Journal of Paleolimnology **13:** 107–118, 1995.

Sediment focusing and ^{210}Pb dating: a new approach *

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Received 7 September 1993; accepted 26 August 1994

Key words: ^{210}Pb, sediments, cores, paleolimnology, lakes, sediment focusing, sampling

Abstract

In this paper we test the utility of the mud deposition boundary depth (mud DBD) theory (Rowan *et al.* 1992) as a means of maximizing sampling efficiency in paleolimnological investigations, particularly those that apply to ^{210}Pb dating. The mud DBD is defined by the relationship between near bottom wave velocity and particle threshold velocity, with wave and particle threshold theory simplified to terms of exposure and depth. Mud DBD theory can be used to define the depositional zone in lakes, and within the depositional zone defined by the mud DBD: 1) there is a high probability of obtaining a representative core, 2) variation in mass sediment accumulation rate (MSAR) is not correlated with water depth, and 3) variation in MSAR is considerably reduced from the whole lake average. This suggests that mud DBD theory can account for the effects of sediment focusing, and that the mud DBD defined depositional zone is the zone to which fine-grained sediments are focused. Finally, we have shown that to optimize sampling effort, 5 to 10 cores within the depositional zone are necessary for a reasonably precise estimate of the mean mass sediment accumulation rate. In addition, the use of mud DBD theory prior to sampling can dramatically reduce the cost associated with analyzing large numbers of cores for ^{210}Pb.

Introduction

^{210}Pb dating is a powerful tool for estimating sediment accumulation rates, and provides a temporal framework in which to evaluate the environmental history of a lake and its catchment. When collecting cores for ^{210}Pb dating, the questions of where to core, how many cores are needed, and how the results can be extrapolated to adjacent areas are essential for proper interpretations.

Håkanson and Jansson (1983) and Håkanson (1984, 1992) addressed the general importance of bottom dynamics on the variability of several sediment parameters and concluded that the most reliable sediment information could be obtained from those areas of the lake where there is continuous accumulation of fine sediment. These conclusions are certainly applicable to ^{210}Pb dating. Although Håkanson (1977, 1981) developed empirical models that predict the area of accumulation and identified the effect of slope, the application of these tools to sediment sampling was not attempted. In a recent study (Rowan *et al.*, 1992), theoretical models were developed that directly link wave theory to sediment distribution, and with the inclusion of slope, provide improvements over the important earlier work of Håkanson (1977, 1981). Here, we will use these new theoretical-empirical relationships to produce sediment distribution maps from bathymetry and from these maps make *a priori* decisions on core locations (i.e. within the depositional zone).

The question of how many cores are needed has been addressed by several authors (Håkanson & Jansson, 1983; Håkanson, 1984; Baudo, 1989; Floderus, 1989; Håkanson, 1992), all using some form of a standard sample formula with the number of cores dependent on the precision required and variability in the parameter. Håkanson & Jansson (1983) and Håkanson (1984, 1992) also proposed a sample formula based on lake area and shore development that yields a rough estimate of the number of samples required for whole

* This is the fifth of a series of papers to be published by this journal following the 20^{th} anniversary of the first application of ^{210}Pb dating of lake sediments. Dr P. G. Appleby is guest editing this series.

lake estimates. This formula is based on the hypothesis that larger lakes and lakes with more complex morphometry, are likely to have more variability in sediment parameters. To our knowledge, no such estimates have ever been made with regard to ^{210}Pb dating or sediment accumulation rates in general.

The extrapolation of core data between sites and the estimation of whole-lake values has also received considerable attention. One promising method is the correlation of dated magnetic markers between cores (Foster *et al.*, 1985). Trend surface analysis (Baudo, 1989), kriging or other weighting functions (Floderus, 1989) and relationships with water depth (Evans & Rigler, 1983) have also been used to obtain whole-lake estimates for a variety of sediment parameters. However, we hypothesize that much of the variability observed by these authors was due to the inclusion of data from diverse sedimentological environments, and that within a properly defined depositional zone (the zone from which representative information is most likely to be obtained (Håkanson, 1992)), variability would be dramatically reduced. Such a reduction in variability may not only make whole-lake estimates more straightforward, but may also reduce the number of cores required.

In this paper we develop a sampling method for ^{210}Pb dating that: 1) is based on sedimentological theory (mud DBD theory of Rowan *et al.*, 1992), 2) provides *a priori* decisions of sampling locations and the number of cores needed, 3) maximizes the probability of collecting representative cores and 4) provides a means to more effectively extrapolate results to the whole lake. First, we test mud deposition boundary depth (mud DBD) theory (Rowan *et al.*, 1992) as a predictor of observed sediment distribution. Second, we test whether representative cores are found within the depositional zone predicted by mud DBD theory. Then we examine variability in sediment accumulation rates within the depositional zone and methods of extrapolation and finally, we develop a relationship to calculate the optimum number of cores needed.

Methods

For this study, we required cores with ^{210}Pb data and some measure of physical sediment character (water content, bulk density or particle size) from all sedimentary environments within a lake. We collected such data for Lake Ontario and Perch Lake, and augmented this with data from Lake Michigan (Robbins & Edgington, 1975; Hermanson & Christensen, 1991) and Costello and Red Chalk Lakes (Evans, 1980). Cores were collected from Lake Ontario and Perch Lake (for locations see Figs 1a and 2a) with gravity corers and sectioned into 0.25 to 1.0 cm slices. Water content was determined by drying at 60 °C. These samples were dated using the techniques described in Cornett *et al.* (1992). All ^{210}Pb profiles, including those obtained from the literature (Hermanson & Christensen, 1991; Robbins & Edgington, 1975; Evans, 1980) were dated using the Constant Flux Constant Sedimentation (CFCS) model. The CFCS model was used because it offers a means of identifying cores with unrepresentative ^{210}Pb profiles. The CFCS model is appropriate for the study lakes because they have relatively undisturbed lake basins (Costello, Perch and Red Chalk lakes) or show little recent change in MSAR.

