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^{210}Pb Dating in shallow moorland pools

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Abstract

Ten cores from seven shallow (average depth less than 2 m) moorland pools in the Netherlands have been analysed for ^{210}Pb in an attempt to obtain reliable chronologies to be used in acidification studies. Although the sediment stratigraphy may be disturbed by many external influences, the shape of ^{210}Pb activity versus depth profiles appears to result in reliable chronologies in agreement with biological data. However, the time resolution is primarily determined by uncertainties about the validity of the basic assumptions in the dating model rather than by the accuracy of the measurements.

Introduction

Acidification of soils is recognized as a wide-spread ecological problem in North-Western Europe. When trying to establish the cause of the problem it is essential to distinguish between long-term effects caused by natural processes and short-term effects induced by human activities. An indication about the relative contribution of both may be obtained from the rates of acidification during the industrialization era (the last 150 years or so). Recently, ^{210}Pb has been applied to date sedimentary deposits containing indications of acidification (Battarbee et al., 1985).

To determine rates of acidification in shallow Dutch moorland pools, so-called "vennen" Dickman et al. (1986) related biological and pollen analytical data with ^{210}Pb ages. Due to the limited water depth (less than 2 m) palaeolimnological studies are not straightforward. Sediments may have been disturbed by wind-induced mixing and bioturbation (e.g. human and/or animal bathers). Furthermore, in periods of great drought some of the moorland pools lost most or even all of their water content, exposing their sediments to oxidizing conditions (Sykora, 1979; Vangenechten et al., 1981). Although the data obtained on the Achterste Goorven (Site II in Fig. 1) were not always consistent, the investigators concluded that this pool was one of the fastest acidifying bodies reported in temperate regions exposed to acid precipitation (Dickman et al., 1986).

This study discusses the detailed chemical and radiochemical procedures as well as the applicability of ^{210}Pb dating on the basis of ten cores from a total of seven "vennen" in the Netherlands.

Age models

^{210}Pb, a member of the ^{238}U-decay series with a half-life of $t_{1/2} = 22.3$ a, is brought into the sediment both by direct in-situ production through the radioactive decay of ^{226}Ra (supported ^{210}Pb), as well as by deposition of ^{222}Rn-produced atmospheric ^{210}Pb. As an inert gas in the ^{238}U series, Radon escapes from the crust of the earth at an average rate of 7 to $7.5 \cdot 10^3$ atoms $m^{-2}s^{-1}$ (Israel, 1951; Wilkening et al., 1975). It decays through a series of short-lived (a few minutes) daughter products to ^{210}Pb which, after an estimated atmospheric residence time of about two weeks (the turn-over time of atmospheric vapour, (Moore et al., 1973; Turekian et al., 1977)), enters the land hydrosphere through either dry or wet precipitation. In surface waters it is easily adsorped on suspended material (Krishnaswamy et al., 1982; Rama & Moore, 1984) and subjected to sedimentation. Assuming a constant average annual rate of deposition D ($cm^{-2}a^{-1}$) of atmospheric ^{210}Pb, the excess activity $^{210}Pb_{xs}$ over the ^{226}Ra supported activity $^{210}Pb_s$ of the sediment layer formed t years ago at present sediment depth z cm can be calculated (see e.g. Appleby & Oldfield, 1978):

$$^{210}Pb_{xs}(z) = \frac{\lambda D}{S(t)} e^{-\lambda t} \qquad (1)$$

in which λ = the decay constant of ^{210}Pb (a^{-1}) and S(t) = the sedimentation rate dz/dt at the time of deposition t of the sediment layer at corresponding depth z ($cm . a^{-1}$). (Note that in equation (1) we express the activity in decay per year.cm^{-3}. If the activity is measured in Bq.cm^{-3} the proper conversion factors have to be used.)

The activity $^{210}Pb_{xs}$ cannot be obtained from direct measurements, but has to be calculated from the measured total ^{210}Pb activity and the estimated supported activity $^{210}Pb_s$. In general there are two ways to estimate this activity:

1. $^{210}Pb_s$ is assumed to be in secular equilibrium with ^{226}Ra and taken equal to the measured ^{226}Ra activity.
2. Assuming a constant contribution of $^{210}Pb_s$ throughout the core it is set equal to the measured total ^{210}Pb activity at a depth older than approximately 150–200 years (where the $^{210}Pb_{xs}$ contribution has diminished).

Substituting S(t) = dz/dt in (1) yields a differential equation from which an expression for the total (integrated) $^{210}Pb_{xs}$ activity over a core to depth z is obtained after integrating both sides with respect to z and t respectively:

$$I(z) = \int_0^z {}^{210}Pb_{xs}(z')dz' =$$

$$I(z) = \int_0^t \lambda D e^{-\lambda t'} dt' = D(1 - e^{-\lambda t}) \qquad (2)$$

As from (2) it follows that

$$D = I(\infty) \qquad (3)$$

the age t of the sediment layer at depth z is given by

$$t = -\frac{1}{\lambda} \ln(1 - I(z)/I(\infty)) \qquad (4)$$

A special case of this so-called Constant Rate of Supply (CRS) model is obtained when the sedimentation rate S is constant (Constant Initial Concentration or CIC model). In this model the $^{210}Pb_{xs}$ activity is given by

$$^{210}Pb_{xs}(z) = \frac{\lambda D}{S} e^{-\lambda z/S} \qquad (5)$$

yielding a straight line of slope $-\lambda/S$ on a semilogarithmic plot of $^{210}Pb_{xs}(z)$ against z.

