The assessment of ^{210}Pb data from sites with varying sediment accumulation rates

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Abstract

The last few years have seen a dramatic growth in the use of ^{210}Pb sediment dating. Despite this, considerable doubt still surrounds the nature of the processes by which ^{210}Pb is deposited in lake sediments, and this has lead to a situation where there is a choice of dating models offering different interpretations of ^{210}Pb data. In assessing ^{210}Pb data it is therefore essential to first of all determine whether data is consistent with the assumptions of the dating model, and to then compare the ^{210}Pb chronology with independent dating evidence. We have tested ^{210}Pb data from a wide variety of sites, and our calculations indicate that the crs (constant rate of ^{210}Pb supply) model provides a reasonably accurate chronology when the total ^{210}Pb contents of cores from neighbouring locations are comparable.

Introduction

In most of the early papers on ^{210}Pb chronology (Krishnaswamy *et al.* 1971; Koide *et al.* 1973; Robbins & Edgington 1975), the methods used assumed a constant rate of sediment accumulation, and were applicable to sediment cores in which the unsupported ^{210}Pb activity declined exponentially down the core. There is, however, abundant evidence for accelerating accumulation rates in many lakes in recent times, and a need therefore to develop a reliable model for calculating ^{210}Pb dates in sites with varying rates of sediment accumulation.

Considerable doubt still surrounds the precise nature of the processes by which ^{210}Pb is deposited in lake sediments, and for this reason ^{210}Pb data from sites with varying sediment accumulation rates is interpreted by different authors in different ways. Since these processes may well vary from site to site it is unlikely that one model will be universally applicable. The purpose of this paper is to outline the principal assumptions used in ^{210}Pb chronology, and to present techniques for assessing the consistency of data with these assumptions.

^{210}Pb Chronology of lake sediments

The processes by which ^{210}Pb is delivered to catchment surfaces have been described in detail elsewhere (e.g. Krishnaswamy & Lal, 1978). The radium isotope ^{226}Ra (half-life 1622 yrs.) decays to yield the inert gas ^{222}Rn. This in turn decays (with a half-life of 3.83 days) through a series of short-lived isotopes to ^{210}Pb (half-life 22.26 yrs.). A fraction of the ^{222}Rn atoms formed by ^{226}Ra decay in soils escape from the soil particles into the interstices and diffuse through the soil into the atmosphere where they decay to ^{210}Pb. This is removed from the atmosphere by rain, snow, or dry fallout, falling either onto the land surface where it is trapped in surface soils (Benninger *et al.* 1975), or into lakes or oceans. ^{210}Pb falling into lakes is scavenged from the lake waters by sediments, and deposited on the bed of the lake. Krishnaswamy & Lal (1978) have estimated that the mean ^{210}Pb flux onto the land surface is about 0.45 pCi cm^{-2} a^{-1}. Local values of the mean ^{210}Pb flux are governed by local or regional meteorological factors, and range from 0.15 pCi cm^{-2} a^{-1} in Australia to 0.96 pCi cm^{-2} a^{-1}

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The ^{210}Pb activity of lake sediments has two components, a supported component C_s deriving from ^{222}Rn decay within the sediment column, and an unsupported (or excess) component C deriving from the atmospheric fallout of ^{210}Pb. C_s can, for most purposes, be approximated by the ^{226}Ra concentration. In the absence of ^{210}Pb fallout, ^{210}Pb and ^{226}Ra would be in radioactive equilibrium. C is determined by subtracting C_s from the total ^{210}Pb concentration.

The unsupported ^{210}Pb concentration in each sediment layer declines with its age in accordance with the usual radioactive decay law. This law can be used to calculate the age of the sediment provided that the initial unsupported ^{210}Pb concentration when laid down on the bed of the lake can be estimated in some way.

