Workshop on radiological techniques in sedimentation studies: methods and applications

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The following document summarises the important issues raised during the 3 hour discussion period of the Workshop on "Radiological Techniques in Sedimentation Studies", held on June 22, 2000. The document includes contributions from the above authors summarising, and in some cases illustrating important features of the discussion. The discussion issues covered:

- problems associated with the use of "mapping" algorithms, particularly CRS, to give unsubstantiated ^{210}Pb "dates";

- the necessity to validate ^{210}Pb deposition histories;

- the trend in research journals to publish ^{210}Pb chronologies with supporting data;

- the effect of drainage basin residence times on fallout nuclide sediment profiles;

- the low activity of fallout tracers in the southern hemisphere, and the implications for sample core collection, analysis and geochronological usage.

These issues have been broadly divided into three sections; the first dealing with problems associated with interpretation and dating of ^{210}Pb profiles; the second describing some aspects of large scale processes and geographical features which affect the sediment profiles of excess ^{210}Pb and "bomb" nuclides. Finally some recommended sampling and analytical procedures are listed.

There was a collective recognition of the need for standards and consistency in reporting data and interpretations in publications. There was concurrence with the idea of trying to influence editorial policies of prominent research journals. Suggestions for editorial policy regarding the use of ^{210}Pb for sediment geochronology included (1) requiring at least one independent method to verify the chronology, (2) provision of all relevant data and details of computational methods to reviewers of submitted papers and (3) publication of relevant data and computational methods either within the paper (possibly as small-type appendices) or as reader-accessible electronic files.

Application of ^{210}Pb as dating tool

Introduction by J. A. Robbins

It has been 37 years since Ed Goldberg first used ^{210}Pb as a dating tool and nearly 30 years since the method was first applied to sediments. Not only did Goldberg introduce the method but, in a short paper presented at an IAEA meeting in Vienna, he proposed computational algorithms (yes, mappings) for obtaining dates – the very mappings popularised by Appleby and Oldfield 15 years later!

The round of applause given Gregg's tongue-in-cheek faulting of W. F. Libby for his "disservice" by development and promotion of the ^{14}C method, nicely underscored a division among those interested in ^{210}Pb: those who consider the radionuclide to be one among many that are enormously useful for understanding processes and associated time scales in lacustrine and marine systems on the one hand, and those who are primarily interested in temporal records of

chemical and biological changes in ecosystems on the other. I suspect the first group consists of mathematicians, physicists and chemists, comparatively well versed in quantitative process modelling, while the second group consists of biologists, ecologists and paleolimnologists. The first group is more inclined to think that when ^{210}Pb can provide chronological information it's nice but if not, it still may tell us something interesting about how a system works. The second group, with first or second hand knowledge of the comparative ease and benefits of ^{14}C dating, wants some analogous ^{210}Pb dates and maybe some associated uncertainties so as to tell a history, but wishes understandably to shun complexities, rigours and equivocations of quantitative process modelling. Of course with ^{210}Pb that's not possible – ever. Thus, while ^{210}Pb can be a valuable tool for dating sediments up to about a century old, its primary use is to evaluate processes of sediment transport, focusing, mixing and accumulation in lacustrine and coastal marine systems. The method is not analogous to ^{14}C dating, is never routine and chronological information culled from sediment ^{210}Pb profiles must always be verified by independent means. Perhaps the most important implication of a quite evident disparity in outlooks is that there should be more cooperation between the explicators of process and the tellers of history!

I am among those who are aggravated by the deterioration in reporting of ^{210}Pb data and interpretations in peer-reviewed publications. I applaud John Smith's forthcoming editorial in Journal of Environmental Radioactivity that addresses the problem and proposes standards for publication of ^{210}Pb results. I believe that we should use the SPERA-2000 Workshop summary document as another vehicle for promoting appropriate standards for journal publications.

