

CESIUM 137 AND LEAD 210 IN ALPINE LAKE SEDIMENTS:
MEASUREMENTS AND MODELING OF MIXING PROCESSES

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Abstract. Simulations of ^{137}Cs distribution in lake sediment cores are presented for slow and rapid mixing processes, for different mixing layers, and for different sampling thicknesses. A parameter characterizing the profile distribution is introduced. Interpretation of the ^{137}Cs profiles of seven alpine lakes is given using those simulations leading to an estimate of the sedimentation rate, the type of mixing and the thickness of the mixing layer. These parameters are compared with those obtained independently from ^{210}Pb profiles in three of the lakes. Agreement is satisfactory. The lakes we studied have similar features. In most cases the lakes have mixing which can be approximated by a rapid diffusion process, sedimentation rate of the order of $0.01 \text{ g cm}^{-2} \text{ yr}^{-1}$, and a mixing layer of the order of 2-4 cm.

Introduction

Sediments are commonly used as records of the past. Often, the surface sediment layer, which corresponds to an event well defined in time, is perturbed by different phenomena (we shall call it mixing) over a depth of several centimeters. This mixing broadens the record of deposition, thus reducing the time resolution of the events recorded in the sediments.

Therefore interpreting a core requires determination of at least two parameters: the sedimentation rate and the mixing characteristics. This field has been extensively investigated during the two last decades. This is usually achieved by measuring the distribution of radionuclides such as ^{210}Pb (natural origin, half-life: 20.4 years) or ^{137}Cs (artificial fission product, half-life: 30.2 years) as a function of the sediment depth. When varves exist, a direct sedimentation rate might be measurable by counting varves.

The development of the ^{210}Pb technique was initiated by Goldberg [Goldberg and Koide, 1962] and first applied to the dating of lake sediment by Krishnaswami et al. [1971]. The two radioelements, ^{210}Pb and ^{137}Cs have been extensively used for studying the sedimentary processes in the American Great Lakes as well as in some large lakes in Europe. A few examples

follow: Lakes Mendota, Trout, Tahoe, and Titicaca [Koide et al., 1973]; Lake Michigan [Robbins and Edgington, 1975]; Lake Superior [Bruland et al., 1975]; Evans et al., 1981]; Greifensee (Switzerland) [Gaggeler et al., 1976]; in Britain [Pennington et al., 1976]; Lake Huron [Robbins et al., 1977]; Lake Ontario [Farmer, 1978]; Lake Erie [Nriagu et al., 1979]; several lakes in Finland [Appleby et al., 1979]; Saguenay Fjord (Quebec) [Smith and Walton, 1980]; Hudson Bay [Olsen et al., 1981]; Lake Constance (Switzerland) [Dominik et al., 1981; Dominik et al., 1984]; Lake Lemán (Switzerland) [Vernet et al., 1984]. A review of lacustrine studies with ^{210}Pb is given by Krishnaswami and Lal [1978].

The ^{210}Pb dating technique is based on the existence of a continuous atmospheric flux of ^{222}Rn giving rise to ^{210}Pb through radioactive decay processes. Lead 210 is incorporated into the sediments through different processes. Despite the great significance of the technique, the precise nature of the processes by which ^{210}Pb accumulates in lake sediments is not yet well understood. A review of these processes is given by Oldfield and Appleby. [1984]. For lakes with constant rates of sediment accumulation this is not of great consequence. This is presumably the case in the lakes we study here. Most of these lakes are small alpine ponds located at high altitude in well-preserved areas where no human activities take place and which have only been used for sheep grazing since historical times. Therefore the sedimentation processes are presumably in a stationary state. Robbins [1978] has treated in detail the principles underlying the ^{210}Pb method and reviewed its applications. He considered models for which (1) both the flux of ^{210}Pb and the sedimentation rate are constant and (2) only the flux of ^{210}Pb is constant. When the accumulation rate is constant, the two methods give identical results, and the sedimentation rate is obtained from the exponential decrease of the unsupported ^{210}Pb activity with depth. In some cases, many authors have observed a nonlinearity in the ^{210}Pb profile of the near-surface sediments in the top few centimeters. These range from depressed ^{210}Pb concentrations to strongly hipped profiles. These profiles have been related to different origins such as chemical origin (oxydoreduction with migration, mobility of dissolved Pb in the surface layer of sediments [Koide et al., 1973]), physical mixing origin [Petit, 1974], or biological activity [Robbins et al., 1977; Robbins et al., 1978]. It is noted that in order to detect this regular increase, if it exists, sediment collection has to be performed carefully.

