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THE CALCULATION OF LEAD-210 DATES FOR McKAY LAKE SEDIMENTS

by

S.R. Joshi[1], B.S. Shukla[2] R. McNeely[3]

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[1]National Water Research Institute
Lakes Research Branch
Canada Centre for Inland Waters
Burlington, Ontario L7R 4A6 Canada

[2]B.S. Shukla
Department of Materials Science
& Engineering
McMaster University
Hamilton, Ontario L8S 4L7 Canada

[3]R. McNeely
Geological Survey of Canada
Energy, Mines and Resources Canada
601 Both Street
Ottawa, Ontario K1A 0E8, Canada

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Management Perspective/Executive Summary

Naturally-occurring Pb-210 is now widely used for deriving dates for sediment core sections.The derivation of 'age' is based on standard assumptions of constant sedimentation and flux and the decay of lead-210 with its 22.3-yr half-life. The present core has been assessed in terms of the less-commonly used CRS (constant rate of supply of Pb-210) model which automatically accounts for compaction of sediment with burial.Mixing is found to be present at very small,but measureable, levels. The derived dates are in agreement with those assignable from other known 'markers'.

Unlike other published accounts of Pb-210 dating,this paper gives a complete account of the actual calculation procedures and reports new expressions for estimating the amount of Pb-210 present below the detection limit of the instrument.

Perspective-gestion

Le Pb-210 présent dans la biosphère est couramment utilisé pour dater les sections de carotte de sédiments. Le calcul de l'âge est basé sur les hypothèses normalisées de sédimentation constante et de flux et de dégradation du plomb-210 dont la demi-vie est de 22,3 ans. La carotte en question a été évaluée à l'aide du modèle TAC (taux d'alimentation constant du Pb-210) moins utilisé qui tient compte automatiquement du tassement des sédiments enfouis. On a trouvé un certain taux de brassage très faible, mais mesurable. Les dates ainsi obtenues sont conformes à celles trouvées à l'aide d'autres "marqueurs" connus.

Contrairement aux autres publications sur la datation au Pb-210, le présent document donne un exposé complet sur les méthodes de calcul actuelles et présente de nouvelles formules permettant d'évaluer la quantité de Pb-210 inférieure au seuil de détection de l'instrument.

Abstract

Lead-210 dates are assigned to a sediment core retrieved from McKay Lake, Ottawa, Canada. Sediment mixing is found to have little, but discernible, influence on the age/depth profile. Consideration of mixing yields lower estimates of the derived ages, in agreement with the prediction based on a mathematical model. The inferred dates support the previous assignments based on *Ambrosia* horizon and the known occurrence of a catastrophic event. The procedures used in the calculation of the age profiles are fully described.

Résumé

La datation au plomb-210 a été effectuée sur une carotte de sédiments prélevée dans le lac McKay à Ottawa, Canada. Le brassage des sédiments semble avoir eu une influence très faible mais discernable sur le profil âge/profondeur. La prise en considération du brassage donne des estimations plus faibles de l'âge calculé, conformément aux prévisions basées sur un modèle mathématique. Les dates ainsi obtenues corroborent les estimations précédentes basées sur l'horizon <u>Ambrosia</u> et l'intervention établie d'un événement catastrophique. On y décrit en détail les méthodes utilisées pour calculer les profils d'âge.

Introduction

McKay Lake is a small, cup-shaped body of water within the village of Rockcliffe Park (Ottawa), Ontario, Canada. The prevailing oxygen and thermal regime within the 10.5-m deep lake creates a depositional basin which is highly suitable for the preservation of the sedimentary record. Both X-radiographs and microfossil assays[1] of the sediment core material suggest that the sediment is not disturbed after deposition. Such measurements, however, fall short of a rigorous confirmation of the presence or absene of post-depositional mobility of sediments. Measurement of atmospherically-delivered or excess ^{210}Pb (i.e., total ^{210}Pb less that supported by ^{226}Ra in the sediment) profile in a sediment core constitutes an independent method of dating sediments and for deriving estimates of sediment mixing[2]. The present communication thus examines the effect of mixing on the ^{210}Pb-derived dates for McKay Lake sediments and gives a detailed account of the procedures used in constructing the age/depth profile. Recently, we used the same core to report the first detection of fallout ^{155}Eu and ^{207}Bi in a freshwater system[3].