Site description and sediment coring

Cores were taken from 7 moorland pools at various localities in the Netherlands (Fig. 1). Full descriptions of the pools are given elsewhere (I: Van de Hurk et al., 1986; II: Dickman et al., 1986; III: Beye, 1976; IV Mansfeld et al., 1975; V: Higler, 1979; VI: Wittgen et al., 1986; VII: Coesel & Smit, 1977). Duplicate cores were analysed from site numbers I, II and IV.

The sediments from pools I–V in the south eastern and middle part of the Netherlands generally are characterized by a thin organic layer (20–30 cm) on a sandy substrate while the sediments of pools VI and VII in the eastern and northern part are found to consist mainly of dark organic (gyttja) material.

Most cores were taken with an Ali Corer (Ali, 1984) during periods of ice cover. Other cores were taken with a PVC liner that was vacuum closed at the moment of extraction by a rubber stopper.

From some cores sections were taken in the field

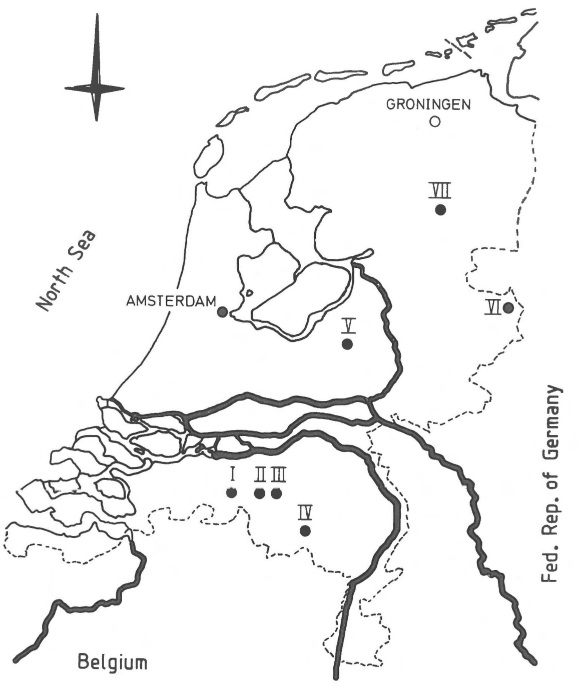

Fig. 1. Locations of 7 moorland pools in the Netherlands where 10 sediment cores were collected: I Galgeven, II Achterste Goorven, III Groot Huisven, IV Beuven, V Gerritsfles, VI Bergven and VII Kliplo.

or directly upon arrival in the laboratory, using a thin stainless steel wire. Several other cores were deepfrozen, extruded from their liners and cut into 1 cm samples in frozen condition, using a diamond saw. In one case (core V.5) the inner, not yet frozen, part of the core was squeezed from its position which may have led to disturbed stratigraphy. Therefore, the remaining cores were transferred to the laboratory in unfrozen condition where the overlying water was siphoned off and the liner was cut overlength. One half was used for ^{210}Pb dating, the other was used for biological analyses. Table 1 summarizes collection date, type of corer and the internal diameter for each core.

Analytical methods

^{210}Pb activities were indirectly determined by measuring the activity of the alpha-emitting granddaughter ^{210}Po (secular equilibrium in approximately two years), using the isotope dilution technique (Flynn, 1968; El-Daoushy, 1981).

A known volume (approximately 10 ml) of wet sediment was weighed and subsequently dried at 40° C for about twelve hours. Weight loss was used to determine the ratio between in-situ volume and dry sediment weight. Approximately 1 g of dry sediment was gently boiled in a 250 ml Kjeldahl flask with concentrated HNO_3 to which 30 vol% of H_2O_2 was added dropwise until no more brown fumes emanated. The thus oxidized sediment was separated from the overlying liquid by centrifugation. The residue was repeatedly washed with demineralized water until no more colour appeared. The washed residue was stored e.g. for future mineral analyses. The extracted liquid and the washings were combined for ^{210}Po-activity determination.

After the addition of a known amount (ca. 100 mBq) of a ^{208}Po-spike solution, the solution was

Table 1. Summary of core localities.

Pool	core no.	collection date	type of corer + int. diam.
Galgeven	I.1	18 feb. 85	ALI, 7.0 cm
Galgeven	I.2/2	12 dec. 85	PVC, 4.2 cm
Achterste Goorven	II.7	30 jan. 85	ALI, 7.0 cm
Achterste Goorven	II.4	30 jan. 85	ALI, 7.0 cm
Groot Huisven	III.1	26 jan. 84	PVC, 1.9 cm
Beuven	IV.2	21 feb. 85	ALI, 7.0 cm
Gerritsfles	V.5	12 feb. 85	ALI, 7.0 cm
Gerritsfles	V.7	28 feb. 85	ALI, 7.0 cm
Bergven	VI.1	18 dec. 85	PVC, 6.5 cm
Kliplo	VII.3	31 jan. 85	ALI, 7.0 cm