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The ^{137}Cs originates mainly from atmospheric nuclear tests performed from 1952 to 1975 and more recently from the Chernobyl event (1986). As the injection dates are well known, the presence of ^{137}Cs in the sediments can be interpreted in terms of time deposition. This field is well documented in the pioneer works on the North America Great Lakes [Robbins and Edgington, 1975; Robbins et al., 1977; Robbins et al., 1978]. The ^{137}Cs distribution is difficult to interpret because a variety of mechanisms come into play up to the final stage where Cs is firmly trapped into the sediment. Its distribution with sediment depth depends on the ^{137}Cs flux at the sediment interface and on the mixing process. Mixing includes the migration of dissolved Cs, bioturbation, and the migration of Cs sorbed onto particles during physical disruption of the sediment. The most direct approach is to associate the maximum in ^{137}Cs activity in the sediment with the date of maximum atmospheric deposition. The consequence is that the peak of Cs distribution is considered to represent the 1963 level in the sediment. A more complex analysis can fit the different parameters in a diffusion mixing model. Simpler interpretation can sometimes lead to quite erroneous results. The more complete treatment is difficult mathematically, involves a number of unknown parameters, and commonly provides a solution which is not unique. Moreover, this analysis requires sophisticated mathematical modeling which is usually not employed by those interested only in measuring sedimentation processes. The latter group usually uses the first type of approach. The present paper is written with the clearly defined purpose of trying to make a link bridging the gap between these two communities.

This article has two purposes:

1. First we want to present a procedure for interpreting the ^{137}Cs distribution in sediment of intermediate complexity relative to the two afore-mentioned methods. This procedure presents the double advantage of being as rapid to use as the crude one and as correct as the second (as far as the hypotheses of mechanisms introduced in the modeling are valid). In a word, to interpret ^{137}Cs distribution we do not want to use an iterative procedure to construct the best fits to each measured ^{137}Cs profile (as done previously), but we want to present a procedure in which we need only to perform a visual comparison between the simulated and measured Cs distribution. This procedure has been already described in a preceding article [Mélières et al., 1988]. In that article the ^{137}Cs distribution was simulated by treating within the framework of the diffusion model, two distinct mixing scenarios corresponding to slow and rapid mixing. The actual situation is probably somewhere in between these two extreme cases. In each scenario the distribution was simulated according to different mixing layer thicknesses. The comparison between the simulated and measured distribution gives access to different sedimentation parameters as sedimentation rate, mixing thickness, and mixing rate. In this previous work we also presented the ^{134}Cs , ^{137}Cs , and ^{210}Pb profiles of a core taken in an alpine mountain lake. The ^{137}Cs profile was interpreted using the simulation, which gave access to sedimentation parameters. An independent determination of the same parameters was done

using the ^{210}Pb profile as a check on the Cs results. The ^{137}Cs distribution originating in the Chernobyl event gave an indication of the mixing thickness as well as an estimation of the Chernobyl fallout on the alpine area.

The present article describes a procedure for interpreting the ^{137}Cs distribution in sediment based on these same assumptions before. This procedure is improved here by introducing the sampling simulation (i.e., a parameter related to the sampling thickness) and a new parameter related to the profile of the ^{137}Cs distribution, called the shape parameter. It shows how sharp the distribution is. This parameter is simulated for different mixing scenarios. The introduction of these two parameters permits a better interpretation of the measured distribution and a better estimation of the uncertainties. The distribution will be simulated using simplified hypotheses; comparison with experimental data will rapidly show the validity of such hypotheses. The advantage of the present simulations is in the limited number of parameters involved, thus allowing us to determine if the neglected parameters or processes are to be considered.

2. In a second part we will present the measured distribution of ^{137}Cs and ^{210}Pb in different lake sediment cores. These lakes are small high-mountain lakes in the French Alps. The ^{137}Cs profiles are interpreted using the above procedure, and the ^{210}Pb profiles (measured only in some cases) are used independently to determine sedimentation rates and mixing. Comparison between the results will allow us to test the validity of the proposed method. Finally, the values of the estimated sedimentation processes obtained for the different lakes are compared.

Methodology

The measured ^{137}Cs distribution in sediment results from the interplay of many factors which can be described briefly as follows: (1) atmospheric ^{137}Cs flux. As the injection from thermonuclear tests was mainly at a stratospheric level, fallout was roughly homogeneous with latitude from 1955 to 1982. This flux is well documented [Reiter, 1978]. Since the Chernobyl event in 1986, a tropospheric injection of ^{137}Cs led to inhomogeneous fallouts [Pourchet et al., 1986; Pourchet et al., 1988]. Thus an experimental evaluation for each site has to be done to estimate this additional flux; (2) transport process from the soil to the lake (soil release process); (3) transport process through the lake (time delay between arrival to the lake and sediment deposit); (4) mixing processes in the sediment (surface deposit is spread out through the sediment column due to bioturbation, chemical, or mechanical diffusion, etc...); (5) accidental sediment perturbation, having multiple causes such as landslides, avalanches, seismologic or volcanic events, or simpler causes, such as a stone being thrown at this place; and (6) sediment sampling which averages the distribution over a given thickness.

The present model is presented on the assumption that the flux of ^{137}Cs deposit on the sediment surface is proportional to atmospheric fallout. This implies that both soil release and

transient time in the lake are negligible. The last assumption is always justified in the case of small ponds. The first one will be justified a posteriori if the measured ^{137}Cs distribution can be fitted with the calculated one. The annual atmospheric fallout is taken from Cambray et al. [1981] and is corrected for decay to 1986 (Figure 1).