Experimental

Analytical procedures

The sediment core sectioning and radionuclide analysis procedures have been described earlier[3].

Calculation of ^{210}Pb dates

The ^{210}Pb dates can be derived using two basic models[4] assuming either a constant initial concentration (CIC) of ^{210}Pb in sediments or a constant rate of supply (CRS) of ^{210}Pb to sediments. Though both models assume a constant flux of ^{210}Pb (P, Bq cm^{-2} y^{-1}) at the sediment/water interface, only the CRS model automatically accounts the variations in the sedimentaton rate. For sediment core dating purposes, therefore, the basic CRS model is likely to afford more realistic dates.

Following the CRS model, the age t (in years) of a sediment core section at depth x below the sediment/water interface is given by

$$t = \frac{1}{\lambda} \ln \frac{A(o)}{A(x)} \qquad (1)$$

where A(o) is the total ^{210}Pb (Bq cm^{-2}) in the sediment column, A(x) is the ^{210}Pb beneath sediments of age t, and λ the decay constant of ^{210}Pb (0.0311 y^{-1}). In practice, the analytical data are given in the form of porosity (ϕ) and concentration, C, of ^{210}Pb as a function of x (or mass depth, m, in g cm^{-2}).

In many a situation, the ^{210}Pb measurements are available only for a limited depth (x_L) whereas ^{210}Pb is actually present to the maximum depth, x_M. For the purpose of deriving a good estimate for A(o), it therefore becomes necessary to estimate x_M. In the present case, the ^{210}Pb data were fitted to the equation $C(x) = C(o) \cdot e^{-\alpha x}$, where α is a constant, and the derived values for C(o) and α were used to derive x_M from the equation $C(e) = C(o) \cdot e^{-\alpha \cdot x_M}$, where C(e) represents the concentration of ^{210}Pb which equals the counting error. The total integrated activity of ^{210}Pb, A(o), can then be calculated using two methods.

In the closed method, A(o) for the sediment core is given as,

$$A(o) = \int_{o}^{x_M} C(o) \cdot e^{-\alpha x} \cdot \rho(x)\, dx \,, \qquad (2)$$

where $\rho(x)$ is the <u>in situ</u> density of the sediments. Since $\rho(x)$ is also given as

$$\rho(x) = \rho(s)\,(1 - \phi(o) \cdot e^{-\beta x}) \,, \qquad (3)$$

with β being a constant, $\rho(s)$ the density of dry solids and $\phi(o)$ the porosity at the sediment/water interface, equation (2) can also be written as

$$A(o) = C(o) \cdot \rho(s) \int_{o}^{x_M} \cdot e^{-\alpha x}(1 - \phi(o) \cdot e^{-\beta x})\, dx \qquad (4)$$

or

$$A(o) = C(o) \cdot \rho(s) \left[\frac{1}{\alpha} - \frac{\phi(o)}{(\alpha+\beta)} + \frac{\phi(o) \cdot e^{-(\alpha+\beta) x_M}}{(\alpha+\beta)} - \frac{e^{-\alpha \cdot x_M}}{\alpha}\right] \qquad (5)$$

Similarly, the integrated ^{210}Pb activity $A(x_L)$ between depths x_L and x_M is given by

$$A(x_L) = C(o)\cdot\rho(s)\ [-\frac{1}{\alpha}(e^{-\alpha x_M} - e^{-\alpha x_L}) +$$

$$\frac{\phi(o)}{(\alpha+\beta)}(e^{-(\alpha+\beta)x_M} - e^{-(\alpha+\beta)x_L})]\ , \qquad (6)$$

and activity $A(x)$ between depths x and x_M is given by

$$A(x) = C(o)\cdot\rho(s)\ [-\frac{1}{\alpha}(e^{-\alpha x_M} - e^{-\alpha x}) +$$

$$\frac{\phi(o)}{(\alpha+\beta)}(e^{-(\alpha+\beta)x_M} - e^{-(\alpha+\beta)x})] \qquad (7)$$

Figure 1 depicts important core parameters required for the calculation of sediment age.

