**Table 1** Sulphur uptake measurements

| Site and times of measurements | Period of measurement (h) | Air concentration ($\mu$g m$^{-3}$) | Gaseous fraction (%) | Mean uptake ± s.e.m. ($\mu$g m$^{-2}$ s$^{-1}$) | Wind (m s$^{-1}$) |
|---|---|---|---|---|---|
| Forest* | | | | | |
| 1030–2000 h | 16 | 6–11 | 60 | <0.01 | 3.2–4.8 |
| 1200–1700 h | 7 | 12–35 | 84 | 0.04 ± 0.02 | 0.8–4.2 |
| Farmland† | | | | | |
| 1200–1730 h | 3 | 3–8 | 50 | 0.03 ± 0.02 | 2.2–5.7<br>(westerly; peas) |
| 1100–1600 h | 5 | 16–50 | 75 | 0.19 ± 0.02 | 2.2–4.4<br>(easterly; rye grass) |

* Forest: Crowthorne, Berkshire. 30-yr-old Scots Pine 14 m high unthinned since planting. Flux measurement 3 m above tops. Measurements are for 9 days between 1 and 20 May 1977.

† Farmland: Blewbury, Berkshire. Easterly fetch; Italian rye grass 75 cm; westerly fetch, peas 40 cm. Flux measurement 4 m above soil surface. Measurements are for six days between 21 June and 5 July 1977.

velocity of about 0.2 cm s$^{-1}$ for these forest measurements and about 0.6 cm s$^{-1}$ for the farmland measurements. All measurements were made in a turbulent atmosphere.

The sulphur detector responds to gaseous and particulate compounds. Particulate sulphur contributes only a fraction of the fluxes reported here, as the sulphate concentration at the field sites, assumed to be similar to that measured at Harwell, was only 20% of the total sulphur at the higher concentrations and the deposition velocity for small particles such as sulphate is much smaller than, or comparable with, that for sulphur dioxide[2,15]

Garland[2] summarises measurements of sulphur dioxide deposition over grass, crops and bare soil made by the profile and radioactive methods that give deposition velocities in the range 0.3–1.2 cm s$^{-1}$ with a median value 0.8 cm s$^{-1}$, in close agreement with that measured by the eddy correlation method here. Profile measurements in a forest[2] suggested an upper limit of the deposition velocity of 2 cm s$^{-1}$. Estimates based on measurements of individual shoots and extrapolation suggest a deposition velocity varying from a daytime maximum value of 0.6 cm s$^{-1}$ in the morning to 0.2 cm s$^{-1}$ in late afternoon to a night-time value of 0.1 cm s$^{-1}$, depending on stomatal resistance (closure) for a dry forest canopy[3]. The measurements presented here for the higher sulphur concentrations suggest a similar low deposition velocity for sulphur on the forest canopy during the afternoon. (We found no evidence of a diurnal variation in surface resistance during the period of our measurements.) Forest measurements were made when the new growth on the forest was just emerging and most of the exposed needles would have been from previous year's growth and are known to display lower uptake rates[3]. Furthermore, the sensible heat flux from the forest was frequently about 50% of the global total incoming solar radiation. This indicates that little evapotranspiration was taking place. The stomatal resistance to gaseous transfer would most probably be high in these conditions. Indeed, stomatal resistance is generally higher during the afternoon[3,16], and the measurements presented here may be for a forest in conditions of maximum resistance to sulphur uptake. The observed fluxes over forest and farmland can be entirely accounted for in terms of sulphur dioxide deposition. However this does not preclude a large deposition velocity for particulate sulphur.

The dry deposition to a dry forest canopy at a mean sulphur dioxide concentration of 10 $\mu$g m$^{-3}$, typical of many rural locations, would be perhaps 2–3 kg sulphur ha$^{-1}$ yr$^{-1}$, if the representative deposition velocity is as low as that measured here. This is a significant fraction of the estimated total sulphur deposition in English and Scottish upland sites of 10–20 kg sulphur ha$^{-1}$ yr$^{1}$ (ref. 1). If as suggested[3] gaseous and particulate uptake onto a wet canopy could account for a much larger fraction of the total deposition, then measurements with the method presented here can resolve this question.