Using bathymetric maps, sites were classified as erosional, transitional or depositional based on mud DBD theory (Rowan *et al.*, 1992). Erosional sites impacted by the largest annual waves were identified at depths shallower than the greater of:

$$\text{mud DBD} = 2.685\ E^{0.305} (\text{no slope effect}) \qquad (1)$$

or

$$\text{mud DBD} = 1.327\ E^{0.370}\ 10^{0.0526\ S} (\text{slope effect}) \qquad (2)$$

where E is exposure (km^2)and S is slope (%) (Rowan *et al.*, 1992). Depositional sites were identified at depths greater than 1.34 $*$ mud DBD (depths greater than those impacted by maximum waves), with transitional sites intermediate. Lakes where maximum depth is less than the results of Eq. 1 are prone to disturbance over their entire bottom area. The data set is summarized in Table 1.

Results

Predicting sediment distribution with mud DBD theory

For each of the study sites, the sedimentary environment was classified as erosional, transitional or depositional using mud DBD theory (Table 1). Examples of the sediment distribution maps prepared for each lake from lake morphometry and mud DBD theory are presented for Lake Ontario and Perch Lake in Figs 1 and 2, respectively. Based upon the mud DBD theo-

Table 1. Data set and indices of core representativity

Core	Depth (m)	Exposure (km^2)	Slope (%)	Water content (fraction ww)	Sediment accumulation rate (g m^2 yr^{-1})	CFCS model mean residual (log)	Mixed layer thickness (cm)	Interbedded stratigraphy (0 = not interbedded, 1 = interbedded)	Mud DBD theory classification (0 = erosional/ transitional, 1 = depositional)
Lake Ontario									
D2	80.0	15452	3.3	0.170	88	0.019	0.0	1	0
DP3	45.0	15263	1.4	0.319	202	0.025	0.0	0	0
DP4	50.0	15263	1.1	0.321	195	0.083	0.0	0	0
PC31	221.0	16263	1.1	0.759	107	0.012	5.0	0	1
PC32	96.2	15763	1.6	0.691	240	0.020	1.5	0	1
PC33	54.6	15445	2.1	0.574	545	0.060	0.0	1	0
PC34	40.7	15390	1.1	0.709	448	0.028	0.0	1	0
PC4	176.0	16475	0.8	0.678	190	0.056	0.0	0	1
18	210.0	16475	0.5	0.708	187	0.055	0.0	0	1
23	155.0	15960	1.4	0.721	2244	0.023	3.0	1	1
71	10.0	16050	1.0	0.365	402	0.037	0.0	0	0
403	175.0	15436	0.3	0.823	358	0.024	8.0	0	1
Perch Lake (46° 02′N, 77° 22′W)									
1	2.5	0.43	0.9	0.854	132	0.110	0.0	0	0
2	2.4	0.43	1.0	0.895	125	0.163	0.0	0	0
3	2.5	0.43	0.9	0.889	94	0.123	0.0	0	0
12	2.2	0.43	11.6	0.480	302	0.049	0.0	1	0
13	2.4	0.43	8.0	0.375	443	0.033	3.5	1	0
14	1.4	0.43	1.9	0.958	58	0.078	1.5	0	0
15	2.8	0.43	1.3	0.940	84	0.024	2.5	0	1
16	2.4	0.43	1.5	0.962	34	0.150	5.5	0	0
17	1.8	0.43	3.1	0.930	56	0.142	2.5	0	0
18	2.0	0.43	3.6	0.927	57	0.089	3.5	0	0
19	2.3	0.43	2.3	0.941	58	0.119	6.0	0	0
22	2.8	0.43	2.0	0.945	150	0.018	3.5	0	1
24	2.1	0.43	4.2	0.962	49	0.119	4.5	0	0
25	1.8	0.43	5.7	0.935	76	0.124	8.5	0	0
Costello Lake (45° 35′N, 78° 20′W) (Evans 1980)									
2	4.6	0.38	14.0	0.352	490	0.090	2.5	0	0
4	0.8	0.09	3.0	0.891	131	0.034	1.5	1	0
5	5.8	0.37	13.5	0.768	249	0.102	1.5	1	0
10	6.7	0.40	33.1	0.483	398	0.067	0.0	0	0
11	10.0	0.39	16.0	0.836	59	0.059	10.0	0	1
12	11.6	0.40	12.7	0.916	58	0.056	9.0	0	1
13	7.6	0.38	45.1	0.666	142	0.129	0.0	1	0
16	16.0	0.37	3.7	0.932	114	0.031	9.0	0	1
20	11.6	0.34	21.5	0.907	76	0.028	5.0	0	0
23	16.5	0.39	2.5	0.947	139	0.042	7.5	0	1
27	9.7	0.37	5.1	0.926	31	0.042	18.5	0	1
28	16.0	0.37	0.0	0.952	66	0.032	9.0	0	1

Table 1. Continued

Core	Depth (m)	Exposure (km²)	Slope (%)	Water content (fraction ww)	Sediment accumulation rate (g m^2 yr^{-1})	CFCS model mean residual (log)	Mixed layer thickness (cm)	Interbedded stratigraphy (0 = not interbedded, 1= interbedded)	Mud DBD theory classification (0 = erosional/ transitional, 1 = depositional)
29	16.0	0.35	0.0	0.929	106	0.027	8.5	0	1
30	13.5	0.35	9.9	0.919	100	0.056	4.5	0	1
31	16.0	0.35	4.0	0.929	86	0.128	4.5	0	1
32	17.2	0.35	5.9	0.922	117	0.029	10.0	0	1
35	12.8	0.36	16.5	0.907	123	0.036	6.0	0	1
Lake Michigan									
(Hermanson and Christensen 1991)									
CLM-L	111.0	46400	0.7	0.790	200	0.044	0.8	0	1
CLH-M	81.0	46400	0.8	0.735	190	0.042	0.8	1	0
NLM-A	235.0	43203	0.9	0.905	113	0.068	2.0	0	1
NLM-B	250.0	43203	0.2	0.899	123	0.081	3.0	0	1
NLM-C	263.0	43203	0.2	0.090	56	0.049	5.0	0	1
NLM-E	263.0	43203	0.5	0.886	105	0.019	2.0	0	1
NLM-G	216.0	45744	1.6	0.861	136	0.178	1.7	1	1
NLM-I	190.0	45744	1.6	0.865	70	0.208	0.8	0	1
SLM-C	88.0	47439	0.3	0.846	208	0.399	2.0	1	0
SLM-D	110.0	47439	0.0	0.838	94	0.032	1.0	0	1
SLM-E	100.0	39815	0.1	0.663	75	0.031	0.0	1	1
SLM-F	90.0	39815	0.3	0.768	257	0.642	1.3	1	0
SLM-H	72.0	37300	0.3	0.760	666	0.063	3.5	1	0
SLM-I	87.0	44050	0.2	0.820	177	0.130	1.8	1	0
SLM-J	160.0	44050	0.3	0.871	338	0.042	0.0	0	1
SLM-K	125.0	44050	0.1	0.867	445	0.050	5.0	0	1
(Robbins and Edgington 1975)									
11	73.0	33885	0.1	0.745	256	0.053	0.0	1	0
17	152.0	44050	0.0	0.800	189	0.050	0.0	0	1
29	61.0	39815	0.3	0.700	383	0.018	6.0	1	0
31	75.0	39815	0.4	0.690	199	0.042	2.0	1	0
54	78.0	47439	0.3	0.675	81	0.017	1.0	1	0
103	256.0	45744	1.2	0.820	119	0.019	2.0	0	1
105	146.0	47439	0.2	0.815	103	0.017	2.5	0	1
100A	146.0	43203	1.5	0.800	301	0.042	1.0	0	1
Red Chalk Lake (45° 11′N, 78° 56′W)									
(Evans 1980)									
1	4.9	0.40	31.4	0.292	684	0.058	0.0	1	0
6	10.0	0.31	32.0	0.849	120	0.050	4.7	1	0
8	4.3	0.38	22.9	0.336	435	0.045	2.0	0	0
9	22.0	0.38	31.8	0.947	100	0.106	13.0	0	0
10	31.9	0.40	16.0	0.956	36	0.055	2.5	0	1
11	18.0	0.40	7.5	0.954	5	0.046	7.8	0	1

