J Paleolimnol
DOI 10.1007/s10933-013-9685-y

NOTES

^{210}Pb dating: thirty-five years on

Peter G. Appleby

Received: 20 January 2013 / Accepted: 23 January 2013

It is now 35 years since I first became involved in ^{210}Pb dating. Until then I had been quietly working away on the mathematics of classical space–time. Little did I anticipate that I was about to continue with this general theme, though in a rather more down to earth (or should I say limnological) setting. Following a chance conversation with Frank Oldfield I soon found myself on quite a different path, investigating the mathematics of paleolimnological space–time where the time dimension was now measured as depth in a column of lake sediment!

I first met Frank in the mid-1970s as a member of that pioneering Interdisciplinary Research Centre of the University of Liverpool, the West Kirby Car Pool (Oldfield 2010). Including at various times mathematicians, geographers, engineers, veterinary scientists, the University Archivist, and the Director of the Computer Laboratory, it really did cover a wide range of academic interests. Frank had recently arrived back in Liverpool from New Guinea, and one day when we were travelling to work he mentioned that he had been using the recently developed ^{210}Pb method (Krishnaswamy et al. 1971) for dating lake sediment cores, though there were problems. Sediments from a lake in the New Guinea Highlands known to date from the mid-eighteenth century or earlier were yielding dates that were far too young. The rest, as they say, is history. Using Frank's diagrams and a little bit of calculus we came up with the constant rate of supply (CRS) model, which managed to produce much more credible results (Oldfield et al. 1978). However, when we tried to publish a paper describing the model, we ran into difficulties. The referees, acknowledged experts in the field at that time, described the model as naïve and not particularly original. In light of what we know now their criticisms were well justified. The only thing wrong about their advice was that the approach we developed, when tested empirically using data from a number of different sites, in fact worked very successfully. The basic methodology, published originally in Appleby and Oldfield (1978), has since been widely used in numerous studies all round the world. We learnt two lessons from this. The first was that there are times when it pays to be a little naïve. The second was that one shouldn't always follow the advice of experts.

A highlight of those early years following my introduction to Paleolimnology was a trip to Joensuu, Finland at the beginning of September 1981 to attend the 3rd International Symposium (Fig. 1). Getting to Joensuu was itself quite an adventure involving a journey by ferry and minibus across Sweden and Finland, in the company of many of the other UK participants. Following the opening session in Joensuu, the Symposium moved 45 miles north to the

---

The author was the recipient of a "Lifetime Achievement Award" presented by the International Paleolimnology Association (IPA) in Glasgow, Scotland on 22 August 2012.

P. G. Appleby (✉)
Department of Mathematical Sciences, University of Liverpool, Liverpool L69 3BX, UK
e-mail: appleby@liverpool.ac.uk

beautiful hilltop hotel at Koli where the lecture sessions took place. The meeting was memorable both scientifically and socially, with many discussions taking place around the sauna and pool. At the conference dinner each national group was expected to make a contribution to the evening's entertainment. The UK's well-lubricated rendition of 'Strip the Willow,' ably lead by Elizabeth Haworth, was an unforgettable introduction to the paleolimnological community. The journey home gave me the opportunity to visit two sites, Laukunlampi and Pääjärvi, that had figured in one of our early papers on ^{210}Pb records in lakes with laminated sediments (Appleby et al. 1979), and see for the first time paleolimnologists in action. Paddy O'Sullivan's love of Sibelius also resulted in another highlight, a visit to Ainola.

After a couple of years of model testing Frank had a second bright idea, why don't we develop a ^{210}Pb radiometric laboratory at Liverpool? Now I knew the meaning of the word radioactivity, but that was about as far as it went—my first-year Physics was mostly long forgotten. The idea seemed fairly adventurous to say the least. Nonetheless, a visit from a supplier was arranged, a demonstration organised, buttons pressed, and it all looked fairly impressive, though the equipment did seem very expensive. In the course of the demonstration, the salesman said—"by the way, they have one of these over in the Physics department, you might like to go and have a look at it." So I went over to Physics, found Paul Nolan, and a bright and shiny well detector sitting on a bench in the old Van de Graaf Laboratory waiting for someone to come along and use it. We quickly loaded it with a lake sediment sample and came back next day to find a beautiful 46.5 keV ^{210}Pb photo-peak in the spectrum. We were in business. So our third lesson was—perhaps fairy godmothers do exist.