We thank L. C. Cox for help with the field work, A. Hadjitofi for developing the sulphur detector, M. M. Davies for programming the computer, C. Healy and Miss J. B. Tarrant for the sulphate analyses, the Director of the Road Research Laboratory and the Manager of Churn Estates farm for access to field sites. I.E.G. thanks the Nuffield Foundation for a Travelling Fellowship and Dr A. C. Chamberlain for his help during the visit. The work was supported by the Department of the Environment.

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Received 27 December 1978; accepted 15 May 1979.

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# Magnetic measurements used to assess sediment influx at Llyn Goddionduon

THE preliminary results of an attempt to estimate sediment influx in a small upland lake using magnetic susceptibility measurements on whole unextruded sediment cores obtained from a grid covering almost the whole area of open water are reported here. The susceptibility variations, reinforced by a wider range of magnetic measurements on individual samples, provide a basis for core correlation over the whole lake. The speed with which such studies can be accomplished makes possible a much more secure empirical basis for calculations of total sediment input versus time than do conventional methods of core correlation and analysis.

0028–0836/79/270050—04$01.00

Increasing attention is being devoted to using lake sediments as sources of information about changing ecological processes in the recent past[1,2]. In many cases a large proportion of the lake sediment can be shown to have been derived from the lake watershed. The palaeoenvironmental record may, therefore, often be interpreted largely in terms of changes in the terrestrial ecosystems draining into the lake[3,4]. A prerequisite of fully quantitative studies designed to relate the sedimentary record in the lake to changing material output from its catchment is some procedure for calculating or estimating sediment influx to the whole lake for defined time intervals. Without this procedure all calculations of influx may be biased by the unrepresentative nature of a small number of coring sites.

Empirical attempts to overcome this problem[5] are limited largely by the time-consuming nature of the techniques normally available for core correlation in the absence of synchronous visual stratigraphic markers. Theoretical models developed to allow calculation of total sediment input from a single central core[6], though valuable are unconvincing in view of the numerous unverified assumptions on which they depend.

Thompson *et al.*[7] have shown that magnetic susceptibility measurements of whole, unextruded sediment cores can provide a rapid method of core correlation. The technique leaves the material unaltered, precludes no subsequent study of any kind and can be followed up by a range of related simple, rapid and non-destructive magnetic measurements[8] which often indicate sediment source[9,10] and are directly related to changes in human activity[7,8,11].

Llyn Goddionduon (Fig. 1*a*) lies 244 m above OD in the Gwydyr Forest area of North Wales, ~4 km north-west of Bettws y Coed (G.R. SH 753 586). It covers 6.2 hectares and receives drainage from a catchment of ~25 hectares. Maximum water depth is 6 m, in a small 'trench' occupying <5% of the area of the lake bed. Of the present sediment surface, 50% is between 0.75 m and 4 m deep. A small mire ~0.6 hectares in extent at the southern, outflow, end of the lake represents overgrowth of peat lying partly on marginal lake sediments. Some 25% of the lake is colonised by macrophytes among which *Schoenoplectus lacustris*, *Phragmites communis*, *Eleocharis palustris*, *Nymphaea alba*, *Potamogeton natans* and *Equisetum fluviatile* are the most abundant species[12].

An accurately surveyed grid of 130 minicores[13] was sampled during a 2-week period in July 1977, using a research team varying from five to nine people. Cores were taken at 20 m × 20 m intersections. Where impenetrable substrate precluded this, intermediate cores were taken. In the small trench area an extremely high density of sampling was achieved (27 cores in 950 m$^2$). Whole core susceptibility measurements were carried out on all cores during the same period of field work using a low-field susceptibility bridge[14] temporarily installed in the Drapers Field Study Centre 3.5 km from the lake. Volume susceptibility ($\kappa$) versus depth graph plots were produced

