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Radionuclide profiles, sedimentation rates, and bioturbation in modern sediments of the Laurentian Trough, Gulf of St. Lawrence

Sedimentation rate
Bioturbation
Radionuclides
Laurentian Trough
Taux de sédimentation
Bioturbation
Radionuclides
Chenal Laurentien

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ABSTRACT

Measurements of the depth-distribution of ^{210}Pb and ^{137}Cs activities, and radiocarbon ages in sediment box cores from the Laurentian Trough were made to determine modern sedimention rates in this deep coastal environment. Estimates of biological mixing coefficients (D_b) were calculated using the depth-distribution of excess ^{228}Th and ^{234}Th activities for the top 2-5 cm of the sediment. Although these surficial D_b's (10^{-7} to 10^{-8} cm^2/s) are low for coastal sediments, they are sufficient to cause serious bioturbational errors in the slopes of uncorrected radionuclide data. Using a model of depth-zoned bioturbation, and estimates of subsurface D_b an order of magnitude smaller, sedimentation rates of several mm/yr are arrived at. These are in good agreement with direct sedimentation rate measurements obtained using sediment traps.

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RÉSUMÉ

Profils de radionuclides, taux de sédimentation, et bioturbation dans les sédiments modernes du chenal Laurentien, Golfe du St-Laurent

Afin de déterminer les taux de sédimentation actuels dans le milieu côtier profond du chenal Laurentien, des mesures de l'activité de ^{210}Pb et de ^{137}Cs et des datations par ^{14}C selon la profondeur dans les sédiments ont été effectuées à l'aide d'un carottier à boîte. L'estimation du coefficient de mélange biologique (D_B) a été calculée à partir de la distribution en profondeur des activités en excès de ^{228}Th et ^{234}Th dans les 2-5 premiers centimètres du sédiment. Les valeurs de D_b obtenues (10^{-7} to 10^{-8} cm^2/s) sont basses pour une région côtière, mais elles peuvent influencer sérieusement des pentes d'évolution des radionuclides. L'utilisation d'un modèle de bioturbation en zones, et l'estimation du D_b en subsurface qui n'est qu'un dixième de celui mesuré en surface, démontrent que les taux de sédimentation sont de l'ordre de plusieurs mm/année. Ceux-ci sont en accord avec des mesures directes obtenues à l'aide de pièges à sédiments .

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INTRODUCTION

Reasonable estimates of modern day, short-term (1-100 yr) sedimentation rates are necessary in the study of particle mass balances, geochemical processes in the benthic boundary layer, and benthic ecology. In the absence of known marker horizons, such as ash falls, recorded slumps or industrial pollutants, the determination of present day sedimentation rates can be particularly difficult.

One very promising approach is the dating of sediment using the depth distribution of excess (non- ^{226}Ra supported) ^{210}Pb, or "^{210}Pb(xs)", whose short half-life (22.3 yrs) permits estimates over very recent time periods (Koide *et al.*, 1972; 1973; Bruland, 1974; Nittrouer *et al.*, 1979). The method was originally tested in Santa Barbara Basin, where anoxic conditions near the sediment eliminate significant bioturbation. In other regions, however, the profile of ^{210}Pb(xs) is subject to disturbance by burrowing organisms, and may yield rates which are anomolously high (Benninger, 1978; Benninger *et al.*, 1979; Schubel, Hirschberg, 1981). The depth and effective rate of sediment mixing by organisms are not always obvious and considerable effort must be expended to verify or correct the apparent rates estimated from the ^{210}Pb data.

We present here a study of the sedimentation rates in a deep coastal environment, the Laurentian Trough (Fig. 1). We present data using different radionuclides, discuss some of the difficulties in interpretation, and try to resolve some of the apparent inconsistencies by using sediment trap measurements and a model for the depth distribution of bioturbational mixing.