Table 1. Continued

Core	Depth (m)	Exposure (km^2)	Slope (%)	Water content (fraction ww)	Sediment accumulation rate (g m^2 yr^{-1})	CFCS model mean residual (log)	Mixed layer thickness (cm)	Interbedded stratigraphy (0 = not interbedded, 1= interbedded)	Mud DBD theory classification (0 = erosional/ transitional, 1 = depositional)
12	18.0	0.40	10.7	0.949	172	0.224	10.0	0	1
13	13.7	0.40	14.2	0.938	54	0.031	5.5	0	1
14	14.0	0.36	13.5	0.939	33	0.085	8.5	0	1
15	11.9	0.35	33.7	0.945	39	0.041	8.0	0	0
16	25.0	0.42	18.3	0.958	62	0.079	11.0	0	1
17	34.0	0.40	9.1	0.988	66	0.044	8.0	0	1
18	22.0	0.40	8.6	0.960	14	0.067	9.0	0	1
19	18.5	0.43	16.8	0.966	24	0.052	14.5	0	1
30	34.5	0.42	4.9	0.977	69	0.048	8.5	0	1
31	29.0	0.43	29.2	0.958	117	0.028	18.0	0	0
32	22.5	0.43	64.0	0.953	35	0.103	5.5	0	0
33	23.5	0.41	14.2	0.954	72	0.020	8.0	0	1
35	17.5	0.43	16.0	0.956	30	0.084	8.5	0	1
37	26.7	0.43	25.8	0.963	87	0.105	9.5	0	0
39	23.0	0.43	23.5	0.952	36	0.073	6.0	0	1
40	19.5	0.38	4.3	0.950	44	0.066	8.5	0	1
41	19.5	0.38	4.3	0.949	54	0.085	8.0	0	1
45	26.1	0.43	9.6	0.961	39	0.042	7.0	0	1

Table 2. A test of the mud DBD theory predictions by a logistic regression of the indices of core representativity. The identity of cores that were misclassified is shown in [ ]

Lake	Above mud DBD (% unrepresentative)	Below mud DBD (% representative)	Overall
Lake Ontario	50% (3/6) [DP3,DP4,71]	83% (5/6) [23]	67% (8/12)
Perch Lake	92% (11/12) [1]	100% (2/2)	93% (13/14)
Costello Lake	83% (5/6) [20]	82% (9/11) [27,31]	82% (14/17)
Lake Michigan	100% (9/9)	80% (12/15) [NLM-G,NLM-I,SLM-E]	88% (21/24)
Red Chalk Lake	75% (6/8) [15,31]	94% (15/16) [12]	88% (21/24)
Totals	83% (34/41)	86% (43/50)	85% (77/91)

ry, erosional sites should have water contents <60% while transitional and depositional sites should have water contents >60% (Rowan *et al.*, 1992). In the total data set, over 90% (10/11) of the sites with water contents < 60% were correctly classified as erosional by mud DBD theory. Over 82% (66/80) sites with water

Table 3. Mean mass sediment accumulation rates for the whole-lake, erosional/transitional zones and representative cores from the depositional zone. Standard deviation in ( )

Lake	Mean mass sediment accumulation rate Whole-lake ($g\ m^{-2}\ yr^{-1}$)	Erosional/ transitional ($g\ m^{-2}\ yr^{-1}$)	Depositional (representative) ($g\ m^{-2}\ yr^{-1}$)
Ontario	434	313	216
	(562)	(162)	(83)
	n = 12	n = 6	n = 5
Perch	123	124	117
	(110)	(118)	(33)
	n = 14	n = 12	n = 2
Costello	146	248	99
	(119)	(151)	(28)
	n = 17	n = 6	n = 9
Michigan	203	268	182
	(140)	(160)	(114)
	n = 24	n = 9	n = 12
Red Chalk	101	202	42
	(148)	(218)	(19)
	n = 24	n = 8	n = 15

contents >60% were correctly classified as either transitional or depositional by mud DBD theory. Overall, the mud DBD theory provides accurate predictions of sediment distribution at 83.5% (76/91) of the study sites (Table 1). Figure 3 is a plot of site depth relative to the mud DBD *vs* sediment water content. Sites in the upper left and lower right quadrants are correctly classified by mud DBD theory.

