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***serac*: a R package for ShortlivEd RADionuclide Chronology of recent sediment cores**

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1 ***serac*: a R package for ShortlivEd RADionuclide Chronology of recent**

2 **sediment cores**

3
4
5

6 **Abstract**

7 Short-lived radionuclides are measured in surface sediment to provide a geochronology for
8 the past century. Age-depth models are produced from $^{210}\text{Pb}_{\text{ex}}$ activity-derived sedimentation
9 rates and confirmed by ^{137}Cs and ^{241}Am activities that are result of fallout from nuclear
10 weapon tests and the Chernobyl accident. Different methods of age depth modelling using
11 such data require expertise in lake sedimentation processes.

12 Here, we present a package, *serac*, that allows the user to compute an age-depth model,
13 output a graph and an age model as a text file, and provide metadata using the free open-
14 source statistical software R. *serac* ensures the reproducibility of age-depth or age-mass depth
15 models and allows testing of several $^{210}\text{Pb}_{\text{ex}}$ models (CFCS, CIC, CRS, CRS piecewise) and
16 sedimentation hypotheses (changes in the sedimentation rates, instantaneous deposits, varved
17 sedimentation, etc.). Using several case studies, including lakes and lagoon in different
18 environments, we demonstrate the use of the programme in diverse situations that may be
19 encountered.

20 The rising number of sediment cores in recent palaeo-studies and the need to correlate them
21 require reproducible methods. *serac* is a user-friendly code that enables age model
22 computation for the past century and encourages the standardisation of outputs.

23

24 **Keywords:** Shortlived radionuclide; R package; ^{210}Pb model; ^{137}Cs ; age model; metadata

25

1. Introduction

Dating sediments is the first and critical step of any palaeo-study. Specifically, accurately dating the past century is crucial in palaeoclimate and palaeoecological studies because of the many socio-ecological changes that took place during that period. Furthermore, there is a great amount of instrumental and historical data (e.g., floods, changes in land use) available for the past century, and a precise age-model is needed to correlate these observational data to sediment proxies. When annual varves are absent, short-lived radionuclides, based on the measurements of the activity of ^{137}Cs , ^{241}Am , ^{210}Pb , and ^{226}Ra , provide the most accurate and widely used age-depth model technique for the past century.

The isotopes ^{137}Cs ($t_{1/2}= 30.15$ years) and ^{241}Am ($t_{1/2}= 432$ years) are by-products from nuclear weapons tests conducted from 1955 and for a decade, by the United-States, the former URSS, and the United Kingdom. The isotope ^{137}Cs peaked in 1963, and was accompanied by a smaller peak in ^{241}Am , itself resulting from the decay of ^{241}Pu ($t_{1/2}= 14$ years), one of the elements in fallout from atmospheric nuclear weapons tests. The Chernobyl accident in 1986 further dispersed ^{137}Cs into the atmosphere of the northern hemisphere (Appleby et al., 1991). Independent of human activities, ^{210}Pb excess activity is used to estimate environmental sedimentation dynamics. The basic methodology of ^{210}Pb dating was first established in a seminal paper by Goldberg (1963). ^{210}Pb is an isotope of lead that forms during the decay sequence of ^{238}U . ^{210}Pb results from the disintegration of ^{226}Ra in rock, sediments and water, and from the disintegration of ^{222}Rn in the atmosphere (Fig. 1). While ^{226}Ra and ^{210}Pb triggered by erosion in the watershed are in secular equilibrium (^{210}Pb supported), the ^{210}Pb produced in the atmosphere by ^{222}Rn decay are removed from the atmosphere by dry and wet fallout and are integrated in soils, lakes and sediments (Fig. 1, excess ^{210}Pb , referred to hereafter as $^{210}\text{Pb}_{\text{ex}}$). As a consequence, it is possible to estimate the atmospheric $^{210}\text{Pb}_{\text{ex}}$ by subtracting the total ^{210}Pb ($^{210}\text{Pb}_{\text{mes}}$) by ^{226}Ra . The $^{210}\text{Pb}_{\text{ex}}$ activity follows an exponential decay (characterised by its half-life $t_{1/2}= 22.3$ years) from which it is possible to calculate age and sedimentation rates for the past 100 to 150 years ($\sim 5 \times t_{1/2}$, eq. 1).

$$^{210}\text{Pb}_{\text{ex}}^z = ^{210}\text{Pb}_{\text{ex}}^0 \times e^{-\lambda t} \quad \text{with} \quad ^{210}\text{Pb}_{\text{ex}} = ^{210}\text{Pb}_{\text{mes}} - ^{226}\text{Ra}_{\text{mes}} \quad (1)$$

where t is the age at depth z , $^{210}\text{Pb}_{\text{ex}}^0$ is the activity at the surface of the sediment expressed in Bq.kg^{-1} or mBq.g^{-1} , $^{210}\text{Pb}_{\text{ex}}^z$ is the activity at depth z and λ the ^{210}Pb disintegration constant ($\ln(2)/22.3$; expressed in y^{-1}).

The isotopes ^{137}Cs , ^{241}Am , ^{210}Pb , and ^{226}Ra are most commonly measured together using a non-destructive gamma-spectrometric analysis, allowing a direct determination

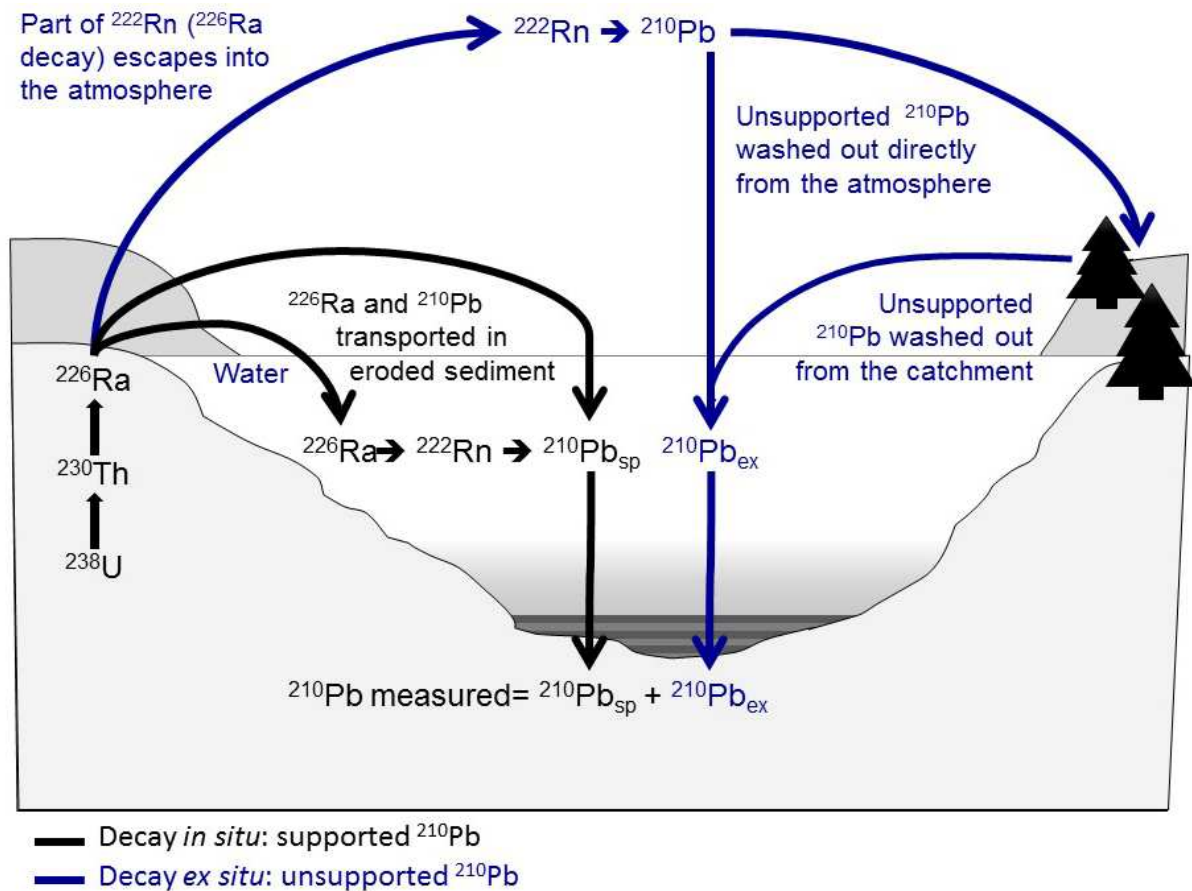
59 of ^{210}Pb supported through the ^{226}Ra activity. ^{210}Pb can also be quantified by alpha-
60 spectrometry determination of its daughter ^{210}Po ($t_{1/2}= 138$ d). Isotopes are used in
61 chronologies for lake sediment (Rapuc et al., 2018; Sabatier et al., 2014), lagoons (Sabatier et
62 al., 2010a), but also corals (Andrews et al., 2009; Druffel et al., 1990; Moore and
63 Krishnaswami, 1972; Sabatier et al., 2012) and speleothems (Baskaran and Iliffe, 1993;
64 Condomines and Rihs, 2006) through excess or ingrowth methods.