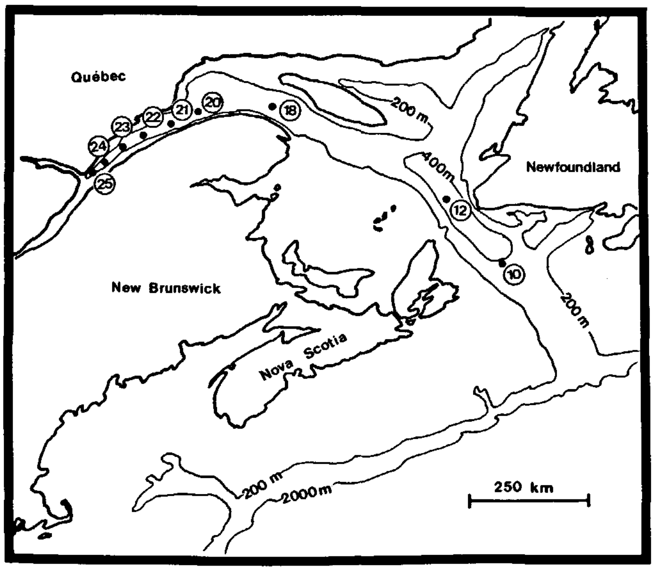

Figure 1
Chart of eastern Canada, showing the Laurentian Trough and the location of stations referred to in the text.

Table 1
^{210}*Pb data (dpm/g).*

Depth (cm)	^{210}Pb	^{210}Pb(xs)	Depth (cm)	^{210}Pb	^{210}Pb(xs)
	Station 12			*Station* 22	
0-0.2	20.5±0.3	17.8	0.4-0.6	7.4±0.2	6.4
1-2	19.2±0.2	16.5	1-2	8.0±0.1	7.0
4-5	10.9±0.3	7.2	4-5	6.2±0.1	5.2
9-10	7.7±0.2	5.0	9-10	3.1±0.08	2.1
14-15	5.6±0.08	2.9	14-15	2.0±0.05	1.0
19-20	3.5±0.08	0.8	19-20	1.0±0.62	–
24-25	2.73±0.05	–	24-25	1.15±0.05	–
29-30	2.67±0.04	–	28-29	0.82±0.008	–
(assumed background-2.7)			(assumed background-1.0)		
Calculated Sedn Rate: 2.0 mm/yr			2.0 mm/yr		
	Station 23			*Station* 24	
0.4-0.6	9.7±0.3	8.2	0-0.2	7.1±0.14	5.6
1-2	9.9±0.6	8.4	0.4-0.6	7.0±0.12	5.5
4-5	9.5±0.4	8.0	1-2	7.7±0.25	6.2
9-10	7.6±0.6	6.1	4-5	7.9±0.26	6.4
14-15	5.61±0.16	4.1	9-10	7.4±0.1	5.9
19-20	3.50±0.12	2.0	14-15	6.9±0.1	5.4
24-25	2.72±0.14	1.2	19-20	6.8±0.09	5.3
29-30	2.32±0.09	0.8	32-33	5.2±0.1	3.7
33-34	2.0±0.1	0.5			
(assumed background-1.5)			(assumed background-1.5)		
Calculated Sed^n Rate: 2.9 mm/yr			16.2 mm/yr		

EXCESS ^{210}Pb DATA

Subsamples of box cores from four stations within the Trough were analysed for ^{210}Pb, using the method of Koide *et al.* (1973). The measured ^{210}Pb activities were then corrected for ^{226}Ra-supported-^{210}Pb by subtracting the stable, low-level activities at the base of the cores, or by assuming a value based upon the trend of the data and the geographic position of the sample site (Tab. 1). The depth profiles of ^{210}Pb(xs) activities are presented in Figure 2. As is often the case, the data in the top few centimeters are almost invariable, and are interpreted as reflecting intense bioturbation near the sediment surface. The slopes of the least-squares exponential curves fitted to the data below these zones,