Indices of core representativity

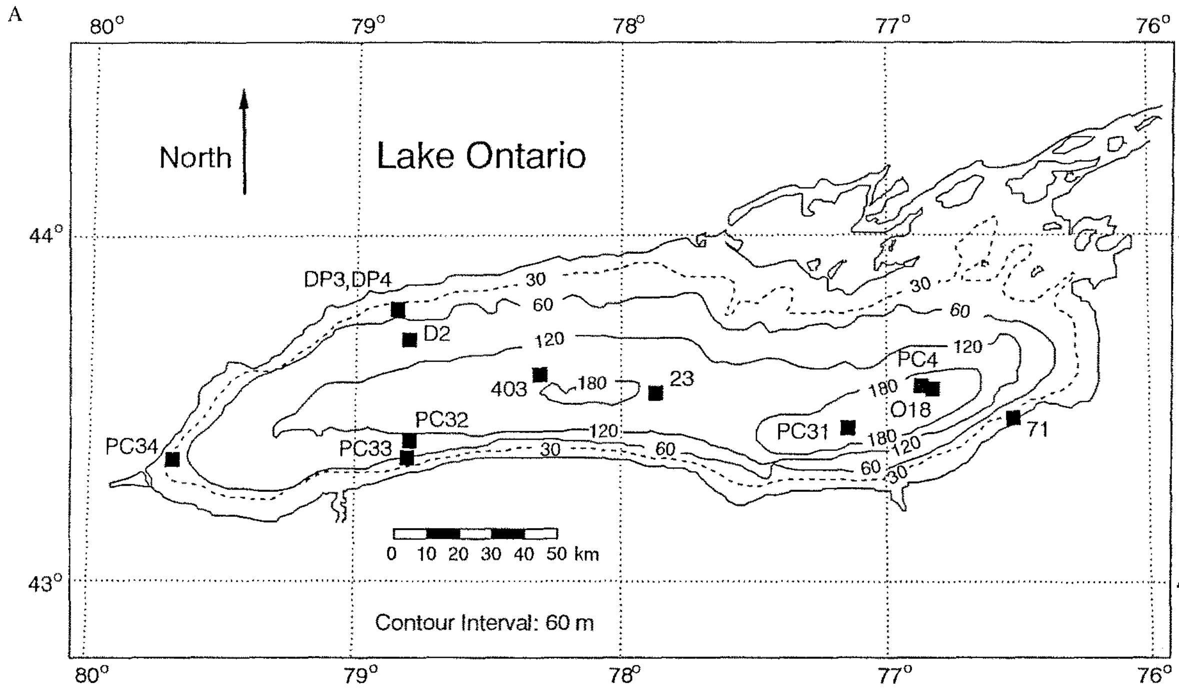
In order to test whether mud DBD theory is useful in identifying sites where representative cores can be collected, criteria for identifying unrepresentative cores must be established. We have identified four indices of core representativity: 1) mean residual of the CFCS model fit, 2) relative mass sediment accumulation rate, 3) relative mixed layer thickness, 4) interbedded stratigraphy of sand and mud. These indices and the following logistic model are presented to demonstrate the utility of the mud DBD theory to ^{210}Pb dating and are only applicable to lakes where the CFCS model is appropriate. The calculation and interpretation of these indices are described below.

As the mean residual of the CFCS model fit to the ^{210}Pb data (log, Bq g^{-1}) increases, uncertainty in the estimate of the sediment accumulation rate also increases. Thus, for lakes where the CFCS model is appropriate, cores with poor fit to the CFCS model are difficult to interpret and prone to large errors in dating. Factors that could result in poor fit to the CFCS model include unstable sedimentary environments, with episodic sediment accumulation or erosion. An unusually thick mixed layer or changes in sediment composition such as interbedded strata of sand and mud may also contribute to large model residuals. The mean residual of the CFCS model fit to the ^{210}Pb data (RESID) was calculated for each core as:

$$\text{RESID} = \frac{\left(\sum_{i=1}^{n} \left|\log(\text{observed}\ ^{210}\text{Pb}) - \log(\text{estimated}\ ^{210}\text{Pb})\right|\right)}{n} \quad (3)$$

where n is the number of sections (Table 1), and the vertical bars indicate that the absolute value of the quantity is being calculated.

The relative mass sediment accumulation rate (RMSAR) is another possible index of core representativity. Sites with anomalously high or low mass sed-



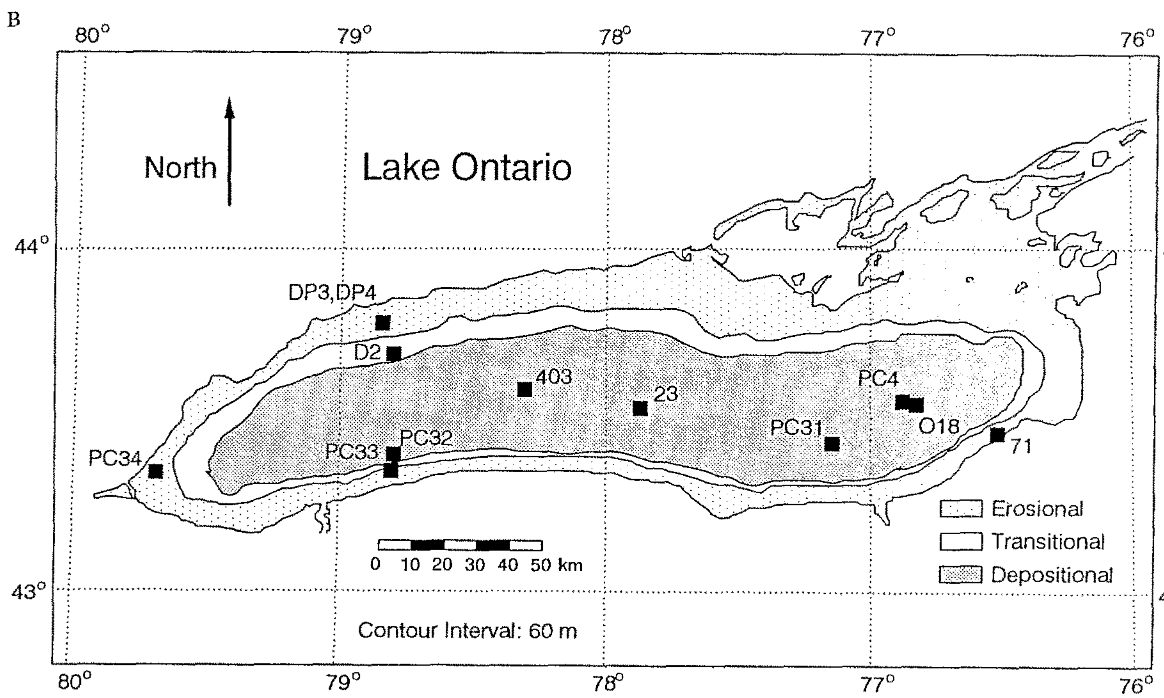


Fig. 1. (A) Morphometry and sample locations for Lake Ontario. (B) Sediment distribution in Lake Ontario as predicted by mud DBD theory.