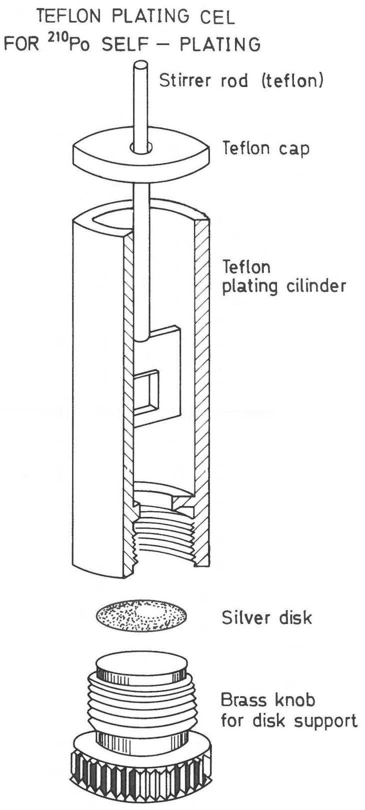

Fig. 2. Plating cell, used for self-deposition of Po. The walls and cap of the cell are made of Teflon to prevent adsorption of Po to the cell material that is in contact with the liquid. No memory effect was found after use and subsequent cleaning of the cell. Four cells were run simultaneously to speed up plating.

evaporated to dry in a 50 ml Teflon beaker. The remaining salts were chlorinated by repeated dissolution (three times) in concentrated HCl.

After redissolution of the chlorinated salt residue in 10 ml of 0.5 M HCl solution and addition of 1 mg of ascorbic acid the solution was left for about half an hour to assure complexation of the ascorbic acid with Fe. Meanwhile, a 1 inch diameter silver disk was polished and mounted in a Teflon plating cell (Fig. 2). The solution was transferred to the cell, rinsing the beaker with another 10 ml of 0.5 M HCl. The self-plating of Po on the silver disk occurred at a constant temperature of 85° C during approximately two hours.

The thinly plated silver disk was carefully washed with demineralized water and, after drying, measured in an alpha spectrometer for ^{208}Po and ^{210}Po activities. The Si surface barrier detectors showed negligible background, even after a large number of runs. Contamination of the detector surface by recoiling nuclei could be prevented by placing a thin formvar foil (20 μg/cm^2) between source and detector. This leads to approximately 10% reduction of the energy resolution of ca. 20–25 keV FWHM (Van der Wijk et al., in preparation). Chemical recovery of the sample treatment after spike addition varied between 85 and 100%.

The absolute activity of the ^{210}Po-spike solution has been determined several times during the project by repeatedly (4 times) self-plating of a known amount of the spike solution and measuring the activity on the silver disk. The statistical spread of the analyses and the one-sigma uncertainties from the counting statistics of the single determinations were of the same order of magnitude (1.8%) so that we concluded to a chemical recovery of 100% for these "spike runs". However, age determination only requires the relative ^{210}Pb$_{xs}$ activities in the core so that the accuracy of the spike activity is not relevant. Only the determination of the ^{210}Pb-deposition rate D (see eq. (2)) requires absolute activities from the spike solution.

Results

Figs. 3a to 3j and Figs. 4a to 4f show the results of the measurements on the ten cores and the deduced age-depth profiles.

We calculated supported ^{210}Pb$_s$ activities under the assumption that they originated from the inorganic fraction of the sediment only. After a first approximation of the sedimentation rate, using total ^{210}Pb activities instead of ^{210}Pb$_{xs}$ activities, we selected suitable samples (over 150 years old) to determine the activity ^{210}Pb$_i$ (mBq/g) of the inorganic material and subsequently calculated the contribution of supported ^{210}Pb at arbitrary depth z:

$$^{210}\mathrm{Pb}_s(z) = f_i(z) \times {}^{210}\mathrm{Pb}_i \text{ (mBq/g sample)} \qquad (6)$$