The development of radiometric assay by gamma spectrometry using hyper-pure germanium well-type detectors proved to be a major step forward. Advantages of this technique included non-destructive measurements, minimal sample preparation, and significantly higher detection efficiencies (particularly when using well detectors) that allowed simultaneous determination of a range of radionuclides, including ^{210}Pb, ^{226}Ra, ^{137}Cs, ^{241}Am, etc. (Appleby et al. 1986) in relatively small samples. Direct measurement of ^{226}Ra (supported ^{210}Pb) concentrations in all samples analysed for ^{210}Pb removed much of the uncertainty in determining the unsupported component of the total ^{210}Pb activity needed for the dating calculations. Further, the determination of ^{137}Cs (and ^{241}Am) records alongside those of ^{210}Pb has proved to be of crucial importance in the assessment of ^{210}Pb data and the validation or correction of ^{210}Pb dates.

At Frank's instigation we formed the "Radiometric, Mineral Magnetic, and Palaeoenvironmental Research Centre," though after a few years we took pity on people and shortened it to the "Environmental Radioactivity Research Centre," ERRC. Any successes that this Centre may have had were very much due to its collaborative nature. Key people have of course included Professor Frank Oldfield (Geography) whose initiatives and leadership were central to this whole development, and Professor Paul Nolan (Physics) who has very generously provided the technical support so essential to the establishment and maintenance of our Environmental Radiometric Laboratory (Fig. 2).

Fig. 1 In conversation with Rick Battarbee at the 3rd international symposium on Paleolimnology, Joensuu, 1981

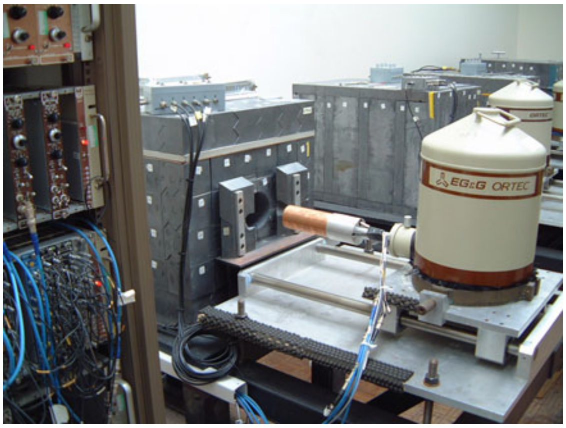

Fig. 2 Well-type hyper-pure germanium gamma detectors in the ERRC Environmental Radiometric Laboratory

A further interesting challenge was the hosting of the 5th International Symposium on Paleolimnology held at Ambleside in the English Lake District in September 1989. This took place just about at the dawn of the internet age when communication systems and software packages were very rudimentary compared to those on display this year in Glasgow, at a time when FAX was dominant. Highlights (apart from the Scottish dancing) included the spectacle of a 6-m Mackereth corer in action, and a display of fieldwork by helicopter.

The main emphasis of my work during the next decade was the development of more precise models of the pathways by which ^{210}Pb and other fallout radionuclides, following deposition on the lake and in the catchment, are transported to the sediment record. A first step was the creation of mass balances for catchment/lake systems that involved determining inputs from the atmosphere, rates of transport from the catchment to the lake, and losses via the outflow. Since many of the key parameters were not well determined, this gave me a wonderful excuse to become involved in some fieldwork myself, a particular treat being trips to a number of high mountain lakes in spectacular settings in the Pyrenees, Austrian Alps, and Tatra mountains. Figure 3 shows colleagues from the University of Barcelona measuring soluble and particulate concentrations of ^{210}Pb and ^{137}Cs in the water column of Redo Lake in the Spanish Pyrenees. Work at these sites, and also at Blelham Tarn in Cumbria (Appleby et al. 2003), revealed that although the bulk of fallout ^{210}Pb remained locked up in the catchment for very long periods of time, losses from the catchment to the lake could make a significant contribution to the amount reaching the sediment record. Although this might sound like bad news for the CRS model, in practice the effects were fairly marginal. It did however emphasise the need to constantly assess ^{210}Pb data and only accept dates as reliable if they have been independently validated. The most important means for achieving this was by comparing them with chronostratigraphic dates, most usually from sediment records of the 1963 ^{137}Cs (or ^{241}Am) fallout maximum from the atmospheric testing of thermonuclear weapons, or more recently, the 1986 Chernobyl reactor accident. In the early days of ^{210}Pb dating the 1963 ^{137}Cs peak was too recent to be of any great value apart from indicating the quality of records in near-surface sediments. As time passes, it is now two ^{210}Pb half-lives old, the 1963 ^{137}Cs peak is becoming of increasing importance in calibrating ^{210}Pb calculations.