In the numerical method, the integrated activity up to depth x_L from the sediment/water interface is calculated as

$$\sum_{i=1}^{i=N} \rho_i(x)\cdot\Delta x_i\cdot C_i(x)\ , \qquad (8)$$

where N is the number of sections, $\rho_i(x)$ is the mass of sediment per cm^3 in the ith section, x is the position of the mid point of the ith slice from the sediment/water interface, Δx_i is the thickness of the ith slice, and $C_i(x)$ the activity of ^{210}Pb per gram of sediment in the ith slice. The total activity is then given by

$$A(o) = A(x_L) + \sum_{i=1}^{i=N} \rho_i(x) \cdot \Delta x_i \cdot C_i(x) \tag{9}$$

For the purpose of the present calculation, as shown in Fig. 2, A(x) is given by $A(x) = A(x_L) + [\{\sum_{i=1}^{i=N} \rho_i(x) \cdot \Delta x_i \cdot C_i(x)\} - 0.5 \cdot \rho_i(x) \cdot \Delta x_i \cdot C_i(x)]$.

The mixing effect is incorporated in the above formulations by considering a mixing zone of a definite thickness (x_s) below the sediment/water interface (Fig. 1). Following OLDFIELD nd APPLEBY[5], the age of a sediment core section at a depth x from the surface in the presence of mixing is given by

$$t = \frac{1}{\lambda} \ln \frac{A(o)}{A(x) + A_m} \tag{10}$$

The value of A_m is calculated by one of the following relations.

$$A_m = W \cdot C(x) , \tag{11}$$

where W is the total dry mass of sediment in the mixing zone, or

$$A_m = \frac{C(x)}{C(s)} \cdot A_m(o) \tag{12}$$

where C(s) is the activity of ^{210}Pb at x = s, i.e. at the bottom of the current mixing zone, and $A_m(o)$ is the integrated activity in the mixing zone.

Results and Discussion

The measured ^{210}Pb profile of the McKay Lake sediment core is shown in Fig. 3. The silt band at a depth of about 23 cm in the core is believed to be exogenous and probably represents a catastrophic event[1]. Although no specific date for the event is available, the 'silt band' is thought[6] to have deposited around 1920. The abnormal nature of this material also shows up on both X-radiographic and microfossil records[1]. In computing ^{210}Pb dates, therefore, both the ^{210}Pb activity and thickness of this section were ignored. The *Ambrosia* horizon (c. 1850) in the core has been located at 35 to 36 cm depth[1].

An inspection of the measured ^{210}Pb profile (Fig. 3) shows two irregularities in the expected exponential decrease of activity with depth. Both anomalies span about 4 to 5 cm in depth and show relatively flat but pronounced (about 0 to 4 cm) or depressed (about 11 to 16 cm) ^{210}Pb contents. Such anomalies are usually thought to indicate mixing or periods of changing rates of supply of ^{210}Pb to sediments. The latter effect is automatically accounted for in the CRS model of ^{210}Pb dating. Equations (10) and (11) or (10) and (12) incorporate the effects of mixing on the age of the sediment slice under consideration. A value of about 0.11 g cm^{-2} is inferred for W and used in equation (11). Figure 4 presents the age/depth profiles for the sediment core both in absence and presence of mixing. The latter profile yields nearly identical ages whether equations (10) and (11) or (10) and (12) are used. The dates derived from both profiles support the dates inferred from the 'silt band' or the <u>Ambrosia</u> horizon, though better agreement is afforded by the dates which account for the effect of mixing. The derived ages are somewhat lower than those suggested by the ^{137}Cs profile[3] in this sediment core. This may be due to dissimilar physical and chemical associations, diffusional characteristics and/or different residence times for the two radionuclides amongst other possible reasons. The present results may, thus, be indicative of yet another failure[7] of ^{137}Cs dating.