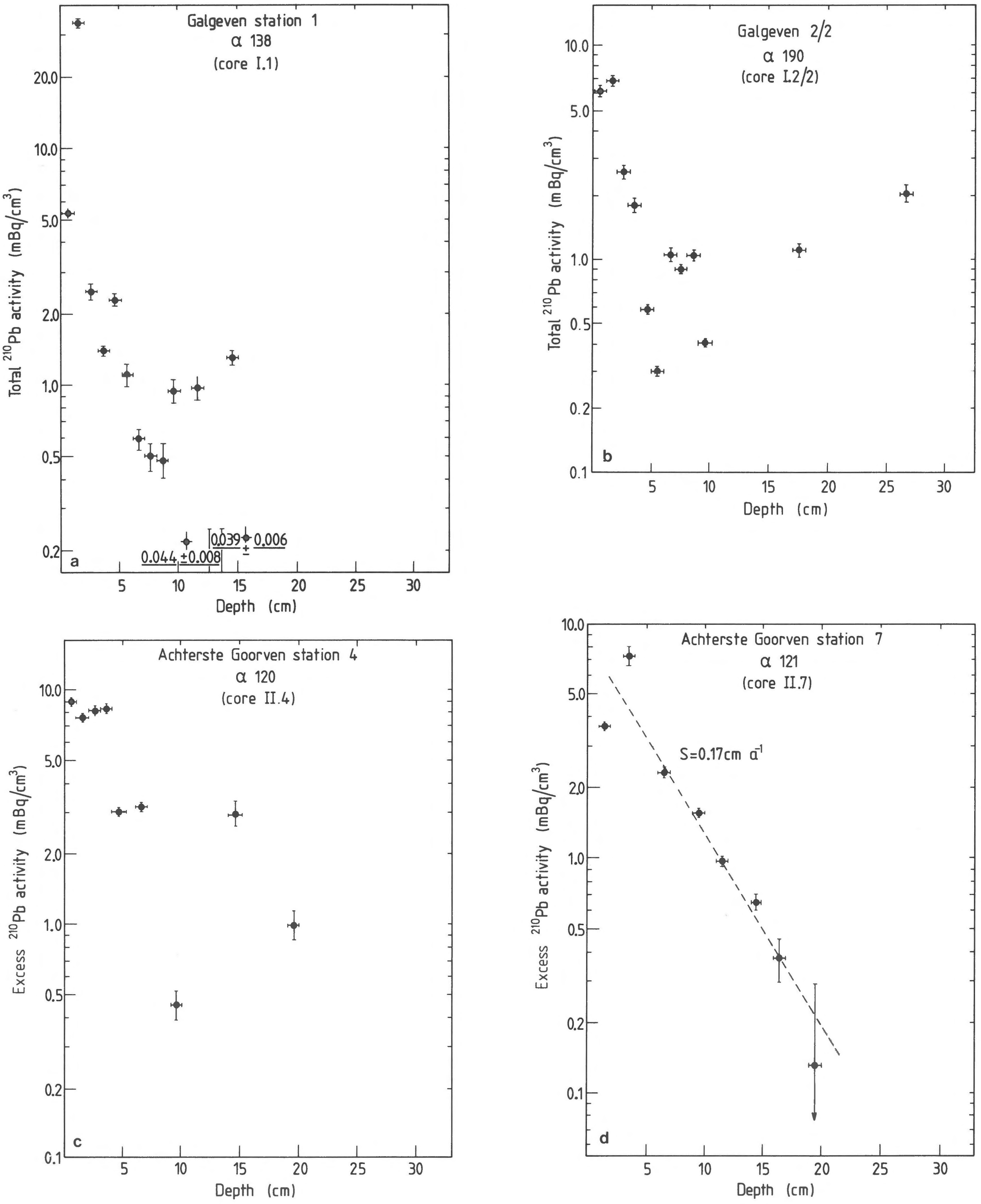

Fig. 3. Semi-logarithmic plot of the excess ^{210}Pb activity (except for cores I.1 and I.2/2 where the total ^{210}Pb activity is given, see text) against the sediment depth for all ten cores. Straight lines show the best linear fit to the distribution, yielding a corresponding average sedimentation rate S in cm.a^{-1}.

