 cores.

Sedimentation rates were calculated from the cumulative weight of sediment above the ragweed horizon in each core divided by the number of years of deposition since 1850. There is considerably more uncertainty in the assignment of a location for the first appearance of ragweed pollen in these particular cores than for the introduction of ^{137}Cs, especially at stations M32 and U42. At these locations, the *Ambrosia* pollen counts are variable and increase gradually. The need for establishing and applying a uniform criterion in locating the *Ambrosia* horizon is apparent from consideration of individual cores below.

On the basis of the measurement of *Ambrosia* pollen in varved sediments from Crawford Lake, Ontario, introduction of this marker is estimated to have occurred between 1846 and 1851 AD (McAndrews, 1976). There are two major sources of uncertainty in determining the date of introduction of pollen into each lake. First, since the clearance of forests is not an instantaneous process, the buildup of ragweed pollen has to have taken place over an extended period of years. Second, since the clearance proceeded westward it might be expected that the date of the pollen horizon in sediments from Lake Erie would be later than that for Lake Ontario. To assign uncertainties to the estimate of sedimentation rates derived from *Ambrosia* pollen profiles, we attributed a 10-yr spread to its time of introduction (i.e., 1850 ± 10 AD). Mass

TABLE 7

A COMPARISON OF MASS SEDIMENTATION RATES (g/cm^2/yr) FOR THE FIVE LOCATIONS

Station locations	Method		
	^{210}Pb	^{137}Cs	*Ambrosia*
KB	0.057 ± 0.01	0.060 ± 0.01	0.063 ± 0.01
WB	0.078 ± 0.01	0.072 ± 0.02	0.027 ± 0.003
M32	0.440 ± 0.03	≥0.35 ± 0.04	$0.27\,^{+0.1}_{-0}$
G16	0.083 ± 0.005	0.080 ± 0.01	0.073
U42	0.096 ± 0.02	≥0.047 ± 0.02	$0.059\,^{+0.03}_{-0}$

TABLE 8

APPROXIMATE LINEAR SEDIMENTATION RATES (cm/yr) FOR THE FIVE LOCATIONS[a]

Station locations	Method		
	^{210}Pb	^{137}Cs	*Ambrosia*
KB	0.28	0.29	0.31
WB	0.34	0.31	0.12
M32	1.4	≳1.2	0.85
G16	0.46	0.44	0.40
U42	0.20	≳0.10	0.12

[a] Approximately the average rate in the upper 10 cm (see text).

sedimentation rates based on analysis of *Ambrosia* pollen profiles are given in Table 7 along with confidence limits incorporating uncertainties in locating the horizon and in the assignment of time. Average linear sedimentation rates provided in Table 8 are computed as described above for ^{210}Pb.

DISCUSSION

Comparative Geochronologies

Site KB (Lake Ontario)

The sedimentation rates (Table 7) computed by the three methods agree well within the experimental uncertainties with an average of 0.060 g cm $^{-2}$yr^{-1}. The observed ^{210}Pb profile (Fig. 2) is in agreement with that calculated from Eq. (1), suggesting that the annual flux of ^{210}Pb to the sediments each year and the sedimentation rate have not varied significantly over the period of observation (~100 yr). However, there are minor departures of data points from the expected theoretical distribution. For example, the ^{210}Pb activity in the 4-6-cm interval is about 50% too high. In contrast the value of the activity at 14-16 cm is too low. Such departures far exceed the experimental uncertainties in individual measurements. If found only in a single core, no significance would be attributed to such features. But these minor anomalies are common and reproducible not only in cores taken at the same location (Edgington and Robbins, 1976; Robbins *et al.*, 1977) but also in cores collected over a wide area in southern Lake Michigan. Such anomalies are a recurrent feature of ^{210}Pb profiles and tend to occur at depths corresponding to specific times in the past. In a previous article (Robbins *et al.*, 1975) we suggested that anomalies in the ^{210}Pb profiles may be associated with the occurrence of major storm surges on the lake. The major storms in this century have occurred in 1958, 1940, 1918, 1916, 1913, and 1905 (U. S. Weather Service, 1976; Murty and Polavarapu, 1975). In this core the 4-6-cm interval (0.84 ± 0.2 g/cm^2) corresponds to a time of 0.84/0.057 = 14.7 yr or a date of 1973 − 14.7 = 1958 ± 4 AD. The 14-16-cm interval (3.55 ± 0.3 g/cm^2) corresponds to a date of 1910 ± 5 AD. An additional low value occurs at the 18-20-cm level (4.80 ± 0.3 g/cm^2) corresponding to a date of 1888 ± 6 AD around which time there is no evidence of unusual storm surge activity according to Murty and Polavarapu (1975). Thus two of the three anomalous points in this ^{210}Pb profile occur within experimental uncertainties at times corresponding to major storm surges on the Great Lakes. It will be clear below that ^{210}Pb profiles in some but not all of the cores have features which can be understood in terms of episodic lake-wide disturbances.

The ^{137}Cs horizon (Fig. 2) is at the correct depth in the sediment as predicted from the sedimentation rate based on ^{210}Pb. The activity of ^{137}Cs is much greater in surface sediments than expected on the basis of direct transfer of the radionuclide from atmosphere to sediments. This feature, common to all of the five cores studied, has also been observed in many cores from Lake Michigan (Edgington and Robbins, 1976c) and Lake Huron (Robbins *et al.*, 1977).

The observed horizon for *Ambrosia* pollen occurs at 38 cm (7.78 g cm^{-2}). This value, chosen by one of us prior to the radiometric measurements, and shown as the solid arrow in Fig. 2, is in good agreement with that found in another core taken previously at this location (Kemp *et al.*, 1974). Based on the ^{210}Pb or ^{137}Cs data the horizon would have been expected to occur at 25.7 cm, for a date of introduction of 1850 (Fig. 2, dashed line). This difference is not very significant in view of the difficulty in locating the pollen horizon with any precision (± about 2 cm). However, it should be noted that if the sedimentation rate based on ^{210}Pb is correct, the shape of the pollen profile in this particular core would indicate a date of introduction of *Ambrosia* pollen as early as 1835 or possibly earlier if values of the *Ambrosia* pollen concentration at 28–30 and 34–36 cm (6.0 and 6.3×10^3 grains/g, respectively) are treated as being sufficiently above background levels to constitute the true horizon.