Comment from D. N. Edgington

Over the last 20 years the measurement of ^{210}Pb in sediment cores has become a very popular method for determining sedimentation rates over a time-span of approximately 100 years. Unfortunately, this method appears to be far simpler than it really is and there is considerable misuse as evidenced by many papers appearing in the

literature. Based on my quick assessment of papers appearing in major journals in the field such as *Environmental Science & Technology* and *Limnology & Oceanography* approximately 75% of the papers published in the last year or so did not present any of the ^{210}Pb data or an age-depth relationship to justify their interpretation, merely presenting the y data versus a totally unsubstantiated x axis. This reflects a serious problem with quality of reviewing, or the understanding of the problems of using ^{210}Pb data to ascribe dates by reviewers, even for the most prestigious journals. It is now very common to assume that this method is so simple and cut-and-dried that it is no longer considered necessary to publish the derived age-depth relationships, let alone the data on which the dating is based. As a result there are many papers appearing in the literature in which the discussion of changes in contaminant concentrations or fluxes with time observed in sediment profiles based on dates derived from ^{210}Pb cannot be evaluated. This is because these discussions are based on an unreviewable or unevaluable time-scale, thus making these papers essentially meaningless. This situation is untenable and very unhealthy for our science.

Comment from G. Brunskill and J. Pfitzner

Libby gave us the ability to estimate the age of an organic or carbonate carbon sample from the ratio $^{14}C/^{12}C$, and Claire Patterson gave us the ability to estimate the age of the earth and meteorites from uranium/lead ratios. Despite the many sources of uncertainty and contamination of samples, the language used for results from these methods suggests that these methods give our best estimate of the real age of each sample analysed. These methods can be used to estimate a unique age (with associated uncertainty) of a single sample.

The use of sedimentation tracers such as excess ^{210}Pb, ^{234}Th, and ^{7}Be is a fundamentally different enterprise, as these particle-reactive tracers provide no unique "age" for one sample of mud. The information package from these tracer methods is contained in the magnitude and shape of the core profile over sediment depth, usually involving 20-100 samples in one sediment core. These isotopes are annually supplied to the sediment surface by natural production, and in most cases we do not know what sedimentary phases hosts

each isotope. The most obvious and useful parameters that can sometimes be derived from these sediment core profiles of short-lived nuclides are the rate of present day accumulation, the core horizons that are mixed, and the excess or depletion of these isotopes related to non-deposition, erosion, resuspension, and focusing of sediment labelled with these tracers. It is helpful to know the source and hopefully "steady state" rate of supply of these isotopes to the sediment column, and this can usually be estimated from atmospheric and water column measurements. If the rate of accumulation of bulk sediment can be estimated from more than one of these isotopes, then something approximating an "average age" for a given core slice can be calculated, and this average age uncertainty should include the time equivalent of the surface mixed layer, pore water diffusion smoothing, and all the analytical uncertainties of field sampling and measurement. Where other sedimentary information provides constraints on depositional history, such as varves, known contaminant inputs, or known natural episodic events, these isotopic tracers usually estimate accumulation rate in a reasonable manner. Except for very few unusual cases, it is inappropriate and misleading to provide a unique age for each sediment core sample.

Comment on Interpreting ^{210}Pb Profiles by J. A. Robbins

Profiles of ^{210}Pb are the end result of a complex of processes controlling the delivery of sediments and the radionuclide to coring sites over a time span of about one century. Proper quantitative modelling of profiles depends on an astute selection of a critical subset of those processes and an accurate mathematical representation of their role. This is not an easy task! ^{210}Pb sediment chronologies, if they can be established at all, should be the result of a self-consistent application of quantitative process models (QPMs) to ^{210}Pb and other ancillary data.

Because QPMs are difficult to develop, often require extensive supporting data as well as long observational (as well as computational) experience with specific systems, several simplified approaches have arisen for extracting chronologies from excess ^{210}Pb profiles: curve fitting and mappings.