Calculating the ^{210}Pb date of a sample in essence requires an estimation to be made of the original ^{210}Pb concentration of the sample when laid down on the bed of the lake. The two simple models for making this estimation are the constant initial concentration (CIC) model, which assumes a steady state system in which sediments laid down at different times all had the same initial concentration, and the CRS model, which assumes that the initial concentrations were inversely proportional to the sedimentation rate, the coefficient of this proportionality being determined from the ^{210}Pb inventory of the core. Dates given by these two models are of course significantly different only at sites where there have been substantial changes in the sedimentation rate during the ^{210}Pb time-span (~130 years). In light of the complexities of the transport processes controlling the supply of fallout ^{210}Pb to the bottom sediments, it is surprising that the simple models work as well as they do. Figure 4 shows results from a site in Finland where in spite of the highly irregular nature of the ^{210}Pb record, the raw CRS model dates are in excellent agreement with the 1963 ^{137}Cs date determined from the well-defined peak in the ^{137}Cs activity versus depth record.

Although the CRS model has proved to be generally the more reliable, there have nonetheless been many cases where there have been significant discrepancies between ^{210}Pb and ^{137}Cs dates. These would typically be due to systematic changes in the rate of supply of ^{210}Pb to the core site, or singular events such as

Fig. 3 Measuring ^{210}Pb concentrations in the water column of Redo Lake, Spanish Pyrenees, with colleagues from the University of Barcelona

Journal : Medium 10933
Article No. : 9685
MS Code :
Dispatch : 31-1-2013
Pages : 6
☐ LE
☑ CP
☐ TYPESET
☑ DISK