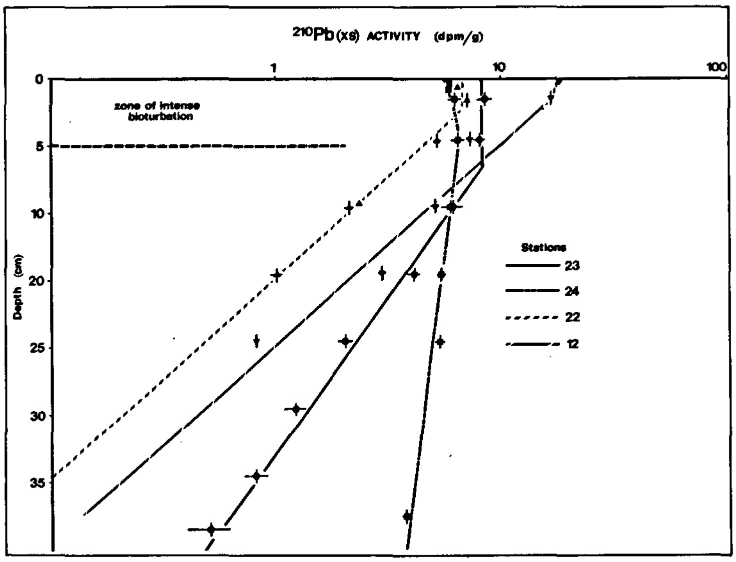

Figure 2
Profiles of ^{210}*Pb(xs) activity with depth in Laurentian Trough box cores.*

assuming steady sedimentation over the past 100-200 years, provide estimates of 2.0, 2.0, 2.9, and 16.2 mm/yr for stations 12, 22, 23, and 24, respectively. While these estimates are in the range commonly reported for estuaries they are an order of magnitude higher than rough estimates based upon radiocarbon dating of shell horizons and interpretation of foraminifera data from stations in the open Gulf of St. Lawrence (Loring, Nota, 1973), and from estimates of the mass budget of particulate matter in the system as presented by Sundby (1974).

RADIOCESIUM DATA

^{137}Cs, derived from nuclear weapons testing, appeared in the environment since the 1950's and the greatest concentration in sediments corresponds to the year 1964 (Livingston, Bowen, 1979). Box-core subsamples from station 23 were analysed for radiocesium by Dr. C. Barbeau, at the Département de Chimie, Université Laval, and the results are presented in Table 2. The maximum activity is situated at 1-2 cm depth and thus implies a sedimentation rate of about 1 mm/yr. The position of the ^{137}Cs maximum, however, may be influenced by bioturbation (Robbins *et al.*, 1979). Furthermore, there is measurable ^{137}Cs at 9-10 cm depth, suggesting bioturbation to a depth at least twice the 5 cm depth assumed for the ^{210}Pb calculations. ^{137}Cs may also be subject to diffusion in marine sediments. The results are thus subject to reasonable doubt.

Table 2
Radiocesium data for station 23.

Depth (cm)	^{137}Cs (pCi/kg)
0-0.1	400 ± 50
0-1	90 ± 30
1-2	1 100 ± 100
2-3	470 ± 50
3-4	450 ± 50
4-5	400 ± 50
5-6	320 ± 60
7-8	190 ± 50
9-10	80 ± 50
14-15	–

RADIOCARBON DATA

Due to the absence of adequate occurrences of shell or woody material in the Trough sediments, 5-10 cm thick sections of gravity cores from two stations were analysed for total organic matter (1.5-2% by weight) ^{14}C ages by Dr. Delibrias' laboratory at the Centre des Faibles Radioactivités. The results, shown in Table 3, are difficult to interpret. The uncertainty in each datum, and the consistent ages of about 2 500 years at all depths in both cores might perhaps be interpreted as due to complete mixing of organic matter to a depth of one meter in the sediment, at least on the time scale of radiocarbon ($T1/2 = 5\,600$ yrs). Such deep bioturbation is inconsistent with the ^{210}Pb dating, for which we assumed insignificant bioturbation below the surface layer.