In curve fitting, excess ^{210}Pb profiles are described by a simple function with a restricted number of parameters evaluated by least-squares optimisation methods: for example a fit of a roughly log-linear ^{210}Pb profile with depth using a straight line or several straight line segments. The value of curve fitting is its simplicity, provision of a test of goodness of fit to the data, and use of relatively large numbers of data points to generate age estimates with improved precision. The drawbacks are that simple functions may not represent the data well, relevant processes may go unrecognised and inaccuracies may result. Curve fitting invites laziness in reflection on system properties.

A mapping is a mathematical formula, algorithm, scheme or procedure by which each excess ^{210}Pb data point (or construction based on a set of data points) is used to calculate a corresponding age or accumulation rate (Robbins and Herche, 1993). Several mappings have appeared in the literature, most notably CRS or CIC, and have become methods of choice for extracting sediment age-depth relations. These are often referred to as "models" but they are not true models in the sense of QPMs. Mappings are relatively easy to use, can inform construction of QPMs, and can be of value in cases where true models are inaccessible. The principal drawback of mappings is that, by construction, they never provide a test of their validity. No comparison of theoretical and measured excess ^{210}Pb profiles ever results from use of a mapping. Mappings require little understanding of system processes, and can thus lead to false interpretations as well as irresponsible reporting of research results. CRS presents particular difficulties because even extremely erratic ^{210}Pb profiles can yield relatively smooth age-depth relations, sediment mixing as well as variability in rates of ^{210}Pb delivery may be mistakenly converted into changes in sediment accumulation rates, and, because the computation demands an accurate estimate of total excess ^{210}Pb inventory, sediment dates and accumulation rates can be incorrectly estimated, especially when supported levels are high.

Quantitative Process Models

The distinction between curve fitting, mappings and QPMs were illustrated at session and workshop presentations. An excess ^{210}Pb

profile in a sediment core from a reservoir from Lake Oahe in South Dakota (Callender and Robbins, 1993) that was constructed in 1958, while "noisy" nevertheless decreased roughly exponentially with depth to background at around 100 cm depth. Both conventional curve fitting and a CRS mapping incorrectly predicted the bottom of the core at 200 cm to correspond to about 1850, while the ^{137}Cs activity appeared down to 200 cm with a peak at 160 cm depth. In contrast a QPM, with an exponentially decreasing sediment accumulation rate since creation of the reservoir, explained both the ^{137}Cs and excess ^{210}Pb profile. Simple curve fitting and the CRS mapping failed because much of the information required by these calculations was lost in the high background of supported ^{210}Pb. In one presentation (Robbins *et al.*, 2001) four excess ^{210}Pb profiles from a high deposition area in Lake Erie collected in 1976, 1981, 1983 and 1991, exhibited progressively greater deviations from exponential with time in the upper 20 cm of core. This was shown to be the result of hypereutrophic conditions in the lake from about 1950 to 1975 and subsequent remediation of the system by reduction in P loads. During the hypereutrophic period near-bottom water in parts of the lake became seasonally anoxic. This resulted in the re-dissolution of Mn, Fe and probably excess ^{210}Pb and horizontal transport to the coring sites in adequately oxygenated depositional basin elsewhere in the lake. Here the CRS mapping failed because human-caused eutrophication had modified the rate of delivery of excess ^{210}Pb to the coring site. The CRS falsely interpreted changes as being due to altered sediment accumulation rates. In another presentation (Robbins *et al.*, 2000) excess ^{210}Pb distributions in highly organic peats from the Everglades (Florida) wetlands, showed almost classic features of mixing that CRS mappings attributed to increasing mass accumulation rates. Here the CRS algorithm was right but proof had to come through use of a QPM in which soil accretion rates were linearly coupled to historical P loadings to the system. Finally, during the Workshop Edgington et al. demonstrated the difficulties of selecting an appropriate computational method (either curve fittings, mappings) or reasonable QPMs in the case of sediment cores collected over more than a decade from Lake Tahoe (USA) even where ^{210}Pb and many radionuclides, as well as stable trace elements, had been determined.