65 Several models to infer ages from $^{210}\text{Pb}_{\text{ex}}$ decay have been proposed over time
66 (Appleby, 2008, 2001; Appleby and Oldfield, 1992; Arias-Ortiz et al., 2018; Sanchez-Cabeza
67 and Ruiz-Fernández, 2012), none of which can be considered as an universal method as the
68 best model must be chosen with consideration to potential variability in watershed erosional
69 input, and ideally, by validating the model with independent markers (Baskaran et al., 2014;
70 Binford, 1990; Cooke et al., 2010; Kirchner, 2011). While there is no doubt, the complexity
71 and heterogeneity of sedimentation processes calls for permanent progression of models
72 (Abril Hernández, 2016) and uncertainties estimations (Aquino-López et al., 2018), the
73 method for the most classic model is so well established that many geochronologist teams
74 working on recent records confidently use it. The downside of its success is that there is often
75 a lack of information on sedimentation hypotheses in published age-depth models (Blaauw,
76 2010), as if mentioning the method certified the age model accuracy. While we are not
77 questioning the validity of every published model, any field benefits from transparency to
78 allow for reproducibility of its results (Wilkinson et al., 2016).

79 As establishing an age-depth model is the first step of any investigation on sediment
80 sequences, ensuring the hypotheses made at this stage are transparent is critical. Blaauw
81 (2010) provided the *clam* R code to the palaeo-community to provide an easy, automated,
82 transparent, documented, and adaptable environment for producing age-models from ^{14}C
83 sequences. Routines in Excel and Matlab exist for some of the ^{210}Pb models (Abril
84 Hernández, 2016), and a promising Bayesian ^{210}Pb model based on constant rate of supply
85 (CRS) is available as a R package (*plum*) (Aquino-López et al., 2018). Herein, we propose a
86 systematic approach to producing chronologies for sediment cores using short-lived
87 radionuclides ($^{210}\text{Pb}_{\text{ex}}$, ^{137}Cs and ^{241}Am) and different types of $^{210}\text{Pb}_{\text{ex}}$ models (constant initial
88 concentration (CIC), **constant rate of supply (CRS)**, constant flux constant sedimentation rate
89 (CFCS), and piecewise versions of CRS and CFCS), based on the free and open-source
90 software R. We first describe the different hypotheses for $^{210}\text{Pb}_{\text{ex}}$ decay and the resulting
91 models; we then introduce the elements of the R function we developed, before applying the

92 *serac* code to six complex case studies. Eventually, we wish our code to supplement *clam* for
 93 chronologies for the past century.

94



95

96 **Figure 1.** ^{210}Pb sources in lake or marine environments

97

98

99 2. ^{210}Pb -based radiometric dating models

100 *serac* allows computation of the 3 most common models (Appleby, P.G. and Oldfield, F.,
 101 1992), CIC, CFCS, CRS, as well as the piecewise version of CRS (age and depth forced) and
 102 CFCS (when instantaneous deposits are present). The models share the initial assumptions: i)
 103 radionuclides are particle-bound tracers which are ideally deposited onto the sediment-water
 104 interface, ii) non-post depositional redistribution takes place except in the surface mixed
 105 layer, and iii) the sedimentary sequence is continuous. Each model has then other varying
 106 assumptions regarding $^{210}\text{Pb}_{\text{ex}}$ fluxes and sedimentation rates. The models and other
 107 assumptions are detailed below (Table 1).

108

109 **Table 1.** Summary of the assumptions for $^{210}\text{Pb}_{\text{ex}}$ models included in serac. CIC, CFCS and
 110 CRS respectively stand for constant initial concentration, constant flux constant sedimentation
 111 rate and constant rate of supply.

Assumption	CIC	CFCS	CRS	CRS piecewise
Radionuclides deposition	Homogeneously deposition onto the sediment-water interface and particle bound.			
Non-post depositional redistribution takes place (except in the surface mixed layer)	x (Does not handle surface mixed layer)	x	x	x
Sedimentary sequence	Continuous	Continuous	Continuous	Continuous
$^{210}\text{Pb}_{\text{ex}}$ fluxes	Increases when sedimentation rate decreases, and <i>vice versa</i> .	Constant	Constant	Could change
Sedimentation rates	Decreases when $^{210}\text{Pb}_{\text{ex}}$ fluxes increases, and <i>vice versa</i> .	Constant	Varies	Varies
Compaction	Use mass-depth instead of depth	Use mass-depth instead of depth	Use mass-depth instead of depth	Use mass-depth instead of depth

112

113 2.1. Constant Initial Concentration

114 The constant initial concentration (CIC) model is based on the hypothesis that any changes in
 115 $^{210}\text{Pb}_{\text{ex}}$ flux or the sedimentation rate are synchronous and reversed so that the initial activity
 116 within the sediment remain constant (Pennington et al., 1976). The model relies on the
 117 following equation:

$$118 \quad t_z = \frac{1}{\lambda} \times \ln \left[\frac{{}^{210}\text{Pb}_{\text{ex}}^0}{{}^{210}\text{Pb}_{\text{ex}}^z} \right] \quad (2)$$

119 where t_z is the age at depth z , $^{210}\text{Pb}_{\text{ex}}^0$ is the activity at the surface of the sediment, and $^{210}\text{Pb}_{\text{ex}}^z$
 120 is the activity at depth z . This model cannot be used if bioturbation has affected the sediment
 121 column or if an instantaneous event perturbed the $^{210}\text{Pb}_{\text{ex}}$ decrease profile (low $^{210}\text{Pb}_{\text{ex}}$ values).
 122 Uncertainties in the CIC model derived ages are computed from equations from Sanchez-
 123 Cabeza and Ruiz-Fernández, (2012).