Site WB (Lake Ontario)

In contrast to cores from site KB, there is considerable disagreement between the rates calculated by the radiometric and pollen methods (Table 7). The ^{210}Pb and ^{137}Cs profiles yield consistent sedimentation rates of 0.078 and 0.072 g cm^{-2}grain^{-1}, respectively, whereas the rate based on *Ambrosia* pollen is approximately a factor of three lower (0.027 g cm^{-2}yr^{-1}). In this core there is a discontinuity in the *total* ^{210}Pb profile between 10.5 and 12.5 cm (2.74 ± 0.3 g cm^{-2}), and the concentration of pollen grains drops abruptly to zero between 12 and 13 cm. Comparison of the *Ambrosia* pollen profile in Fig. 3 with pollen profiles in the other cores shows that such a sharp break occurs only in this core. These features could result from an event which removed an appreciable quantity of sediment from this location at a time given by 2.74/0.078 = 35 yr or 1935 ± 6 AD. Again, within experimental uncertainties this date is consistent with the 1940 storm surge event on Lake Erie. The effect of the 1958 event, if apparent, would occur at [(1970 − 1958) × 0.078 = 0.94 g/cm^2] or at about 5 cm (Table 3). Interestingly, the value of the excess ^{210}Pb in the 4–5-cm interval departs from the theoretical fit (Fig. 3) more than other measured values although the deviation is only slightly greater than experimental uncertainties.

Since the concentration of pollen grains is zero below 13 cm, the loss of sediment in 1935 AD must have included all material which had accumulated from some date prior to the introduction of ragweed pollen into the environment. The ^{210}Pb date associated with the bottom of the break at 15 cm is 1860. This date was calculated from the ratio of the excess ^{210}Pb activity at the bottom of the break over that at the surface of the sediments. This date is subject to considerable uncertainty (±25 yr) because the total activity of ^{210}Pb is very close to the background value. The mass of sediment lost could therefore be between 4.30 and 7.43 g cm^{-2}. Thus according to the self-consistent picture developed here, it follows that the sedimentation rate derived from analysis of *Ambrosia* (and *Pinus*) pollen profiles is in error because of appreciable losses of sedimentary material in post-settlement times. Without supplementary information such as that provided by radiometric measurements, the effect of such losses might lead to an incorrect interpretation of pollen profiles.

Site M32 (Lake Erie)

This core, collected from the deepest part of Lake Erie, is remarkable because of the very high sedimentation rate of over 1 cm/yr (Table 8). Measurable excess ^{210}Pb occurs at depths of at least 70 cm. The core is also remarkable because of the very well-defined break in the ^{210}Pb profile at around 15-cm depth (4.65 ± 0.28 g cm^{-2}). Because the ^{210}Pb distribution is essentially exponential except for this feature, each section has been analyzed separately. The upper section (above 15 cm) yields a sedimentation rate of 0.52 ± 0.2 g cm^{-2} yr^{-1}, while the lower section (>15 cm) yields a rate of 0.44

± 0.03 g cm^{-2} yr^{-1}. The larger uncertainty in the rate for the upper section results from the limited number of data points and their greater scatter. The theoretical fits to each section have slopes corresponding to the computed sedimentation rate. The two rates are consistent with each other within the experimental uncertainties. It is therefore assumed that the rate is best represented by 0.44 ± 0.03 g cm^{-2} yr^{-1}. On this basis the break in the excess ^{210}Pb distribution corresponds to a time of 1960 ± 2 AD. Again this date corresponds closely to the date of the 1958 storm surge, suggesting that even in the deepest part of Lake Erie storm events of sufficient intensity may result in the redistribution of fine-grained sediments. The ^{210}Pb profile shown in Fig. 4 represents a classic response of sediments to an erosional process. The profile expected in the absence of such a disturbance is illustrated in Fig. 5. The data have been replotted assuming that in the absence of the postulated event there would have been a normal logarithmic distribution of excess ^{210}Pb in the core. On this basis, it is clear that the loss of sediment, equivalent to 5.9 g cm^{-2}, corresponds to material accumulated for the previous 13 years. No significant departures from the theoretical distribution occur at depths corresponding to dates of other major storm surges.

The location of the maximum in the distribution of ^{137}Cs shown in Fig. 4 is in good agreement with its expected position in the core. However, low levels of ^{137}Cs should be found deeper than observed (Fig. 4). That they are not is consistent with the inferred loss of material around 1960 AD, but only partly so. If the hypothesis is correct, the true ^{137}Cs horizon is contained within the portion of sediment lost, that is, the material accumulated in the 13-yr period between 1947 and 1960. But in fact a small but measurable activity of ^{137}Cs occurs in samples below 15 cm. However, these analyses are subject to uncertainties as great as 100% (Table 4) because of the small size of sample taken (2.0 g) and their extremely low specific activity. Possibly slight downward mixing could have occurred at the time of the erosional event. Just below the breakpoint the ^{210}Pb activity tends to a constant value for several centimeters which is also consistent with downward mixing. Because of the difficulties in interpreting the exact position of the horizon for ^{137}Cs, the sedimentation rate of 0.35 ± 0.04 g cm^{-2} yr^{-1} given in Table 7 has been calculated from the position of maximum activity, 9 cm, in the core which corresponds to 1963. The agreement between the values calculated from the ^{210}Pb and ^{137}Cs data is not as good as in the other cores discussed so far.