Verification

In the absence of supporting information, no ^{210}Pb profile can be "explained" and no chronology derived from ^{210}Pb should be considered reliable! The proof of this is easy enough. A perfectly exponential decrease in an excess ^{210}Pb profile with depth can be due to radioactive decay plus sedimentation alone, uniform diffusive mixing alone or some combination of these two alternative transport processes. In the extreme case where there is no net sedimentation, an exponential ^{210}Pb profile cannot yield a chronology. Only independent information can resolve the profound ambiguity. Knowing the relevant process is critical to whether meaningful dates can be obtained even from an ideal ^{210}Pb profile.

It is common practice in the published literature to make limited use sediment profiles of fallout ^{137}Cs as a primary source of independent chronological information. Rather typically, ^{210}Pb chronologies are considered "verified" if subsurface ^{137}Cs peaks in sediments are located at depths where ^{210}Pb dates "agree" with the "date" fallout maximum, 1963-1964. Rarely is any attention paid to what constitutes acceptable agreement. The ^{137}Cs peak method is weak since it confirms, at best, merely one curve fitting or mapping date assignment. If mappings such as CRS or CIC are inappropriately applied to sediments subject to near-surface, steady-state mixing, they generate artificially high estimates of accumulation rates that can, in turn, falsely agree with ^{137}Cs peak locations which have been displaced downward by mixing. At minimum, one should also try to test the ^{210}Pb chronology by comparing the age assignment of the ^{137}Cs horizon (deepest level where activity can be detected) against a 1952 date of onset of atmospheric nuclear testing. Agreement strengthens the assertion of a valid ^{210}Pb chronology, while disagreement is an invitation to consider reasons and present them in published discussions. Horizon is more sensitive than peak depth to steady-state sediment mixing and diffusive migration. In the southern hemisphere horizons may be artificially closer to the surface in sediment cores due to detection problems.

More satisfactory approaches include building QPMs that account for entire ^{210}Pb and ^{137}Cs profiles, and the use of tracers such as stable Pb (at least in the northern hemisphere) where a well-developed,

roughly 100 year-long record of atmospheric Pb concentrations may be compared with sedimentary Pb temporal records based on ^{210}Pb dating. In this case, QPMs must account for ^{210}Pb, ^{137}Cs and Pb (Robbins *et al.*, 2000).

Comment on CRS and model validation by D. N. Edgington

The lack of published data supporting ^{210}Pb dates (outlined above) is made worse by the almost universal use of the Constant Rate of Supply mapping or transformation (CRS) to calculate ages, where each data point translates into an independent age or sedimentation rate. The method requires the assumption that the input of excess ^{210}Pb is invariant and the observed sediment column is in steady-state (i.e. the inventory of excess ^{210}Pb is constant). Under these conditions any variation from a perfect exponential decay of ^{210}Pb downcore must be ascribed to changes in sedimentation rate.

In most of the papers published where data have been presented, there has been no attempt either to validate the assumptions, or to show that age-depth relationships are reproducible from core to core or from sampling time to sampling time. The problem is confounded by the easy availability of ^{210}Pb data from a variety of commercial analytical services. It must be stressed that while gamma-ray spectrometry may be essentially a turn-key operation, the interpretation of the data is the crucial step in the assignment of sedimentation rates and requires a strong knowledge of local conditions. It must also be understood that all profiles are not interpretable. In those few cases where ^{210}Pb data were presented, there was no verification of the interpretation using either ^{137}Cs or other non-radiological markers in the sediment.

Several years ago John Robbins put together a set of "regrettable facts" regarding the use of ^{210}Pb for sediment dating. They deserve reiterating:

1 Not all cores have interpretable profiles;

2 Sediment dating is critical for paleolimnology. Often dating is given short schrift;

3 Assignments of dates requires calculations;

4 Calculations require appropriate models and reasonable assumptions;

5 Models require understanding the relevant processes;

6 Bad models lead to bad dates (garbage in = garbage out);

7 Defining appropriate models can be mathematically difficult;

8 Date assignments require verification;

9 Appropriate verification is generally non-trivial;

10 Self-consistency is a necessary but not a sufficient condition for model selection;

11 The ^{210}Pb method appears to be so easy and reliable that journals no longer require publication of even age-depth relationships – let alone the data.