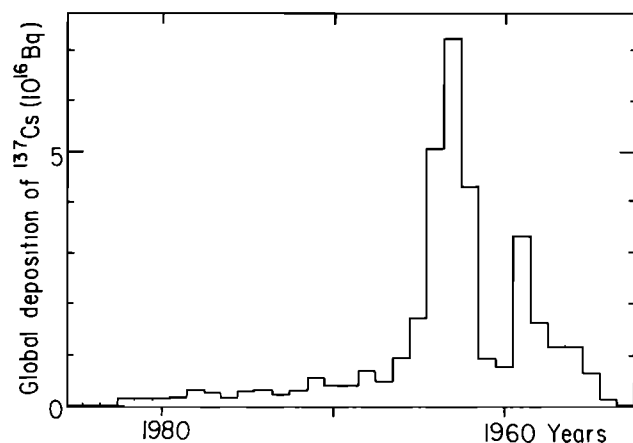


Fig. 1. The estimated annual north hemisphere atmospheric ^{137}Cs fallout, 1986 decay corrected [after Cambray et al., 1981].

A number of numerical models have been developed by using both diffusive and advective approximations of net particle transport to help to evaluate the effect of the sediment mixing on various vertical distributions [Goldberg and Koide, 1962; Goldberg, 1963; Berger and Heath, 1968; Guinasso and Schink, 1975; Robbins and Edgington, 1975; Peng et al., 1977; Benninger et al., 1979; Fisher et al., 1980; Officer and Lynch, 1980; Olsen et al., 1981; Boudreau, 1986a]. As shown by many authors [Rhoads, 1974; Krezoski et al., 1984; Krezoski and Robbins, 1985], the diffusive advective approximation does not represent exactly the mixing processes. Nevertheless, it is commonly admitted that this approximation represents reasonably well the reality, leading to a simpler mathematical formalism than the formalism used in the nondiffusive approach [Boudreau, 1986b; Boudreau and Imboden, 1987]. In our case, mixing is treated as the result of a diffusion process.

The mixing simulation has been previously reported [Mélières et al., 1988] and is summarized as follows. We use here the result of the time dependent mixing model developed by Guinasso and Schink [1975]. This model simulates the concentration profile of a conservative tracer resulting from a unit impulse falling on the sediment surface at a given time, as a function of depth and time. The vertical mixing takes place in a layer of thickness L , at a rate characterized by a constant eddy diffusion coefficient D , in sediment accumulating at a rate S . The hypothesis of a constant eddy diffusion coefficient D is justified by the fact that to introduce different mixing layers with decreasing D values as depth increases does not strongly affect the value of the fitted parameters [Olsen

et al., 1981]. Mixing is therefore characterized by a dimensionless coefficient, the Peclet number: $G = D/(LS)$. Guinasso and Schink [1975] present the simulation for different G values. For a given G value there corresponds a well-defined mixing function. The conservative tracer distribution resulting from the unit pulse is presented for each mixing function after different lapses of time. It is therefore possible to reconstruct the signal at a given time, t_0 , resulting from an annual input of a radioelement like ^{137}Cs : the signal is the convolution of the mixing function with the annual input distribution (decay corrected to t_0). Such a simulation is presented here for sediments cored in $t_0 = 1986$, for two different mixing cases corresponding to two different groups of G values: (1) a slow mixing covering the cases $G \leq 0.03$. This group of values corresponds to situations in which the distribution maximum is only very slightly displaced compared to the distribution maximum without mixing. This function is approximated in our case by a triangular shaped function of constant area, centered at the input depth; and (2) a rapid mixing covering the cases with $G \geq 3$, corresponding to uniform, rapid mixing with slow sedimentation rate. The mixing function can be closely approximated by the exponentially decreasing function developed by Berger and Heath [1968]. This mixing function corresponds to very rapid mixing where the tracer is equally distributed in the mixing layer. It corresponds to the maximum displacement of the center of the unperturbed signal. The two functions have been described by Mélières et al. [1988].

The ^{137}Cs distribution as a function of depth has been simulated for these two types of mixing and for various mixing layer thicknesses, L . In order to simplify graphical representation, the depth variable is not expressed in terms of length, z , but in terms of time of deposit. Mixing layer thickness, L , is converted to equivalent time units $\tau = L/S$. In that representation the family of distributions as a function of z corresponding to different sedimentation rates can be deduced from the single curve of mixing depth τ .

In order to simulate, as closely as possible, the measured signal, we now take the sampling into account. The sampling thickness, l , usually of the order of 1 cm, corresponds to time deposition Δ (sampling time) which can be expressed using ρ the "mean density" (dry matter per unit volume) in the region where density is constant (this excludes the two or three first samples).

$$\Delta = \frac{\rho l}{S} \quad (1)$$

The Cs distribution is given for sampling times ranging from 1 year to 41 years. Sampling is performed starting from the surface sediment. The Cs simulations are presented in Figures 2a and 2b corresponding to rapid (R) and slow (S) mixing processes; respectively for mixing thickness varying from 2 years to 40 years.