124

125 2.2. Constant Flux Constant Sedimentation

126 The constant flux constant sedimentation rate (CFCS) model method is based on the
 127 hypothesis that there is neither mixing nor Pb diffusion in the sediment (Goldberg, 1963;
 128 Krishnaswamy et al., 1971). In a semilogarithmic diagram $^{210}\text{Pb}_{\text{ex}}$ activities relative to the
 129 depth have a linear relationship, as follows:

$$130 \quad \text{From (1) :} \quad \ln({}^{210}\text{Pb}_{\text{ex}}^z) = \ln({}^{210}\text{Pb}_{\text{ex}}^0) - \lambda \frac{z}{\text{SAR}} \quad \text{with} \quad t = \frac{z}{\text{SAR}} \quad (3)$$

131 $^{210}\text{Pb}_{\text{ex}}^0$ is the $^{210}\text{Pb}_{\text{ex}}$ activity at the sediment surface ($t=0$), z is the depth and SAR is the
 132 sediment accumulation rate expressed in (mm.yr^{-1}). Any instantaneous event has to be
 133 removed before computation (low $^{210}\text{Pb}_{\text{ex}}$ values). In the *serac* package, this model supports
 134 up to two changes in sedimentation rate.

135 To take into account compaction process, age model can be computed as a function of
 136 mass depth (m_z , g.cm^{-2}) instead of depth (z , mm) with:

$$138 \quad m_z = \sum_{j=0}^{j=i} DBD_j \times \Delta z_j \quad \text{with} \quad DBD_j = \frac{\Delta m_j}{S \Delta z_j} \quad (4)$$

137
 139 Dry bulk densities (DBD, g.cm^{-3}) for each section is required to compute MAR; Δz is the
 140 section width and S is the core cross section (cm^2). Then, sedimentation rates are then
 141 expressed as mass accumulation rates (MAR) in ($\text{g.cm}^{-2}.\text{y}^{-1}$). The CFCS model applied versus
 142 mass depth (by cluster or not) presents a very interesting alternative to CRS model (Abril,
 143 2019; Tylmann et al., 2016). DBD relative uncertainties are fixed at 7% as suggested by
 144 Appelby (2001).

145 146 2.3.Constant Rate of Supply

147 The constant rate of supply (CRS) model is based on the hypotheses that $^{210}\text{Pb}_{\text{ex}}$ (P) flux is
 148 constant, but the SAR varies with time (Appelby and Oldfield, 1978). As a result, the $^{210}\text{Pb}_{\text{ex}}$
 149 activity decreases when sediment fluxes increase. This model defined the cumulative activity
 150 $A(t)$ (mBq.cm^{-2}) during time t , corresponding to a depth z , as follows:

$$151 \quad A(t) = \int_0^t P(t) \cdot \partial t \quad (5)$$

152 The $^{210}\text{Pb}_{\text{ex}}$ inventory can then be calculated (6) by taking in account the decay of $^{210}\text{Pb}_{\text{ex}}$ over
 153 time, as follows:

$$154 \quad I = P_0 \int_0^\infty e^{-\lambda t} \partial t = \frac{P_0}{\lambda} = \sum_{z=0}^\infty (^{210}\text{Pb})_{\text{ex}}^z m_z \quad (6)$$

155 where $\sum_{z=0}^\infty (^{210}\text{Pb})_{\text{ex}}^z m_z$ represents the $^{210}\text{Pb}_{\text{ex}}$ activity integrated over the total sediment
 156 column until $^{210}\text{Pb}_{\text{ex}}$ reaches equilibrium, and m_z is the dry mass depth thickness of the
 157 measured section at z depth, express in g.cm^{-2} . If the section dry masses (m_z) are not known,
 158 but we know those of the section DBD, the mass depths m_z can be calculated as:

$$159 \quad m_j = DBD \times \Delta z_j \quad (7)$$

160 The use of this model assumes that all depths are measured (or interpolated) and that secular
 161 equilibrium is reached (i.e., no more $^{210}\text{Pb}_{\text{ex}}$ activities are observed in the deeper sample). The
 162 age (t_z) at the depth Z is obtained by the equation (8), as follows:

163
$$t_z = \frac{1}{\lambda} \times \ln \left[\frac{\sum_{z=0}^{\infty} ({}^{210}\text{Pb})_{ex}^z m_z}{\sum_{z=z}^{\infty} ({}^{210}\text{Pb})_{ex}^z m_z} \right] \quad (8)$$

164 where $\sum_{z=z}^{\infty} ({}^{210}\text{Pb})_{ex}^z m_z$ represents the ${}^{210}\text{Pb}_{ex}$ activity integrated below depth Z .

165 When the CRS model is applied, a “too-old” age error described by Binford (1990) is
 166 always present for the deeper core sections. The “too-old” age error arises from
 167 underestimation of ${}^{210}\text{Pb}_{ex}$ and may result from analytical limitations, sampling strategy or
 168 both. This underestimation is that their ${}^{210}\text{Pb}_{ex}$ ages are older than their true ages, hence the
 169 name “too-old” age error. Thus, ${}^{210}\text{Pb}_{ex}$ dating based on the CRS model must be conducted
 170 with caution (Blais et al., 1995) or corrected for (Tylmann et al., 2016) by [reference age](#)
 171 [\(Appleby, 2001\)](#) to avoid “too-old” age error for deeper core sections (Binford, 1990).
 172 Uncertainties in the CRS model derived ages are computed from equations from Sanchez-
 173 Cabeza and Ruiz-Fernández (2012).

174
 175 Discrepancies between the derived CRS model and independent dates (from ${}^{137}\text{Cs}$
 176 peak for example) can indicate variations in ${}^{210}\text{Pb}_{ex}$ flux. Appleby (2001) proposes a
 177 piecewise CRS model for cases where the fluxes pre and post-dating of a known reference
 178 date (1986 and 1963 AD artificial fallouts) are different. This model was then successively
 179 applied (Abril, 2019; Putyrskaya et al., 2020; Tylmann et al., 2016). If z_1 and z_2 are the
 180 depths of the two ${}^{137}\text{Cs}$ peaks dated at t_1 (1986) and t_2 (1963) or between the sampling year
 181 and a ${}^{137}\text{Cs}$ peak in the core and the mean ${}^{210}\text{Pb}_{ex}$ flux (P) during the period is:

182
$$P = \frac{\lambda \sum_{z=z_1}^{z_2} ({}^{210}\text{Pb})_{ex}^z m_z}{e^{-\lambda t_1} - e^{-\lambda t_2}} \quad (9)$$

183 Where $\sum_{z=z_1}^{z_2} ({}^{210}\text{Pb})_{ex}^z m_z$ is the ${}^{210}\text{Pb}_{ex}$ inventory between z_1 and z_2 . Assuming the flux to
 184 be uniform within the identified section, dates and sedimentation rates for intermediate depths
 185 can be calculated by applying the principles of the CRS model with the flux calculated from
 186 (8). From the CRS model equations, having calculated P for this interval, the age t of the
 187 depth z between z_1 and z_2 is determined by the following equation:

188
$$t_z = -\frac{1}{\lambda} \ln \left(e^{-\lambda t_1} + \frac{\lambda}{P} \sum_{z=z}^{z_2} ({}^{210}\text{Pb})_{ex}^z m_z \right) \quad (10)$$

189 Where $\sum_{z=z}^{z_2} ({}^{210}\text{Pb})_{ex}^z m_z$ is the ${}^{210}\text{Pb}_{ex}$ inventory between z (the dated depth) and z_2 . The
 190 piecewise CRS age of a sediment horizon in the interval (t_2, ∞) is given by Abril (2019) by
 191 the following equation:

192
$$t_z = t_2 + \frac{1}{\lambda} \ln \left(\frac{\sum_{z=z}^{\infty} ({}^{210}\text{Pb})_{ex}^z m_z}{\sum_{z=z_2}^{\infty} ({}^{210}\text{Pb})_{ex}^z m_z} \right) \quad (11)$$

193 Such model could be applied for more than 2 known reference dates such historical events
194 (pollution, flood, artificial fallouts, etc). Uncertainties for this last model are derived from
195 analytical propagated error.