Recommended standards for reporting ^{210}Pb results

Of course the general principle is that readers should be provided with all data and computations necessary to mount effective challenges to published data and interpretations at any future time.

It is beyond the scope of the workshop summary document to get into a lot of detail here. But we collectively recognised the need for standards and consistency in reporting data and interpretations in publications. There was concurrence with the idea of trying to influence editorial policies of journals such as L&O, ES&T, J. of Environmental Radioactivity, J. of Paleolimnology and perhaps Quaternary Research.

The following recommendations and are derived primarily from the text of an editorial by J.N. Smith to be published in the Journal of Environmental Radioactivity, probably next year. Similar recommendations have already been conveyed to editors of other Journals by D. Edgington.

Validation of ^{210}Pb geochronology

^{210}Pb geochronology must be validated using at least one independent tracer that separately provides an unambiguous time-stratigraphic horizon. This should be considered as fundamental to the validation of ^{210}Pb sedimentation models in as much as the use of radioactive tracers and standards is to the quality control and verification of analytical methodologies. Independent validation of ^{210}Pb geochronologies must become an integral part of the overall experimental methodology. If the validation is inconclusive, then either a more appropriate particle transport model must be formulated and applied to the interpretation of the experimental results or the core must be considered to be undateable.

Data Presentation

At the time of review, (1) all authors submitting manuscripts to research journals must be expected to provide figures of the data or a hard-copy appendix containing the data and a description of the methods of calculation, including verification, and (2) the editors publish the figures and/or this appendix in smaller type or provide an easily accessible electronic version for readers.

Large scale effects on ^{210}Pb and "bomb" nuclide sediment profiles

Comment on Drainage basin residence times by J. N. Smith

It has been shown over the past 20 years that radionuclide tracer distributions in sediments are a function of the rates of tracer transport through various phases (soils, water column, biota, transient sediment reservoirs, etc.) of the environment. For radionuclides

that can be considered to have a constant steady-state input flux (such as ^{210}Pb under many conditions), their retention in various environmental reservoirs will affect the overall flux to the sediments, but not necessarily the shapes of the sediment-depth profiles. In contrast, radionuclide tracers having time-dependent input functions (such as fallout ^{137}Cs and $^{239,240}Pu$) will have sediment-depth distributions whose both shape and magnitude are affected by their history of transport through the different phases of the environment.

In some cases, the effect of a "delay" of the fallout radionuclide in an environmental phase prior to final deposition in permanently deposited sediments can be simulated by a box model employing a single residence time representing tracer transport through the pertinent environmental phase. This is commonly observed in lake sediments having relatively small drainage basins where there is transient tracer pooling in near shore sediment regimes prior to resuspension and subsequent deposition in the deeper, permanent sediment deposits. In other types of aquatic or marine systems, several environmental phases having very different tracer residence times must be employed to simulate the experimental results. One example of this latter system is a lake or estuary with a relatively large drainage basin having a soil/litter phase in which tracers are delayed (on average) by thousands of years and a second environmental phase (eg. water column) that causes delays of only months to years.

One of the primary confounding factors of tracer "delay" in environmental phases prior to permanent deposition in the sediments may be to produce sediment distributions that appear to have undergone mixing. For example, the 1963-64 peak in the sediment-depth distribution of fallout radionuclides corresponding to the period of maximum atmospheric deposition will tend to be skewed towards the surface depending on the extent of tracer "delay" in various environmental phases. Further, recent sediments will be characterised by a significant depositional flux of fallout radionuclides despite the fact that the present-day atmospheric depositional flux is practically zero. The point is that these features can also be simulated by various combinations of sedimentation and

mixing and tracer delays in the environment can be mis-interpreted as having been caused by sediment mixing. It is therefore critical to properly evaluate tracer transport mechanisms and rates for their passage through the environment by comparisons of the distributions of tracers (such as ^{137}Cs) having time-dependent input functions with those of tracers (such as ^{210}Pb) having steady-state input functions.