iment accumulation rates (MSAR) are certainly not representative of the whole lake or basin. A very low MSAR in the depositional zone could be due to scouring or removal of material, while an unusually high MSAR could reflect a region of rapidly deposited local material. Anomalously high MSARs are sometimes found in shallow water sands, where even a low linear SAR results in a high MSAR due to the high bulk

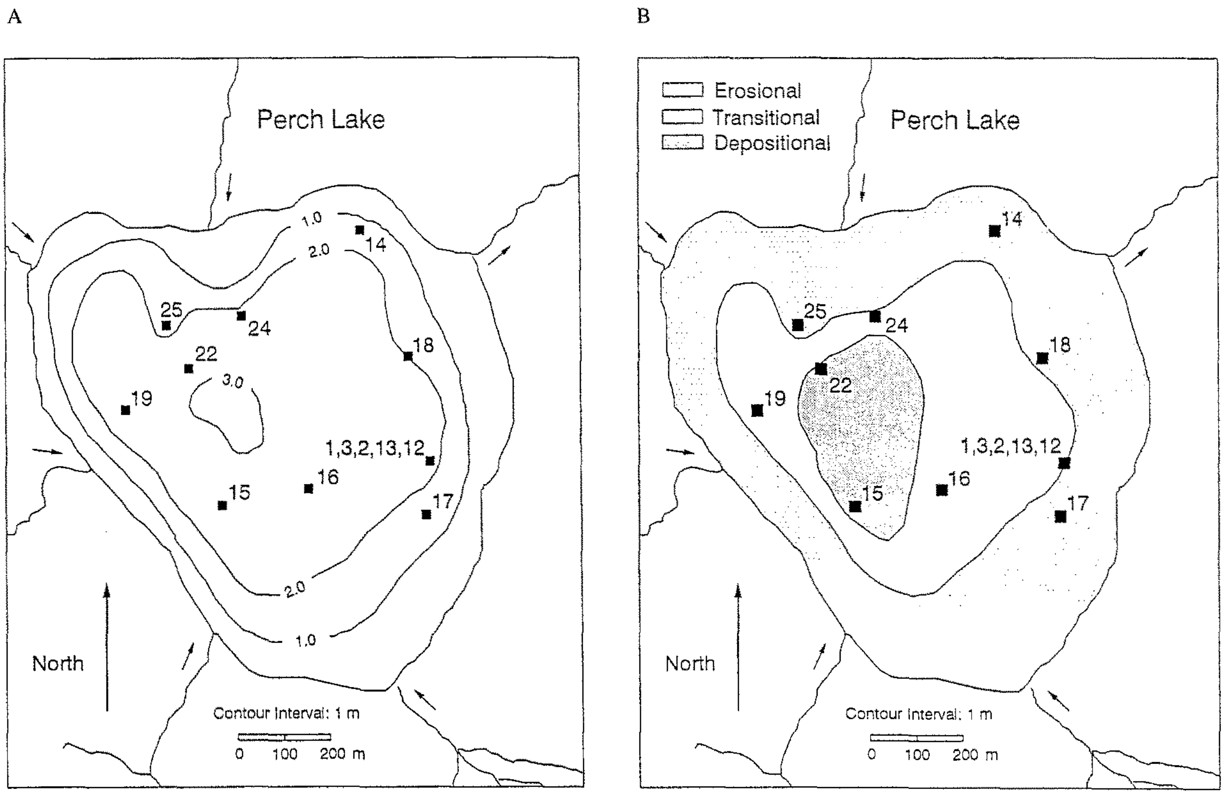


Fig. 2. (A) Morphometry and sample locations for Perch Lake. (B) Sediment distribution in Perch Lake as predicted by mud DBD theory.

density of these sediments. The relative mass sediment accumulation rate (RMSAR) was calculated for each core as:

$$\mathrm{RMSAR} = |\log \mathrm{MSAR} - \log \text{geometric mean MSAR}| \quad (4)$$

The geometric mean MSAR (g m^{-2} yr^{-1}) was specific to each lake (Table 1).

The relative mixed layer thickness (RMLT) is another possible indicator of core representativity. Most cores from depositional zones have a mixed layer thickness (MLT) of 2 to 5 cm due to bioturbation by amphipods or chironomids (Robbins *et al.*, 1977). Coarse-grained shallow water sediments, although prone to physical mixing by waves, are unlikely to be mixed to any degree by these benthic invertebrates. Thus, a thin or non-existent mixed layer could reflect a site poorly utilized by benthic invertebrates due to physical instability, or where surficial sediments have been scoured by waves. A very thick mixed layer could be due to unusual rates of bioturbation, physical mixing of the surficial sediments by waves or currents, or the deposition of a thick layer of slumped material. The relative mixed layer thickness (RMLT, cm) for each core was calculated as:

$$\mathrm{RMLT} = |\mathrm{MLT} - \text{mean MLT}| \quad (5)$$

and the mean MLT was specific to each lake (Table 1).

Interbedded sand and mud is indicative of an unstable sedimentary environment. Unstable sedimentary environments include the transitional zone which is intermittently impacted by infrequent storms with waves capable of transporting sand. Interbedded sediments are also likely to be found on or at the base of slopes, where slope induced slumping results in the mass transport of sediments, with removal of sediments from upslope sites and deposition at the slope base. In our data set, 22/91 cores exhibited interbedded stratigraphy. 14/22 of these cores occurred within or at depths within several meters of the transitional zone described by mud DBD theory. Of the remaining interbedded cores, 5 were located on steep slopes. Only 3 cores with interbedded stratigraphy were well within either the depositional or erosional zones. Therefore, cores with mixed stratigraphy are likely to be unreliable and non-representative of the depositional environment. In this analysis, cores with interbedded sand and mud (ISM) were classified by a value of 1, while sites with no interbedding were assigned a value of 0 (Table 1).