By comparing measured and simulated distributions, it is possible to approximate the following parameters if and only if mixing corresponds to a diffusional process, and if soil released is negligible: rate of mixing (R or S),

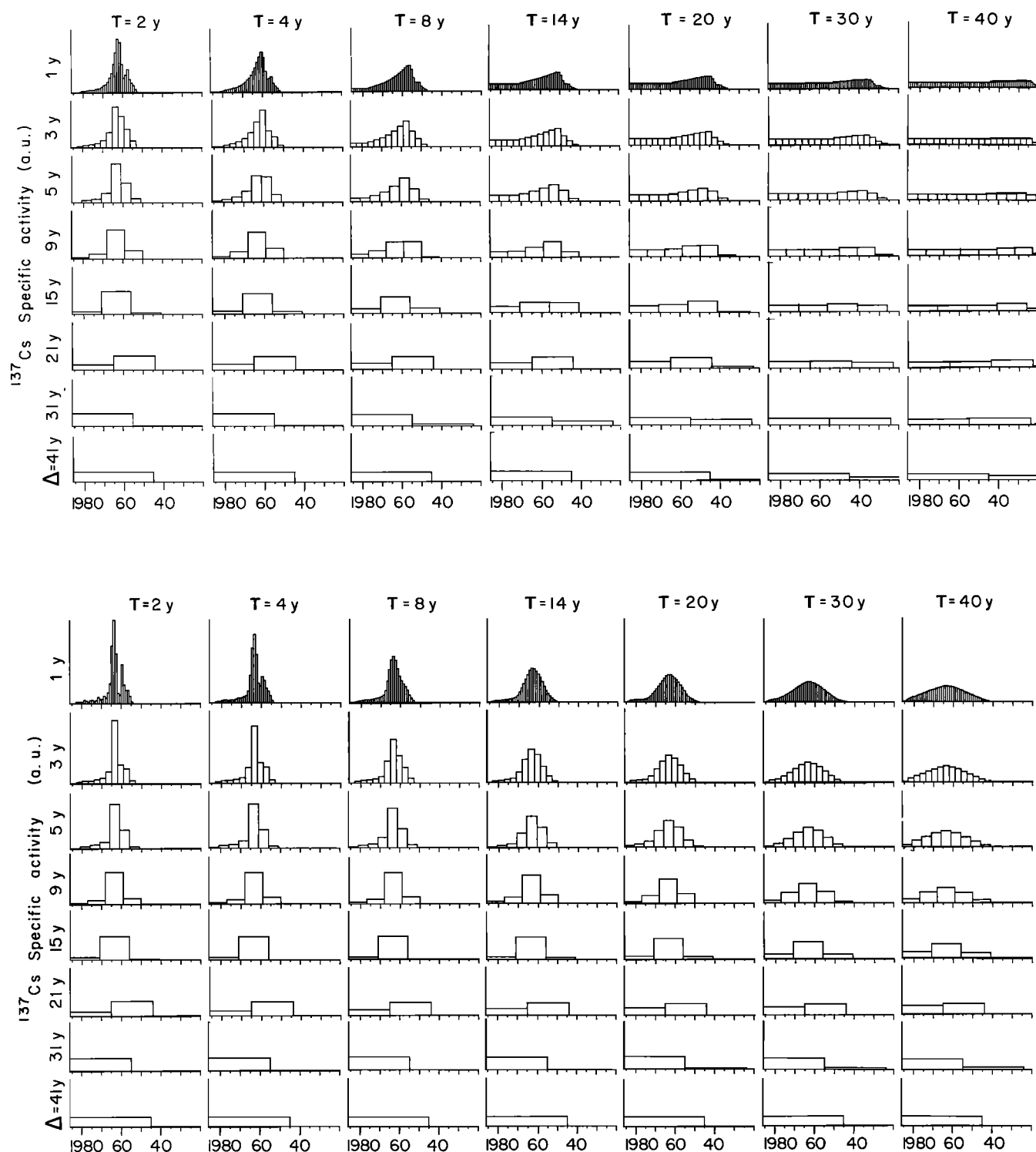


Fig. 2. Simulation of the distribution of ^{137}Cs originating in thermonuclear tests with sediment depth after sampling, in the scenario of (a) "rapid" mixing with $G \geq 3$ and (b) "slow" mixing with $G \leq 0.03$. Mixing thickness, τ , sampling, and depth are expressed in equivalent time. To each value of τ , ranging from 2 to 40 years, correspond different values of Δ from 1 to 41 years.

and mixing depth (τ), sampling thickness (Δ), and sedimentation rate (S).