Comment on Southern Hemisphere Fallout by G. Brunskill and J. Pfitzner

The flux of ^{210}Pb from the atmosphere to the land and sea is much smaller in the southern hemisphere, due to the large ratio of ocean/land. Rain fluxes and soil inventories suggest that the annual supply of excess ^{210}Pb in tropical Australia is about 50 $Bq.m^{-2}.yr^{-1}$, whereas European and North American excess ^{210}Pb supply is approximately 300-400 $Bq.m^{-2}.yr^{-1}$.

The situation is similar for "bomb" fallout nuclides, although for a different reason. Most of the bombs were exploded in the northern hemisphere, and many of the bomb nuclides commonly used as chronological markers in the northern hemisphere ($^{238, 239}Pu$, ^{241}Am) are very difficult to detect south of the equator. The history and magnitude of bomb fallout nuclide supply to North American ecosystems are known to be sharply focused in 1962-65, with a peak input that is 10+ times greater than 1950-60, and 1970-present activities (Figure 1). Inventories of ^{137}Cs in North American soils and sediments are typically 2-5 $kBq.m^{-2}$. Fallout history and magnitude is different in the southern hemisphere, and particularly in tropical Australia and New Zealand. The peak input is only 2 times greater than 1950-1960 or 1980-present, and the peak input was supplied over 1954-1974 as a result of smaller local bomb explosions (Murorora, Maralinga, Monte Bello Island) in the late 1950s and early 1970s. Undisturbed soil profiles in north Queensland usually have ^{137}Cs inventories of <400 $Bq.m^{-2}$. Therefore, we should not expect sediment core profiles of ^{137}Cs to have a sharp 1963 peak (as in North American examples), but rather a broad plateau of low activity (Figure 1).

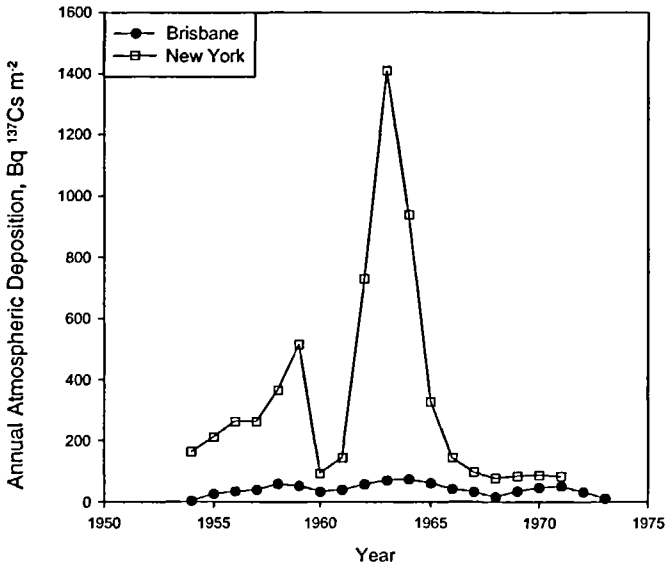

Figure 1
The history of bomb fallout ^{137}Cs deposition (as calculated from ^{90}Sr measurements) in New York city, NY, USA and Brisbane, Queensland, Australia. The data are from the Environmental Measurements Laboratory website (http://www.eml.doe.gov/databases/). The year 2000 inventory of ^{137}Cs in New York city is 2501 Bq.m^{-2}, and the corresponding value for Brisbane in the southern hemisphere is 352 Bq.m^{-2}. The peak/trough ratios for New York are 1964/1960, 15.0, and 1964/1966, 9.8, and for Brisbane are 1958/1955, 2.27, 1958/1960, 1.80, 1964/1967, 2.25, 1964/1967, 2.29, and 1971/1968, 3.23, 1971/1973, 4.94.