196

197 The classic $^{210}\text{Pb}_{\text{ex}}$ models (CIC, CFCS, CRS) included in *serac* are not adapted for situations
198 with a continuous trend of change (increase/decrease) in fluxes and/or sedimentation rates
199 which can be encountered in perturbed aquatic sedimentary systems. Many other models exist
200 and have recently been summarized in Arias-Ortiz et al., (2018). More complex models allow
201 for example for independent variability in $^{210}\text{Pb}_{\text{ex}}$ fluxes and sedimentation rates such as SIT
202 (Sediment Isotope Tomography) (Carroll and Lerche, 2003), but also for statistical correlation
203 between $^{210}\text{Pb}_{\text{ex}}$ fluxes and sedimentation rates (Abril Hernández, 2016). Other models can
204 apply when deposition is non-ideal or when there is diffusion or mixing (Abril and Gharbi,
205 2012; Robbins et al., 1977). The piecewise version of classic models (CFCS, CRS) are well
206 suited in cases with stepped changes in the sedimentary conditions (Abril, 2020, 2019); and
207 *serac* allows these piecewise applications, as demonstrated in some of the case studies
208 thereafter.

209

210 3. R code

211 We developed a package on the open-source software R (R Core Team, 2020). The package
212 can be downloaded from the GitHub repository <https://github.com/rosalieb/serac>, or with the
213 package *devtools* (Wickham et al., 2018) and the code:

```
214     library(devtools)  
215     devtools::install_github("rosalieb/serac", build_vignettes = TRUE)  
216     library(serac)
```

217 The package includes several function allowing to prepare the input file, generate age
218 model, edit metadata, and create a map locating systems of interest (Table 2). This section
219 focuses on the main function allowing to generate age depth model, *serac()*.

220 In any given working directory (e.g., *~/serac*, but the working directory can bear any
221 name the user chooses), a folder called “Cores” must be created. The input files must then be
222 placed in a sub-folder of the “Cores” folder, e.g., *~/serac/Cores/MyCore/MyCore.txt*. Table 3
223 illustrates typical data input for *serac()*. The file, as the other input data files, must be saved in
224 a tab separated ‘.txt’ format, with periods as decimal delimiters. Depth top (depth_min) and
225 bottom (depth_max) represent the sampling interval of each sample. The ^{137}Cs , ^{241}Am , and
226 density columns are optional, but the latter (density) is required for inventory calculations,

227 CFCS mass depth calculations and the CRS model. Even if all depths were not analyzed for
 228 short-lived radionuclides, all depths and corresponding densities are emplaced in the input
 229 file, in order to avoid extrapolating density data (NA in Table 3), which could present
 230 different patterns in regard to different environmental systems. If density data is not available,
 231 the analysed depths are sufficient to compute the CFCS and CIC models.

232 The function *serac_input_formatting('MyCore')* can be used to help format the input
 233 file. To use it, place the raw input file (column names in first row, data starting from the
 234 second row) in the folder as described above. This function asks the user to identify columns,
 235 rename them, and replace the input data file automatically.

236

237 **Table 2. Summary of the functions around *serac*, for a core named 'MyCore'.**

Function	Use	Output
<code>user_infos()</code>	New users run this function once to enter professional details	A .txt file in the ~/Cores folder with user's metadata
<code>core_metadata(name = 'MyCore')</code>	Before running <i>serac</i> , but once a folder 'MyCore' had been created in the ~/Cores folder, this function questions the user on metadata specifically related to the core (see Table 5 for details)	A <i>serac_metadata_suppmetadata.txt</i> file in the ~/Cores/MyCore folder This supplementary data will be included to the general metadata after each model computation.
<code>serac_input_formatting(name = 'MyCore')</code>	Input data file can be formatted outside R. This function can help correct several errors (columns names, unit for depth, density calculation, etc.)	Replace MyCore.txt in the ~/Cores/MyCore folder by a correctly formatted file and save the raw data in the same folder under the name MyCore_raw.txt
<code>serac(name = 'MyCore', coring_year = 2019)</code>	Main age-depth model computation function. Refer to Table 4 and case studies	Generate a plot in the ~/Cores/MyCore folder (if <i>plotpdf=TRUE</i>), a metadata file, and depth-age correspondence (raw and interpolated, according to resolution chosen by the <i>stepout</i> argument) for each type of model selected in the <i>model</i> argument.
<code>serac_map()</code>	<i>Function not describe in this paper – if GPS coordinates are given for the different cores (through the core_metadata() function), serac_map() will generate a map with the location of the different sites around the world</i>	A world map with the location of the different study sites

238

239

240 **Table 3. *serac* input file for an example (Lake Iseo). Units are given as an indication, but should not be included in the**
 241 **input file to prevent any issues with file reading. * indicates input data that are optional. NA correspond to missing**
 242 **data: we recommend including continuous density data as ²¹⁰Pb_{ex} can be interpolated (or depth not considered) if**
 243 **needed, while density cannot.**

depth_min (mm)	depth_max (mm)	density* (g/cm ³)	Pb210 _{ex} (Bq/kg)	Pbex210_er (Bq/kg)	Cs137* (Bq/kg)	Cs137_er* (Bq/kg)	Am241* (Bq/kg)	Am241_er* (Bq/kg)
0	6	0.059	370	8	18.1	0.5	0.6	0.3
6	11	0.042	414	11	25.5	0.8	0.2	0.4
11	17	0.048	381	9	26.9	0.7	0.3	0.3
17	22.5	0.065	322	11	29.9	0.8	0.2	0.35

22.5	27.5	0.074	284	7	43.7	0.8	0.6	0.3
27.5	40.5	0.063	247.5	NA	NA	NA	NA	NA
40.5	48	0.052	211	8	77.5	1	0	0
48	54	0.053	249.5	NA	NA	NA	NA	NA
54	58.5	0.054	288	9	233	1.9	0.4	0.35
58.5	64.5	0.055	232	8	631	2.7	0.27	0.4
64.5	70.5	0.069	225	NA	NA	NA	NA	NA
70.5	75	0.082	218	9	1305	5	3.307	0.7
75	83	0.055	166	6	67.1	1	0.1	0.3
83	88.5	0.079	143	NA	NA	NA	NA	NA
88.5	95	0.065	120	6	38.4	0.6	0.7	0.25
95	101	0.057	139	NA	NA	NA	NA	NA
101	111	0.048	158	7	26.7	0.6	0.26	0.26
111	119	0.049	156	NA	NA	NA	NA	NA
119	130	0.050	154	6	47.9	0.8	1.2	0.3
130	139.5	0.072	129	6	155.6	1.5	3.79	0.4
139.5	150	0.087	88	5	96	0.9	1.09	0.29
150	159.5	0.101	96	6	61.6	1	1.1	0.4
159.5	164	0.107	82	6	19.1	0.4	0.55	0.28
164	173	0.097	63	6	7.7	0.3	0.14	0.3
173	179.5	0.107	55.5	NA	NA	NA	NA	NA
179.5	187.5	0.117	48	5	2.4	0.2	0.3	0.3
187.5	199.5	0.107	47	NA	NA	NA	NA	NA
199.5	209	0.106	46	3	0.7	0.1	0.2	0.16
209	234	0.107	40	NA	NA	NA	NA	NA
234	244.5	0.108	34	5	0.5	0.1	0	0
244.5	254	0.107	34	NA	NA	NA	NA	NA
254	264	0.105	34	5	0.23	0.14	0	0
264	283.5	0.108	31	NA	NA	NA	NA	NA
283.5	295	0.110	28	3	0.7	0.1	0	0
295	305	0.110	23	NA	NA	NA	NA	NA
305	317	0.109	18	4	0.19	0.13	0	0