The *Ambrosia* pollen horizon is taken to be at 76.5 (±2) cm, corresponding to 31.4 gm cm^{-2} of sediment (A.L.W.K.). The position of this horizon is the same as that found in cores previously collected at this station (Kemp *et al.*, 1974). If this horizon corresponds to a date of 1850 AD then the sedimentation rate would appear to be 0.26 g cm^{-2} yr^{-1}, which is far lower than rates calculated from the radiometric methods. On the basis of the ^{210}Pb mass sedimentation rate, the horizon corresponding to 1850 should appear at 120 cm, as indicated in Fig. 4. If allowance is made for the sediment which appeared to be lost in 1960 AD, the sedimentation rate is given by

$$(31.4 + 5.90)/(1971 - 1850) = 0.31 \text{ g cm}^{-2} \text{ yr}^{-1},$$

which is in better accord with the radiometric measures. If the sedimentation rate determined from ^{210}Pb is correct and the *Ambrosia* horizon is at an adjusted "depth" of 31.4 + 5.90 = 37.3 g cm^{-2}, the inferred date of introduction of *Ambrosia* pollen into Lake Erie could be as late as 1886 AD. Alternatively the criterion for locating the *Ambrosia* horizon may not be adequately defined in this case. If the horizon is taken to be the depth in the sediment column above which the concentration of *Ambrosia* pollen grains is *consistently* at least two standard deviations above background levels, a very different result is obtained. For purposes of determining background levels, the set of lower most data points which are not significantly different from each other is averaged. The first point which is significantly different is that at 100–101 cm (44.2 g/cm^2) corresponding to 1.88 × 10^3 grains/g (Table 4). All values above this point are significantly greater than background values. In terms of this criterion, the sedimentation rate is of course more consistent with that calculated from ^{210}Pb (44.2/121 = 0.365 g/cm^2/yr). Including the material lost, the sedimentation rate is 44.2 + 5.9/121 = 0.41 g/cm^2/yr. Clearly the inferred sedimentation rate is strongly dependent on the criterion used to specify the location of the horizon in this case.

At this site where the sedimentation rate is very high, the pollen record indicates that the *Ambrosia* influx increased slowly over a period of about 30 yr (87 to 60 cm). This slow rise probably corresponds to the gradual clearing of the land. It should be noted, however, that a large increment in the pollen concentration occurs at the assigned horizon (Fig. 4). As the buildup of pollen should presumably be a smooth function of time, it is possible in a core such as this that a further loss of sediment occurred at a time corresponding to the assigned horizon. Unfortunately, this feature occurs beyond the limits of the ^{210}Pb method.

Site G16 (Lake Erie)

In this core sedimentation rates calculated from each of the three methods are in good agreement (Table 7). The ^{210}Pb profile (Fig. 6) has the expected exponential form and shows no evidence of major disturbances. However, minor variations in the ^{210}Pb distribution again are consistent with the storm surge hypothesis. It can be seen (Fig. 6) that slight but statistically significant departures from the theoretical profile occur at 8–9, 12–13, and 23–24 cm with corresponding cumulative weights of 1.44, 2.50, and 5.88 g cm^{-2}. These intervals correspond to dates of 1956 ± 3, 1943 ± 3, and 1903 ± 4 AD. Thus in this core, as in the others, small perturbations in the ^{210}Pb profiles occur at certain characteristic times in the past. We do not see evidence of anomalies corresponding to the dates 1913, 1916, 1918.

The ^{137}Cs horizon occurs at a depth corresponding to that calculated from the ^{210}Pb data. As has been seen in previous cores from this and other lakes, the activity in the upper few centimeters is greater than would be expected from recent inputs from fallout. As this core was collected with care by diver, it is unlikely that high values in the upper 4 cm are the result of core disturbances. Contributions of ^{137}Cs from the watershed would tend to elevate post 1963–1964 levels in the lake, but as the loss rate is only a fraction of a percent per year (Ritchie *et al.*, 1974) this source would appear to be unimportant. Previously it has been suggested that lake-wide redistribution and integration of ^{137}Cs might account for high near-surface values. This process appears to occur preferentially for ^{137}Cs because of the time-dependent nature of the inputs. Because the influx of ^{210}Pb has been constant and redistribution processes are essentially continuous, the flux of ^{210}Pb to surface sediments has attained a steady state value.

Unfortunately, the core at G16 was not quite long enough to penetrate below the *Ambrosia* pollen horizon. A comparison of the pollen concentrations in this core with those at Station M32 indicates that the horizon would be just below 32 cm. In a core collected at this same location in 1970, the *Ambrosia* horizon was located at 28 cm (Kemp *et al.*, 1974). As with previous cores, pine pollen concentrations are decreasing from the base of the core upwards. In view of the difficulties in locating the horizon in this core, the inferred sedimentation rate is given in Table 7 as a lower limit. If in fact the choice of 32 cm for this core is correct, then the ^{210}Pb results

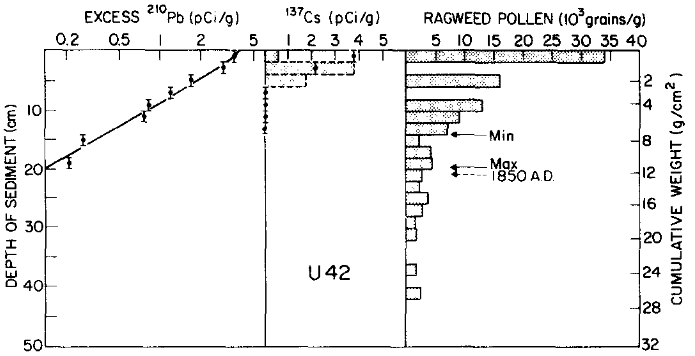

FIG. 7. Distribution of excess ^{210}Pb, ^{137}Cs, and ragweed (*Ambrosia*) pollen in cores collected at site U42 (Lake Erie) in 1975. Sedimentation rates based on ^{210}Pb and pollen are 0.1 and 0.06 g/cm^2/yr, respectively. The nearly exponential rise of pollen concentration toward the sediment surface does not provide any clear horizon. These profiles may be artifacts resulting from biological or physical mixing of sediments deposited in shallow waters (11 m). See text.

suggest the use of a somewhat later date (about 1865) for introduction of *Ambrosia* pollen into Lake Erie. Thus there is marginal evidence that the cultural rise in *Ambrosia* pollen occurred at a later time in recent sediments of Lake Erie than in Lake Ontario. The trend, if real, is of course consistent with the westward progression of forest clearance through the Great Lakes region.