If the erosive processes in the catchment are steady, and give rise to a constant rate of sediment accumulation, it is reasonable to suppose that every sediment layer will have the same initial unsupported ^{210}Pb concentration. In this case the unsupported ^{210}Pb concentration will decline exponentially with the cumulative dry mass of sediment. When the unsupported ^{210}Pb concentration C is plotted on a logarithmic scale, the resulting ^{210}Pb profile will be linear. The sediment accumulation rate can be determined graphically from the mean slope of the profile, or analytically by using a least squares fit procedure. In this model, sometimes referred to as the constant flux–constant sedimentation rate (cf:cs) model, the exact mechanism by which the sediment accumulated ^{210}Pb is immaterial.

^{210}Pb chronology under varying sediment accumulation rates

In many cases it is clear that rates of erosion and sedimentation have varied significantly during the past 150 years. In this event the ^{210}Pb profile may be expected to be non-linear. Many authors have observed such profiles. Figure 1 shows ^{210}Pb profiles from Lough Erne in N. Ireland which are both non-linear and non-monotonic over depths of up to 30 cm. Since changing accumulation rates may well result in variations in the initial ^{210}Pb concentra-

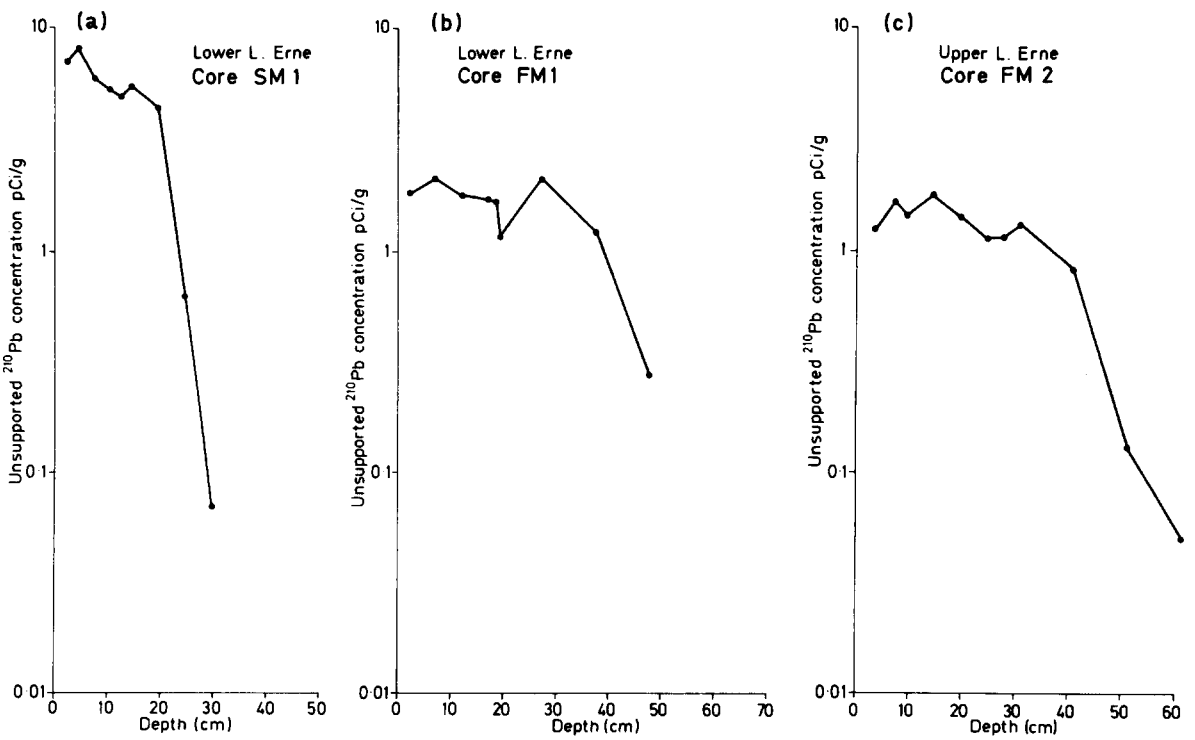

Fig. 1. Non-linear ^{210}Pb profiles from Lough Erne, N. Ireland (Oldfield *et al.* 1978).

tions of sediments, in order to construct a reliable ^{210}Pb chronology it is necessary to understand more precisely the processes by which sediment particles adsorb ^{210}Pb. The problem is further complicated by the fact that non-linear profiles may be caused by a number of other factors, including migration of ^{210}Pb through interstitial waters near the sediment water interface (Koide *et al.* 1973), mixing of near-surface sediments by physical (Petit, 1974) or biological (Robbins *et al.* 1977) processes, post-depositional redistribution of sediments either discontinuously through slumping (Edgington & Robbins 1977) or more or less continuously by sediment erosion.