A test of mud DBD theory predictions by logistic regression of indices of core representativity

We hypothesized that sites classified by mud DBD theory as depositional should have ^{210}Pb profiles that were representative of the depositional environment, while sites classified as erosional or transitional should have ^{210}Pb profiles that were unrepresentative of the depositional environment. To test this hypothesis, we classified each core by assigning a value of 1 to depositional sites and a value of 0 to erosional or transitional sites as classified by mud DBD theory. Then we tested the accuracy of these classifications by a nonlinear logistic regression (Wilkinson, 1989) of the indices of core representativity. We obtained the following nonlinear logistic regression equation:

$$1/(1+e^{(-12.5+128\ \mathrm{RESID}+5.29\ \mathrm{RMSAR}+0.350\ \mathrm{RMLT}+10.3\ \mathrm{ISM})}) \quad (6)$$

where RESID is the mean residual to the CFCS model, RMSAR is the relative mass sediment accumulation rate, RMLT is the relative mixed layer thickness, and ISM is the presence of interbedded sand and mud. Unrepresentative cores (Eq. 6<0.5) were obtained at most of the erosional/transitional sites (82.9%) and most of the depositional sites (86.0%) had representative cores (Eq. 6>0.5) (Table 2). Figure 4 illustrates the difference between unrepresentative and representative ^{210}Pb profiles with examples of unrepresentative cores from above the mud DBD and representative cores from below the mud DBD in both Lake Ontario and Perch Lake. Thus, the mud DBD theory can predict both sediment distribution and the locations where representative cores can be obtained for ^{210}Pb dating.

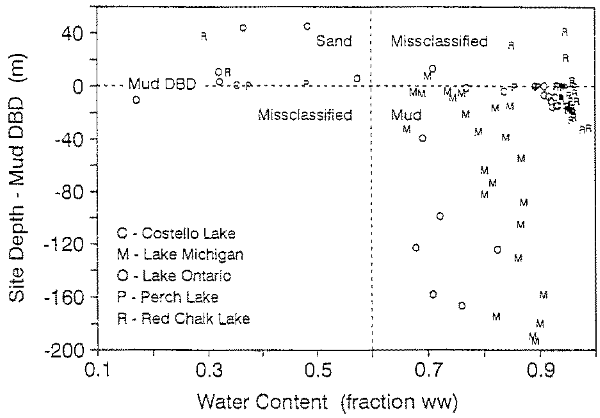


Fig. 3. Plot of site depth relative to the mud DBD vs. sediment water content. Sites that lie within the upper left quadrant are shallower than the mud DBD, and have sediment water contents <60% as predicted by mud DBD theory. Sites that lie within the lower right quadrant are deeper than the mud, low energy, and have sediment water contents >60% as predicted by mud DBD theory. Overall, 83.5% (76/91) are correctly classified by mud DBD theory.

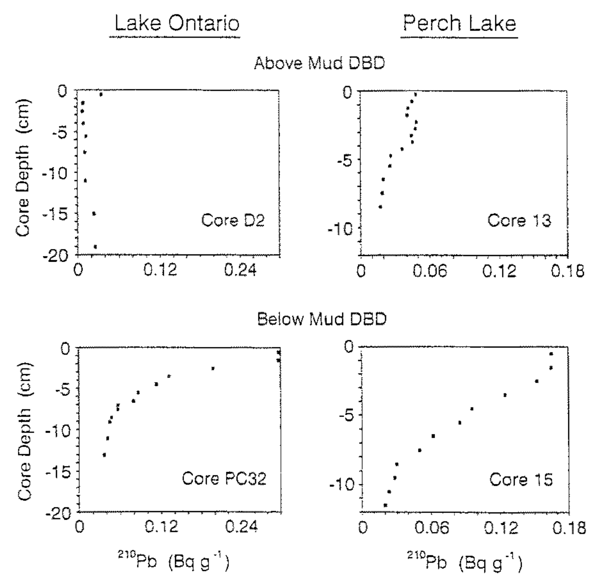


Fig. 4. Plot of ^{210}Pb activity as a function of core depth for unrepresentative cores above the mud DBD and representative cores below the mud DBD. Core D2 and core 13 have interbedded stratigraphy.

Variation in MSAR within the depositional zone: extrapolating results to the whole lake

We hypothesized that within the depositional zone identified by mud DBD theory, there would be no variation in MSAR with the depth of the water at the coring site and that the spatial variability observed for the whole-lake would be much reduced within the depositional zone. We tested this hypothesis by regressing the MSAR values against the water depth of the sampling site. Regressions of MSAR vs. depth for sites classified both as depositional by mud DBD theory and representative by the logistic regression yielded no statistically significant results (Fig. 5). This result is not consistent with the conclusions of Evans & Rigler (1983). To estimate MSAR, Evans (1980) selected three or four of the sections analyzed for ^{210}Pb that were pre-

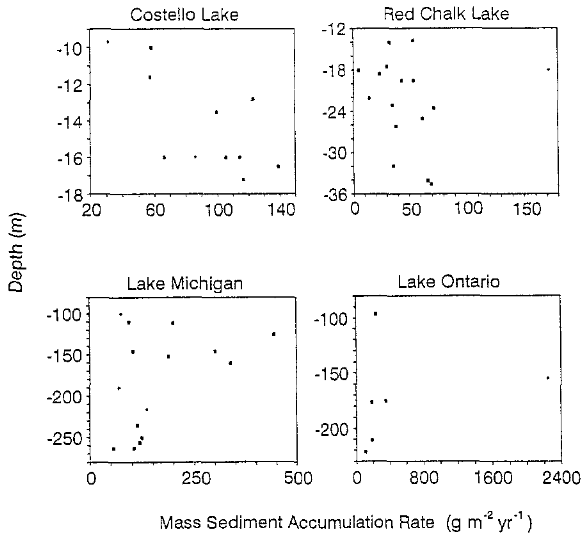


Fig. 5. Plot of MSAR as a function of water depth within the depositional zone defined by mud DBD theory. There are no statistically significant relationships between the MSARs of representative cores vs. depth for any of the lakes. Unrepresentative cores are indicated by (+).