Site U42 (Lake Erie)

The profile of excess ^{210}Pb (Fig. 7) has the expected exponential form and yields a sedimentation rate of 0.096 g cm^{-2} yr^{-1}. The larger uncertainty in the calculated sedimentation rate (Table 7), compared with values for other cores, reflects a greater sensitivity of the value of A_f. Here background levels of ^{210}Pb comprise a larger proportion of the total ^{210}Pb activity. A 10% change in the value of A_f results in a 10% change in the value of the calculated sedimentation rate. No major disturbances are apparent from the distribution of ^{210}Pb although minor departures from exponential form occur at depths of 2–4, 10–12, and 18–20 cm. On the basis of the ^{210}Pb rate and cumulative weight, these intervals correspond to dates of 1964 ± 3, 1918 ± 3, and 1862 ± 7 AD, respectively. While the 1964 date is significantly out of line with the date of the 1958 storm surge, the latter dates do correspond with experimental uncertainties to known storm events (Murty and Polavarapu, 1975).

Little information can be gained from the distribution of ^{137}Cs in this core because of the limited depth over which measurable activity is found and because, unfortunately, one significant interval of sediment (4–6 cm) was not analyzed for ^{137}Cs. The sedimentation rate given in Table 7 is therefore a lower limit. If measurable activity does in fact occur in the 4–6-cm interval, the inferred sedimentation rate would be consistent with that obtained from ^{210}Pb. On the other hand, if it does not, the radiometric rates could still be consistent if only a small amount of surface material was lost during coring. Clearly the sedimentation rate derived from ^{137}Cs is very sensitive to any disturbance of the sediment–water interface.

In this particular core there are difficulties in adequately specifying the location of the *Ambrosia* horizon. A somewhat arbitrary a priori assignment (A.L.W.K.) at 14 cm (7.36 g/cm^2) indicated by solid arrow in Fig. 7, yields a sedimentation rate of 0.059 g cm^{-2} yr^{-1} which is about 60% lower than the value derived from ^{210}Pb. In the absence of any firmly established criterion for placement of the 1850 horizon or for the assignment of uncertainties in its location, it is not possible to determine if sedimentation rates calculated by the two methods are significantly different. The assigned location of the horizon is consistent with the definition previously discussed (e.g., M32). But if the single unusually low value of the *Ambrosia* concentration in the 14–16-cm section ($2.2 \pm 3 \times 10^3$ grains/g, Table 6) were higher by a factor of two, then the 1850 horizon would occur at 20 cm as predicted from ^{210}Pb results because all sections above 20 cm would have *Ambrosia* concentrations significantly above background levels ($2.17 \pm 1 \times 10^3$ grains/g). Thus the apparent lack of agreement can easily reflect the poor definition in the location of the *Ambrosia* horizon. For this reason Kemp *et al.* (1977) assigned minimum and maximum levels of 14 and 20 cm in discussing this core.

It should be noted that under certain restrictive conditions both radioactivity and pollen profiles may be artifacts resulting from sediment reworking. The sediments in western Lake Erie are located in shallow water where resuspension is significant. The deposits are inhabited by a variety of abundant deposit-feeding benthic organisms which can mix sediments to depths of about 10 cm or so (Britt *et al.*, 1973). Thus if significant reworking of sediment is likely to occur anywhere in these lakes, it should occur in the area where this core was collected. In addition, the sedimentation rates based on ^{210}Pb at stations G16 and M32 are consistent with the known thickness of the most recent postglacial sedimentary unit (~12,000 yr old, see Kemp *et al.*, 1977). In contrast, the long-term rate of sedimentation inferred on the basis of this unit for Station U42 is around 0.03 g/cm^2/yr (unpublished data) which is about a factor of 3 less than our measured value. Possibly, of course, the recent or short-term accumulation rates in this area are appreciably highly than average postglacial rates. However, processes of reworking are likely to produce radioactivity and pollen profiles which lead to erroneously high sedimentation rates. In the Appendix, details of a mathematical model are presented which illustrate how exponential profiles of both ^{210}Pb and *Ambrosia* pollen may result solely from sediment reworking provided the process has an eddy-diffusional character. By introducing the concept of deep, eddy-diffusive mixing discussed previously by others (Goldberg and Koide, 1962; Bruland, 1974; Guinasso and Schink, 1975) it is possible to build a self-consistent, quantitative picture of the sedimentation process at this location. But the treatment is necessarily ad hoc and the mechanisms which give rise to the eddy diffusive character of the mixing process are not clear.

That exponential profiles of ^{210}Pb can arise from processes other than sedimentation and radioactive decay raises the question of the reliability of the ^{210}Pb method. This problem has recently been discussed in some detail by one of us (Robbins, 1978). In general, proper interpretation of ^{210}Pb profiles requires supplementary information. In the present study we have seen that a self-consistent picture of the evolution of radioactivity and pollen profiles may be developed for four of the five cores without reference to sediment reworking. In fact, application of the model developed in the Appendix for cores other than U42 is inconsistent with experimental results.