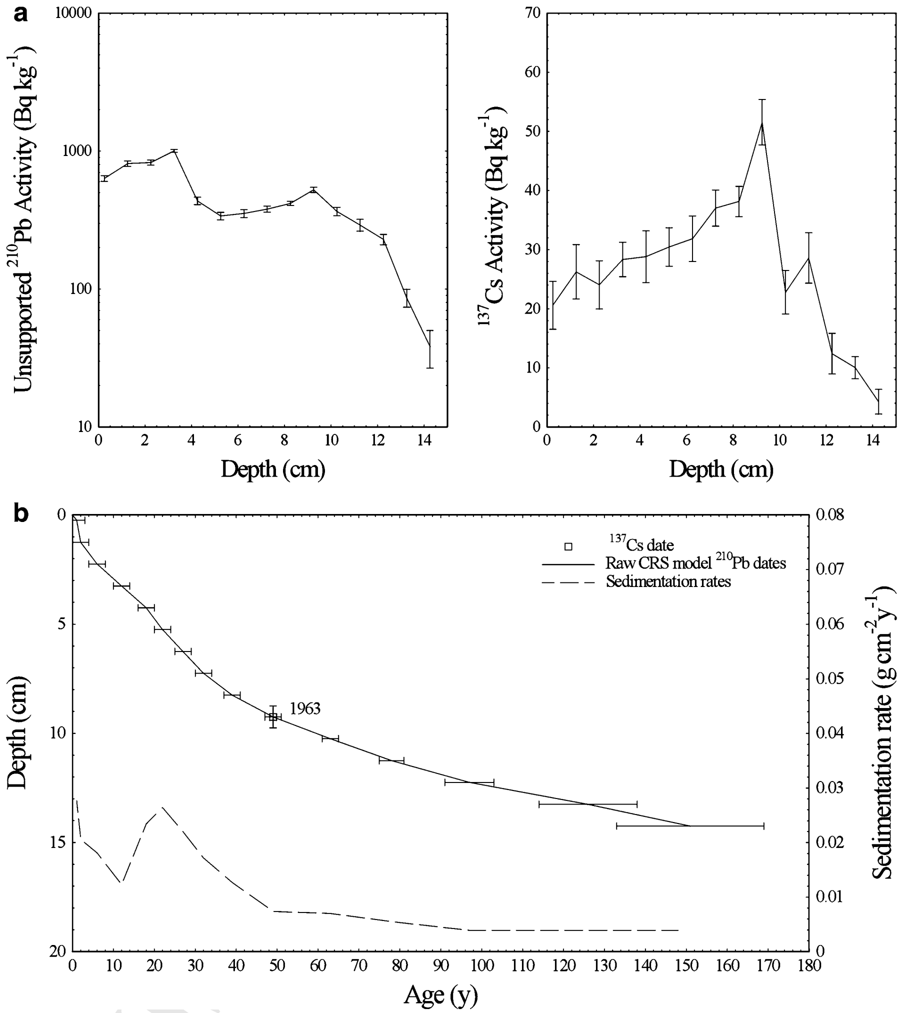

Fig. 4 **a** Radionuclide records in a core from Finland. Although the ^{210}Pb record is highly irregular, the ^{137}Cs record does have a well-defined peak identifying the 1963 depth. **b** The raw CRS model ^{210}Pb dates are in excellent agreement with the 1963 ^{137}Cs date. The irregular ^{210}Pb record is attributed to a large increase in the sedimentation rate in recent decades

sediment slumps, or hiatuses in the sediment record that have affected the ^{210}Pb inventory. Where dating discrepancies are significant it may be necessary to apply corrections to the ^{210}Pb calculations. Any correction procedure must however be *simple, practicable*, and *evidence-based*. Although such discrepancies imply a departure from the assumptions of one or the other of the simple models, the complicated nature of the transport processes governing the supply of ^{210}Pb makes it unlikely that any more general and widely applicable process-based model can be found. The approach we have taken is to apply the CRS model in a piecewise way to different sections of the core, using ^{137}Cs or other chronostratigraphic dates as reference points (Appleby 2001). Figure 5 shows results from a lake in northern Germany in which the raw CRS model dates, calculated by assuming a single ^{210}Pb supply rate, differed significantly from those determined from the ^{137}Cs record which had two distinct peaks identifying the 1986 and 1963 depths. Figure 5b shows mean ^{210}Pb supply rates for each of the three different time periods, post-1986, 1963–1986 and pre-1963, calculated from the ^{210}Pb inventories contained within those sections of the core, and also the corrected ^{210}Pb dates calculated by applying the CRS model in a piecewise way using these values.

Quite apart from their role in dating lake sediments, in view of their well-defined origin, radionuclide records also play an important role as indicators of the quality of sediment records. If a core has good-quality ^{210}Pb and ^{137}Cs records it is reasonable to suppose that records of other environmental indicators should also be well preserved. Although judgement of quality and reliability from the record in a single core at

