Journal of Environmental Radioactivity 143 (2015) 40–46

Contents lists available at ScienceDirect

Journal of Environmental Radioactivity

journal homepage: www.elsevier.com/locate/jenvrad

Why would we use the Sediment Isotope Tomography (SIT) model to establish a ^{210}Pb-based chronology in recent-sediment cores?

José-María Abril Hernández*

Departamento de Física Aplicada I, ETSIA Universidad de Sevilla, Carretera de Utrera km 1, D.P. 41013 Seville, Spain

ARTICLE INFO

Article history:
Received 28 November 2014
Received in revised form
7 February 2015
Accepted 7 February 2015
Available online 25 February 2015

Keywords:
SIT model
^{210}Pb dating
Recent sediments
Chronological line
Sediment dating

ABSTRACT

After half a century, the use of unsupported ^{210}Pb (^{210}Pb$_{exc}$) is still far off from being a well established dating tool for recent sediments with widespread applicability. Recent results from the statistical analysis of time series of fluxes, mass sediment accumulation rates (SAR), and initial activities, derived from varved sediments, place serious constraints to the assumption of constant fluxes, which is widely used in dating models. The Sediment Isotope Tomography (SIT) model, under the assumption of non post-depositional redistribution, is used for dating recent sediments in scenarios in that fluxes and SAR are uncorrelated and both vary with time. By using a simple graphical analysis, this paper shows that under the above assumptions, any given ^{210}Pb$_{exc}$ profile, even with the restriction of a discrete set of reference points, is compatible with an infinite number of chronological lines, and thus generating an infinite number of mathematically exact solutions for histories of initial activity concentrations, SAR and fluxes onto the SWI, with these two last ranging from zero up to infinity. Particularly, SIT results, without additional assumptions, cannot contain any statistically significant difference with respect to the exact solutions consisting in intervals of constant SAR or constant fluxes (both being consistent with the reference points). Therefore, there is not any benefit in its use as a dating tool without the explicit introduction of additional restrictive assumptions about fluxes, SAR and/or their interrelationship.

1. Introduction

Accurate methods for establishing chronologies for recent-sediment cores are necessary to provide reliable estimates of sediment accumulation rate (SAR) and deposition processes, which are the key for reconstructing past environmental conditions. This is possible from true varves, which occur rarely in most sedimentary sequences with the exception of lakes in glacierized basins (Ojala et al., 2012). Other non-radioactive dating methods (e.g. fossil markers, pollen, pollution markers) can provide important stratigraphic time-markers. However, radiometric dating is the only technique of general applicability that claims to provide an absolute age determination (Carroll and Lerche, 2003).

Goldberg (1963) first proposed the use of unsupported ^{210}Pb (^{210}Pb$_{exc}$ hereafter) for dating glacier ice. The method was then applied to lacustrine sediments by Krishnaswamy et al. (1971), and to marine sediments by Koide et al. (1972). After half a century, its use has been widely spread, with new models of increased complexity and applying to a large diversity of scenarios, including lakes, estuaries, reservoirs, riverine floodplains, wetlands, salt-marshes, coastal areas and marine environments (see the review papers by Appleby, 2008; Mabit et al., 2014). Nevertheless, the method is still far off from being a well-established dating technique applicable to all situations. Thus, Smith (2001) pointed out the constraints in the use of stand-alone ^{210}Pb-based models and claimed for the need of validation of the so derived chronologies against independent stratigraphic time marks. These latest can be provided by some bomb-fallout radionuclides (mainly ^{137}Cs, ^{241}Am and $^{239+240}$Pu) through the identification of their characteristic peak values within their respective depth profiles in the sediment core. Consequently, in recent years the combined use of ^{210}Pb and these bomb-fallout radionuclides has been widely popularized in the radiometric dating of recent sediments, accounting for one of the most interesting applications of the environmental radioactivity. As result, our level of understanding of the potentials and limitations of these dating tools has been also considerably improved.

Different models (each one being a set of assumptions about the functioning of the studied sedimentary system) arise as particular

Abbreviations: SIT, Sediment Isotope Tomography; SWI, sediment–water interface; SAR, sediment accumulation rate.

* Tel.: +34 954486473; fax: +34 954486436.
E-mail address: jmabril@us.es.

http://dx.doi.org/10.1016/j.jenvrad.2015.02.008
0265-931X/

solutions of a unique physical problem of advective-diffusive transport of particle-associated radionuclides in sediments, treated as continuous media that have undergone accretion and compaction (Abril, 2003a, 2011). In some cases the behavior of the dissolved fraction of radionuclides requires handling separate equations for the dissolved and the particle-bound phases (Robbins and Jasinski, 1995; Abril and Gharbi, 2012). Almost all models assume ideal deposition as a boundary condition at the sediment water interface (SWI), i.e. new radioactive inputs will be deposited above the previously existing material. Abril and Gharbi (2012) have shown how this assumption may be unrealistic in sediment cores with very high porosities.