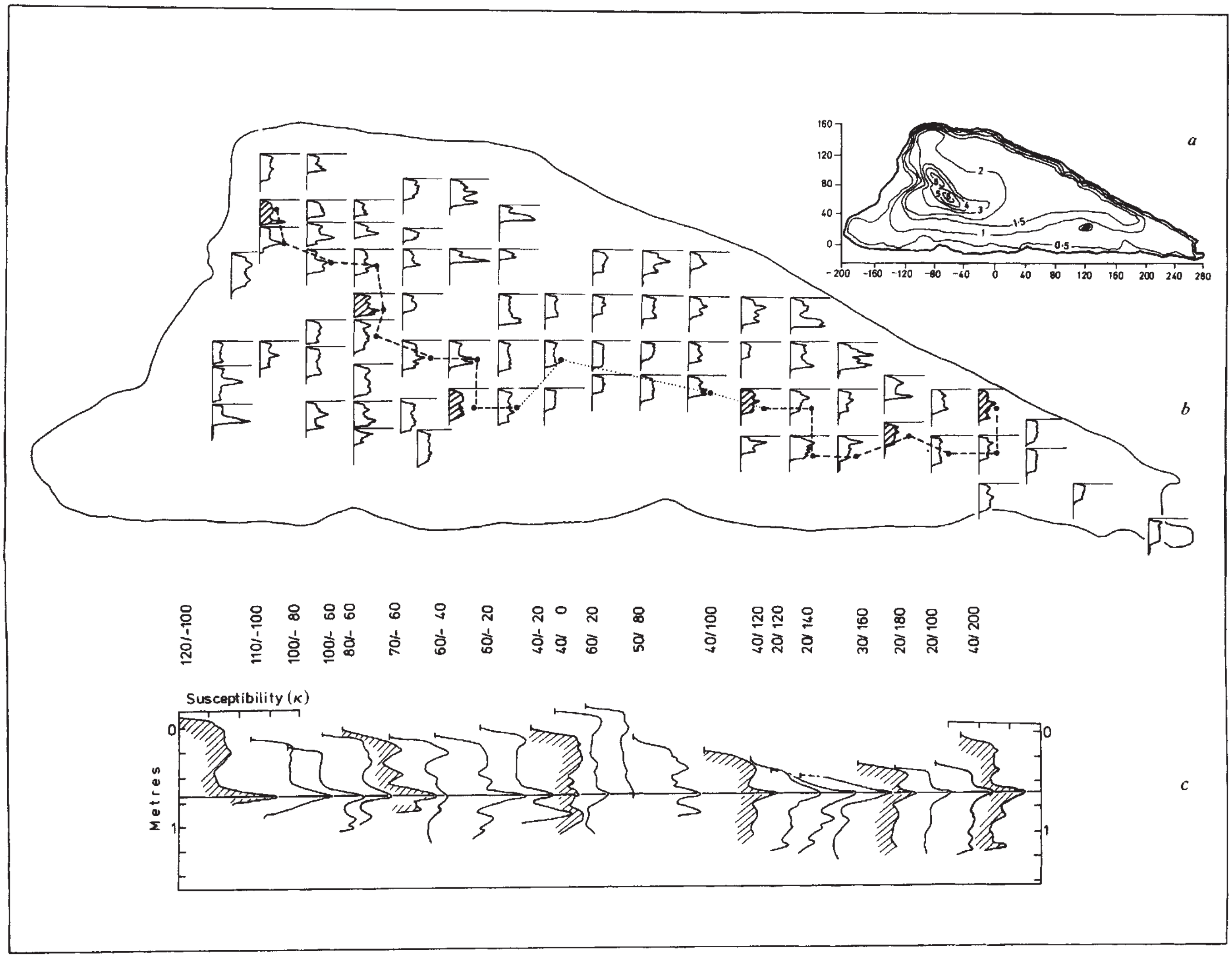

**Fig. 1** Llyn Goddionduon: *a*, Bathymetric map and coring grid coordinates; *b*, whole-core susceptibility traces from the main coring grid. The 'tie-line' joins the cores from which the linked and correlated traces shown below in *c* were obtained. The cores for which single sample $\chi$, SIRM and $\chi$/SIRM ratios are plotted in Fig. 2 are identified by shaded traces.