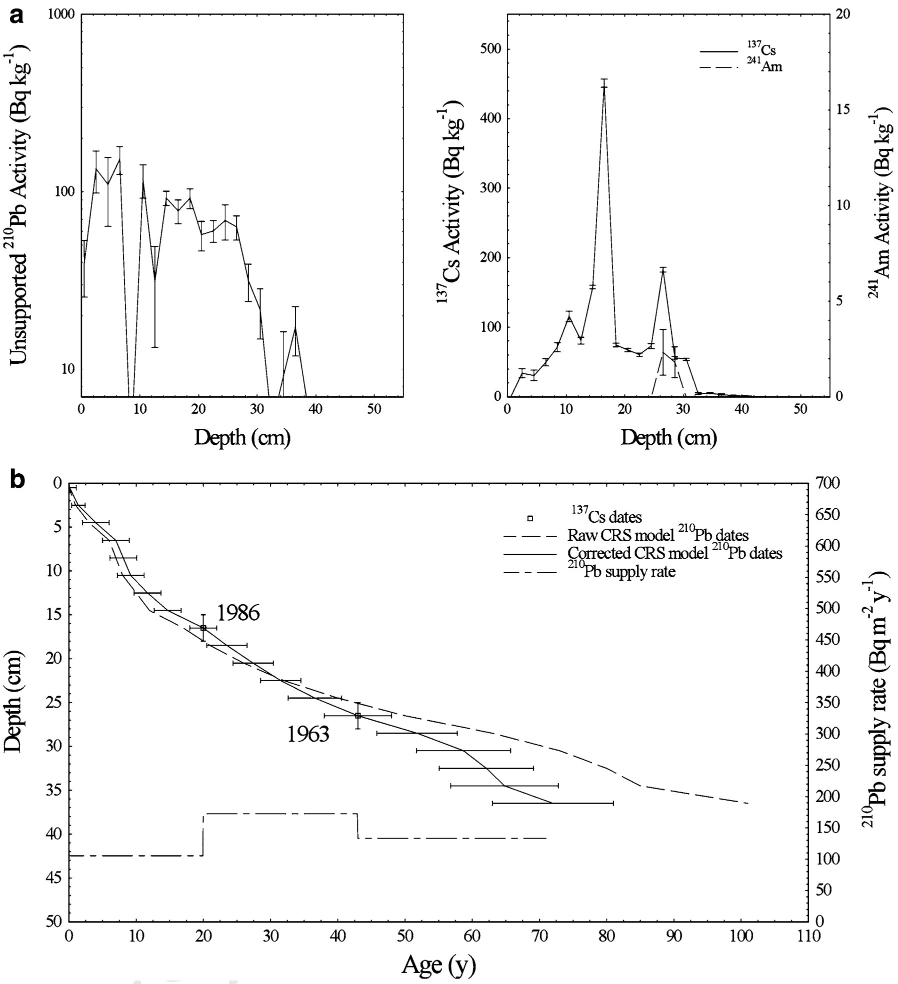

Fig. 5 **a** Radionuclide records in a core from northern Germany. Well-defined peaks in the ^{137}Cs record identify the 1986 and 1963 depths, and also demonstrate that the irregular ^{210}Pb record is not caused by sediment mixing. **b** Errors in the raw CRS model ^{210}Pb dates are attributed to changes in the ^{210}Pb supply rate calculated using the 1986 and 1963 ^{137}Cs dates as reference points. The corrected ^{210}Pb dates were calculated by applying the CRS model in a piecewise way using different ^{210}Pb supply rates for each time period

a particular point in time is somewhat circumstantial, the evident mobility of ^{137}Cs having led some authors to question the reliability of ^{137}Cs dates, we are now in the fortunate position of being able to investigate directly the stability of sediment records by revisiting sites that were cored decades earlier. This has been demonstrated in a recent study by Klaminder et al. (2012) using varved sediment cores from Nylandssjon (Sweden) collected over a 21-year period, 1986–2007. The ^{137}Cs records from these cores (Fig. 6) clearly demonstrate the persistence and accuracy of the key 1963 and 1986 ^{137}Cs chronostratigraphic features over a period of several decades. Annual laminations allowed very precise dating of sediments from this lake. The pre-1986 core collected just before the Chernobyl accident preserved a well-defined peak in the 1964 layer recording the year of maximum fallout from the atmospheric testing of nuclear weapons. The post-1986 cores, collected in 1988, 1989, 1996 and 2007, all had well-defined peaks in the 1986 layer recording fallout from the Chernobyl nuclear reactor fire. The evident mobility of a soluble fraction, presumably by pore water diffusion, in no way diminished the reliability of these ^{137}Cs dates. Because of the very high levels of Chernobyl fallout at this site, downward migration of ^{137}Cs from this source did however mask the weapons fallout peaks in the post-1986 cores.