For the most popular and simple models, their formulation also can be established in a more straightforward way from their involved basic assumptions (see the review by Sánchez-Cabeza and Ruíz-Fernández, 2012). Thus, continuous, constant flux of $^{210}Pb_{exc}$ to the SWI, along with the absence of post-depositional redistribution, constitute the basis for the constant rate of supply (CRS) model, which contains, as a particular case, the constant flux with constant SAR (CFCS) model. The more restrictive assumption of constant fluxes and steady–state profiles is common in most ^{210}Pb models because it enables analytical solutions (Robbins, 1978; Abril, 2003a). The constant initial concentration (CIC) model (Goldberg, 1963) assumes that the fluxes of matter through the SWI always carry the same activity concentration. Recently, Abril and Brunskill (2014) revisited these assumptions through the statistical analysis of a database of laminated sediments. The reconstructed historical records of $^{210}Pb_{exc}$ flux onto the SWI, SAR, and initial $^{210}Pb_{exc}$ activity, showed large temporal fluctuations. They found that there was no statistically significant correlation between initial activity and SAR, violating an assumption of most ^{210}Pb-based radiometric dating models. Nevertheless, $^{210}Pb_{exc}$ fluxes were linearly related with SAR (at 99% confidence level, and explaining 2/3 of the observed variability). These results can be explained through a two-component mass flow model with intrinsic scatter (Abril and Brunskill, 2014).

The Sediment Isotope Tomography (SIT) model (Carroll and Lerche, 2003) claims its ability for dating sediment cores under varying conditions for both SAR and $^{210}Pb_{exc}$ flux. After Abril and Brunskill (2014), there are serious constraints in the applicability of models that assume constant flux, and then the SIT model could be seen as the definitive modelling tool for routinely use (restricted to situations with ideal deposition and non post-depositional mixing). Its use has remained perhaps limited by its mathematical complexity and the challenges of its programming, what could be surpassed by a broad availability of suitable software. This paper revisits the physical basis behind the mathematical formulation of the SIT model, and explores its limitations.

2. Material and methods

Instead of complex mathematics, a quite intuitive graphical method for establishing $^{210}Pb_{exc}$ chronologies will be enough for present purposes.

The following assumptions stand behind the application of the basic SIT model: 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 (what implies that compaction does not involve true mass-transport processes, such as transport of colloids and small-grain size particles through the connected water pores); iii) continuity of the sequence (i.e., there is not any missing layer by erosion).

For conceptual simplicity it will be considered that the sediment core can be sliced with an extremely high resolution, and that $^{210}Pb_{exc}$ can be estimated as accurately as desired. The actual depth 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 must be used instead. A $^{210}Pb_{exc}$ versus mass depth profile can be plotted as a continuous line which extends till m_{max}, corresponding to the end of the sampled core or to the deepest measured slice. Although the profile usually is an overall decreasing function that can contain some intermediate relative maxima, it is not necessary to include any additional hypothesis at this stage. An example is shown in Fig. 1 (a synthetic profile generated by the analytical function $A(m) = 500\,(1 + 0.2\,sin(\pi\, m/2))\,exp(-\lambda m/0.07))$ with $m_{max} = 6$ g cm^{-2}). The goal is to find out a chronology from this data set.

A chronology can be plotted as a continuous line (by the assumption of the continuity of the sequence) in the age (T) versus mass depth (m) plane. The chronological line must be confined within a rectangle defined by m_{max} and the practical upper limit associated to the radioactive measurements (usually ^{210}Pb cannot be measured in sediment slices older than 100–150 years). Any continuous and increasing ($dT/dm > 0$) function confined within such limits is a mathematical solution for our problem (i.e. any continuous line that one can plot with a pencil without moving it down). Some examples appear in Fig. 2 (which also includes other details that will be presented further below). The local derivative at any value of m (related to the local slope of the chronological line) is related with the mass sediment accumulation rate (SAR), w, at the former position of the SWI (when took place the formation of the layer now being at a mass depth m):

$$w = \frac{dm}{dT} \quad ; \quad \frac{dT}{dm} = \frac{1}{w} \qquad (1)$$

Thus, an almost horizontal segment in the chronological line corresponds to an episode of extremely high SAR, and a vertical segment corresponds to a period of time without sedimentation. Any straight line within the admissible boundaries is a chronological line that represents a sedimentary scenario under constant SAR.

For any given chronological line $T(m)$, one can obtain for each value of m the corresponding value of $w(T)$ by using Eq. (1). $A(m)$ is the value of $^{210}Pb_{exc}$ activity concentration in the sediment slice at mass depth m. From the involved assumptions it is possible to estimate the $^{210}Pb_{ex}$ activity at the former SWI, $A_{SWI}(T)$:

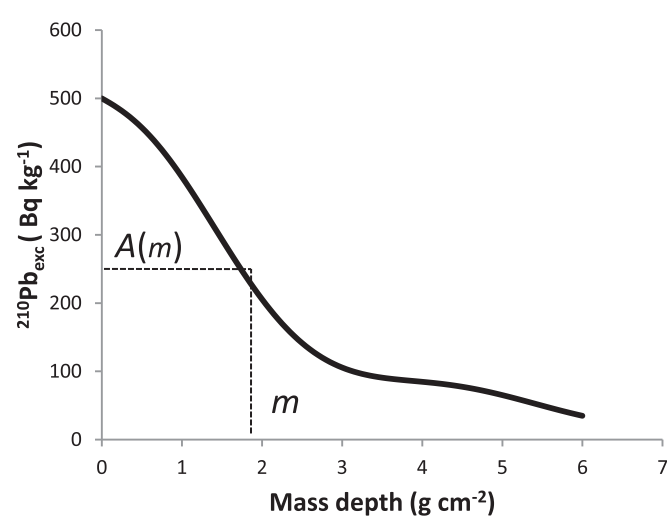

Fig. 1. Example of $^{210}Pb_{exc}$ activity (A) versus mass depth (m) profile. Synthetic profile generated by the analytical function $A(m) = 500\,(1 + 0.2\,sin(\pi\, m/2))\,exp(-\lambda m/0.07))$ with $m_{max} = 6$ g cm^{-2}.