TIME DEPENDENCE OF POLLEN INFLUXES

Modern sediments of the Great Lakes receive pollen originating from an extensive region because of the atmospheric residence time of pollen grains, the size of the lakes, and the mixing which occurs in the water column. Therefore pollen profiles in cores from different areas of a given lake should reflect the same historical record of regional changes in vegetation although the absolute rate of addition to sediments may vary considerably with location (McAndrews and Power, 1973). This is the basis for applying the palynological method uniformly to dating sediments in each lake.

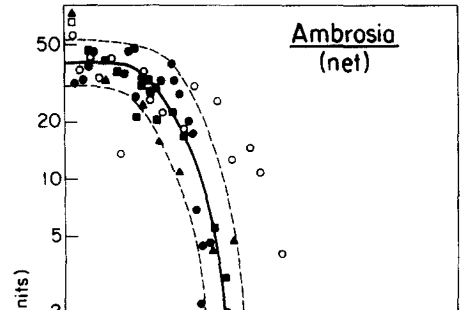

FIG. 8. The concentration of *Ambrosia*, *Pinus*, and *Castanea* pollen versus date based on ^{210}Pb. Profiles are normalized by adjusting scaling factor and background counts (for *Ambrosia*) to minimize distances between neighboring points. The resultant composite figure and solid line approximate the time-dependent part (source function) of the influx of each pollen species to sediments.

Provided the influx of pollen to sediments reflects lakewide average inputs, profiles in undisturbed sediments should be similar from core to core apart from scaling and background variations. Under these conditions the concentration of pollen may be expressed in terms of separated spatial time variables as

$$C(\xi,t) = F(\xi)f(t) + G(\xi) \qquad (2)$$

where ξ represents the spatial variables and $G(\xi)$ is a time-independent background pollen concentration. The net pollen concentration is the product of the time-dependent part, $f(t)$, and a scaling factor, $F(\xi)$, which depends on location only. As the ^{210}Pb method provides an independent and accurate geochronology, pollen profiles from different cores may be compared on a time-equivalent basis.

In Fig. 8 the concentration of each of the three pollen species are plotted versus date based on ^{210}Pb (with corrections made where necessary for erosional events, e.g., M32). Values of F and G were found which minimize the sum of the squares of the distances between nearest neighboring points using pairs of profiles ($t \geq 1800$). In this way it is possible to construct an approximation for the time-dependent part $f(t)$, or "source function" (Edgington and Robbins, 1976) shown as the solid line and envelope in Fig. 8. In the case of *Ambrosia* pollen profiles, a significantly better matching results from subtraction of a small and variable background, while for *Pinus* and *Castanea*, G is essentially zero.

The sharp rise in net *Ambrosia* pollen concentration occurs about 1860 AD, depending on background subtracted. As can be seen in Fig. 8, the onset of net *Ambrosia* in Lake Ontario (core KB) is probably somewhat earlier as discussed previously. The "source function" $f(t)$ is reasonably well defined by the data. The concentration of *Pinus* pollen shows a corresponding reduction starting at essentially the same time but decreases more gradually. The distribution of *Pinus* pollen is not significantly different in the Lake Ontario core from distributions in the Lake Erie cores. Again the source function is reasonably well defined except for increased scatter in the data before 1820. The scatter in the *Castanea* pollen data is very great, and, taken on a core by core basis, no clear trends are apparent. However, the normalization of profiles on a time-equivalent basis reveals a significant decrease in the concentration of *Castanea* pollen commencing about 1900–1920 and continuing at least through 1940. Evidently information obscured by "noise" in a single distribution may be obtained combining profiles on a time-equivalent basis.

The normalization method indicates the existence of a time-dependent source function possibly differing for each lake. With improved precision and accuracy in determining pollen counts it should be possible to sharpen the definition of source function for various pollen species as well as to establish limits on the validity of the concept. By comparing well-defined source function with a pollen profile considerable accuracy and precision may be gained in the application of palynological methods to geochronological studies. The entire pollen distribution rather than the horizon alone can be used in determining an average sedimentation rate and profiles inconsistent with established source functions may lead to insights about local sedimentation processes.

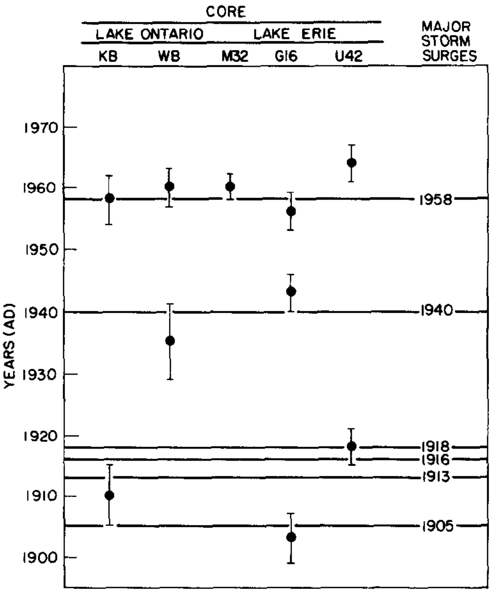

FIG. 9. The year of occurrence of anomalies (slumping or erosional features) in the distribution of excess ^{210}Pb. Times tend to correspond to the dates of major storm surges on the Great Lakes but records of such events are not left uniformly in every core.

SUMMARY

^{210}Pb profiles indicate uniform rates of sedimentation in Lakes Erie and Ontario over about the past 100 yr or so, although there are occasional major discontinuities consistent with the occurrence of erosional events. Such major effects seen particularly in one core from deep waters of eastern Lake Erie, as well as minor anomalies (slumps or erosional features), are interpreted as arising from several large lake-wide storm surges which have occurred during the past century. Evidence for this effect is summarized in Fig. 9. The most consistent perturbation, found in all cores, occurs in 1958. Anomalies occurring at earlier times are not seen in all cores, for reasons which are not immediately clear. Generally consistent rates of sedimentation are obtained from analysis of ^{137}Cs profiles. Therefore as the location of the ^{137}Cs horizon is very sensitive to loss or disturbance of surface sediments on coring and to sediment reworking, these effects appear to be of negligible importance in the cores studied. *Ambrosia* pollen profiles generally yield estimates of sedimentation rates comparable to or lower than those derived from radiometric measures. Lower average rates appear to result from erosional events which are detected in ^{210}Pb but not in pollen profiles. There is marginal evidence of an earlier introduction of cultural pollen into Lake Ontario than into Lake Erie.