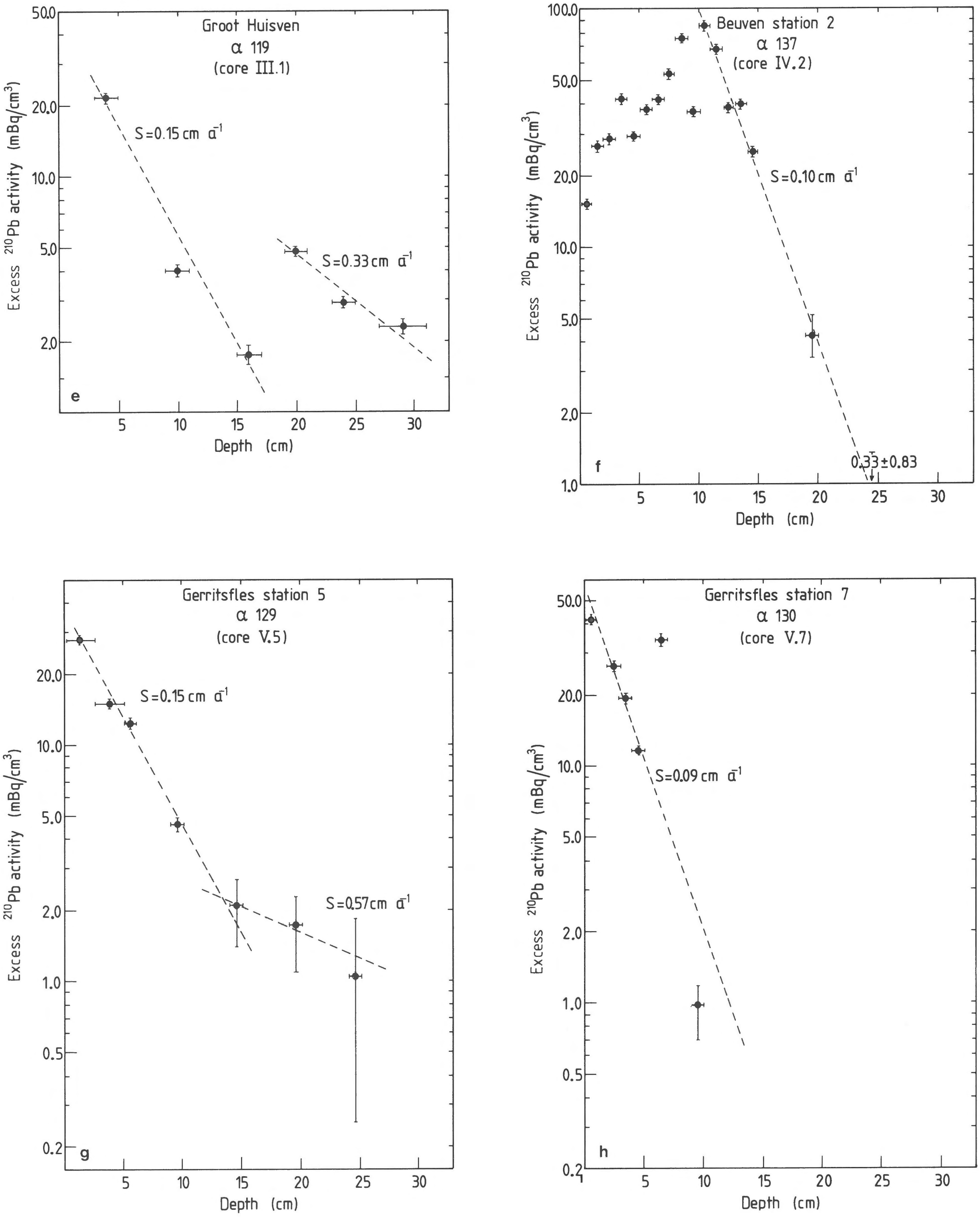

Fig. 3. Continued.

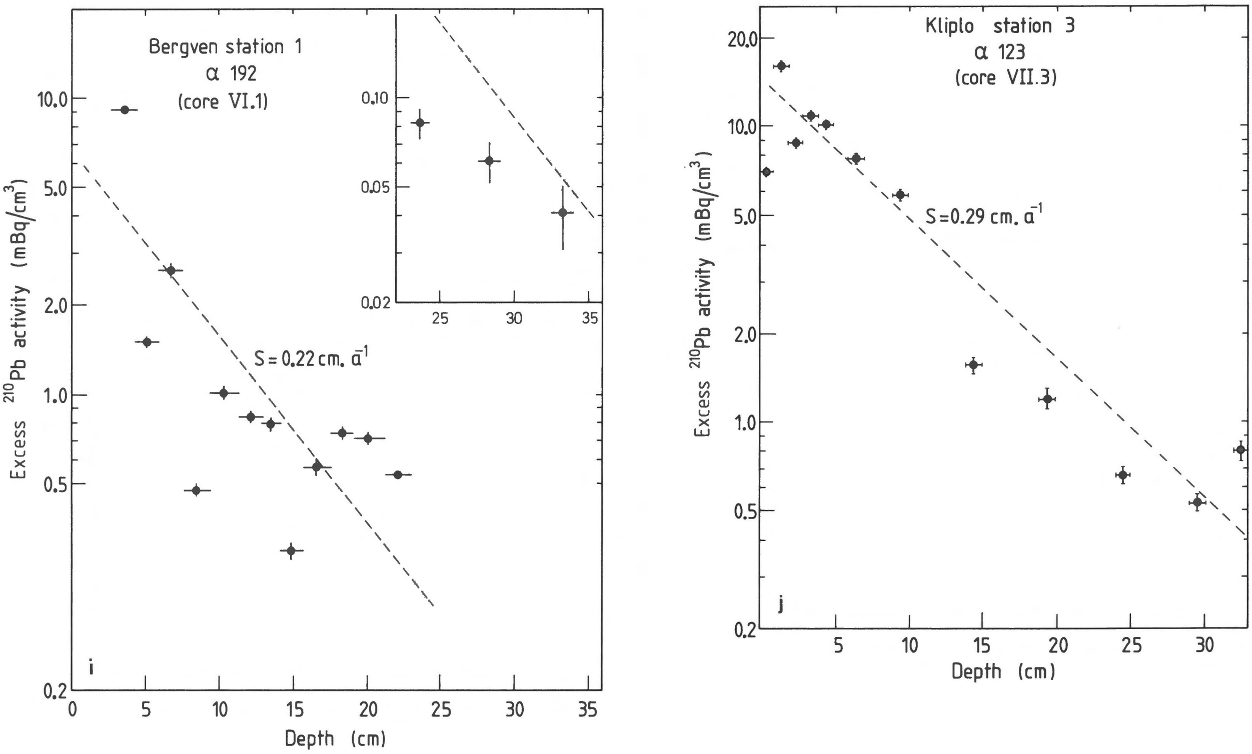

Fig. 3. Continued.

in which $f_i(z)$ = weight fraction of inorganic material at depth z.

The assumption that ^{210}Po is in equilibrium with ^{210}Pb in the samples leads to some additional uncertainties on the true value of the ^{210}Pb activities, especially in the upper sediment layers:

1. (Diffusional) movement of fresh water in which ^{210}Po is not yet in secular equilibrium with ^{210}Pb across the sediment-water interface is very well possible due to the flocculant structure of the upper sediment layers. This leads to dilution of the ^{210}Po activity with respect to the ^{210}Pb activity
2. In sediment layers younger than approximately 2 years ^{210}Po and ^{210}Pb are not necessarily in secular equilibrium.

These two effects usually lead to an apparent constant (see e.g. core II.4) or even lower (see e.g. core VII.3) ^{210}Pb activity in the upper 3 to 4 cm. The CRS model now allows two approximations to estimate the effect of this uncertainty:

1. The ^{210}Pb activity is assumed to be constant in the upper 3 to 4 cm of the core, due to infiltration of fresh water and mixing of the flocculant organic material
2. The sedimentation rate calculated from the ^{210}Pb activity below the "mixing" zone is extrapolated to the sediment-water interface.