Comment on Large sediment fluxes by G. J. Hancock

Many South Pacific and other southern hemisphere countries share a common history of land use over the last 100-150 years. This can be summarised as large scale and rapid conversion of forested river catchments to European farming practices, mining activities, and urban developments. These changes have, in many cases, lead to the mobilisation of large amounts of sediment to lakes, water storages

and estuaries. The rapid rates of sediment accumulation associated with these catchment changes has resulted in the dilution of the activities of fallout tracers used in sediment dating (excess ^{210}Pb and ^{137}Cs), compounding the problem of low southern hemisphere activities of these nuclides described above by Brunskill and Pfitzner. The presence of ^{137}Cs and excess ^{210}Pb in undisturbed sediment usually means that layer has been deposited in the last 40 years and 100 years respectively, although chemical mobility of ^{137}Cs in some sediments may invalidate its use as a chronometer. However, the combined effects of high sediment fluxes and low fallout activities means that the lack of detectable ^{137}Cs and excess ^{210}Pb in sediments does not necessarily mean that the sediment has been deposited prior to the release of bomb ^{137}Cs into the atmosphere. This is illustrated by a core from the Murrah floodplain in SE Australia. Excess ^{210}Pb and ^{137}Cs is undetectable in the upper one meter layer of sediment. This layer overlies a deeper layer containing high ^{137}Cs activity, proving the upper one meter of sediment has been laid down within the last 40 years. This example illustrates the extreme effects that variable sediment fluxes can have on the sediment profiles of fallout nuclides, and highlights the necessity to corroborate dates by independent methods.

Recommended sample collection and analysis procedures

Comment on Core Collection by J. A. Robbins

Where possible we use modified Soutar type box cores and take open tube sub-cores from the box core and achieve alignment of interfaces inside and outside of the tube by hand regulated variations in a partial vacuum applied to the air space above sediments insider the tube.

We also have used piston coring in situations where there is visually verifiable preservation of the sediment-water interface.

Gravity coring, especially using core catchers or plunger type valves, can distort the sediment column and is not a desirable, although sometimes necessary collection method.

In many cases it is desirable to X-ray cores (or replicate ones) to characterise sediment stratigraphy.

Core Sectioning

Sectioning should be quantitative with respect to wet sediment content. Where it is necessary to trim an annulus from sediment sections, the trimmed material should be saved for calculating total sediment wet weight of each section.

Measurements

Section interval thickness, z (cm).

Section dry weight g, ($g.cm^{-2}$ of core cross-sectional area).

Fractional dry weight of section, fdw, (g.dry/g.wet).

Grain size distribution, (especially % less than ca. 65 microns). This is especially indicated where there appear to be localised anomalies in ^{210}Pb and other profiles.

Gamma counting of sealed whole-dry sediments, equilibrated for radon in-growth, preferably using detectors with enhanced efficiencies below 100 KeV, is the method of choice in many cases. Report ^{210}Pb, ^{7}Be, ^{226}Ra, ^{137}Cs and ^{40}K and sometimes ^{228}Th. At least near-surface samples should be counted soon enough to detect ^{7}Be ($t_{1/2}$ = 53.4 days). This radionuclide is useful for confirming recovery of surface sediments. However there are circumstances in which Be-7 may decay away before reaching sediments! There are cases where excess ^{228}Th ($t_{1/2}$=1.9 years) occurs in near-surface sediments. Lake Tahoe is an example. This nuclide may be useful for determining rates of near-surface mixing and/or sediment accumulation. Look for the ^{208}Tl peak at 583.19 KeV and the ^{212}Pb peak at 238.63 KeV. In the case of this latter peak, there may be a removable interference due to ^{214}Pb from ^{226}Ra at 241.98 KeV to deal with. The ^{40}K is use-

ful for identifying stratigraphic anomalies and should be reported when gamma counting is done. ^{226}Ra can best be determined from several peaks associated with decay of ^{222}Rn (295.21, 351.92 and 609.31 KeV) using a weighted average of activities. The gamma at 186.21 KeV arising directly from ^{226}Ra may be subject to interference from an unresolvable peak at 185.7 KeV from ^{235}U.