The consideration of mixing lowers the age of a sediment core section as is evident from Fig. 4. Assuming mixing to be a diffusive process characterized by the diffusion coefficient K, it can be shown that this indeed is compatible with the prediction based on the foregoing model. Following equation (4), the total ^{210}Pb in a sediment core of infinite length is given by

$$A(o) = C^*(o) \cdot \rho(s) \int_0^\infty e^{-a'x}(1 - \phi(o) \cdot e^{-\beta x})dx \tag{13}$$

where a' = -a. Following KRISHNASWAMI and LAL[2], the constant a is defined as

$$a = \frac{S - (S + 4K\lambda)^{1/2}}{2K}, \tag{14}$$

where S is the sedimentation rate (cm y^{-1}). C*(o) is defined with the boundary condition C(x) = C*(o) for x = 0. Integration of equation (13) yields

$$A(o) = C^*(o) \cdot \rho(s) \left[\frac{1}{a'} - \frac{\phi(o)}{a' + \beta}\right]. \tag{15}$$

If $a' \gg \beta$,

$$A(o) = \frac{C^*(o) \cdot \rho(s)\{1 - \phi(o)\}\ 2K}{\{(S^2 + 4K\lambda)^{1/2} - S\}} \qquad (16)$$

The substitution of this value of A(o) in the rewritten equation (1) yields

$$A(x) = \frac{C^*(o)\rho(s)\{1 - \phi(o)\} \cdot 2K}{\{(S^2 + 4K\lambda)^{1/2} - S\}} \cdot e^{-\lambda t} \qquad (17)$$

This equation incorporates the effect of K on A(x). Thus, if A(x) increases due to K, the calculated age will decrease since A(x) appears in the denominator of equation (1). the influence of K on A(x) can be discerned assuming $4K\lambda \gg S^2$ in which case equation (17) can be written as

$$A(x) = C^*(o) \cdot \rho(s)\{(1 - \phi(o)\} \cdot e^{-\lambda t}\ (K/\lambda)^{1/2} \qquad (18)$$

Thus, for the same value of t, A(x) is higher for the higher value of the diffusion coefficient provided S is considerably small.

In conclusion, the described procedures suggest the presence of little mixing in the sediments of McKay Lake. This mixing has small, but estimable, influence on the derived dates which are found to be in general agreement with the historical markers located earlier. It is to be noted that the derivation of the mixing effects is based on the visual observation of a zone of flattening ^{210}Pb activity profile in the sediment core. It remains yet to be conclusively shown that such a flattening of activity is indeed due to a diffusive mixing process as is generally assumed in such studies. On the other hand, the absence of a 'characteristic' mixing zone does not necessarily imply absence of mixing .