It is useful to introduce a new parameter, A , characterizing to some extent the shape of the activity distribution in the sediment. This parameter, which we will call the shape parameter, expresses how sharp the ^{137}Cs activity distribution in the sediment is. It will be obtained by comparing the maximum value of the distribution with the total activity deposited per surface unit in the sediment. The sample activity is given per mass unit (Bq g^{-1}), but it is necessary to express the maximum of activity per surface unit and per time unit ($\text{Bq cm}^{-2} \text{ yr}^{-1}$) in order to have density independent values. Hence this maximum value is given by the product of the measured maximum activity, $A(\text{max})$, by the sedimentation rate S . The total activity, $A(\text{total})$, is the activity per surface unit integrated over depth, expressed in becquerels per square centimeter. The shape parameter is defined as the ratio of the maximum activity to the total activity; it will be given in yr^{-1} .

$$A = \frac{A(\text{max}) S}{A(\text{total})} \quad (2)$$

The shape parameter has been calculated for each simulated distribution presented in Figure 2, where the activity is expressed per unit time as a function of depth expressed in units of time. The value of A corresponds to a given case of mixing (slow or rapid), to a given sampling parameter Δ , and to a given mixing thickness τ . The calculated values of A are represented as a function of Δ , for different values of τ (Figure 3). This type of representation will be helpful for interpreting the experimental results (see next section). In this calculation, the sampling is centered on the maximum value of the distribution. For a given distribution it corresponds to the highest value of the sampled maximum and therefore of A . In reality, sampling is performed starting from the surface, and the maximum is usually not centered in one sample. This implies that the measured A value might have a lower value than that calculated.

We now interpret the ^{137}Cs distribution of some high-mountain lakes using the above procedure. In some cases the ^{210}Pb measurements provide an independent value of the sedimentation rate and let us test the validity of such a procedure.

Measurements

We present measurements on sediment cores of seven small shallow high-mountain lakes. These lakes are situated between 911 m and 2440 m altitude in the French Alps. As pointed out previously, they are located in areas where no recent anthropogenic disturbance has occurred. Their characteristics such as altitude, depth, area, and drainage area are given in Table 1. Cores were collected in the deepest part of the lakes by a skindiver using an 8-cm-diameter plastic tube and were immediately sectioned at 1-cm intervals. Samples were dried at 70°C for 48 hours. Lead 210 was measured for three lakes through the first daughter, ^{210}Pb , using α spectrometry [Hasanen, 1977]. The excess ^{210}Pb

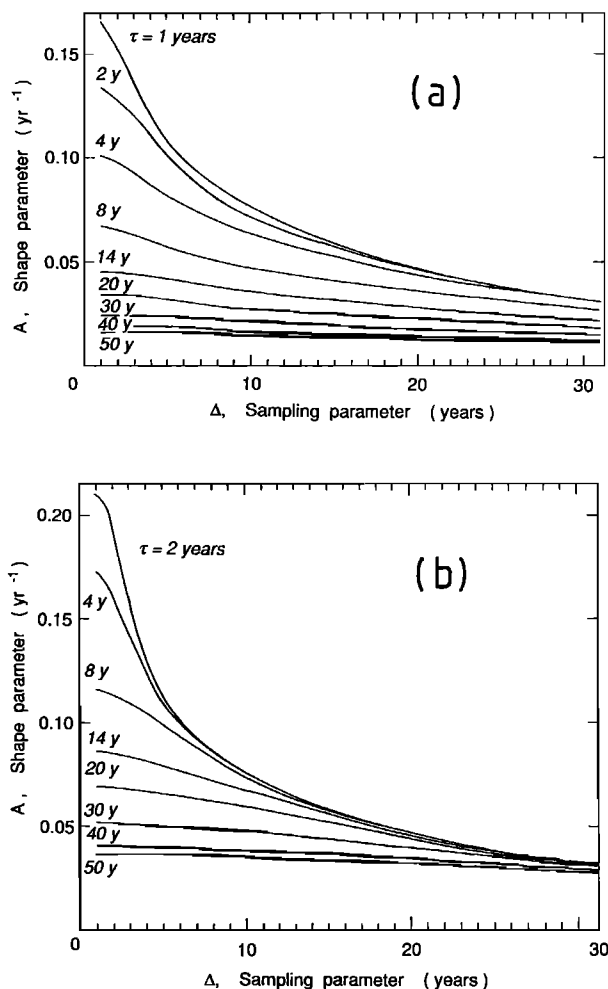


Fig. 3. The shape parameter, A , as a function of the sampling thickness, Δ (in time units), for different values of the mixing depth, τ (in time units) in the scenario of (a) "rapid" mixing with $G \geq 3$ and (b) "slow" mixing with $G \leq 0.03$.

was estimated by subtracting the mean minimum value. Cesium 137 γ activity was measured in bulk samples with a 70 keV/channel spectrometer in most of the cases; this low resolution gives rise to an additional signal and explains the ^{137}Cs signal baseline.

In Lake Lévié, however, the Cs γ activity was measured with a high-resolution spectrometer (0.4 keV/channel). This lake was the only one to be cored after the Chernobyl event, and the corresponding measurements in ^{134}Cs , ^{137}Cs , and ^{210}Pb have been previously reported [Mélières et al., 1988]. We present here the ^{137}Cs values originating only from the thermonuclear tests. We have subtracted the contribution due to Chernobyl.

The depth distribution of ^{137}Cs and of unsupported ^{210}Pb are presented in Figures 4 and 5, respectively. The integrated ^{137}Cs activity, A (total), and the maximum activity A (max) (the baseline having been subtracted when necessary) are presented in Table 1, together with the mean density ρ .