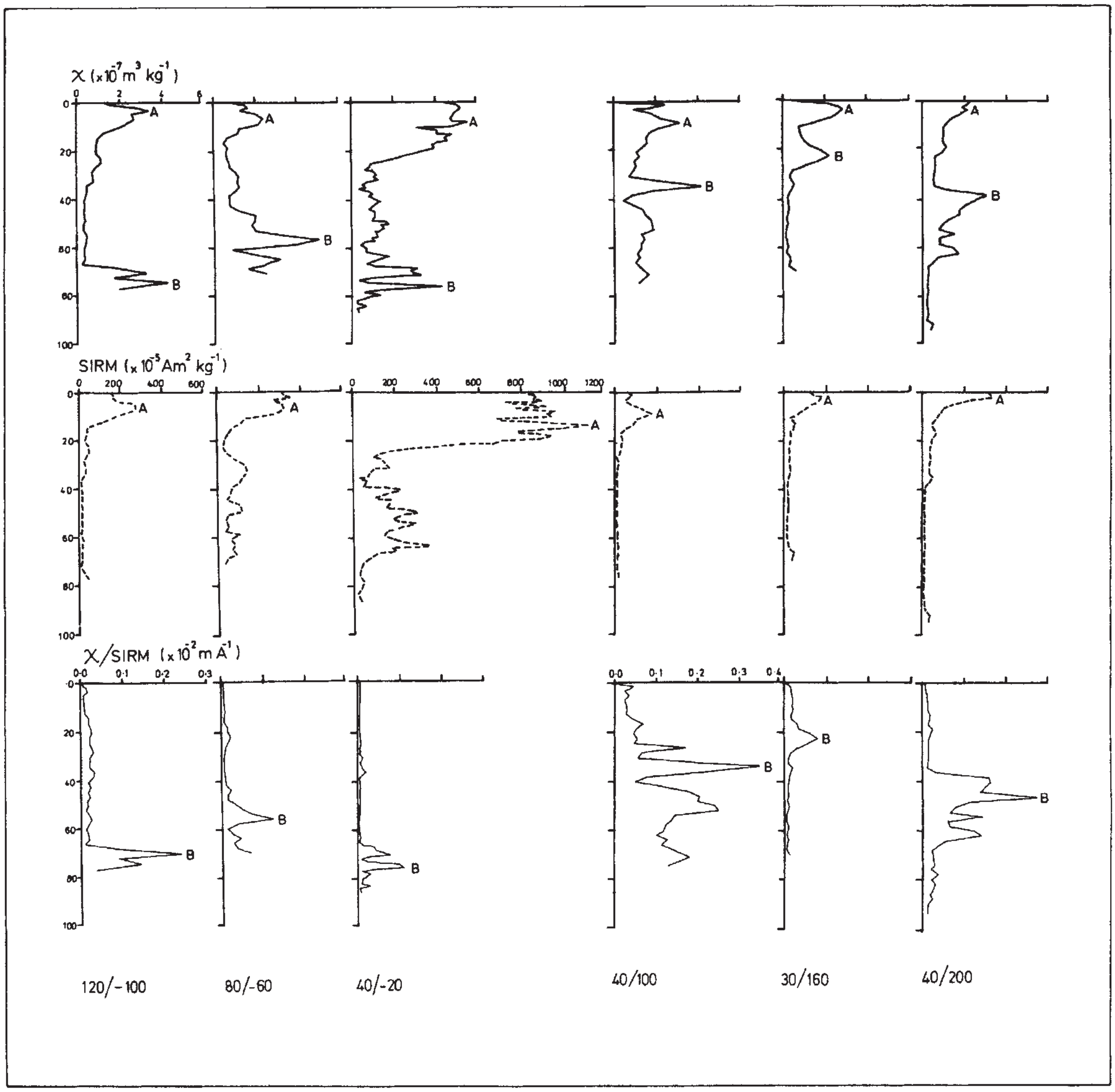

**Fig. 2** Llyn Goddionduon. Single sample plots of $\chi$, SIRM and $\chi$/SIRM for six widely separated cores from the main grid. In all cases, the upper peak in $\chi$ and SIRM which gives low $\chi$/SIRM values corresponds with the influx of magnetic minerals subsequent to a forest fire in 1951. The lower peak is clearly distinguishable from this in all cores by virtue of its high $\chi$/SIRM ratios.

automatically immediately after sensing and it was thus possible to plan day-to-day field sampling priorities in the light of the results obtained within a few hours of taking each set of cores.