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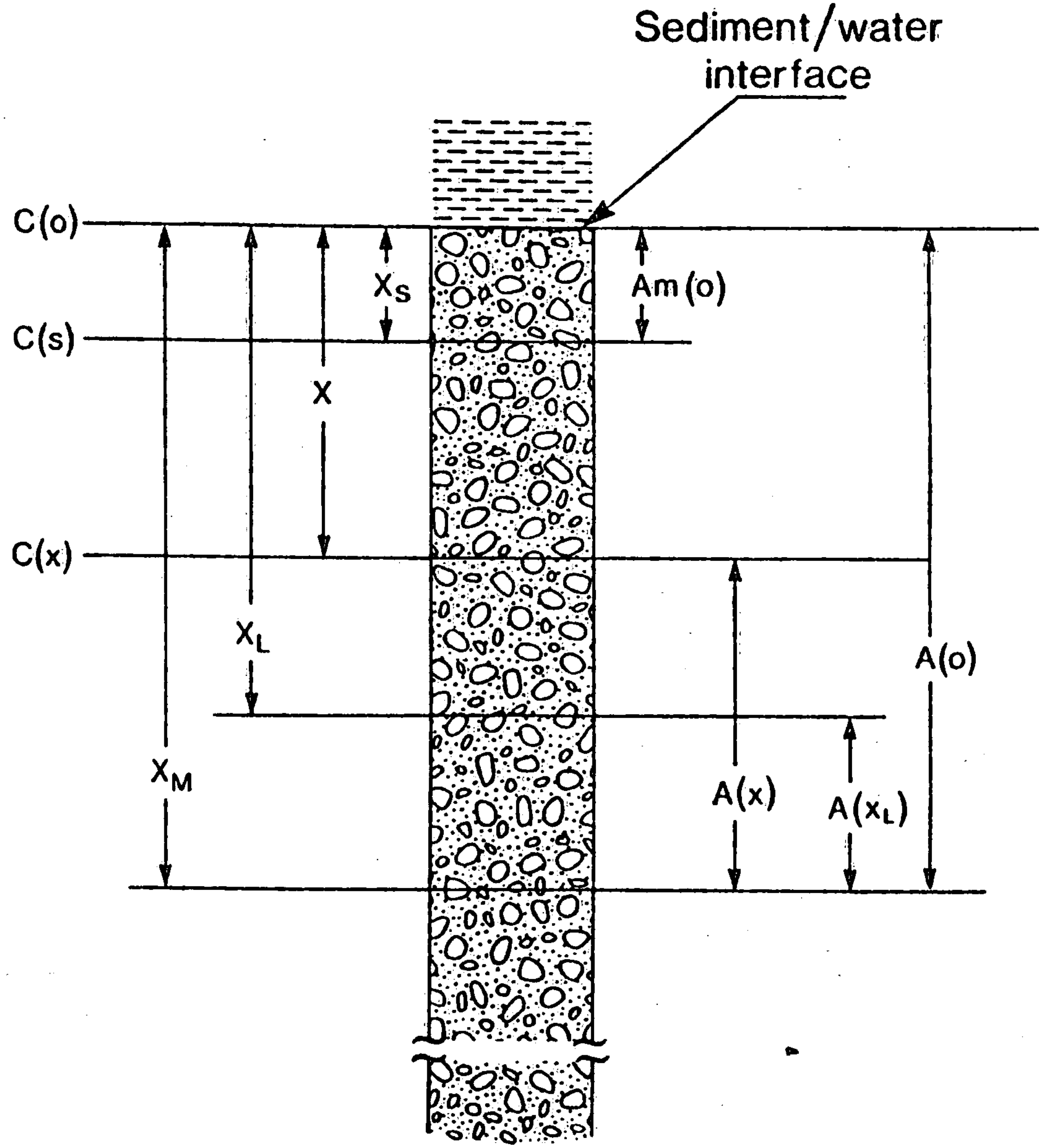
FIGURE CAPTIONS