In practice we used the first approximation because, as mentioned before, it is realistic to assume some mixing in the upper sediment layer.

A least squares linear fit gives a straight line in the semi-logarithmic plot (Fig. 3) of the ^{210}Pb$_{xs}$ activity. The CIC model, using a ^{210}Pb half life of 22.3 years, produces average sedimentation rates. We also calculated ages for the CRS model. Error bars in the activity-depth profiles indicate one sigma uncertainties in the counting statistics. In the age-depth profile (Fig. 4) these result in regions of

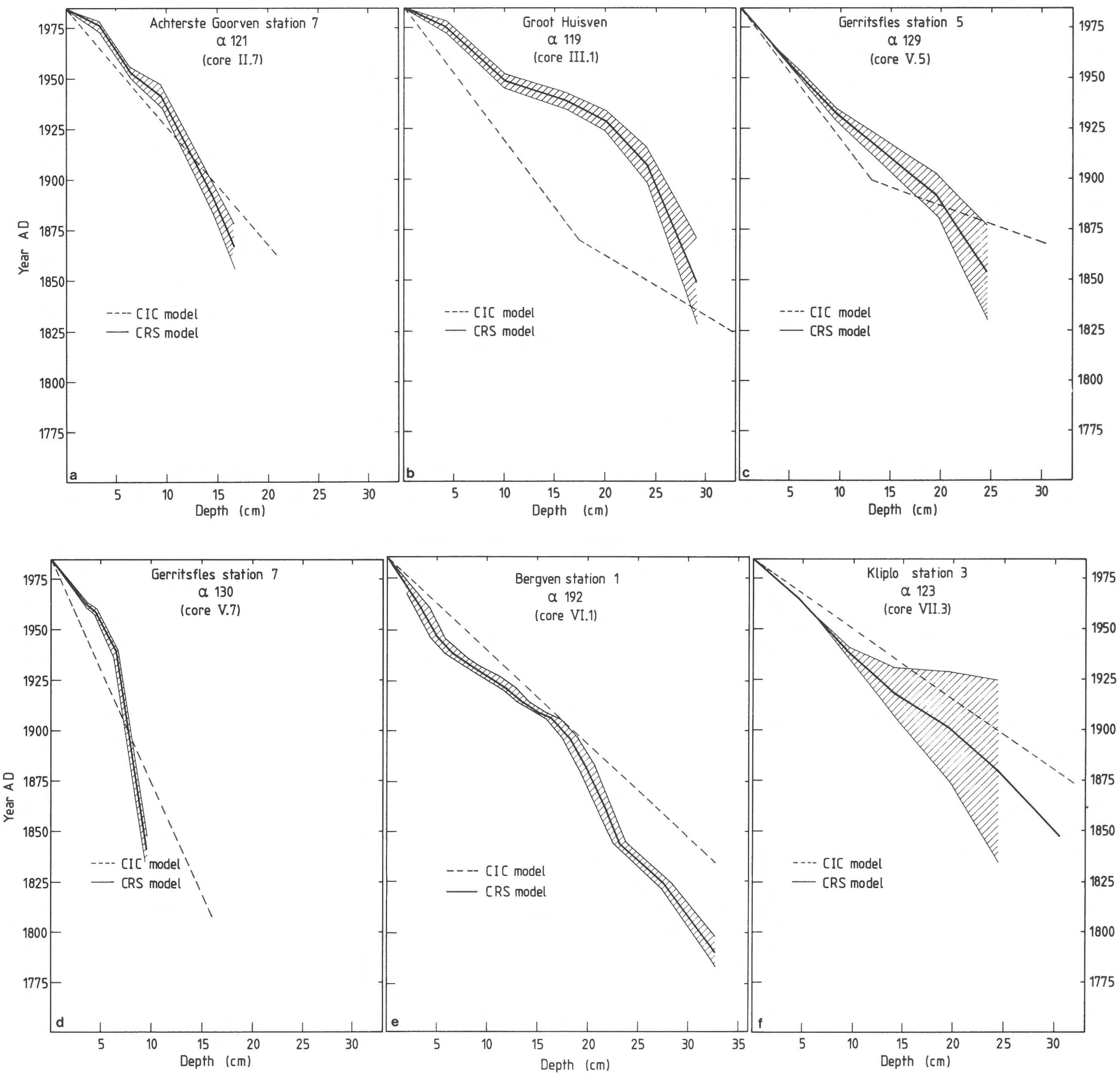

Fig. 4. Age-depth profiles for cores in which ages could be calculated. Dashed lines show the results from the CIC model, continuous lines show CRS results and accompanying one sigma uncertainties.

uncertainty around the CRS calculated values. We did not take into account the uncertainties in the validity of the basic assumptions of the model.

Sediment focussing

The average atmospheric ^{210}Pb deposition can be estimated from the average Rn exhalation of the earth crust as given by Wilkening et al. (1975) to be approximately 23 mBq.cm^{-2}a^{-1}. Preliminary results on ^{210}Pb activity in rain water close to our laboratory gave no reason to believe that this deposition in the Netherlands should deviate much from the measured average annual deposition as reported by Crozaz et al. (1964) for the northern hemisphere (7.8 mBq.cm^{-2}.a^{-1}) and by El-Daoushy (1978) for Scandinavia (approximately 6.3 mBq.cm^{-2}a^{-1}).