There are essentially two models which are mathematically practicable for calculating ^{210}Pb dates under varying sediment accumulation rates, the constant rate of ^{210}Pb supply (c.r.s.) model and the constant initial concentration (c.i.c.) model. The physical bases for these models are discussed in more detail in Oldfield & Appleby (in press).

The constant rate of supply (or constant flux) model assumes that there is a constant fallout of ^{210}Pb from the atmosphere to the lake waters resulting in a constant rate of supply of ^{210}Pb to the sediments irrespective of any variations which may have occurred in the sediment accumulation rate. This model was proposed by Krishnaswamy *et al.* (1971). In support of this model, Benninger *et al.* (1975) have estimated that, at least in some cases, $>99\%$ of the ^{210}Pb deposited on the land surface is trapped in the soil layers. The dominant source of the ^{210}Pb in lake waters is then direct fallout onto the lake surface. Studies of the residence time of dissolved ^{210}Pb in lake waters (Schell 1977; Durham & Joshi 1980) have shown that this ^{210}Pb is rapidly transferred from the water to particulates.

If the assumptions of the c.r.s. model are satisfied, it may be shown that the cumulative residual unsupported ^{210}Pb, A, beneath sediments of age t varies according to the formula:

$$A = A(o)e^{-kt}$$

where A(o) is the total residual unsupported ^{210}Pb in the sediment column and k is the ^{210}Pb radioactive decay constant. A and A(o) are calculated by direct numerical integration of the ^{210}Pb profile. The age of sediments of depth x is then given by:

$$t = \frac{1}{k} \ln \frac{A(o)}{A}.$$

The sedimentation rate can be shown to be given directly by the formula (Appleby & Oldfield 1978):

$$r = \frac{kA}{C}$$

The ^{210}Pb supply rate is given by:

$$P = kA(o)$$

This procedure for calculating ^{210}Pb dates was first outlined by Goldberg (1963), and is set out in detail in Appleby & Oldfield (1978), and Robbins (1978).

The constant initial concentration (or constant specific activity) model assumes that an increased flux of sedimentary particles from the water column will remove proportionally increased amounts of ^{210}Pb from the water to the sediments. Under the assumptions of this model sediments will have the same initial unsupported ^{210}Pb concentration irrespective of any variations in sediment accumulation rate.

If the assumptions of the c.i.c. model are satisfied, the unsupported ^{210}Pb concentration will vary with depth in accordance with the formula:

$$C = C(o)\, e^{-kt},$$

where C(o) is the unsupported ^{210}Pb concentration of sediments at the sediment water interface. The age of a sediment layer with ^{210}Pb concentration C is therefore

$$t = \frac{1}{k} \ln \frac{C(o)}{C}$$

The calculation of ^{210}Pb dates by this procedure is illustrated in Pennington *et al.* (1976).

Assessment of ^{210}Pb data for consistency with dating models

The ^{210}Pb supply for a given core is likely to depend in a complex way on both the atmospheric input and sediment accumulation rate. The determination of a ^{210}Pb chronology will be feasible only

if one or other of these factors is dominant. In considering a given data set it is therefore necessary to establish whether it conforms to either the c.r.s. model or c.i.c. model.

If the c.r.s. model is applicable, the following consequences may be noted.