244

245 On the next step, the user can then choose to compute age depth model(s) using any or
246 all of the sedimentation hypotheses described in the previous section (CIC, CFCS, CRS, and
247 CRS_pw). Note that the only requested arguments in the *serac()* function are the name of the
248 core (must be the same than the folder and data input file names) and the coring year. All
249 other arguments have default values and do not have to be filled on the first run. Some
250 arguments are logical (i.e., TRUE or FALSE), other are entered in the form of vectors (e.g.,
251 list of sedimentation hypotheses, upper and lower limits for instantaneous deposits). All
252 argument related to depth (e.g., depth of the Chernobyl peak) must be entered in millimetres.
253 Table 4 summarises the main options, and the case studies included in the next section

254 showcase different scenarios. A 'cheat sheet' summarising the steps and main functions is
 255 available in Supplementary Materials 1.

256

257 **Table 4. Main options included in *serac*. Refer to Supplementary Material 2 for complete list of functions.**

Category	Description
Site ID	Only two arguments are mandatory to run the code: the name of the core and the coring year. Other arguments have default values that can be used. The name of the core has to match the folder name and the file name with the input data.
$^{210}\text{Pb}_{\text{ex}}$	The user can choose to plot $^{210}\text{Pb}_{\text{ex}}$ measurements, with or without potential instantaneous deposits. One of the three models can be visualised. The choice to include or not include instantaneous deposits will automatically remove the corresponding measurements.
^{137}Cs	The user can choose to plot ^{137}Cs , and if so, to identify Chernobyl, the fallouts from nuclear war tests, and the firsts fallouts (logical arguments).
^{241}Am	The user can choose to plot ^{241}Am and identify the fallouts from nuclear war tests
Model	List of model(s) the user wants to test. Choice among CFCS, CRS, CIC, CRS_pw.
Photo	A photo of the sediment sequence can be added, upon precision of the upper and lower limit of the core (in mm). The photo will be automatically cropped.
Instantaneous deposit	Instantaneous deposits (flood, earthquake, slump layers) that should be excised can be added with this argument.
Ignore	For several reason, the user may want to ignore a measurement that is not part of an instantaneous deposit. This can be managed with this argument.
Sedimentation change	Up to two changes in the sedimentation rate can be tested. The depths of the changes are added in a vector.
Plot options	The user can choose whether to export the age-depth model figure using logical arguments. Colours and character size can also be modified.
Historic events	Historical events (e.g., flood, construction of a dam...) can be plotted on the last window.
Supplementary descriptor(s)	Up to two supplementary descriptors can be plotted. If done, an additional input file with these data should be included in the working folder.
Varves	Varve counting can be added on the age-depth model plot. If done, an additional input file with depths (in mm) and corresponding years must be included in the working folder.
Surface Layer	Mixed A depth in mm above which the sediment is considered to be mixed.
Mass depth	Logical (TRUE/FALSE) argument, to decide whether radionuclides should be plotted against mass accumulated depth. Default entries for sediment changes ignore instantaneous deposits and surface mixed layers, are in mm. Another argument (input_depth_mm) allows these depths to be entered in g.cm ⁻² when turned to FALSE.

258

259 4. Case studies

260 *4.1. Lake Bourget – A classic situation with one model (CFCS), one instantaneous event, and*
 261 *varves counting available*

262 Lake Bourget (45°44.7420N, 5°51.6850E) is an 18 km long and 2.8 km wide lowland hard-
 263 water lake in the Northern French Alps. This core was sampled in the deepest part of the lake
 264 at 145 m water depth and records the recent eutrophication (Giguet-Covex et al., 2010). We
 265 used the CFCS model, identified one instantaneous deposit layer between 197 and 210 mm,
 266 and calculated a sediment accumulation rate $\text{SAR} = 4.09 \pm 0.17 \text{ mm.y}^{-1}$. Varve counting
 267 being available since the appearance of hypoxia (Jenny et al., 2013), we requested these ages
 268 to be added to the output figure (*historic_d=c(197,210)*). We further identified dates from the

269 nuclear war tests (first fallouts (220-230 mm), peak fallout (172-180 mm)), as well as traces
 270 of the Chernobyl accident (75-85 mm). In this example, we requested the output file to be
 271 produced at a 1 mm resolution (*stepout = 1*), and that the known earthquake of 1958 be
 272 visualized (*historic_d, historic_a, historic_n*, for depth, age, and name of the event). The full
 273 code is:

```
274 serac(name = "LDB", coring_yr = 2004, model = c("CFCS"), plotphoto = TRUE, minphoto =  

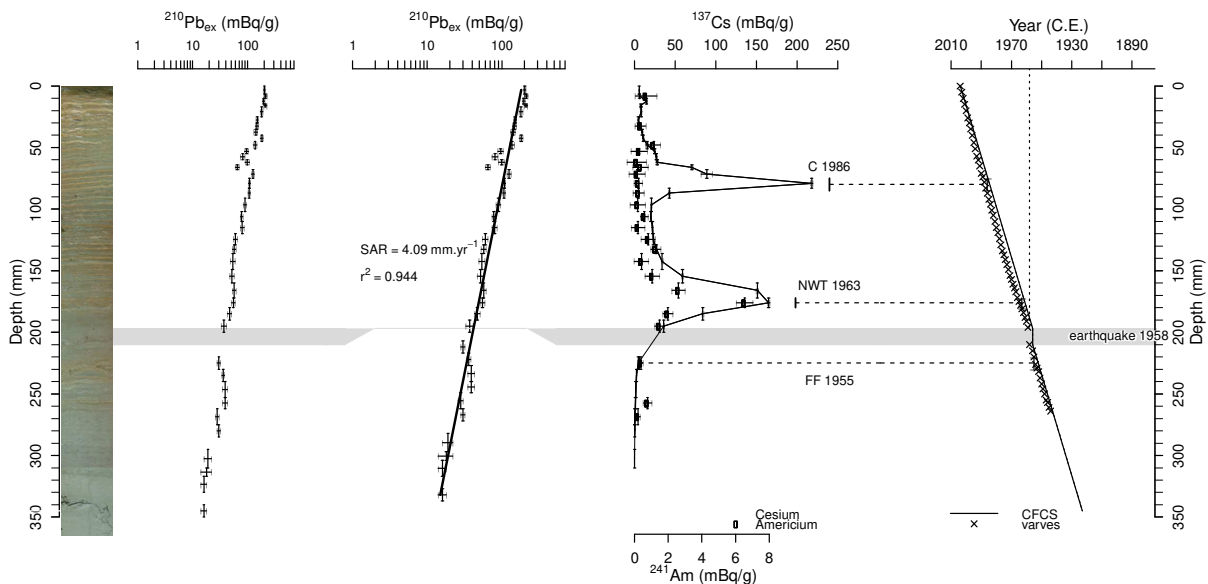
  275 c(0), maxphoto = c(370), plot_Pb = T, plot_Pb_inst_deposit = T, plot_Cs = T, plot_Am = T,  

  276 Cher = c(75, 85), Hemisphere = c("NH"), NWT = c(172, 180), FF = c(220, 230), inst_deposit =  

  277 c(197, 210), historic_d = c(197, 210), historic_a = c(1958), historic_n = c("earthquake 1958"),  

  278 varves = T, plotpdf = T, stepout = 1)
```

280 The high r^2 and the good adequation between ^{137}Cs and ^{241}Am , and historical ages,
 281 suggest the CFCS model is a good solution for this sediment core. More details on the several
 282 arguments are available in Supplementary Material 1.