Subsequent studies based on extruded sediment have included measurements of specific susceptibility ($\chi$), the intensity and direction of natural remanence (NRM), anhysteretic remanence (ARM), saturation isothermal remanence (SIRM) and coercivity of SIRM ($B_{CR}$). These magnetic measurements provide a wide range of rapidly calculated parameters and ratios which may be used to test core-correlation schemes. In addition chemical, particle size, loss-on ignition, pollen-analytical and radiometric studies are in progress.

Figure 1*b* shows whole core susceptibility traces for a selection of cores from the main grid of cores for the whole lake. In view of the paucity of Flandrian (Post-glacial) sediments in the tiny trench zone (<1 m in all 27 cores from only 5% of the lake), the complex deposition pattern of these cores has little effect on 'whole lake' investigations and the trench results can be satisfactorily assessed on the main 20-m grid. A 'tie-line' has been drawn down the length of the lake. The tie-line cores have been provisionally correlated using the scheme of whole core susceptibility peak matching indicated in Fig. 1*c* and substantiated in more detail by the plots of specific magnetic parameters from dried contiguous 1- or 2-cm subsamples presented in Fig. 2. The central zone in Fig. 1*b* reflects an area of more extended deposition within which the main susceptibility peak used in correlation lies below the depth of sediment penetrated by 1.3-m cores.

Figure 2 shows down core $\chi$, SIRM and $\chi$/SIRM ratios for dried sub-samples in, six widely separated cores located on Fig. 1. Peak $\chi$/SIRM ratios associated with the main tie-line linking the sites, and low $\chi$/SIRM ratios characteristic of the near surface peak (masked by the core tops in whole-core measurements) are common to all the cores and support the proposed correlation scheme. The uppermost sediment with low $\chi$/SIRM ratio is attributable to the forest fire of 1951 (ref. 11) which occurred on the north-east edge of the drainage basin.

Studies in progress are designed to confirm the full pattern of correlation, to date each stage in accumulation, to characterise sedimentologically, chemically and magnetically the variations in deposition rate portrayed, and to relate them to the history of land use at the site decipherable in the pollen record. These studies will provide a basis for empirically based calculations of changing net sediment input versus age for almost all the lake basin for the time interval spanned by the majority of the cores.

Magnetic measurements now open up the prospect of core scanning and correlation with a speed, and on a scale, orders of magnitude greater than conventional techniques allow. Well founded empirical calculations of total sediment input versus time thus becomes feasible even for lakes as complex as the present example. In the case of Llyn Goddionduon the anticipated pattern of sediment focusing into what is at present the deepest part of the lake has not been characteristic of the Flandrian period. Nevertheless, correlatable patterns emerge from the magnetic studies even within and between zones of relatively shallow marginal deposition.

We thank the NERC, the Leverhulme Trust and the Universities of Liverpool and Edinburgh for financial support, also colleagues and students from both Universities for field assistance, and we are grateful for the facilities in the Draper's Field Centre, Rhyd-y-Creuau.

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Received 6 March; accepted 24 May 1979.

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# $^{210}$Pb dating of annually laminated lake sediments from Finland

USE of $^{210}$Pb dating is increasing rapidly and applications include studies of accelerated eutrophication in major lakes[1], salt-marsh accretion[2], the recent history of heavy metal pollution[3] and accelerating soil erosion resulting from subsistence agriculture[4]. As dating models have increased in variety and complexity, it is important to compare models against precise and unambiguous independently derived time scales. In each area of application of $^{210}$Pb dating, the inferences drawn from the calculated age–depth curves and the estimates of changing flux rates are often highly dependent on the $^{210}$Pb dating model used. In this report $^{210}$Pb-derived estimates of lake sediment age and dry-mass sedimentation rates are compared with ages and rates calculated directly by counting annual laminations. The results support a model of $^{210}$Pb dating which assumes a constant net rate of supply (c.p.s.) of unsupported $^{210}$Pb to the sediment despite fluctuations in dry mass sedimentation rates. Our findings underline the need for empirical evaluation of alternative $^{210}$Pb dating models in the widest possible range of contexts. They also cast doubt on some published studies in which strongly 'kinked' profiles of unsupported $^{210}$Pb concentration have been interpreted within the framework of conventional constant initial concentration (c.i.c.) assumptions.