TABLE 1. Geographical Characteristics of the Lakes

Lake	Coring Date	Altitude, m	Depth, m	Lake area, m	Drainage area, km ²	ρ , g cm ⁻³	A (total), Bq cm ⁻²	A (max), Bq g ⁻¹
Besson	Sept. 1982	2070	~10	0.06	5	0.08	0.429	0.555
Laffrey	July 1982	911	~20	1.3	40	0.13	0.045	0.068
Luitel	Oct. 1982	1300	~5	0.005	1.7	0.07	0.118	0.165
Noir	Sept. 1983	2440	~6	0.01	0.11	0.1	0.518	0.836
En Paris								
Plan du Lac	Aug. 1984	2362	6.2	0.01	0.98	0.23	0.155	0.359
Tourbière du lait	Aug. 1984	2190	1.6	0.002	0.11	0.04	0.170	1.014
Léridé	Sept. 1986	2400	~2	0.003	0.05	0.1	0.377	1.00

The parameter ρ is the "mean density" of the sediment (dry matter per unit volume), A (total) is the total ¹³⁷Cs activity per square centimeter in the sediment, and A (max) is the maximum value of the ¹³⁷Cs activity distribution in the sediment. The two last quantities refer to the net ¹³⁷Cs activity, i.e., baseline subtracted.

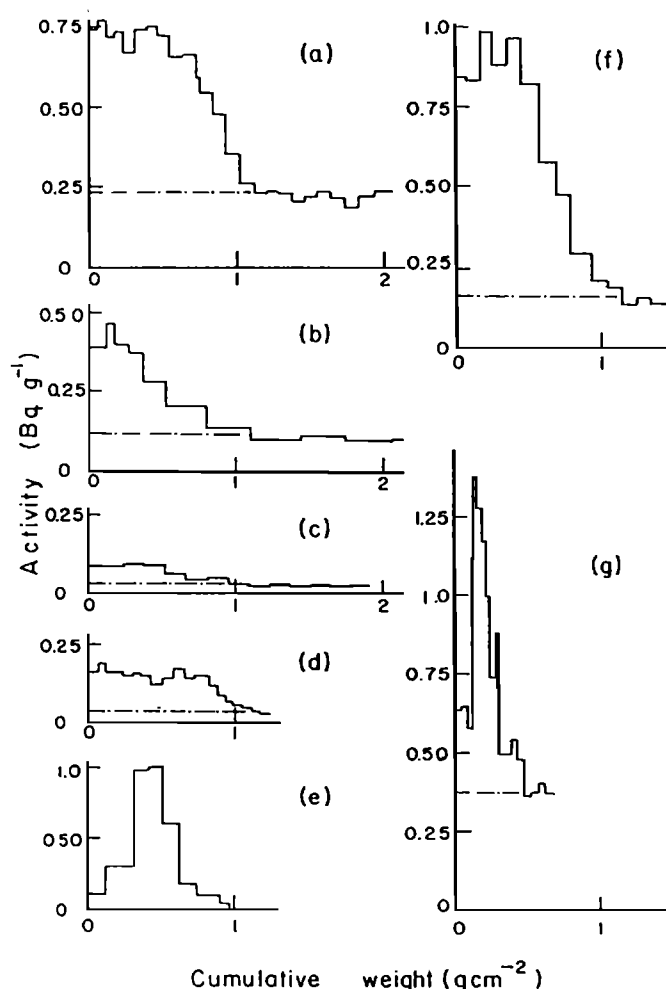


Fig. 4. Cesium 137 activity as a function of depth sediment for (a) Lake Besson, (b) Lake "Plan du Lac", (c) Lake Laffrey, (d) Lake Luitel, (e) Lake Léridé, (f) Lake "Noir d'En Paris", and (g) Peat bog "Tourbière du lait". The additional base line is related to the low resolution γ spectroscopy (see text).

Interpretation

Cesium 137 results

In Table 2 are listed the values from the different lakes, obtained in the following way. We compare the measured Cs activity (Figure 4, base-line being subtracted) with the simulated activity presented in Figure 2. To perform this comparison, we choose the simulated curve which presents the best fit with the measured one. The optimum fit is done subjectively. Note that this fit is visual; as pointed out before, we do not want to use an iterative procedure to construct the best fit to each measured profile of ¹³⁷Cs but only the graphic simulation which allows the consideration of a number of situations. This visual comparison does not require familiarity with the treatment of diffusion. When this fit is possible, we deduce from the calculated curve the following parameters characterizing the sedimentation process for the individual lake at the coring place: the mixing process (rapid or slow), the value of the mixing depth τ and of the sampling thickness Δ , and the sedimentation rate S which can be obtained by locating, when possible, the maximum position (noted as event a in Table 2). We then assign the date corresponding to the position of the maximum of the simulated signal (and not the date of 1963 corresponding to the maximum of the atmospheric fallout). When no maximum is noticeable, we locate the position where the signal begins to decrease as depth increases (event b).