283
 284 **Figure 2.** Short-lived radionuclides measurements, and age-depth model for Lake Bourget sediment core. From left to right:
 285 core photo, $^{210}\text{Pb}_{\text{ex}}$, $^{210}\text{Pb}_{\text{ex}}$ corrected of instantaneous deposits, ^{137}Cs and ^{241}Am activities and the CFCS age model with
 286 varve counting, ^{137}Cs and ^{241}Am peaks and the identification of the 1958 earthquake

287 **4.2. Lake Iseo – An example of a sediment sequence where the three sedimentation hypotheses**
 288 **could be tested. Varve counting is also available.**

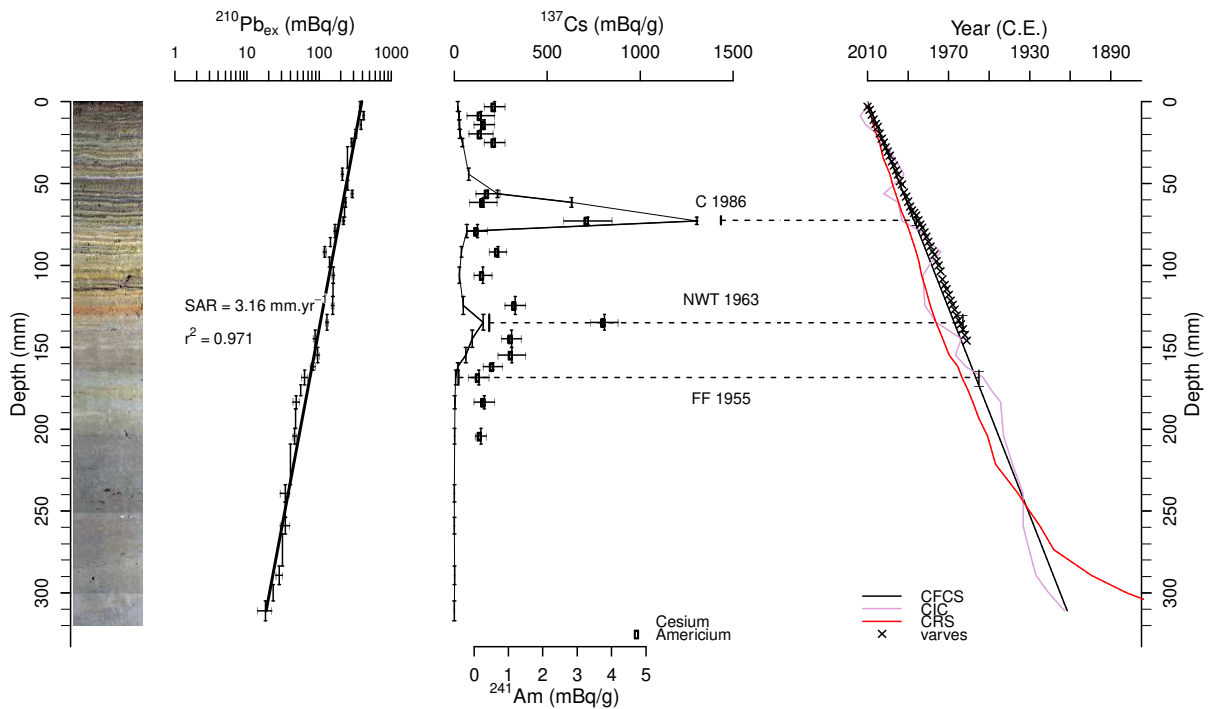
289 Lake Iseo (45°44.205'N; 10°4.340'E) is a large lowland lake in Northern Italy 25 km long
 290 and 60.9 km² in surface area. This core is a sample from the Monte Isola plateau at
 291 approximately 70 m depth and contains evidence for a recent eutrophication (Rapuc et al.,
 292 2018). From short-lived radionuclides data on this core (Table 3), we calculated SAR = 3.16
 293 mm.y⁻¹. In the script below, note that we request to visualise all three $^{210}\text{Pb}_{\text{ex}}$ models, ^{137}Cs

294 and ^{241}Am peaks and varve counting (Fig. 3), and used a 5 mm resolution for our interpolated
 295 model.

```

  296 serac(name = "Iseo", coring_yr = 2010, model = c("CFCS", "CIC", "CRS"), plotphoto = TRUE,
  297 minphoto = c(0), maxphoto = c(320), plot_Pb = T, plot_Am = T, plot_Cs = T, Cher = c(70, 75),
  298 Hemisphere = c("NH"), NWT = c(130, 140), FF = c(164, 173), varves = TRUE, plotpdf = T,
  299 stepout = 5)
  300
  
```

301 The comparison between varve counting, artificial radionuclides and the $^{210}\text{Pb}_{\text{ex}}$
 302 model shows that the CFCS model is preferable for this core and that there is evidence for the
 303 “too-old” age error described first by Binford (1990) for the CRS model in the deeper core
 304 sections and now widely observed (Abril, 2019; Tylmann et al., 2016, 2013). The “too-old”
 305 age error arises from an underestimation of $^{210}\text{Pb}_{\text{ex}}$ in deeper core sections in relation to
 306 analytical limitations, sampling strategy or both.



307
 308 **Figure 3.** Short-lived radionuclides measurements, and age-depth model for Lake Iseo sediment core. From left to right: core
 309 photo, $^{210}\text{Pb}_{\text{ex}}$, ^{137}Cs and ^{241}Am activities and age model (CFCS, CIC, CRS) with varve counting and ^{137}Cs and ^{241}Am peaks.

310
 311 *4.3. Lake Luitel – an example of sediment sequence plot versus mass depth*

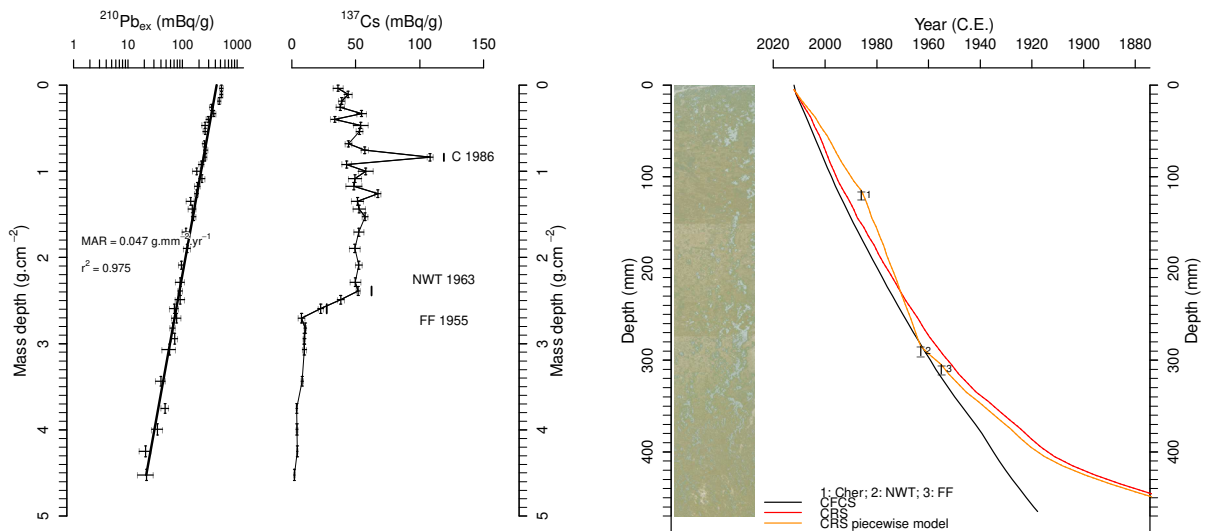
312 Lake Luitel (FR) is a very small system (1.94 ha) located 1262 m above sea level, in a
 313 depression within the crystalline Belledonne range bedrock (Western Alps). The lake colour
 314 is black, typical of organic rich water and is encircled by bog type vegetation. An 80-cm-long

315 core (LUI12P1) was collected from the deeper part of the lake (6 m) in 2012 to reconstruct
316 the history of multiple industrial and urban mercury (Hg) emissions (Guédron et al., 2016).