In contrast with previous studies, it has not been necessary to introduce the concept of mixing of surface sediments to interpret ^{210}Pb profiles except possibly in the case of a core collected in shallow water of western Lake Erie. There the distributions of both radioactivity and *Ambrosia* pollen may be artifacts resulting from reworking of sediments. A model of deep eddy-diffusional mixing provides a self-consistent explanation of the radioactivity profiles and the occurrence of an exponential profile for *Ambrosia* pollen, but the mechanism giving rise to such profiles remains unspecified.

By careful application of the ^{210}Pb method and improved accuracy in the determination of pollen counts, it should be possible to detect systematic variability in the correspondence between the location of the *Ambrosia* horizon and the date of onset of cultural pollen influxes throughout the Great Lakes. More generally, the application of a precise and independent geochronological tool allows the time dependence of pollen influxes to be constructed from multiple profiles and the question of their coherence to be critically examined. This study shows that independent radioactive and pollen geochronologies of sediments can provide considerable information about the nature of recent sedimentation processes in the Great Lakes.

APPENDIX: POSSIBLE EFFECTS OF SEDIMENT REWORKING ON RADIOACTIVITY AND POLLEN PROFILES

The observation of nearly constant activity of ^{210}Pb and ^{137}Cs within a well-defined zone at the sediment–water interface in sediment cores from Lakes Michigan (Robbins and Edgington, 1975) and Huron (Robbins *et al.*, 1977) prompted development of a simple model of rapid steady state mixing. The model, similar to that discussed by Berger and Heath (1963) and used by Davis (1967) to treat pollen profiles in Maine lakes, accounted satisfactorily for previously observed distributions of ^{210}Pb and ^{137}Cs.

However, in the present case, the previous model cannot adequately describe the data, because mixing, if it occurs, is not sufficiently intense to produce a constant activity of ^{210}Pb anywhere in the cores. When mixing is sufficiently rapid, the nature of the process can be left completely unspecified. It is required only that particles within the mixed zone redistribute rapidly in comparison with the rate of addition of new material so that the net effect is one of complete homogenization. When mixing is incomplete, in the above sense, the distribution of activity becomes sensitive to details of how particles are redistributed within the mixed zone. Although the process of mixing by deposit feeding benthos, for example, is known to be particle selective (Davis, 1974) and to involve enhanced transfer between certain layers, as in the case of "conveyor belt" species (Rhoads, 1974), representation of mixing as a process akin to diffusion has met with some success (see Goldberg and Koide, 1962; Bruland, 1974; Guinasso and Schink, 1975). Thus the distribution of ^{210}Pb may be described in terms of a diffusion equation

$$\frac{\partial}{\partial Z}\left(K_b \frac{\partial A}{\partial Z}\right) - \omega \frac{\partial A}{\partial Z} - \lambda A = \frac{\partial A}{\partial t} \qquad \text{(A1)}$$

where K_b is the eddy diffusion of mixing coefficient for sediment particles (cm^2/yr) characteristic of the mixing process and is dependent on depth. In this equation compaction effects are neglected and the activity, A, is expressed in terms of depth, Z, in centimeters; ω is the sedimentation rate in centimeters per year. Existing models employing the concept of eddy-diffusive mixing retain the concept of a well-defined zone of mixing ($Z < S$) over which K_b is constant, while for $Z > S$, $K_b = 0$. Under these conditions the above equation becomes

$$\begin{aligned} K_b \frac{\partial^2 A}{\partial Z^2} - \omega \frac{\partial A}{\partial Z} - \lambda A &= \frac{\partial A}{\partial t} \\ &\text{for} \quad Z \leq S \\ -\omega \frac{\partial A}{\partial Z} - \lambda A &= \frac{\partial A}{\partial t} \\ &\text{for} \quad Z > S. \end{aligned} \qquad \text{(A2)}$$

For ^{210}Pb we may assume that the distribution is steady state so that $\partial A/\partial t = 0$. It can be seen that when there is no mixing (i.e., $K_b = 0$) the above equation reduces to

$$\frac{\partial A}{\partial Z} = \frac{-\lambda}{\omega} A \qquad \text{(A3)}$$

which has a solution ($A = A_0 e^{-\lambda Z/\omega}$) that is equivalent to Eq. (1) if compaction is ignored. Consider the case of core U42. Suppose that the interval over which mixing occurs is much greater than the depth over which there is measurable activity of ^{210}Pb ($\sim$15 cm) and that sedimentation is negligible ($\omega = 0$). These assumptions are consistent with the picture developed about the nature of the sedimentation process at this site. Under these conditions Eq. (A2) simplifies to

$$K_b \frac{\partial^2 A}{\partial Z^2} - \lambda A = 0 \qquad \text{(A4)}$$

which has the solution

$$A = A_0 e^{-Z(\lambda/K_b)^{1/2}}. \qquad \text{(A5)}$$

In other words, provided that the zone of mixing is sufficiently deep and the mixing process has an eddy diffusive character, the observed activity profile of ^{210}Pb will be exponential. This alternative model leads to the same theoretical dependence but provides very different information. Previously a sedimentation rate had been inferred from the ^{210}Pb distribution using Eq. (1) whereas using the above equation (A5) a mixing coefficient is calculated. A least squares fit yields a value of 1.0 cm^2/yr for K_b. In reality the addition of ^{210}Pb to this core may be a combination of sedimentation as well as diffusive mixing. But the extreme case illustrates the approach. Thus ^{210}Pb is distributed downward from the sediment surface as a result of mixing alone and the exponential decrease in activity with depth represents the dynamic balance between diffusive transfer and radioactive decay.