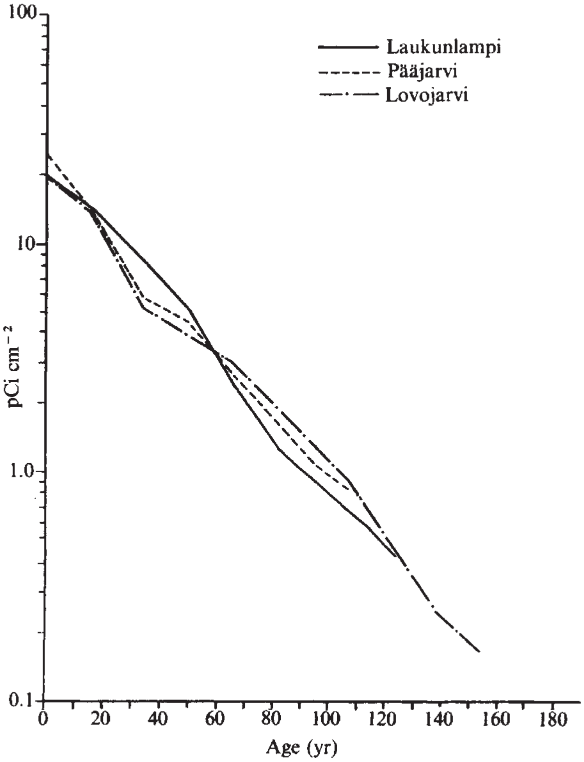

**Fig. 1** Cumulative residual unsupported $^{210}$Pb versus age in three annually laminated sediment profiles from lakes in east Finland. The approximation to a negative exponential function in each case confirms the validity of this as the appropriate dating parameter.

Most workers using $^{210}$Pb dating have assumed the initial unsupported $^{210}$Pb concentration to be constant throughout a dated profile, or at least in large sections of the profile. This assumption can be satisfied in theory by a direct association between sedimentation and unsupported $^{210}$Pb supply[5], or by a combination of constant unsupported $^{210}$Pb flux and constant dry-mass sedimentation for all of[6], or segments[7] of, each profile. Authors using c.i.c. models have dealt with sharply inflected or non-monotonic $^{210}$Pb-versus-depth profiles, or individual 'anomalous' values, by invoking alternative explanations such as physical mixing[8], bioturbation[9], diffusion[10] and co-precipitation of $^{210}$Pb with manganese[11]. Where authors have referred to the alternative basic assumption of a constant net rate of supply (c.r.s.) of unsupported $^{210}$Pb to the sediment independent of fluctuations in bulk sedimentation rate this alternative has usually been dismissed in favour of some variant of the c.i.c. model[12,13], or else it has been used but not empirically tested in a rigorous manner[2,14,15]. Recent applications of c.r.s. model calculations[16] to lake sediment sequences in Northern Ireland, the Highlands of Papua New Guinea[17] and Lake Michigan[18] provide strong, varied, but essentially circumstantial evidence for the validity of c.r.s.-derived age–depth relationships and dry-mass sedimentation rates. In each of these case studies, as in the example by Robbins[15], the choice between alternative models has a major impact on the results and their interpretation.

The sites from which the present evidence has been obtained provide a very precise and unambiguous basis for testing the alternative dating models. Not only are their recent sediments in the form of distinctive annual laminations, confirmed both biostratigraphically[19,20] and by $^{239,240}$Pu and $^{137}$Cs analyses (T. Jaakola, K. T., P. H. and S. Tiainen, unpublished), but they have also experienced disturbance in each catchment which has given rise to fluctuations in sedimentation rate strong enough to 'kink' the unsupported $^{210}$Pb concentration-versus-depth curve.

In the c.r.s. model, the age $t$ of sediments of depth $x$ is calculated from[16]

$$A(x) = A(0)\,e^{-kt} \qquad (1)$$