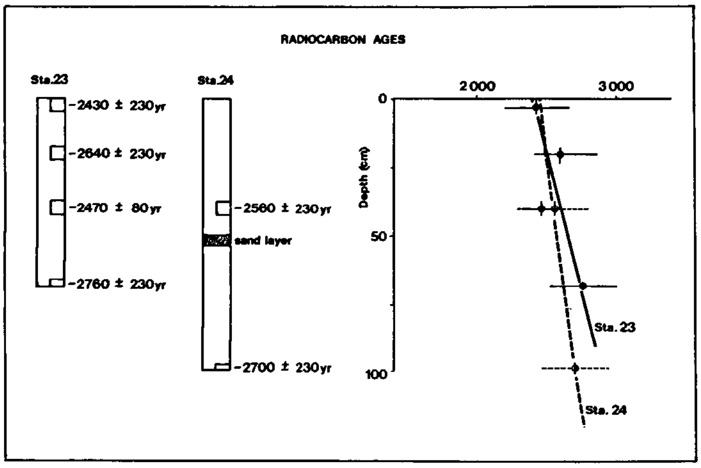

Figure 3
Radiocarbon ages determined from total organic carbon extractions at stations 23 and 24. Shown are the sampling depths in the gravity cores of the predominantly silty-clay sediments, and the profiles with depth in the sediment.

Another interpretation is more likely, however, for these data. There is a weak trend towards increasing age with depth in these cores. The profiles (Fig. 3) resemble those reported by Benoit *et al.* (1979) from Long Island Sound. These authors interpreted surface ages of about 2 300 years as due to refractory, soil-derived organic material, which would be abundant in coastal environments. If we adopt a similar assumption, then the true ages of the Laurentian Trough samples are less than a few hundred years, and the interpretation of intense mixing down to one meter could be abandoned. The presence of a sand layer, with sharp upper and lower contacts, between the two dated intervals in the core from Station 24 strongly supports the interpretation of very weak mixing at depth.

Using this interpretation, the age difference of 330 years over 65 cm at station 23 would imply a sedimentation rate of 2 mm/yr. At station 24 the increase of 140 years over 58 cm implies a rate of about 4 mm/yr. Given the uncertainty of about 325 years in the raw data, these rates must be considered imprecise.

Table 3
Radiocarbon data.

Station 23		*Station 24*	
Depth (cm)	Age (yrs B.P.)	Depth (cm)	Age (yrs B.P.)
0-5	2 430 ± 230	37.5-42.5	2 560 ± 230
17.5-22.5	2 640 ± 230	97-99	2 700 ± 230
37.5-42.5	2 470 ± 80		
66.5-69	2 760 ± 230		

ESTIMATES OF NEAR-SURFACE SEDIMENT MIXING RATES

Short-lived isotopes of Thorium (^{234}Th, 24.1 days; ^{228}Th, 1.9 yrs) are scavenged from the water column on settling particles and account for excess activities at the sediment surface over ^{238}U and ^{228}Ra supported Thorium. Because their half-lives are so short in relation to the rate of burial due to simple sedimentation, their occurrence in excess below the sediment surface can be used to estimate short-term biological mixing coefficients. Aller and Cochran (1976), Cochran and Aller (1979), and Aller *et al.* (1980) have developed this procedure using the depth distribution of ^{234}Th (xs). Assuming mixing to infinite depth, diffusion-like mixing, sedimentation rate small in comparison to mixing, and an exponential decrease in activities with depth of the form

$$A = A^0 e^{-ax} \tag{1}$$

An apparent biological diffusion coefficient can be estimated as

$$D_b = \lambda / a^2 \text{ (where } \lambda \text{ is the radioactive decay constant)} \tag{2}$$

Fresh box-core samples from several stations were analysed for ^{234}Th and ^{228}Th activities at the Centre des Faibles Radioactivités using high resolution gamma spectrometry. Values for ^{228}Th(xs) were obtained by correcting for ^{228}Ra-supported thorium. Excess activities were calculated for ^{234}Th using background values of parent ^{238}U from old samples (in which the excess ^{234}Th had decayed to essentially zero), alpha spectrometry of chemically isolated Uranium of selected samples, and equilibrium models between ^{238}U, ^{226}Ra, and ^{222}Rn (C. E. Lambert, pers. comm., 1982: more detail on the method will be available in Nguyen *et al.*, in prep.). Uncertainties in the background ^{238}U lead to some difficulty in interpreting the very low values of ^{234}Th(xs) near the base of the data but the near-surface values are not significantly affected.