Can this process account for the observed distribution of *Ambrosia* pollen? According to the above picture, markedly increased numbers of these pollen grains would have been presented to the sediment surface after about 1850 and transported downward at a rate characteristic of the eddy-diffusive mixing of sediment solids. This process is represented by a non-steady state form of Eq. (A4) in which there is of course no radioactive decay ($\lambda = 0$). Thus

$$K_b \frac{\partial^2 C}{\partial Z^2} = \frac{\partial C}{\partial t}. \qquad \text{(A6)}$$

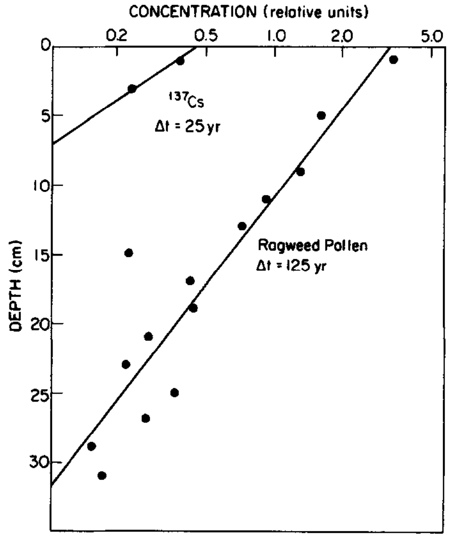

FIG. 10. The predicted distribution of ^{137}Cs and ragweed pollen at site U42 if the occurrence of these species results solely from a process of deep eddy-diffusional mixing. Measured values of ^{137}Cs and ragweed pollen are plotted on the log scale for comparison. Only the normalization of the theoretical distribution at the surface is arbitrary. The slope is determined entirely by the rate of mixing inferred fom ^{210}Pb and from the time of onset of the influx of these species to the sediments.

If the pollen flux F is represented approximately as a step function with onset about 125 ya ($t = 0$) then the boundary conditions are:

$$\begin{aligned}
&(1)\ z \to \infty, \quad c \to 0; \\
&(2)\ c = 0, \quad Z > 0, \quad t = 0; \\
&(3)\ F = 0, \quad t < 0, \quad Z = 0; \\
&(4)\ F = -K_b \frac{\partial C}{\partial Z}, \quad t > 0, \quad Z = 0.
\end{aligned} \qquad \text{(A7)}$$

Conditions (3) and (4) represent the abrupt onset of pollen flux at $t = 0$. We shall assume that the value of K_b obtained from analysis of the ^{210}Pb distribution applies to mixing of pollen grains. The solution to Eq. (A6) with the above boundary conditions is

$$C(Z,t) = 2F(t/K_b)^{1/2} \operatorname{ierfc} [Z/2(K_b t)^{1/2}] \qquad \text{(A8)}$$

where the modified error function complement (ierfc) is defined by Crank (1975). This function is very similar to an exponential in the present case. Note that the argument $[Z/2(K_b t)^{1/2}]$ is completely specified as the value of K_b is derived from ^{210}Pb and t is about 125 yr for *Ambrosia*. The only undefined parameter is the flux, F, which is chosen to normalize the theoretical distribution to the pollen concentration at the sediment surface. The agreement between the experimental and model profiles shown in Fig. 10 is striking. Interestingly, the model proposed is also consistent with the ^{137}Cs distribution, although only two points are involved in this fit.

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REFERENCES

Anderson, T. W. (1974). The chestnut pollen decline as a time horizon in lake sediments in eastern North America. *Canadian Journal of Earth Sciences* **11,** 678–685.

Berger, W. H., and Heath, G. R. (1968). Vertical mixing in pelagic sediments. *Journal of Marine Research* **26,** 134–143.

Barry, P. J. (1973). Estimating dose commitments to populations from radioactive waste disposals into large lakes. *In* "Environmental Behavior of Radionuclides Released in the Nuclear Industry," pp. 499–505. I. A.E.A., Vienna.

Boyko, M. (1973). "European Impact on the Vegetation around Crawford Lake in Southern Ontario." M. S. Thesis, University of Toronto, Toronto, Ontario.

Bortleson, G. C., and Lee, G. F. (1972). Recent sedimentary history of Lake Mendota, Wisconsin, *Environmental Science and Technology* **6,** 799–808.

Bruland, K. W. (1974). "Lead-210 Geochronology in the Coastal Marine Environment." Ph.D. Thesis, University of California, San Diego.

Bruland, K. W., Koide, M., Bowser, C., Maher, L. J., and Goldberg, E. D. (1975). Lead-210 and pollen geochronologies on Lake Superior sediments. *Quaternary Research* **5,** 89–98.

Crank, J. (1975). "The Mathematics of Diffusion," 2nd ed. Clarendon Press, Oxford.

Davis, R. B. (1967) Pollen studies of near-surface sediments in Main lakes. *In* "Quaternary Paleoecology" (E. J. Cushing and H. E. Wright, Eds.), pp. 153–157. Yale Univ. Press, New Haven, Conn.

Davis, R. B. (1974). Statigraphic effects of tubificids in profundal lake sediments. *Limnology and Oceanography* **19,** 466–488.

Edgington, D. N., and Robbins, J. A. (1976a). Patterns of deposition of natural and fallout radionuclides in the sediments of Lake Michigan and their relation to limnological processes. *In* "Environmental Biogeochemistry" (J. O. Nriagu, Ed.), pp. 705–729. Ann Arbor Science, Ann Arbor, Mich.

Edgington, D. N., and Robbins, J. A. (1976b). The behavior of plutonium and other long lived radionuclides in Lake Michigan. II. Patterns of deposition in the sediments. *In* "Impacts of Nuclear Releases into the Aquatic Environment," pp. 245–260. I. A.E.A., Vienna.