The CRS model provides an estimate of the average annual deposition of ^{210}Pb (see eq. (3)). In a closed system for ^{210}Pb and an undisturbed vertical sedimentation, this should reflect the local atmospheric ^{210}Pb deposition. However, lateral sediment transport may either increase or decrease the annual deposition of ^{210}Pb (sediment focussing, see e.g. Irlweck & Danielopol, 1985). Due to the fact that the sediments in the moorland pools usually show little or no topographic relief, we believe that such lateral sediment transport is mainly wind-induced. Table 2 shows the average annual deposition of ^{210}Pb for eight of the ten cores as obtained from the CRS model. The calculated uncertainties do not include the uncertainty in the absolute spike activity. We estimate this to be less than ± 5%.

Although Krishnaswamy & Lal (1978) reported that the ^{210}Pb flux shows a significant geographical variation, we believe that, regarding the small distance between our cores, the deviating numbers in Table 2 are an indication of (either positive or negative) sediment focussing rather than variations in the atmospheric flux.

Table 2. Average annual ^{210}Pb deposition D at the coring sites as deduced from the total integrated ^{210}Pb activity I (∞) (see eq. (3)). For cores I.1 and I.2/2 no value could be calculated for lack of data on the supported ^{210}Pb activity. Without sediment focussing, the figures should reflect the local atmospheric ^{210}Pb deposition which is estimated between 6 and 8 mBq.cm^{-2}a^{-1} (Crozaz et al., 1964; El-Daoushy, 1981). Deviations are probably caused by sediment focussing.

Core number	average annual ^{210}Pb deposition (mBq · cm^{-2} · a^{-1})
I.1	?
I.2/2	?
II.4	2.1 ± 0.2
II.7	1.5 ± 0.2
III.1	6.9 ± 0.5
IV.2	22.2 ± 0.8
V.5	5.9 ± 0.4
V.7	7.0 ± 0.5
VI.1	1.7 ± 0.2
VII.3	3.5 ± 0.3

Chemical effects

Recently Simola & Liehu (1985) reported a correlation between ^{210}Pb minima and diatom-inferred pH minima in lake sediments, that they tentatively related to decreased adsorption affinity of Pb into the sediment particles at low pH. However, they state that, although the phenomenon could be predicted on chemical grounds, the empirical evidence appears to be little. Where data on diatom-inferred pH (according to Renberg & Hellberg, 1982) are available, we have tried to include this phenomenon in our discussion in an attempt to comment on its validity.

Discussion

Site I, Galgeven

Measurements on core I.1 yielded a rather disturbed activity-depth profile. No supported ^{210}Pb activity could be determined due to the fluctuating total ^{210}Pb activity (by one order of magnitude) at greater depths. Furthermore, hardly any remains of macrofauna were found. The same is true for core I.2/2 so that both cores from Galgeven were rejected from further analysis.

Site II. Achterste Goorven

The ^{210}Pb activity-depth profile of core II.7 is one of the most regular profiles we have found in these type of pools. The unexpected low activity at the sediment-water interface is attributed to the occurrence of mixing processes in the upper few centimetres, rather than by a decreased absorption capacity of the sediment due to the low diatom-inferred pH (4.8). This seems to be confirmed by the ^{210}Pb distribution at the sediment-water interface of core II.4, where a rather constant ^{210}Pb activity was found.

Some vertical reworking of the sediment was also confirmed by the biological data, as was extensively discussed by Dickman et al. (1986). By treating vertical mixing throughout the sediment column as a diffusional process, Kirshnaswamy & Lal (1978) have shown that only the slope and the intercept at $z = 0$ in the semi-logarithmic activity-depth profile do change. This implies that an exponential activity-depth profile does not necessarily coincide with an undisturbed sedimentation rate. However, we have no conclusive evidence for such a diffusion-like mixing process. Therefore, we assume that mixing is only important in the top few centimetres of the core, leaving the slope of the distribution below the mixing zone unaffected (Robbins & Edgington, 1975; Robbins, 1978).

Both cores II.4 and II.7 show a deficiency in ^{210}Pb deposition. If lateral sediment transport is assumed there should be an excess value of the deduced ^{210}Pb deposition elsewhere in the pool. However, without a clear picture of the distribution of these values throughout the pool, we can only speculate about the cause of the deficiency.

Due to the ^{210}Pb deduced disturbed stratigraphy core II.4 was rejected from a detailed biological study. However, its ^{210}Pb results contributed to our understanding of the mixing processes in the upper part of core II.7, showing the value of ^{210}Pb analysis in duplicate cores.

Site III, Groot Huisven

Because of the limited diameter of the core, samples of 2 cm length had to be taken, reducing the resolution of the ^{210}Pb profile. Using the CIC model, the $^{210}\mathrm{Pb}_{xs}$ distribution can be divided in two regions of different sedimentation rate. However, in the CRS model this discontinuity can be explained by a sudden, temporary increase in sedimentation rate at 20 cm depth. Therefore, both methods yield strongly deviating age-depth profiles. Fortunately, additional biological data clearly indicate a historically recorded rise of the groundwater table (about 20 cm) at a sediment depth of approximately 10 cm around 1950 (Klink, 1985). In the deeper sections of the sediment the chironomid composition does not indicate any changes in pH that might have provided an explanation for the discontinuity in the ^{210}Pb activity-depth profile. Therefore, the data strongly support the results of the CRS model, showing that the negative slope of the semi-logarithmic activity-depth profile between 15 and 20 cm is the result of a sudden rapid increase of the sedimentation rate (Appleby & Oldfield, 1978).