317 This lake is rich in organic matter and thus presents a large amount of poral water; the
318 classic CFCS model does not match the ^{137}Cs fallouts well (note that ^{241}Am was under the
319 detection limit and is thus not presented in Fig. 4). In such a lake system, a semilogarithmic
320 plot of $^{210}\text{Pb}_{\text{ex}}$ activities versus mass depth allows us to consider density variations in regard
321 to sediment compaction (Abril, 2019; Tylmann et al., 2016). We thus present the CRS,
322 CRS_pw and CFCS models based on the mass depth model (Fig. 4). The CIC model displays
323 several ages inversions, which we want to avoid, and is not shown here. For the CFCS model,
324 the MAR is well defined ($0.047 \text{ g}\cdot\text{mm}^{-1}\cdot\text{y}^{-1}$, $r^2= 0.975$) and the age model is in good
325 agreement with the 1955 and 1963 AD ^{137}Cs markers and in a lesser extent with the
326 Chernobyl fallout, although better than CFCS based on depth age model (not shown). The
327 CRS model also provides a good age model in regard to the ^{137}Cs data, but still present too
328 old ages for the deeper samples. The CRS_pw model is by definition in good agreement with
329 ^{137}Cs markers as we use 1986, 1963 and 1955 AD as forced time-markers (Fig. 4). Therefore,
330 CRS_pw model is better than the CFCS one for the upper part of the core until ~350 mm.
331 Below 350 mm, similar to the CRS model, CRS_pw presents too old ages. For the deeper part
332 of the core as no sedimentary variation is observed it is better to use the mass depth CFCS
333 model which do not present large MAR variation. The best age modelling is done thanks to
334 *serac* and includes the CFCS or CRS_pw mass depth calculation with the following
335 arguments:

```
336 | serac(name = "LUI", coring_yr = 2012, model = c("CFCS", "CRS", "CRS_pw"), mass_depth =  
337 | T, plotphoto = T, minphoto = c(0), maxphoto = c(470), plot_Pb = T, plot_Cs = T, Cher = c(115,  
338 | 125), Hemisphere = c("NH"), NWT = c(285, 295), FF = c(305, 315), plotpdf = TRUE,  
339 | depth_forced_CRS = c(115, 285, 305), age_forced_CRS = c(1986, 1963, 1955))
```

340 Note that the ^{137}Cs peaks (or other depth-related arguments) were identified in the *serac*
341 function in mm (the default), but could also be entered in $\text{g}\cdot\text{cm}^{-2}$ by adding the argument
342 *input_depth_mm = F*.



343
 344 **Figure 4.** Short-lived radionuclides measurements, and age-depth model for Lake Luitel sediment core. From left to right:
 345 $^{210}\text{Pb}_{\text{ex}}$ activities, ^{137}Cs activities, photo of the core, and the age models (CFCS_mass_depth, CRS and CRS_pw). Note that
 346 in the left and central parts, data are plotted against mass depth, while in the right part, data are plotted against depth.

347
 348 *4.4. Lake Saint André – an example of sediment sequence with changes in the sedimentation*
 349 *rate*

350 Lake Saint André (FR) is a relatively small system (7.64 ha), formed in 1248 after a large
 351 landslide. Vineyards have occupied approximately 36% of its 48.5 ha watershed since the
 352 beginning of World War II. A 1-m core (SAN11P2) was collected from the deepest part of
 353 Lake Saint André (12 m) in 2011 to investigate long-term succession and the diffuse transfer
 354 of herbicides, fungicides, and insecticide treatments (Sabatier et al., 2014).

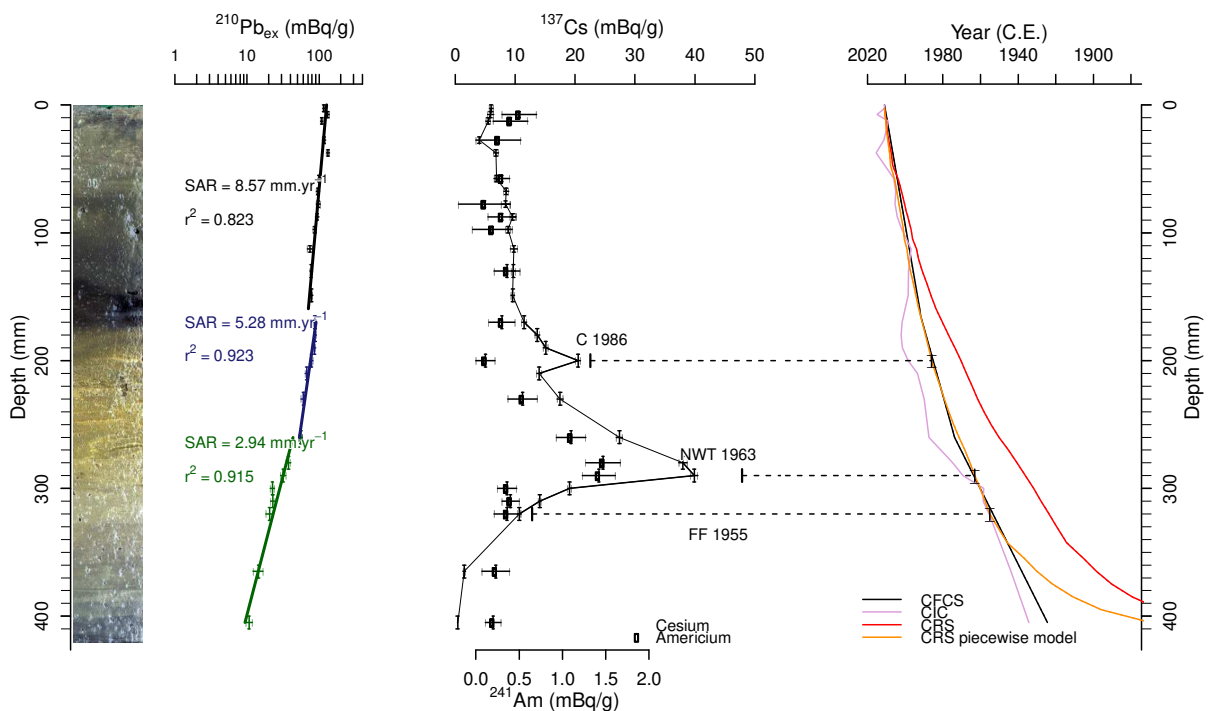
355 A logarithmic plot of $^{210}\text{Pb}_{\text{ex}}$ activity (Fig. 5) shows a general decrease with three
 356 distinct linear trends. According to the (CFCS) model applied to each part of the profile, we
 357 can define mean accumulation rates of $2.9 \pm 0.2 \text{ mm.y}^{-1}$ between depths of 41 and 26 cm, 5.3
 358 $\pm 0.6 \text{ mm.y}^{-1}$ between 26 and 16.5 cm, and $8.6 \pm 1.3 \text{ mm.y}^{-1}$ in the upper 16.5 cm of the core.
 359 ^{137}Cs and ^{241}Am activities are in good agreement with the ages derived from the $^{210}\text{Pb}_{\text{ex}}$ -CFCS
 360 model and support the interpretation of two primary sedimentation rate changes in *ca.* $1973 \pm$
 361 5 y and $1994 \pm 2.5 \text{ y}$ (Fig. 5). These two changes in the sedimentation rate are related to
 362 vineyard practices increasing erosion in the watershed during two periods: (1) in the early
 363 1970s, with the local use of heavy farm machinery and (2) in the early 1990s, with increasing
 364 applications of postemergence herbicides (Glyphosate, see Sabatier et al., 2014 for more
 365 details). The age modelling conducted through *serac*, including the two changes in
 366 sedimentation rate, takes the following arguments:

```

367 serac(name = "SAN", coring_yr = 2011, model = c("CFCS", "CIC", "CRS", "CRS_pw"),
368 plotphoto = TRUE, minphoto = c(0), maxphoto = c(420), plot_Pb = T, sedchange = c(165,
369 260), plot_Am = T, plot_Cs = T, Cher = c(195, 205), Hemisphere = c("NH"), NWT = c(285,
370 295), FF = c(315, 325), plotpdf = TRUE, depth_forced_CRS = c(200, 290, 320),
371 age_forced_CRS = c(1986, 1963, 1955), archive_metadata = T)

