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A ^{210}Pb-based chronological model for recent sediments with random entries of mass and activities: Model development

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ABSTRACT

Unsupported ^{210}Pb (^{210}Pb$_{exc}$) vs. mass depth profiles do not contain enough information as to extract a unique chronology when both, ^{210}Pb$_{exc}$ fluxes and mass sediment accumulation rates (SAR) independently vary with time. Restrictive assumptions are needed to develop a suitable dating tool. A statistical correlation between fluxes and SAR seems to be a quite general rule. This paper builds up a new ^{210}Pb-based dating tool by using such a statistical correlation. It operates with SAR and initial activities that closely follow normal distributions, what leads to the expected correlation between fluxes and SAR. An intelligent algorithm solves their best arrangement downcore to fit the experimental ^{210}Pb$_{exc}$ vs. mass depth profile, generating then solutions for the chronological line, and for the histories of SAR and fluxes. Parametric maps of a χ-function serve to find out the solution and to support error estimates. Optionally, the model's answers can be better constrained through the use of time markers. The performance of the model is illustrated with a synthetic core, and with real cases using published data for varved sediment cores.

1. Introduction

Without accurate methods of dating recent sediment cores it is not possible to provide a quantitative description of sediment accumulation rate (SAR) and deposition processes, which are the key for reconstructing past environmental conditions. High resolution chronologies are possible for sediments with varves, but they rarely occur in most sedimentary sequences (Ojala et al., 2012). The radiometric dating is the only technique of general applicability that claims to provide an absolute age determination (Carroll and Lerche, 2003).

The most common technique for dating recent sediments uses fallout ^{210}Pb, a natural radionuclide (see the reviews by Appleby, 2008; Sánchez-Cabeza and Ruíz-Fernández; 2010; Mabit et al., 2014). In recent years the combined use of ^{210}Pb and some bomb-fallout radionuclides (e.g., ^{137}Cs, ^{241}Am and $^{239+240}$Pu) has been widely popularized in the radiometric dating of recent sediments, accounting for one of the most interesting applications of the environmental radioactivity.

Abril (2015) has shown that under the assumptions of continuity of the sequence, ideal deposition of ^{210}Pb$_{exc}$ fluxes, and non post-depositional redistribution, any ^{210}Pb$_{exc}$ activity versus mass depth profile, even with the restriction of a discrete set of time markers (reference points), is compatible with an infinite number of chronological lines. Consequently, there are an infinite number of mathematically exact solutions for histories of initial activity, SAR and flux onto the sediment to water interface (SWI). Such histories may contain values of SAR and flux ranging from zero up to infinity. Thus, the development of a suitable dating tool is not possible without the explicit introduction of restrictive assumptions about flux, SAR and/or their interrelationship. These may be the assumptions of constant flux, constant SAR or constant initial activity, in those sedimentary scenarios where they would be properly applicable. The recent work by Abril and Brunskill (2014) showed that a statistical correlation between fluxes and SAR can be a quite general rule. The aim of this paper is to develop a new ^{210}Pb-based dating tool based on such correlation and the basic assumptions of continuity of the sequence, ideal deposition of fluxes and non post-depositional redistribution. The performance of the model is illustrated with a synthetic core, and with the study of two real cases of varved sediment taken from the scientific literature.

Abbreviations: TERESA, Time estimates from random entries of sediments and activities; SWI, sediment-water interface; SAR, mass sediment accumulation rate.

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2. Material and methods

2.1. Time estimates from random entries of sediments and activities (TERESA) model

The model stands on the following set of assumptions: i) $^{210}Pb_{exc}$ behaves as a particle-associated tracer and new inputs are ideally deposited at the SWI over the previously existing material; ii) there is not any post-depositional redistribution; iii) continuity of the sequence (i.e., there is not any missing layer by erosion); iv) $^{210}Pb_{exc}$ fluxes are governed by 'horizontal inputs' (as defined in Abril and Brunskill, 2014). At the present stage the model will operate with continuous probability distributions for initial activities and SAR; and thus, it will be assumed that there are not any flood layers or other instantaneous inputs to the sediment column.

After coring, the standard method proceeds with the cutting of the sediment core into a certain number of slices. Each sediment slice (labelled with index $i = 1,2, \ldots$ N) is the result of the accumulated mass flow over a certain time interval ΔT_i. Let be w_i the average value of the mass flow into the SWI (SAR) over ΔT_i. For a sediment core composed by N slices, the magnitude $\overline{w}$ will be defined as the arithmetic mean of all w_i. Abril and Brunskill (2014) have shown that the values of w_i are distributed around $\overline{w}$ following approximately a normal distribution with standard deviation σ_w. These mass flows onto the SWI carry initial $^{210}Pb_{exc}$ activities, which similarly can be characterized by their mean value $\overline{A}_0$ and standard deviation σ_A. This random and independent variability naturally leads to a lack of correlation between initial activities and SAR, and it results in $^{210}Pb_{exc}$ fluxes ($F_i = A_{0,i}w_i$) that increase with SAR (Abril and Brunskill, 2014). This is summarized in Fig. 1. Thus, each sediment slice can be characterized by a pair of values ($A_{0,i}$, w_i).