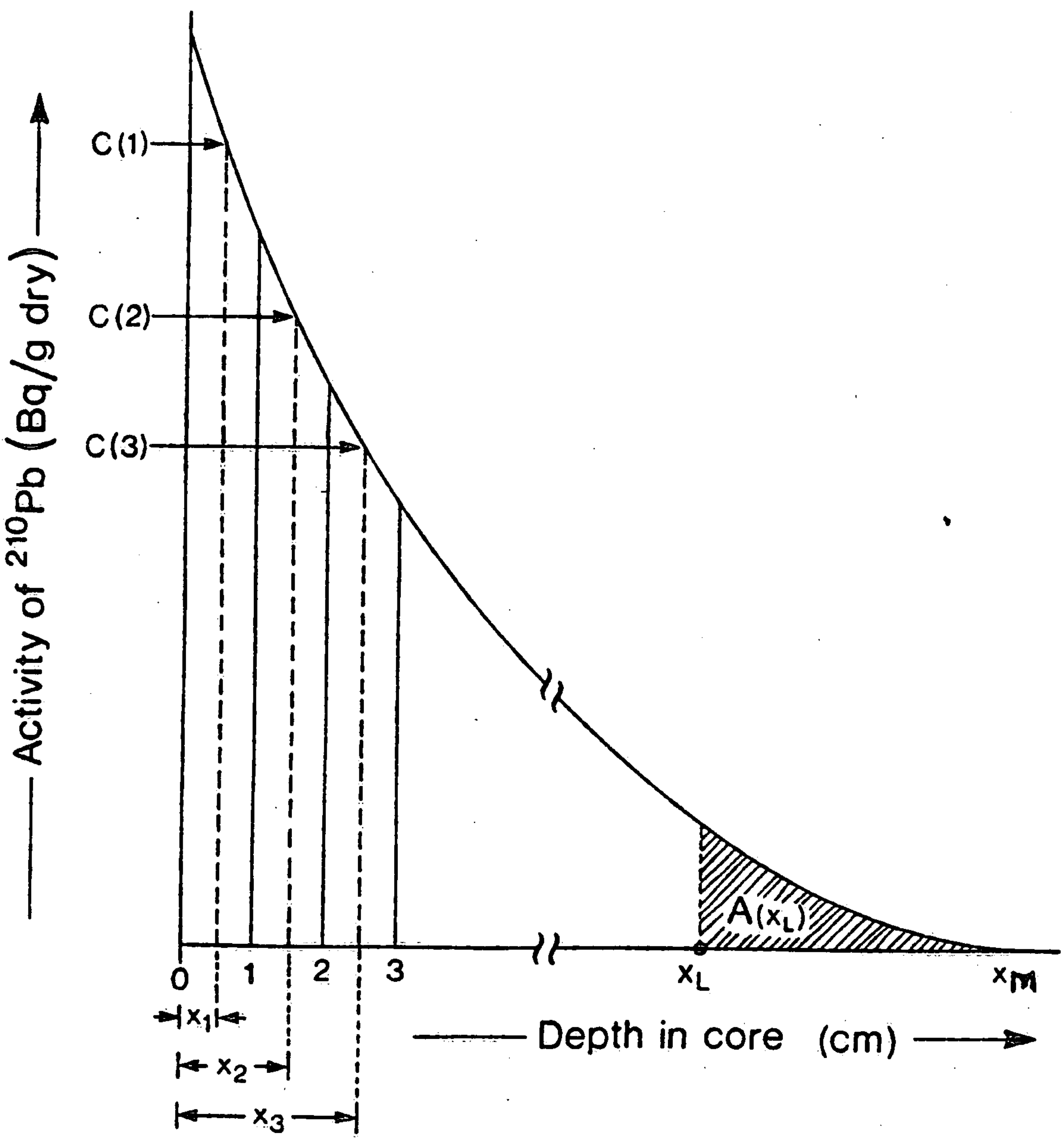
Figure 1. Depiction of important core parameters required for the calculation of sediment age by the CRS mdoel.

Figure 2. Depiction of important core parameters required for the calculation of integral activity of ^{210}Pb (Bq cm^{-2}) in the sediment column . C's and X's are activity and position co-ordinates of the sediment core sections, respectively. The broken lines divide a section in two halves and the adjacent solid lines define the measured thickness of a section.