Edgington, D. N., and Robbins, J. A. (1976c). Records of lead deposition in Lake Michigan sediments since 1800. *Environmental Science and Technology*, **10,** 266–274.

Goldberg, E. D., and Koide, M. (1962), Geochronological studies of deep sea sediments by the ionium/thorium method. *Geochimica et Cosmochimica Acta*, **26,** 417–445.

Guinasso, N. L., and Schink, D. R. (1975). Quantitative estimates of biological mixing rates in abyssal sediments, *Journal of Geophysical Research* **80,** 3032–3043.

Health and Safety Laboratory Fallout Program, U.S.A.E.C., HASL-258, A-40-41, A-93-94 (1972).

Johansen, K. A., and Robbins, J. A. (1977). Fallout cesium-137 in sediments of southern Lake Huron and Saginaw Bay. *In* "20th Ann. Conf. Great Lakes Research of Int. Assn. Great Lakes Res., Ann Arbor, Mich., May 10–12, 1977." Abstr.

Kemp, A. L. W., Savile, H. A., Gray, C. B. J., and Murdochova, A. (1971). A simple corer and a method for sampling the mud–water interface. *Limnology and Oceanography* **16,** 689–694.

Kemp, A. L. W., Gray, C. B. J., and Murdochova, A. (1972). Changes in C, N, P and S in the last 140 years in three cores from Lakes Ontario, Erie and Huron. *In* "Nutrients in Natural Waters" (H. E. Allen and J. R. Kramer, Eds.), pp. 251–279. Wiley, New York.

Kemp, A. L. W., Anderson, T. W., Thomas, R. L., and Murdochova, A. (1974). Sedimentation rates and recent sedimentary history of Lakes Ontario, Erie and Huron. *Journal of Sedimentary Petrology* **44,** 207–218.

Kemp, A. L. W., and Harper, N. S. (1976). Sedimentation rates in Lake Ontario. *Journal of Great Lakes Research,* in press.

Koide, M., Soutar, A., and Goldberg, E. D. (1972). Marine geochronology with lead-210. *Earth and Planetary Science Letters* **14,** 442–446.

Koide, M., Bruland, K. W., and Goldberg, E. D. (1973). Th-228/Th-232 and lead-210 geochronologies in marine and lake sediments. *Geochimica et Cosmochimica Acta* **37,** 1171–1187.

Krishnaswami, S., Lal, D., Martin, J. M., and Meybeck, M. (1971). Geochronology of lake sediments. *Earth and Planetary Science Letters* **11,** 407–414.

McAndrews, J. H. (1976). Fossil history of man's impact on the Canadian flora; an example from southern Ontario. *In* "Man's Impact on the Canadian Flora" (J. K. Morton, Ed.), Canadian Botanical Association, Supplement to Vol. 9, No. 1, pp. 1–6.

McAndrews, J. H., and Power, D. M. (1973). Palynology of the Great Lakes: the surface sediments of Lake Ontario. *Canadian Journal of Earth Sciences* **10,** 777–792.

Murty, T. S., and Polavarapu, R. J. (1975). Reconstruction of some of the early storm surges on the Great Lakes., *Journal of Great Lakes Research* **1,** 116–129.

Rhoads, D. C. (1974). Organism-sediment relations on the muddy sea floor. *Oceanography and Marine Biology Annual Review* **12,** 263–300.

Ritchie, J. C., McHenry, J. R., and Gill, A. C. (1974) Fallout cesium-137 in the soils and sediments of three watersheds. *Ecology* **55,** 887–890.

Robbins, J. A. (1978) Geochemical and geophysical applications of radioactive lead isotopes. *In* "Biogeochemistry of Lead" (J. O. Nriagu, Ed.), pp. 285–393. Elsevier Amsterdam.

Robbins, J. A. (1977). Recent sedimentation rates in southern Lake Huron and Saginaw Bay. *In* "20th Ann. Conf. Great Lakes Research of Int. Assn. Great Lakes Res, Ann Arbor, Michigan, May 10–12, 1977." Abstr.

Robbins, J. A. and Edgington, D. N. (1972). The use of natural and fallout radionuclides to measure recent sedimentation rates in southern Lake Michigan. *In* "Radiological and Environmental Research Division Annual Report Part III," pp. 31–53. Jan–Dec 1972. Argonne National Laboratory, ANL-7960.

Robbins, J. A., and Edgington, D. N. (1975). Determination of recent sedimentation rates in Lake Michigan using lead-210 and cesium-137. *Geochimica et Cosmochimica Acta* **39,** 285–304.

Robbins, J. A., Edgington, D. N., Gustinis, J., and Karttunen, J. O. (1975). Geochronology of Lake Michigan sediments: anomalies in lead-210 distributions. *In* "Radiological and Environmental Research Division Annual Report, Ecology, III, pp. 40–50. Jan–Dec 1974, Argonne National Laboratory, Argonne, Ill.

Robbins, J. A., Krezoski, J. R., and Mozley, S. C. (1977). Radioactivity in sediments of the Great Lakes: post-depositional redistribution by deposit-feeding organisms. *Earth and Planetary Science Letters* **36,** 325–333.

Thomson, J., Turekian, K. K., and McCaffrey, J. (1975). The accumulation of metals in and release from sediments of Long Island Sound. *In* "Estuarine Research" (L. E. Cronin, Ed.), pp. 28–43. Academic Press, New York.

U. S. Weather Service, "Climatological data, Michigan Annual Summary, 1914–Present." National Weather Service, National Oceanographic and Atmospheric Administration, Dept. of Commerce, Washington, D. C.

Wahlgren, M. A., and Nelson, D. M. (1973). Residence times for plutonium-239 and cesium-137 in Lake Michigan water. *In* "Radiological and Environmental Research Division Annual Report, Ecology," pp. 85–89. Jan–Dec 1973, Argonne National Laboratory, Argonne, Ill., ANL-3060, Part III.