In a second stage the sedimentation rate is used to calculate the shape parameter A , using relation (2), and the sampling thickness in time units using the fact that samples are 1 cm thick (relation (1)); this last value might be different from the first evaluation of sampling thickness and is referred to as Δ_1 . Using the values of A and Δ_1 , it is possible to estimate with the diagram $A(\Delta)$ (Figure 3) the mixing thickness τ_1 . Note that Δ_1 and Δ_2 as well as τ_1 and τ_2 are obtained independently (within the framework of the diffusive model). These values are given in Table 2. The degree of agreement between the different estimates of Δ_1 and Δ_2 , τ_1

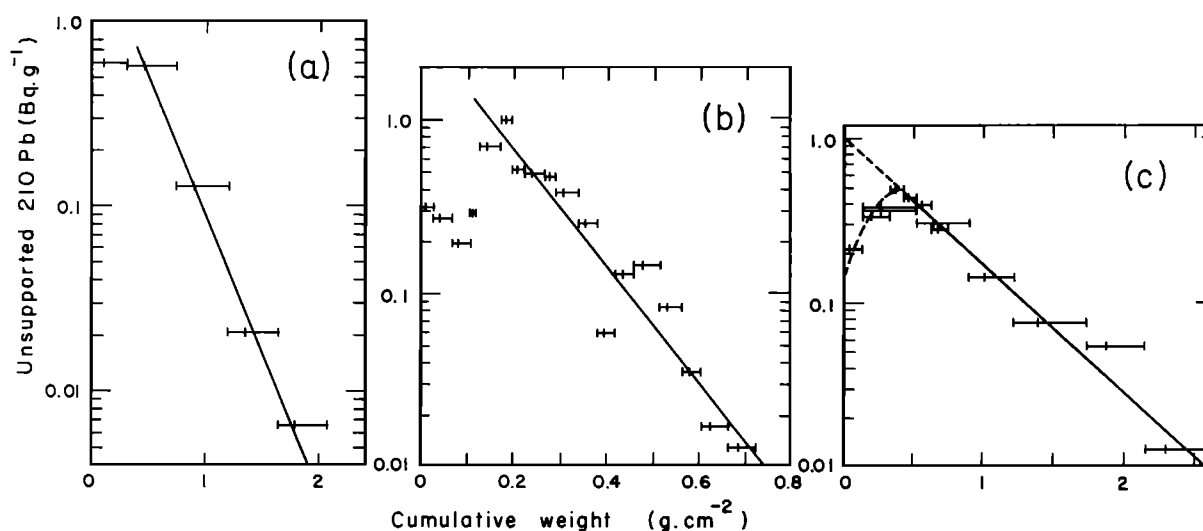


Fig. 5. Unsupported ^{210}Pb activity as a function of depth sediment, corresponding to (a) Lake "Noir d'En Paris", (b) Peat bog "Tourbière du lait", and (c) Lake Léridé.

and τ_2 , will give a measure of the uncertainty. The final estimated values for S and τ (average of τ_1 and τ_2) are given in the last columns together with the mean mixing thickness calculated from

$$L = \frac{S \tau}{Q} \quad (3)$$

The uncertainty in S originates from the uncertainty in the estimated date of the event a or b.

Lead 210 results

We measured the ^{210}Pb distribution for three of the lakes. As can be seen from Figure 5, the profile of the unsupported ^{210}Pb in the near-

surface sediment presents a non-linear behavior. As previously mentioned, this type of distribution has already been reported by different authors and might be attributed to mechanical mixing in the case of Lake Noir d'En Paris, or to chemical process as suggested by Koide et al. [1973] in the case of the peat bog Tourbière du Lait and Lake Léridé. The linear part of the distribution (in a semilog representation) of the unsupported ^{210}Pb activity has been interpreted in terms of the sedimentation rate S , using the constant flux model. In the same way as previously, A is calculated from the Cs distribution using (2), and Δ using (1). These parameters together lead to the value of τ and L for the mixing case determined by the Cs results. Values are given in Table 3.

TABLE 2. Different Parameters Deduced from the Comparison Between Simulated and Measured ^{137}Cs Distributions

Lake	<div><div></div><div></div><div></div><div></div><div></div><div></div><div></div><div></div><div></div><div></div><div></div><div></div></div>											
	Mixing Type	τ_1 , years	Δ_1 , years	Event Date	Depth, g cm ⁻²	S_2 g cm ⁻² yr ⁻¹	Δ_2 , years	A_2 yr ⁻¹	τ_2 , years	S_2 g cm ⁻² yr ⁻¹	τ , years	L, cm
Besson	R	30	3-5	b 1938	0.70	0.016	5	0.020	30-40	0.016 ± 0.003	33 ± 3	6.6 ± 2
Laffrey	R	14-30	5-15	b 1945	0.44	0.012	11	0.018	30-40	0.012 ± 0.004	29 ± 7	2.7 ± 1
Luitel	R	30	3-5	b 1938	0.8	0.018	4	0.025	30	0.018 ± 0.004	30 ± 2	7.7 ± 2
Noir En Paris	R	20-30	9	b 1940	0.5	0.011	9	0.018	40	0.011 ± 0.003	33 ± 8	3.6 ± 2
Tourbière du lait	R	8	3	a 1958	0.15	0.0055	8	0.032	14-20	0.005 ± 0.002	12 ± 5	1.5 ± 1
Lérié	R	8	5	a 1963	0.4	0.017	6	0.045	12	0.017 ± 0.004	10 ± 2	1.7 ± 1

R refers to rapid mixing, and τ and Δ refer to the mixing depth and sampling thickness (in time units), respectively. Event a refers to a distribution where the maximum is located by the date in the reconstructed signal and the depth in the measured one; event b refers to a distribution where the signal decrease is located. S , A , and L are the sedimentation rate, the shape parameter calculated from relation (2), and the mixing depth calculated from (3), respectively. The arrows indicate the way those parameters are deduced. In the last three columns are reported the final estimated values of S , τ , and L .