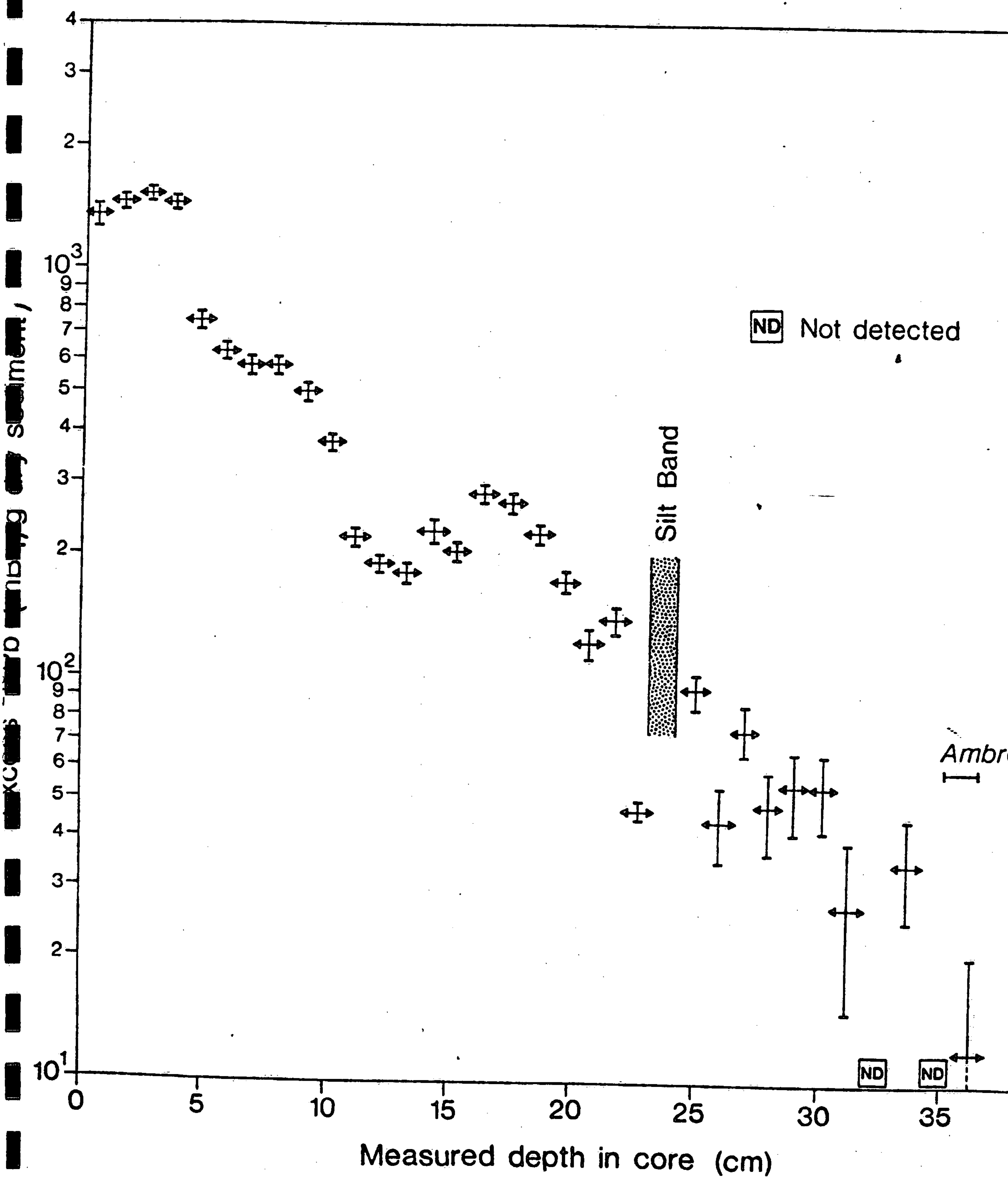
Figure 3. Measured ^{210}Pb profile in the McKay Lake sediment core.

Figure 4. Age/depth profiles for the McKay Lake sediment core in absence [equation (1)] and presence [equations (10) and (11) or (10) and (12)] of sediment mixing.