Table 4
Estimates of the biological mixing coefficient.

Station	Season	Db (wet volume basis-dpm/cm^3) ^{234}Th	^{228}Th
12	June 1981	2.6×10^{-6} (?)	3.7×10^{-8} cm^2/s
18	July 1981	3.1×10^{-8}	1.3×10^{-8}
20	July 1981	6.7×10^{-7}	8.2×10^{-9}
	June 1980		1.2×10^{-8}
21	June 1980	1.1×10^{-7}	
23	June 1980	1.2×10^{-7}	1.8×10^{-7}
24	July 1981	2.1×10^{-7}	3.4×10^{-6} (*)
	June 1980	4.6×10^{-7}	1.2×10^{-7} (*)

(*) St. 24 sedimentation rate may not be negligible in relation to the ^{228}Th decay constant.

Table 4 lists the various estimates for the biological mixing coefficient for the Laurentian Trough box-cores. Note that the assumption of negligible sedimentation rate may not be valid for the ^{228}Th data for station 24. There is some scatter in the results, particularly between the estimates based upon ^{228}Th and ^{234}Th. This is partly due to an imperfect correspondence between the real data and the assumed exponential decrease with depth (*i.e.* bioturbation is more complex than the model assumes), analytical uncertainties, and the problems of subsampling heterogeneous sedimentary environments on a small scale. Most of the values, however, are between 10^{-7} and 10^{-8} cm^2/s. In general, it can be concluded that surficial mixing rates in the 300-500 m deep sediments of the Laurentian Trough are intermediate between rates for shallow coastal environments, such as Long Island Sound (10^{-6}, 10^{-7}: Aller *et al.*, 1980) and the Irish Sea (Duursma, Gross, 1971), and those reported for the deep sea (10^{-9} to 10^{-11}, Guinasso, Schink, 1975; DeMaster, Cochran, 1982).

^{210}Pb SEDIMENTATION RATES AND SUBSURFACE BIOTURBATION

The depth distribution of the activity of a chemically unreactive radionuclide within the sediment can be described by an advection-diffusion model of the form

$$\delta A/\delta t = \delta/\delta x (D \delta A/\delta x) - U(\delta A/\delta x) - \lambda A \tag{3}$$

(A = activity, t = time, x = depth, D = diff. coeff., v = adv. coeff., = decay constant).

Assuming steady state ($\delta A/\delta t = 0$), $D = D_b$, and simple burial (V = w, sedimentation rate), and appropriate boundary conditions, then a solution for the depth distribution of activity is:

$$A = A^0 \exp - \{w - (w^2 + 4\,\lambda D_b)^{1/2}) / 2D_b\} x \tag{4}$$

If we set the exponent equal to "a", then

$$A = A^0 e^{-ax} \tag{5}$$

and the sedimentation rate can be evaluated as:

$$w = aD_b - \lambda / a. \tag{6}$$

The sedimentation rate (w) can thus be evaluated from the slope of the ^{210}Pb(xs) profile if the D_b's estimated from the Thorium data are introduced. In most cases the results (Tab. 5) are negative. This means that the surficial mixing rates are sufficient in themselves to produce the apparent exponential decrease in ^{210}Pb activity below 5 cm depth, even if actual sedimentation rates are non-existent.

These calculations assume that biological mixing rates are constant to depths of 20-30 cm below the surface. This is probably an unreasonable assumption. In Long Island Sound, Benninger *et al.* (1979), using ^{210}Pb and

Table 5
Effect of D_b on calculated sed^n rate (w) from ^{218}Pb(xs) data.