Site IV, Beuven

The ^{210}Pb activity-depth profile shows a tremendous distortion of the upper 10 to 15 cm of the core, probably representing rapid sedimentation of allochthonous material, deposited by the river Peelrijt in the past 10 to 15 years (G. Arts, pers. comm.). This conclusion seems to be confirmed by the extremely high value for the calculated ^{210}Pb deposition (Table 2). Although an estimate of the sedimentation rate at greater depths can be made, it seems clear that the conditions for applying ^{210}Pb dating are not fulfilled throughout this core. The stratigraphy probably has not been preserved, especially in the upper 15 cm, and therefore other investigations requiring such conditions are doubtful. Post collection evidence for this conclusion was obtained from investigators of the University of Nijmegen, the Netherlands, who found over 6 tons of fish (possible bio-turbators) after the pool was emptied and cleaned to stop the extreme eutrophication process (G. Arts, pers. comm.).

Site V, Gerritsfles

As was stated before, the results on core V.5 are suspect because of possibly disturbed stratigraphy in the freezing process. However, this core shows a very regular and continuous ^{210}Pb distribution. The same is true for core V.7, except at 6 cm. The diatom-inferred pH again does not show changes that could explain the irregularity in this last core (4–5 cm: pH = 4.8; 6–7 cm: pH = 5.0; 9–10 cm: pH = 4.8; Van Dam, pers. comm.). Both cores yield a ^{210}Pb deposition rate that agrees with the values reported by Crozaz et al. (1964) and El-Daoushy (1978), although at very different sedimentation rates. Ages calculated from CIC and CRS are in good agreement in both cores. This indicates that this pool has been relatively undisturbed and that it may be suitable for further analysis, assuming that vertical mixing occurs only in the upper few centimetres of the core. The synthesis of the biological data, pollen analyses and ^{210}Pb dating is in progress now. Unfortunately the one reliable core V.7 shows a low sedimentation rate, thus reducing the resolution of the time scale.

Site VI, Bergven

The ^{210}Pb distribution in the core from Bergven shows some fluctuation. About the causes can only be speculated because biological data and a diatom-inferred pH profile are not yet available. Ages calculated from both the CIC and the CRS model are in good agreement and preliminary results from biological studies are not contradictory.

Site VII, Kliplo

The fluctuating specific inorganic ^{210}Pb activity (mBq/g inorganic material) at greater depths ($\gtrsim$20 cm) and the strong variation of the inorganic content at the base of the core (13.2 weight% at 29–30 cm and 0.9 weight% at 32–33 cm) renders it difficult to calculate a reliable value for the supported $^{210}Pb_s$ activity. Therefore we used the total ^{210}Pb activity in the calculations, assuming $^{210}Pb_{xs} >> {}^{210}Pb_s$. This, however, may lead to a slight underestimation of the true age at these depths.

Nevertheless, excellent agreement is found between CIC and CRS calculated ^{210}Pb age-depth profiles. From the ^{210}Pb distribution we conclude that the sedimentation has been rather undisturbed (except maybe for some mixing in the upper few centimetres). The core shows the highest sedimentation rate obtained in this investigation, which enables high resolution age determination. The synthesis of the biological data, pollen analysis and ^{210}Pb dating will be published elsewhere.

Reliability of ^{210}Pb chronologies

In our discussion we touched upon the possibility of post-depositional (molecular) diffusion of ^{210}Pb (or ^{210}Po). Although this process seems rather unlikely to occur under the reducing conditions generally valid in these types of sediments, we can not disregard the possibility entirely, because, as stated before, part of the sediment may have been exposed to oxidizing conditions at periods of drought. If this has resulted in some redistribution of ^{210}Pb, our deduced sedimentation rates are over-estimated (Krishnaswamy & Lal, 1978; Robbins, 1978). The same is true for redistribution of ^{210}Pb and/or ^{210}Po by bacterial activity. The influence of these effects on the ^{210}Pb activity-depth profile may vary from site to site, which in some cases renders the results obtained from ^{210}Pb alone questionable. In this study the pollen analytical and biological data provided additional information about the reliability of the ^{210}Pb deduced ages. However, in general independent radiometric dating methods, using e.g. ^{137}Cs, may provide evidence for the validity of the ^{210}Pb results.

Conclusions

^{210}Pb analysis in shallow moorland pools in the Netherlands has provided valuable information about sedimentation rates and possible mixing processes that is of direct importance in palaeolimnological studies in general and acidification studies in particular.

However, ^{210}Pb distributions alone are not always sufficient to determine reliable age-depth profiles. In a multidisciplinary approach providing additional pollen and biological data, it was possible to obtain reliable ^{210}Pb chronologies for more than half of the cores. Furthermore, in the other cores ^{210}Pb activity-depth profiles provided valuable information about possible distortions of the sediment stratigraphy and thus prevented unnecessary additional analyses. We have found no direct evidence for a decreased absorption affinity of ^{210}Pb or ^{210}Po into the sediment at lower pH.

In the future additional independent dating methods (e.g. ^{137}Cs) may be required to improve the reliability and time resolution of dating.

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