1. Non-monotonic profiles may be expected in response to major changes in the accumulation rate, since faster net sediment accumulation will tend to depress initial unsupported ^{210}Pb concentrations, and vice versa.
2. Different cores from the same lake, or from the same depositional zone within a very large lake, or from different lakes within the same general area will have comparable ^{210}Pb residuals (i.e. total residual unsupported ^{210}Pb contents) despite differences in the accumulation rates.
3. The ^{210}Pb residuals of the cores should reflect the ^{210}Pb fallout from the atmosphere. Since the ^{210}Pb fallout lies in the range 0.2–0.9 pCi cm^{-2} a^{-1}, depending on the locality, the ^{210}Pb residuals should lie in the range 6–30 p Ci cm^{-2}.

All three points are well illustrated by the data from Lower Lough Erne. The profiles (Fig. 1) are non-monotonic. The ^{210}Pb residuals are virtually identical, 19.2 pCi cm^{-2} for FM1 and 20.7 pCi cm^{-2} for SM1 despite a 3-fold difference in the accumulation rates. The corresponding ^{210}Pb supply rates are 0.6 pCi cm^{-2} a^{-1} and 0.64 pCi cm^{-2} a^{-1} respectively. Table 1 summarises results from a variety of sites which satisfy the c.r.s. criteria. Figure 2 illustrates the convergence of the cumulative ^{210}Pb residuals for cores from two sites.

Table 1. ^{210}Pb parameters and sedimentation rates for cores from a variety of sites satisfying the c.r.s. criteria.

Coring site		Total residual unsupported ^{210}Pb content A(o) (pCi cm^{-2})	Unsupported ^{210}Pb conc. at surface C(O) (pCi g^{-1})	Mean sedimentation rate during		^{210}Pb flux equivalent to ^{210}Pb residual pCi cm^{-2} a^{-1}
				(a) past 30 years r(o) (g m^{-2} a^{-1})	(b) past 100 years $\bar{r}$(g m^{-2} a^{-2})	
Ireland (Oldfield *et al.* 1978)						
Lower L. Erne	Core SM1	20.7	7.13	0.08	0.037	0.64
	Core FM1	19.2	1.82	0.31	0.12	0.60
Upper L. Erne	Core FM2	14.9	1.26	0.35	0.13	0.46
L. Augher (1977)		12.7	1.81	0.19	0.11	0.40
Wales (Elner & Wood 1980)						
Llyn Peris	Core A	38.8	1.08	1.07	0.27	1.21
	Core E	42.8	1.99	0.67	0.28	1.33
England						
Rostherne Mere	Core RMII	6.5	2.24	0.084	0.055	0.20
	Core N79	5.4	1.87	0.088	0.052	0.17
Newton Mere		5.3	4.43	0.032	0.029	0.17
Belgium (Oldfield *et al.* 1980)						
L. Mirwart	Core 1	10.5	3.29	0.092	0.14	0.33
	Core 2	10.0	2.21	0.13	0.055	0.31
	Core 3	10.7	2.34	0.14	0.12	0.33
Finland (Appleby *et al.* 1979)						
Laukunlampi		20.5	36.7	0.011	0.0072	0.64
Lovojarvi		20.1	5.55	0.078	0.059	0.63
Paajarvi		24.5	14.2	0.044	0.059	0.76
L. Michigan U.S.A. (Robbins & Edgington 1975)						
S. Margin	Core 54	3.98	10.08	0.0075	0.0069	0.12
	Core 31	5.09	6.72	0.018	0.011	0.16
S. Central	Core 11	5.37	7.10	0.020	0.019	0.17
	Core 17	6.04	11.42	0.013	0.013	0.19
N. Central	Core 105	8.14	14.5	0.014	0.010	0.25
	Core 103	8.31	15.1	0.014	0.011	0.26