Station	Range of D_b at surface	Calculated values of (w) D_b	$D_b/5$	$D_b/10$	(w) Table 1 ($D_b = 0$)
12	2.6×10^{-6}	—124.86	—23.36	—10.68	2.01
	3.7×10^{-8}	0.20	1.65	1.83	
22	1.1×10^{-7} (from St. 21)	—3.36	0.94	1.47	2.01
23	1.2×10^{-7}	—1.04	2.15	2.55	2.95
	1.8×10^{-7}	—3.03	1.75	2.35	
24	3.6×10^{-6}	—5.64	11.82	14.00	16.18
	1.2×10^{-7}	15.51	16.05	16.11	

$^{239+240}$Pu data and model calculations, found that subsurface D_b's were about two orders of magnitude lower than those measured at the surface. The depth distribution of living macrobenthos in the inner trough, in fact, shows a very rapid drop-off in organism densities below 5 cm depth (Ouellet, 1982).

If we re-examine the ^{137}Cs data in this light there is a further indication for much slower mixing below the surface. Assuming that the activity distribution below the peak position is due to bioturbation (and neglecting the fact that about 150 years are required for obtaining steady state), we calculate a rough D_b of 9.25×10^{-9} cm^2/s, as compared to 1×10^{-7} calculated for the top few centimeters using the thorium data. Robbins *et al.* (1979) have shown for fresh-water sediments that the molecular diffusion coefficient for this isotope is in fact about 10^{-9} cm^2/s, so the same distribution might have developed if there was no deep bioturbation at all.

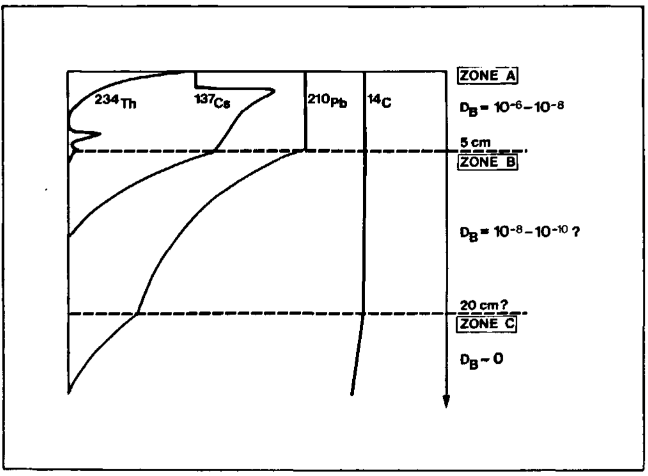

Figure 4

Schematic profiles with depth of different radionuclides, modelled after Benninger et al. (1979), *assuming depth-zoned bioturbation.*

The radionuclide data set from the St. Lawrence comforms best with the model of depth-zoned bioturbation proposed by Benninger *et al.* (1979). Plotted schematically in Figure 4, the data follows a pattern of greater mixing at successive depths for radionuclides of increasingly greater half-life. We thus conclude that it is reasonable to assume that mixing coefficients below 5 cm depth are an order of magnitude smaller than those estimated from the near-surface thorium data.

Table 5 compares the computed sedimentation rates, assuming D_b's in the subsurface are one-fifth and one-tenth as great as the surface D_b's, with the rates obtained previously from the ^{210}Pb (xs) data. For many of the stations a decrease in subsurface mixing of only one-fifth yields rates approaching those of the ^{210}Pb dating, while at one-tenth the surface mixing the calculated rates are very close to the ^{210}Pb rates.

SEDIMENT TRAP DATA

Free-drifting sediment traps, each having four cylinders with a diameter to height aspect ratio of 1:3, a total collecting surface area of 5 028 square centimeters, and modelled after the design of Staresinic *et al.* (1978) have been deployed at various stations in the Laurentian Trough since 1980. Sampling periods between 9.6 and 24 hours provide sufficient material for accurate weighing. There is little time available for invasion of the traps by ambient organisms and the use of poisons is unnecessary. Table 6 lists the results of a series of such direct sedimentation rates for the Laurentian Trough. Although there is some loss of mass due to organic matter degradation after settling, this loss represents less 5% of the total (Silverberg *et al.*, 1985) and no correction factor has been applied. The equivalent rates in mm/yr were calculated assuming a particle density of 2.65 g/cm^3 and a mean porewater content of 50%, the consistent water content measured below about 5-10 cm depth in these sediments.