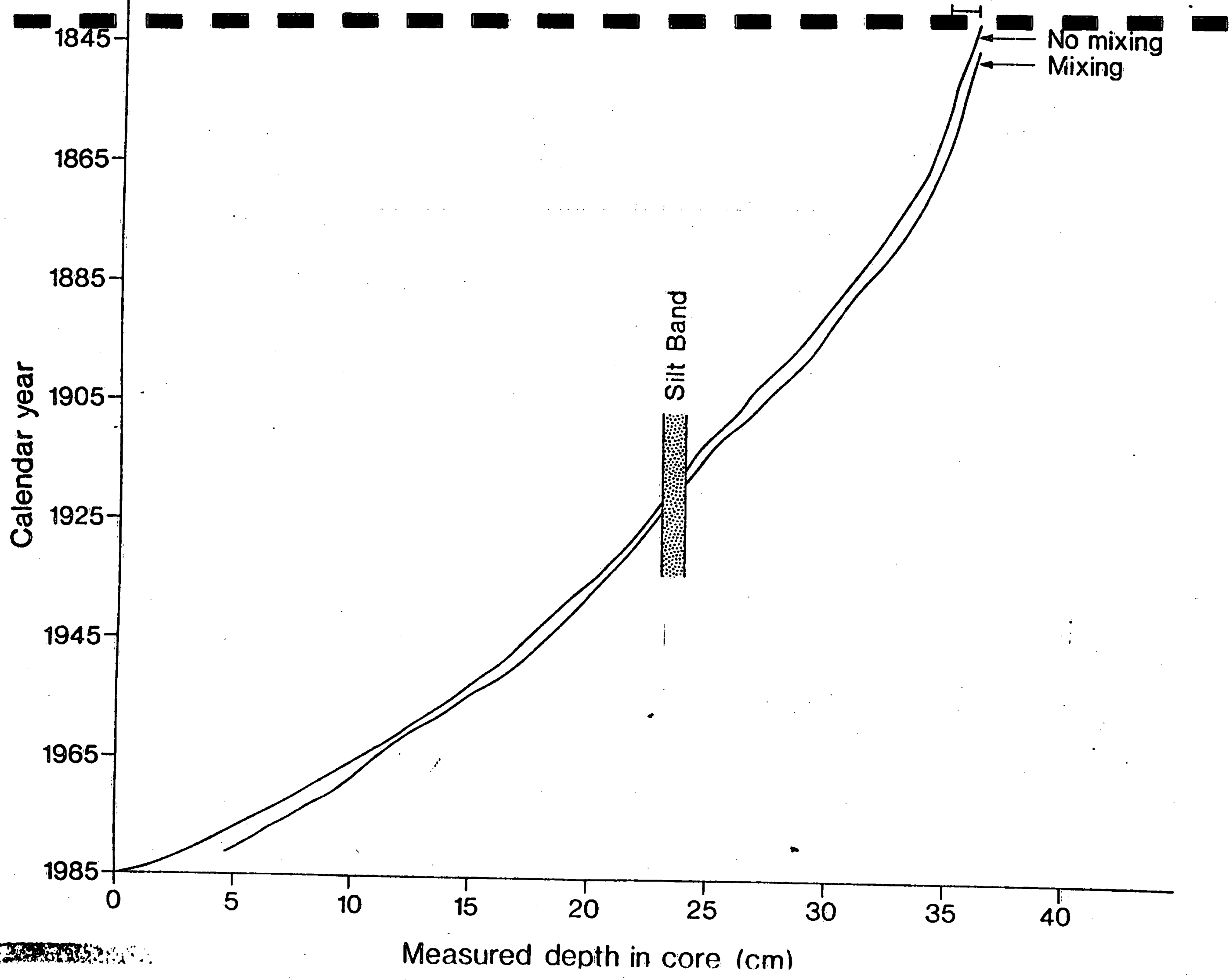

Sediment/water
interface
C(o)
C(s)
C(x)
Xs
X
XL
XM
Am(o)
A(o)
A(x)
A(xL)



Activity of ^{210}Pb (Bq/g dry)
C(1)
C(2)
C(3)
0
1
2
3
x_L
x_M
$A(x_L)$
x_1
x_2
x_3
Depth in core (cm)



ND Not detected
Silt Band
ND
ND
0
5
10
15
20
25
30
35
Measured depth in core (cm)


No mixing
Mixing
Silt Band
Calendar year
1845
1865
1885
1905
1925
1945
1965
1985
0
5
10
15
20
25
30
35
40
Measured depth in core (cm)