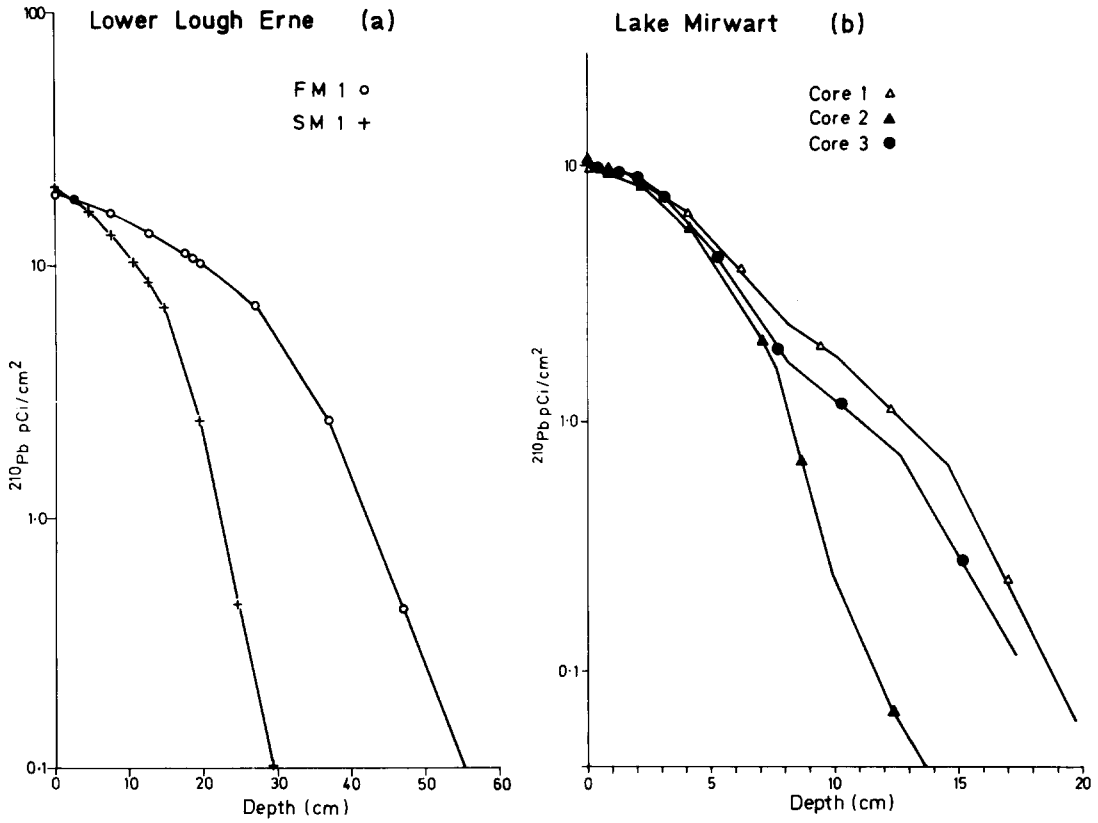

Fig. 2. Cumulative total residual unsupported ^{210}Pb contents for cores from (a) Lower Lough Erne and (b) Lake Mirwart, Belgium (Oldfield *et al.* 1980).

If the c.i.c. model is applicable, the following consequences may be noted.

1. The unsupported ^{210}Pb concentration must show a monotonic decline with depth.
2. The total cumulative residual unsupported ^{210}Pb in sediment cores from the same lake should vary roughly in proportion to the mean sediment accumulation rate.

In view of the efficiency at which ^{210}Pb is scavenged from lake waters by particulates, it is unlikely that this model will be widely applicable except possibly at sites where sediment focusing is a major factor.

In order to assess whether one or other of the models is generally valid, we have plotted the ^{210}Pb residuals A(o) and surface ^{210}Pb activities C(o) for about 50 cores against the corresponding mean sedimentation rates $\bar{r}$ (Fig. 3). If the c.r.s. model were generally valid, there should be no significant relation between A(0) and $\bar{r}$. On the other hand, since the ^{210}Pb activity is inversely proportional to the sediment accumulation rate the graph of C(o) against $\bar{r}$, plotted on log-log paper, should approximately follow a line making an angle of 45° with each axis. If the c.i.c. model were generally valid, A(o) should be proportional to $\bar{r}$, and there should be no significant relation between C(o) and $\bar{r}$. The graphs clearly support the c.r.s. model. The great majority of the cores have a ^{210}Pb residual in the range 6–30 pCi cm^{-2}. The average value of 17.7 pCi cm^{-2} corresponds to a mean ^{210}Pb supply rate of 0.55 pCi cm^{-2} a^{-1}. This compares well with estimates of the mean ^{210}Pb fallout.