Enhanced efficiency gamma counting for ^{210}Pb (46.5 KeV) is generally not as rapid in terms of counting or as precise as the standard isotope-dilution alpha spectroscopy method in which ^{210}Po (in equilibrium with ^{210}Pb) in acid extracts of samples receiving calibrated ^{209}Po or ^{208}Po spikes are plated on to silver planchets and counted. We use this method in combination with gamma counting in many cases where establishing sediment chronologies as the primary goal.

A complete profile (with no missing intervals) should be generated and extend well into the background region of supported ^{210}Pb.

Estimating mean ages and time resolution of core sections

In cases where there is no evident mixing of near-surface sediments at a site, precision in mean ^{210}Pb ages of sediment sections can be calculated by conventional error estimation procedures including Monte Carlo methods for mappings and QPMs. However mean age precision can be somewhat misleading because it is not necessarily indicative of the time resolution with which historical records may be developed. Another time that we routinely calculate for " ^{210}Pb datable" cores is the ratio of the sediment section thickness ($g.cm^{-2}$) to the mass accumulation rate for the section ($g.cm^{-2}.yr^{-1}$). Since sections are presumably homogenized prior to analysis, this time indicates the best attainable time resolution for tracer "events" measured in a particular sectioned core. For example if the ratio is 5 years in a core section dated at 1945 ±1 year, then two spikes of a given tracer delivered to the sediment coring sites a times less than five years apart (say 1943 and 1946) cannot be separated (resolved) in the sedimentary record. Where there is evidence of mixing, mean age assignments, precision and time resolution can sometimes be meaningfully estimated by time averaging over appropriate QPM-

derived distributions of sediment deposition ages within sections. Finally, although it seems likely that most near-surface sediment mixing, as evidenced by ^{210}Pb profiles, must be steady state in character, it may not always be so. Consider an extreme example of sediments accumulating at a constant rate without mixing until last year, when Mayfly larvae populated coring sites. Their mixing actions (non-steady state by definition) may produce similar ^{210}Pb profiles, but QPMs as well as mean section ages, errors and time resolution estimates would, of course, be markedly different.

Special considerations for southern hemisphere (low activity) sediments by G. Brunskill J. Pfitzner and G. J. Hancock

The much lower fallout fluxes of ^{210}Pb and ^{137}Cs experienced in the southern hemisphere (described above) require special sampling and analytical considerations. Sampling requires large core barrel diameters to yield large samples of 1-2 cm slice thickness for radiochemical counting, and the resulting core profiles of excess ^{210}Pb have larger errors relative to ^{226}Ra. Because of these factors, we should anticipate more problems with the routine use of ^{210}Pb as a sedimentation tracer. Alpha spectrometry is the recommended detection system for both ^{210}Pb and ^{226}Ra, because it offers greater precision with a reasonable sample mass. We measure ^{210}Pb and ^{226}Ra by gamma counting, but we use large sample mass (>100 g dry weight), and accept larger error bars on the profile. In estuarine and marine sediment cores, we expect ^{137}Cs to have lower K_d than in freshwater sediments, and pore water diffusion of ^{137}Cs should be accommodated in geochronological models.

As noted above, a 1963 peak in ^{137}Cs profiles is not observed in the southern hemisphere. Where ^{137}Cs is assumed to have remained physically and chemically immobile in a sediment profile, such as freshwater flood-plain deposits which have remained mostly dry, the use of ^{137}Cs as a chronological marker equates its deepest penetration into the sediment profile to a date no earlier than the date where sufficient fallout activity has accumulated in sediments and soils to become detectable. Due to atmospheric circulation patterns,

and much lower fallout input, this date is later in the southern hemisphere than the northern. At CSIRO in Canberra we currently calculate the date of first detectable appearance of ^{137}Cs in Australian fine-grained soil and sediment to be 1958. This date is based on the performance of our gamma-ray detectors, counting system, sample geometry and sample weight. Because atmospheric input of ^{137}Cs has essentially ceased, the activity of ^{137}Cs in the landscape is decaying. The date of first detection is therefore not stable, and is moving forward at a rate dictated by the ^{137}Cs half-life and fallout history.

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