TABLE 3. Different Parameters Obtained from the Unsupported ^{210}Pb Distribution

Lake					
	$S, \text{ g cm}^{-2} \text{ yr}^{-1}$	$\Delta, \text{ years}$	$A, \text{ yr}^{-1}$	$\tau, \text{ years}$	$L, \text{ cm}$
Noir	0.010	10	0.016	40 ± 10	4 ± 1
En Paris	± 0.002				
Tourbière du lait	0.0045	9	0.027	25 ± 3	2.8 ± 1
	± 0.001				
Lérié	0.018	6	0.048	11 ± 2	2 ± 0.5
	± 0.002				

Parameters are described in Table 2.

Comments

The Cs distribution is, in most cases, interpretable mainly as resulting from a rapid mixing process.

For five lakes (Besson, Laffrey, Luitel, Noir d'En Paris, Lérié) the agreement between Δ_1 and Δ_2 on one hand and τ_1 and τ_2 on the other hand is satisfactory. For those lakes the mixing process is well represented by a rapid diffusional process. However, in most of these cases the decrease of signal as depth increase is slightly slower than predicted by the model. This can be related to the fact that the mixing cannot be exactly assimilated to a diffusional mechanism [Robbins et al., 1977].

In the case of the peat bog "Tourbière du Lait," the distribution can also be interpreted in the framework of a rapid mixing process, but the agreement between Δ_1 , Δ_2 and τ_1 , τ_2 is worse than for the previous lakes. When we try to identify this distribution with the slow mixing simulations, we obtain a much larger discrepancy; this indicates that the rapid mixing is a better approximation. Nevertheless, the estimate of the sedimentation rate in the slow scenario ($0.006 \text{ g cm}^{-2} \text{ yr}^{-1}$) is not very different from the one obtained in the rapid scenario.

For the lake "Le Plan du Lac" the Cs distribution cannot be explained by a diffusion mixing process. It might be due either to perturbations or to a different mixing process.

We now compare estimates of the sedimentation rate obtained independently by ^{137}Cs and ^{210}Pb distributions. The two estimates agree to within 10%, suggesting that the procedure is fruitful. In the case of Lake Lérié, the mixing depth was previously roughly estimated [Mélières et al., 1988] using the ^{137}Cs distribution. A value of 10-15 years has been found, which appears to be consistent with the present one.

When comparing the different results, it appears that in most cases the sedimentation processes in shallow high-mountain lakes can be represented by a rapid mixing process based on a diffusion model. The sedimentation rate is slow, ranging from 0.01 to $0.02 \text{ g cm}^{-2} \text{ yr}^{-1}$ excluding the peat bog value of $0.004 \text{ g cm}^{-2} \text{ yr}^{-1}$. Mixing depth ranges over a few centimeters. The Cs release from the drainage area appears not to be significant, otherwise an important Cs release would lead to a broadening of the Cs maximum toward the surface sediment, and therefore the present simulation would not fit the reality.

These sedimentation rate values are similar to those obtained by El Daoushy [1986] in many Scandinavian and Finnish lakes.

Conclusion

We have presented a procedure for interpreting the ^{137}Cs distribution in lake sediment cores. For this purpose we have simulated the ^{137}Cs distribution assuming that the mixing is a diffusional process. We have treated separately mixing cases corresponding to slow and rapid diffusion, assuming that the real case lies somewhere in between. In the simulations, soil release is not included nor is the Chernobyl release which is highly variable from place to place. This signal, after mixing, will distort the upper part of the distribution. Modeling can easily be done once the local atmospheric fallout is known. The sampling was taken into account and the distribution profile was characterized by introducing the shape parameter A. Comparison between simulated and measured distributions allows one to determine the type of mixing (rapid or slow), the mixing depth, the sampling thickness, and the sedimentation rate. A double check for the value of sampling and mixing thickness is therefore possible and gives an idea of the consistency of the different estimates.

For three lakes it was possible to test the preceding estimates by measuring the ^{210}Pb distribution, which provides an independent estimate of S. Agreement is very satisfactory. The proposed procedure was motivated by the need to interpret directly, by visual comparison, the ^{137}Cs sediment signal of several cores and to deduce an order of magnitude of sedimentation rate, type of mixing, and mixing thickness within a simplified framework. In the case where sedimentation processes are more complicated, a discrepancy between measurements and simulation will occur.

The results show that common features appear in the sedimentation process of these shallow high-mountain lakes: rapid mixing processes with a mixing depth of a few centimeters, slow sedimentation rate around $0.01 \text{ g cm}^{-2} \text{ yr}^{-1}$ (within a factor of 2), and no large Cs release from the drainage area.

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