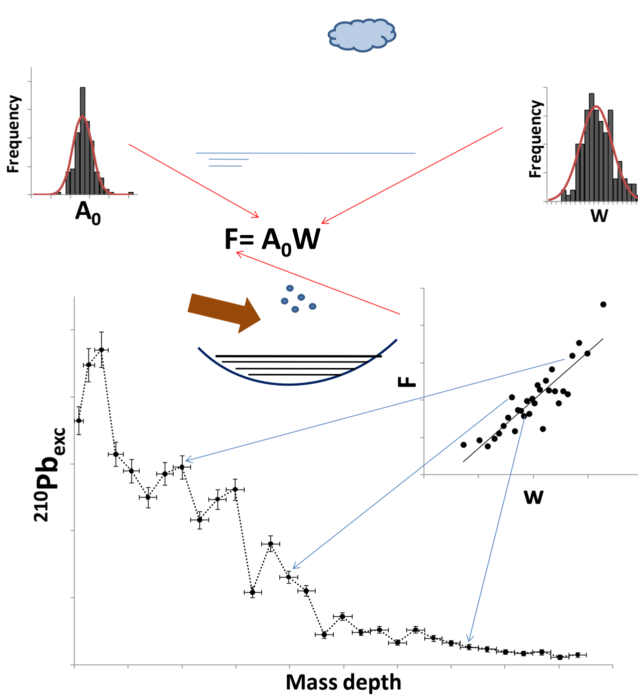

Fig. 1. Scheme with TERESA's model fundamentals. On the time scale associated to experimental sediment slices, the mass flow into the SWI (SAR, w) and its associate initial $^{210}Pb_{exc}$ activity (A_0) show a natural and independent variability that closely follow normal distributions. Consequently, the $^{210}Pb_{exc}$ fluxes (F) and SAR are linearly correlated. The sequence (or the sorting in time) of each pair of values of SAR and initial activity leads to the particular SAR history, the chronology and the $^{210}Pb_{exc}$ vertical profiles found in the sediment core.

These pairs occur in a certain order or sequence in time, what leads to the measured $^{210}Pb_{exc}$ profile (Fig. 1).

It will be helpful to introduce the relative deviations$s_w = \sigma_w/\overline{w}$; $s_A = \sigma_A/\overline{A}_0$. The first parameter had values of 0.30, 0.34, 0.27, 0.28, 0.32, 0.42, 0.24, 0.51 and 0.59 for the cores C1 to C9 studied by Abril and Brunskill (2014), while the second took values of 0.20, 0.25, 0.10, 0.43, 0.30, 0.29, 0.10, 0.15 and 0.22 for such cores C1 to C9, respectively.

The actual depth (with physical dimensions L) is not an appropriate magnitude due to compaction during the sediment accretion and to the shortening during the coring operation and later handling. The mass depth magnitude, m (with dimensions M L^{-2}), must be used instead. Data from the studied $^{210}Pb_{exc}$ versus mass depth profile will consists in a discrete set of N values of experimentally averaged specific $^{210}Pb_{exc}$ activities, $A_i(m)$, one for each sediment slice of mass thickness Δm_i, provided with their respective uncertainties, σ_i. Ages, T_i, will be referred at the bottom of each sediment slice, and SAR to their averaged values over the time interval associated to each slice. Thus, the experimental data can be arranged into a three column file with N triplets (m_i, A_i, σ_i). The mass depth magnitude (referred to the bottom of each slice) can be consistently handled within calculation for extracting the respective mass thickness intervals, and to calculate values referred to the centre of each slice.

Step 1. The model requires first-estimate values for $\overline{w}$,$\overline{A}_0$, and for their respective standard deviations (σ_w,σ_A). One possibility for achieving this goal is through an exponential fit (CF-CSR model) to the $^{210}Pb_{exc}$ vs. m profile; and by ascribing typical values of 35% and 20% for s_w ands_A, respectively.

Step 2. Generation of N random pairs of values for initial activities and SAR ($A_{o,i}$, w_i). A practical way for achieving this is to generate two sets of N values, $z_{1,i}$ and $z_{2,i}$, following normal typified distributions (this is, with mean value 0 and standard deviation 1.0). One can use the random number generator by Excel or others, but to avoid inaccuracies with low values of N, a systematic procedure is presented in Appendix A. The numbers within the series $z_{1,i}$, and a $z_{2,i}$ must be randomly ordered, and maintained during all the routine calculations. The pairs ($A_{o,i}$, w_i) will be then generated as follows:

$$A_{0,i} = \overline{A}_0(1 + s_A z_{1,i})$$
$$w_i = \overline{w}(1 + s_w z_{2,i}) \tag{1}$$

It can be tested that the fluxes $F_i = A_{0,i}w_i$ follow the expected trend of increasing with SAR. It will be assumed that the pairs ($A_{o,i}$, w_i) provide a reasonable proxy to the true values, and the question now is their appropriate ordering downcore.

Step 3. Sorting the pairs ($A_{o,i}$, w_i). As in a puzzle, one must decide which of these pairs is the best option for ascribing it to each particular sediment slice of index j (hereafter the index $j = 1,2,\ldots$ N will be used to refer the sequence of slices in the core, which is different from the initial and random ordering of pairs $A_{o,i}$, w_i). Their sorting leads to a chronology (the cumulative sequence of ΔT_i), and the application of corrections by radioactive decay transforms initial activities $A_{o,i}$ into the measured values at each sediment slice, A_j.

Treatment for the first sediment slice (j = 1). Let be $T_{up} = 0$ the age at the SWI. If the pair ($A_{o,k}$, w_k) $- k \in (1,N)$ denotes a particular value instead of a free index, was ascribed to the first slice, with a known mass thickness Δm_1, the age interval associated to this slice will be $\Delta T_1 = \Delta m_1/w_k$. Then, the expected (theoretical) averaged