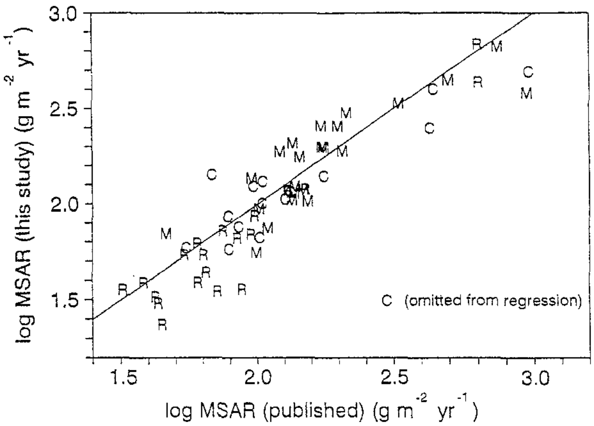


Fig. 6. Plot of MSARs estimated for this study vs. those published previously. The line represents the 1:1 relationship. Our estimate of MSAR for the core omitted from the regression differs from that of Evans (1980) in that we used all 18 determinations of ^{210}Pb while Evans (1980) used only 3.

sumed representative of the exponential portion of the depth/activity curve. Since we used all of the data and accounted for mixing in our MSAR calculations, we hypothesized that there might be some significant differences between our interpretation and that of Evans (1980) for the Costello and Red Chalk Lakes data. We tested this hypothesis by regressing our estimates of MSAR vs. those of Evans (1980) for Costello and Red Chalk Lakes and obtained the following regression:

$$\log \text{MSAR (this study)} = 0.062(0.129) + 0.931(0.063) \log \text{MSAR (Evans, 1980)} \quad (7)$$

$$r^2 = 0.864,\ SE_{cst} = 0.133, n = 36$$

We then added the Lake Michigan data (Hermanson & Christensen, 1991; Robbins & Edgington, 1975) and obtained:

$$\log \text{MSAR (this study)} = 0.084(0.116) + 0.936(0.054) \log \text{MSAR (published)} \quad (8)$$

$$r^2 = 0.839, SE_{cst} = 0.144, n = 59$$

The slopes of these relationships are not significantly different from 1 and the intercepts are not significantly different than 0 (Fig. 6). Thus, our results do not depend upon the interpretations of the profiles by other authors and the variations in MSAR below the mud DBD are indeed uncorrelated with the water depth of the coring site.

We also compared the variability in MSAR over the whole lake and erosional/transitional zones to that within the mud DBD theory defined depositional zone (Table 3). In each lake except Lake Michigan, the variation about the mean MSAR was reduced significantly (3 to 8 fold) when only representative cores from the depositional zone were considered. In Lake Michigan, the variability was also reduced, but only by a factor of 1.23. We then compared the variability (variability = 100 $*$ SD/mean) in our data with that of Håkanson (1992) and Baudo (1989). Variability in whole-lake MSAR for our data averaged 103%, while that of the erosional and transitional zones averaged 75% and in the depositional zone averaged 41%. This is similar to the variability Håkanson (1992) found for Pb and organic content in several Swedish lakes (about 60% in erosional and transitional zones, 32% in depositional zones), even though we would expect greater error in the estimation of sediment accumulation rates than in these parameters. For a whole-lake average, Baudo (1989) found variability of 127% in sediment copper concentration, and five different trend surface analyses yielded a mean value not significantly different from that of the original data. Therefore, to estimate the mean MSAR for depositional zone, we averaged the MSARs for representative cores within the zone. Extrapolating this average over the entire depositional zone to estimate the total fine-grained sediment accumulated can be done by multiplying this average by the area of the depositional zone. The total accumulation of sediment in the erosional or transitional zones can be estimated by multiplying the average MSAR for these zones by their area. However, such estimates will be prone to larger uncertainties because the MSAR value often cannot be accurately estimated from these cores.

How many cores should be collected and analyzed for ^{210}Pb dating?

Now that the depositional zone has been identified and a means to extrapolate core data over that zone has been suggested, the final question prior to sampling is how many cores should be collected and analyzed for ^{210}Pb dating in order to estimate the mean MSAR for the depositional zone? In order to address this question we estimated the sample size (n) required for a given precision in MSAR (δ, g m^{-2} yr^{-1}) from the variance in MSAR (s^2):

$$n = \frac{s^2}{\delta^2}(t_{\alpha v} + t_{\beta v})^2 \quad (9)$$

We performed a two tailed test, accounting for both type 1 and type 2 errors, and conservatively set $\alpha = \beta = 0.5$ (Peterman, 1990). A plot of sample size *vs* precision in MSAR is shown in Fig. 7. Initially, modest increases in sample size result in dramatic increases in precision. We suggest that once the increased precision per additional core is less than 5% of the true mean, there is little to be gained by collecting additional cores. Although the selection of a 5% change is somewhat arbitrary, we recommend this value because the precision of each MSAR estimate is usually no better than 5% so that little is gained from more analyses. For Costello Lake this is achieved with 5 cores, for Red Chalk Lake with 7 cores, for Lake Michigan with 9 cores and for Lake Ontario with 7 cores. Therefore, to optimize sampling effort we recommend that no more than 5 to 10 cores are needed from the depositional zone in order to estimate the mean MSAR and the total sediment accumulation.

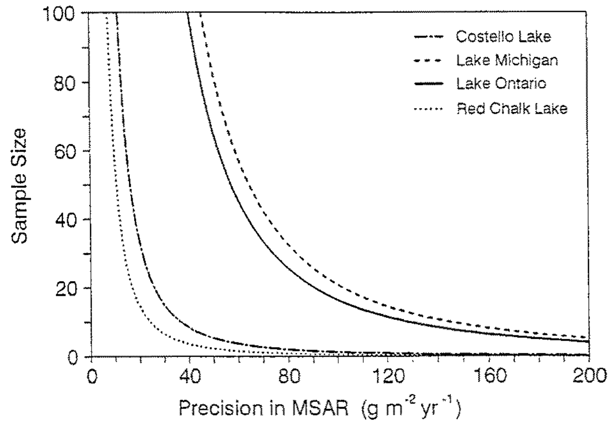


Fig. 7. Plot of sample size *vs* precision in MSAR.