Table 6

Laurentian Trough sediment trap data.

Station	Season	mg/cm^2/day	mm/yr*
10	June 1981	0.20	0.99
12	June 1981	0.10	0.49
	August 1982	0.14	0.67
18	July 1981	0.51	2.49
	August 1982	0.03	0.16
20	July 1981	0.31	1.51
21	August 1982	0.28	1.39
23	August 1980	0.46	2.27
	August 1980	0.47	2.32
	July 1981	0.47	2.32
	mean of 25 measurements (1980-1984)	0.51	2.50
24	August 1980	1.18	5.82
	July 1981	2.81	13.82
	July 1981	2.46	12.10
	August 1982	0.43	2.13
25	July 1981	0.62	3.04
	August 1982	0.35	1.73

* Assuming water content of 50% and particle density of 2.65 g/cm^3.

These results are in very good agreement with the estimates based upon the ^{210}Pb (xs) profiles. Data obtained at station 23 in 1983-84 on a monthly basis during the ice-free season reveal some seasonal variability but the mean rates are consistent (within a factor of 2) with the ^{210}Pb estimates. Such good agreement is likely due to the relatively low content of degradable organic matter of the material settling in these coastal waters, even during the periods of high productivity, to the avoidance of contamination by resuspended sediment, and the relatively weak near-bottom transport in the deep Laurentian Trough. No sediment trap data is available for the period of ice cover but recent studies of zooplankton distributions (De Ladurantaye, Therriault, 1985) indicate that significant population densities persist over the winter months. Microscopic examination of the trap material reveals a strong dominance of fecal matter and it is probable that winter sedimentation rates are not significantly lower than those recorded in the late fall.

DISCUSSION

We have performed all of these different measurements because we felt that reasonable estimates of sedimentation rates were essential to our other work on the biogeochemistry of the benthic boundary layer. Each of the various data sets presented in this study is subject to a measure of doubt: ^{210}Pb (xs) profiles because of uncertain influence by bioturbation and the lack of a detailed mass budget for the trough system; ^{137}Cs, because of possible shifting of the depth of the maximum and downmixing due to bioturbation, as well as some chemical mobility; ^{14}C, because of anomolously old ages and possible deep bioturbation; D_b estimates because of inconsistencies between different nuclides and imperfect exponential decrease with depth; and the sediment trap data because of the short sampling interval, subjective decisions concerning the acceptance or rejection of whole organism particles (mainly copepods) as true sedimenting particles (in our case, we rejected only those that floated either before or after centrifugation). In combination, however, and using justifiable assumptions, it is clear that sedimentation rates on the order of mm/yr are reasonable estimates for the Laurentian Trough.

A depth-zoned bioturbational mixing model, with an order of magnitude decrease in mixing intensity below the top few centimeters, best explains the observed data. ^{210}Pb (xs) slopes below the surface zone of intense bioturbation serve as an accurate basis for the calculation of sedimentation rates over the last hundred years. They are in agreement with short-term rates measured with sediment traps and the ^{137}Cs data, as well as the radiocarbon data. For these latter data, slow mixing rates below the surface are again required, and for ^{14}C a source of old, refractory, soil-derived carbon is also postulated.

While it would seem that the ^{210}Pb (xs) data alone (if the well-mixed surface layer is ignored) are apparently sufficient for estimating modern sedimentation rates, we cannot yet conclude that this is the case for all coastal or oceanic environments. From Table 6 it is apparent that sedimentation rates in the open Gulf of St. Lawrence (stations seaward of station 20) are considerably smaller than those in the maritime estuary. This is not reflected clearly in the ^{210}Pb estimates and bioturbation probably has had some effect in the estimate for station 12. Variable results from the sediment traps at station 24 also suggest a somewhat lower long-term sedimentation rate than the ^{210}Pb estimate.

To date there is a scarcity of published estimates of effective sediment mixing rates even for surficial sediments. Subsurface mixing rate estimates are even more scarce, and more quantitative determinations are required before radionuclide profiles in sediments can be accepted without correction.

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