Working with the many friends and colleagues I have made and met in the paleolimnology community has in itself been an immense source of satisfaction quite apart from that gained from working in a field with direct relevance to many contemporary issues. In particular I owe a great debt of gratitude to Frank Oldfield whose guidance, advice and encouragement were instrumental in setting me off on this particular journey, and also to Rick Battarbee and his colleagues

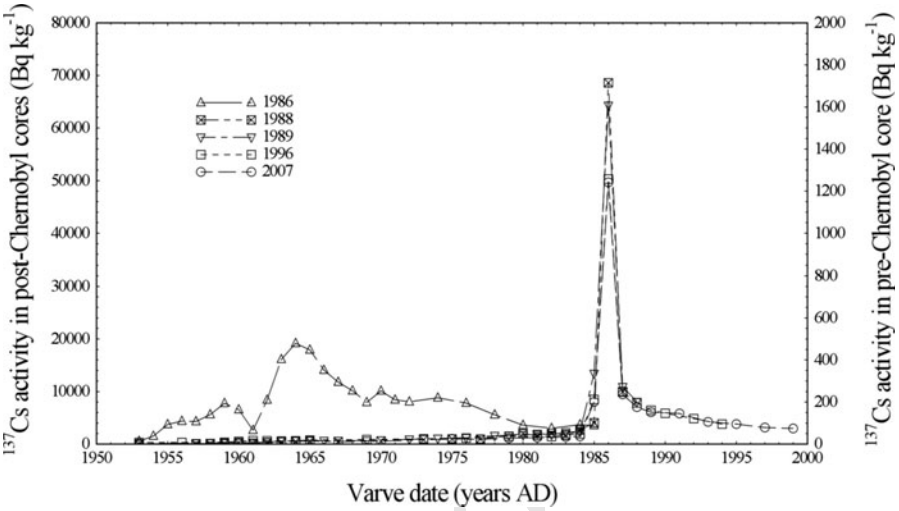

Fig. 6 Records of fallout ^{137}Cs in annually laminated sediment cores collected during the period 1986–2007 from Nylandssjon, Sweden (Klaminder et al. 2012). The 1986 core was collected just before the Chernobyl reactor fire

at the UCL Environmental Change Research Centre with whom we at Liverpool have enjoyed an extremely valuable and fruitful collaboration over many years. I am also greatly indebted to Elizabeth Haworth and her colleagues at the IFE/FBA Ferry House Laboratory on Windermere for their invaluable help and advice, and also for providing me with an excellent excuse for visiting the many lakes and tarns of the English Lake District.

References

Appleby PG (2001) Chronostratigraphic techniques in recent sediments. In: Last WM, Smol JP (eds) Tracking environmental change using lake sediments volume 1: basin analysis, coring, and chronological techniques. Kluwer Academic, Dordrecht, pp 171–203

Appleby PG, Oldfield F (1978) The calculation of lead-210 dates assuming a constant rate of supply of unsupported ^{210}Pb to the sediment. Catena 5:1–8

Appleby PG, Oldfield F, Thompson R, Huttenen P, Tolonen K (1979) Pb-210 dating of annually laminated lake sediments from Finland. Nature 280:53–55

Appleby PG, Nolan PJ, Gifford DW, Godfrey MJ, Oldfield F, Anderson NJ, Battarbee RW (1986) Pb-210 dating by low-background gamma counting. Hydrobiologia 143:21–27

Appleby PG, Haworth EY, Michel H, Short DB, Laptev G, Piliposian GT (2003) The transport and mass balance of fallout radionuclides in Blelham Tarn, Cumbria (UK). J Paleolimnol 29:459–473

Klaminder J, Appleby P, Crook P, Renberg I (2012) Post-deposition diffusion of ^{137}Cs in lake sediment: implications for radiocesium dating. Sedimentology 59:2259–2267

Krishnaswamy S, Lal D, Martin JM, Meybeck M (1971) Geochronology of lake sediments. Earth Planet Sci Lett 11:407–414

Oldfield F (2010) Palaeolimnology: personal reflections and early UK contributions. J Paleolimnol 44:505–510

Oldfield F, Appleby PG, Battarbee RW (1978) Alternative Pb-210 dating: results from the New Guinea Highlands and Lough Erne. Nature 271:339–342

Journal : **Medium 10933** Dispatch : **31-1-2013** Pages : **6**
Article No. : **9685** ☐ LE ☐ TYPESET
MS Code : ☑ CP ☑ DISK