Discussion

Since the concept of sediment focusing was introduced by Likens & Davis (1975), there has been considerable discussion surrounding the processes involved in focusing and the extrapolation of core data from single sites to the entire lake. With the exception of the conceptual models of Hilton (1985) and Lehman (1975), and simple depth regressions such as those of Evans & Rigler (1983), there has been no attempt to put sediment focusing into a theoretical sedimentological framework. The concept that thermal convective mixing at fall and spring overturn is responsible for sediment redistribution (Davis, 1968) remains anecdotal and untested. A simple calculation of the velocities required for such a phenomenon indicates that even a small, shallow lake would have to overturn in matter of minutes to generate current velocities capable of transporting fine-grained sediment (>0.05 m s^{-1}). Many studies show that this does not occur. A second objection to this hypothesis is that in small lakes, the mud DBD occurs within the epilimnion. For example, Kimmel (1978) notes that soft sediment accumulates in water depths of 2 to 5 m, well within the mixed layer (5–8 m). We calculate that this sediment is accumulating below the mud DBD estimate of 1.7 m. Thus, it is probable that the redistribution of sediment noted by many authors during the spring and fall isothermal periods is a result of severe weather, with accompanying annual maximum waves rather than any phenomenon associated with thermally driven mixing. This is supported by the data of Saulesleja (1986) for the Laurentian Great Lakes which clearly indicates that the largest waves are produced by fall and winter storms.

The results of this study do not support the hypothesis of Evans & Rigler (1983) that a simple depth regression of MSAR *vs* water depth can be used to integrate whole lake sediment accumulation rates by accounting for the effects of sediment focusing. Cornett *et al.*

(1984) and Cornett & Chant (1988) also found no correlations between radionuclide flux and water depth, and within the depositional zone of Castle Lake (Kimmel, 1978), there is no correlation between sediment accumulation rate and water depth.

There still exists unexplained variation within the depositional zone, but this is much smaller once the depositional zone is defined by mud DBD theory (Table 3). Irregularities in bottom topography, currents and local sediment sources could be responsible for these variations, but at present there is no means to account for such effects. Thus, the results of this study suggest that with a well defined depositional zone, the effects of sediment focusing associated with water depth are no longer evident. That is, the depositional zone defined by mud DBD theory is the zone to which fine-grained sediments are focused.

The use of mud DBD theory has been shown to be useful in predicting sediment distribution, the location of representative sedimentary records, and in the extrapolation of core data to the area below the mud DBD. The use of the mud DBD theory in the location of sampling sites can save both time and money. Had the mud DBD theory been available to Evans & Rigler (1983), the number of sites sampled could have been reduced from 41 to 12, a reduction of 70%, without losing precision in MSAR. We encourage other groups to use this predictive tool to optimize future studies that require coring and dating sediment stratigraphies.

References

Baudo, R., 1989. Uncertainty in description of sediment chemical composition. Hydrobiologia 176/177: 441–448.

Cornett, R. J. & L. A. Chant, 1988. ^{239,240}Pu residence times in freshwaters and accumulation in shield lake sediments. Can. J. Fish. Aquat. Sci. 45: 407–415.

Cornett, R. J., L. A. Chant & B. A. Risto, 1992. Arsenic transport between water and sediments. Hydrobiologia 235/236: 533–544.

Cornett, R. J., L. A. Chant & D. Link, 1984. Sedimentation of ^{210}Pb in Laurentian Shield lakes. Wat. Pollut. Res. J. Can. 19: 97–109.

Davis, M. B., 1968. Pollen grains in lake sediments: redeposition caused by seasonal water circulation. Science 162: 769–799.

Evans, R. D., 1980. Measurement of sediment accumulation and phosphorous retention using lead-210 dating. PhD. Thesis, McGill University.

Evans, R. D. & F. H. Rigler, 1983. A test of lead-210 dating for the measurement of whole lake soft sediment accumulation. Can. J. Fish. Aquat. Sci. 40: 506–515.

Floderus, S., 1989. Sediment sampling evaluated with a new weighting function and index of reliability. Hydrobiologia 176/177: 451–464.

Foster, I. D. L., J. A. Dearing, A. Simpson, A. D. Carter & P. G. Appleby, 1985. Lake catchment based studies of erosion and denudation in the Merevale catchment, Warwickshire, U.K. Earth Surface Processes and Landforms 10: 45–68.

Håkanson, L., 1977. The influence of wind, fetch, and water depth on the distribution of sediments in Lake Vanern, Sweden. Can. J. Earth Sci. 14: 397–412.

Håkanson, L., 1981. On lake bottom dynamics – the energy-topography factor. Can. J. Earth Sci. 18: 899–909.

Håkanson, L., 1984. Sediment sampling in different aquatic environments: statistical aspect. Wat. Resour. Res. 20: 41–46.

Håkanson, L., 1992. Sediment variability. In Sediment Toxicity Assessment (ed. G. A. Burton, Jr.), Lewis Publishers, Boca Raton: 19–35.

Håkanson, L. & M. Jansson, 1983. Principles of Lake Sedimentology. Springer-Verlag, Heidelberg, 316 pp.

Hermanson, M. H. & E. R. Christensen, 1991. Recent sedimentation in Lake Michigan. J. Great Lakes Res. 17: 33–50.

Hilton, J., 1985. A conceptual framework for predicting the occurrence of sediment focusing and sediment redistribution in small lakes. Limnol. Oceanogr. 30: 1131–1143.

Kimmel, B. L., 1978. An evaluation of recent sediment focusing in Castle Lake (California) using a volcanic ash layer as a stratigraphic marker. Verh. Int. Ver. Limnol. 20: 393–400.

Lehman, J. T., 1975. Reconstructing the rate of accumulation of lake sediment: the effect of sediment focusing. Quat. Res. 5: 541–550.

Likens, G. E. & M. B. Davis, 1975. Post-glacial history of Mirror Lake and its watershed in New Hampshire, USA: an initial report. Verh. Int. Ver. Limnol. 19: 982–993.

Peterman, R. M., 1990. Statistical power analysis can improve fisheries research and management. Can. J. Fish. Aquat. Sci. 47: 2–15.

Robbins, J. A. & D. N. Edgington, 1975. Determination of recent sedimentation rates in Lake Michigan using Pb-210 and Cs-137. Geochim. Cosmochim. Acta. 39: 285–304.

Robbins, J. A., J. R. Krezoski & S. C. Mozley, 1977. Radioactivity in sediments of the Great Lakes: post-depositional redistribution by deposit-feeding organisms. Earth Planet. Sci. Lett. 36: 325–333.

Rowan, D. J., J. Kalff & J. B. Rasmussen, 1992. Estimating the mud deposition boundary depth in lakes from wave theory. Can. J. Fish. Aquat. Sci. 49: 2490–2497.

Saulesleja, A., 1986. Great Lakes climatological atlas. Supply and Services Canada, Ottawa, Ont., 145 pp.

Wilkinson, L., 1989. SYSTAT: the system for statistics. SYSTAT, Inc., Evanston, Il., 822 pp.