Figure 3(a) includes data from Lake Michigan in the U.S.A. and Lough Neagh in N. Ireland which appears to be consistent with the c.i.c. model. In the case of the Lake Michigan data (from Robbins & Edgington 1975), six of the cores (see Table 1) have

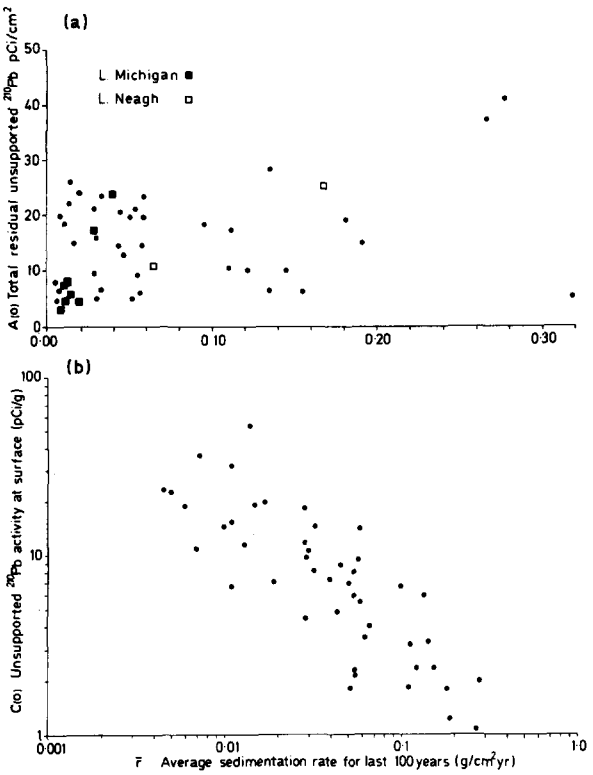

Fig. 3. ^{210}Pb parameters vs mean sediment accumulation rate $\bar{r}$ during the past 100 years for about 50 cores from various localities. Fig. 3(a) plots the total residual unsupported ^{210}Pb content A(o) vs $\bar{r}$. Fig. 3(b) plots the unsupported ^{210}Pb concentration at the surface C(o) vs $\bar{r}$.

^{210}Pb residuals which correspond more or less to the measured atmospheric ^{210}Pb fallout of ~ 0.2 pCi cm^{-2} a^{-1}. The two remaining cores, however, 29 and 100A, have ^{210}Pb residuals well in excess of these values. Both sets of results can be interpreted in terms of post-depositional sediment focusing (Oldfield & Appleby, in press).

When the ^{210}Pb profiles satisfy the assumptions of either model, errors in the chronology may still arise as a result of vertical mixing processes in the near surface sediments. Robbins *et al.* (1977) have modified the constant flux-constant sedimentation rate model to allow for such processes. A modified c.r.s. model which takes account of sediment mixing is set out in Oldfield & Appleby (in press).

Summary

Perhaps the most important conclusion that we would reach is that there is no single model that will give a reliable ^{210}Pb chronology in all cases, and that each data set must be evaluated independently for consistency with one or other of the dating models. A tentative procedure for evaluating data is as follows:

I Linear Profiles
All models give the same chronology

II Non-linear Profiles

(a) If the ^{210}Pb residuals are comparable with the known atmospheric flux, or with the ^{210}Pb residuals or nearby cores, the c.r.s. model would appear to be applicable. In our experience, ^{210}Pb dates calculated in this way have generally been consistent with independent dating evidence.

(b) If the ^{210}Pb residuals do not satisfy the requirements of the c.r.s. model, but there is independent evidence that the primary sediment accumulation rate has been constant, the c.i.c. model will be applicable. This case may occur in situations where sediment focusing takes place.

(c) If the ^{210}Pb residuals do not satisfy the requirements of either model, a ^{210}Pb chronology cannot be reliably established. We have found that ^{210}Pb dates calculated in these circumstances have in most cases been in conflict with independent dating evidence.

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