```

372 The piecewise CFCS and CRS_pw models are in best agreement with $^{137}\text{Cs}/^{241}\text{Am}$
373 markers. CRS_pw models with 3 forced depths seems good until 350 mm and deeper present
374 large chronology deviation but provide more smoothed SAR changes than CFCS model.
375 Knowing the environmental context of this lake system with 2 strong changes in agricultural
376 practices we expect a rapid change in SAR derived from rapid change in erosional processes
377 and thus we prefer the piecewise CFCS model (Sabatier et al., 2014).



378
379 **Figure 5.** Short-lived radionuclides measurements, and age-depth model for Lake Saint André sediment core. From left to
380 right: photography, $^{210}\text{Pb}_{\text{ex}}$ activity, ^{137}Cs and ^{241}Am activities, and the age model (CFCS, CRS, CIC and CRS_pw).

381 4.5. Lake Allos – an example of a sediment sequence with instantaneous deposits

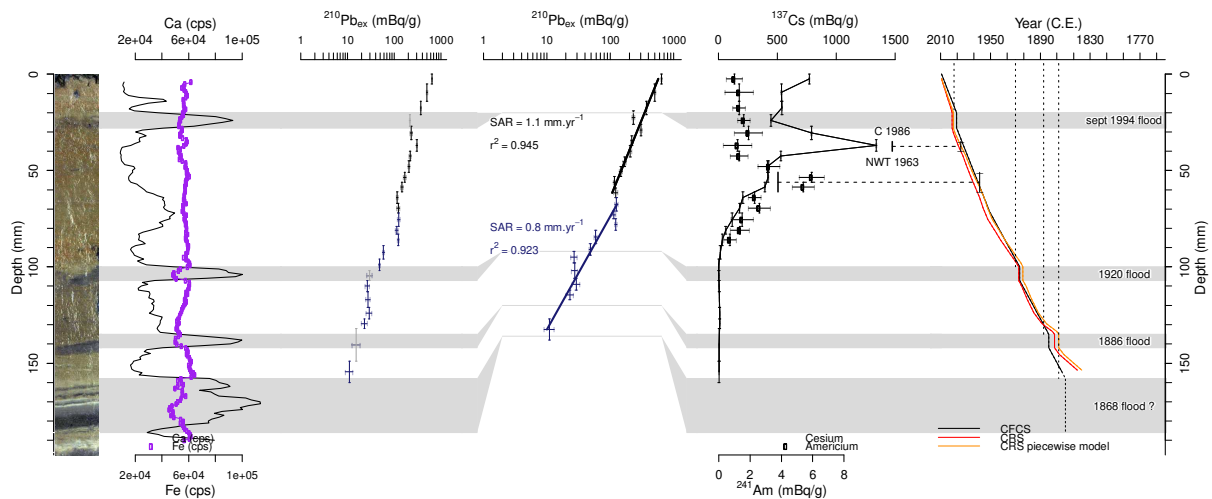
382 Lake Allos is a high-altitude lake in the French Alps (2230 m a.s.l., 0.6 km²). Half of the 5-
383 km² catchment is drained by three permanent torrents that transport terrigenous flows towards
384 the lake mainly during extreme precipitation events (Wilhelm et al., 2015, 2012). A plot of
385 $^{210}\text{Pb}_{\text{ex}}$ activity (Fig. 6) shows a general decrease with low activities at several depths that
386 correspond to graded beds. To illustrate these sedimentary events, we add one to two
387 supplementary descriptors (*suppdSCRIPTOR*) to the age model figure, such as geochemical data
388 (XRF). Calcium (*Ca*) enrichment associated with coarser grain size evidence four
389 instantaneous deposits in the Allos sediment sequence, indicating a large input from the

390 watershed, while iron (*Fe*) content is associated with continuous sedimentation (Fig. 6, see
391 Wilhelm et al., 2012 for more details). As these instantaneous events are removed before
392 computing the CFCS model, which assumes a linear sedimentation rate. In this case, $^{210}\text{Pb}_{\text{ex}}$
393 activities, corrected for instantaneous deposits, show a change in the mean sedimentation rate
394 at 71 mm. CRS and CRS_pw models were also computed without all these instantaneous
395 events and provide very similar results than piecewise CFCS model. The age modelling is
396 conducted through *serac* and includes the historical events and one change in sedimentation
397 rate with the following arguments:

```
398 serac(name = "ALO09P12", coring_yr = 2009, model = c("CFCS", "CRS","CRS_pw"),  
399 plotphoto = TRUE, minphoto = c(0), maxphoto = c(210), plot_Pb = T, plot_Pb_inst_deposit =  
400 T, inst_deposit = c(20, 28, 100, 107, 135, 142, 158, 186), sedchange = c(71), plot_Am = T,  
401 plot_Cs = T, Cher = c(35, 40), Hemisphere = c("NH"), NWT = c(51, 61), suppdSCRIPTOR =  
402 TRUE, descriptor_lab = c("Ca (cps)", "Fe (cps)"), historic_d = c(20, 28, 100, 107, 135, 142,  
403 158, 186), historic_a = c(1994, 1920, 1886, 1868), historic_n = c("sept 1994 flood", "1920  
404 flood", "1886 flood", "1868 flood ?"), min_yr = c(1750), dmax = c(180), plotpdf = TRUE,  
405 depth_forced_CRS = c(37.5,58.5), age_forced_CRS = c(1986, 1963))
```

406

407 The final age model is supported by the ^{137}Cs and ^{241}Am activities and by historical
408 floods that correspond to these four instantaneous events. Note that for larges figures as Fig.
409 6, R may sometimes not create the preview (and gives an error) because the plotting window
410 is too narrow. The user can try to extend the plotting zone (which is easy in RStudio, RStudio
411 Team, 2016). We added a logical argument, *preview*, which can be turned to FALSE to
412 address this issue; in this case, the preview is simply not displayed. If the argument *plotpdf* is
413 left to its default value, i.e., TRUE, the figure will still be created in the core subfolder.



415

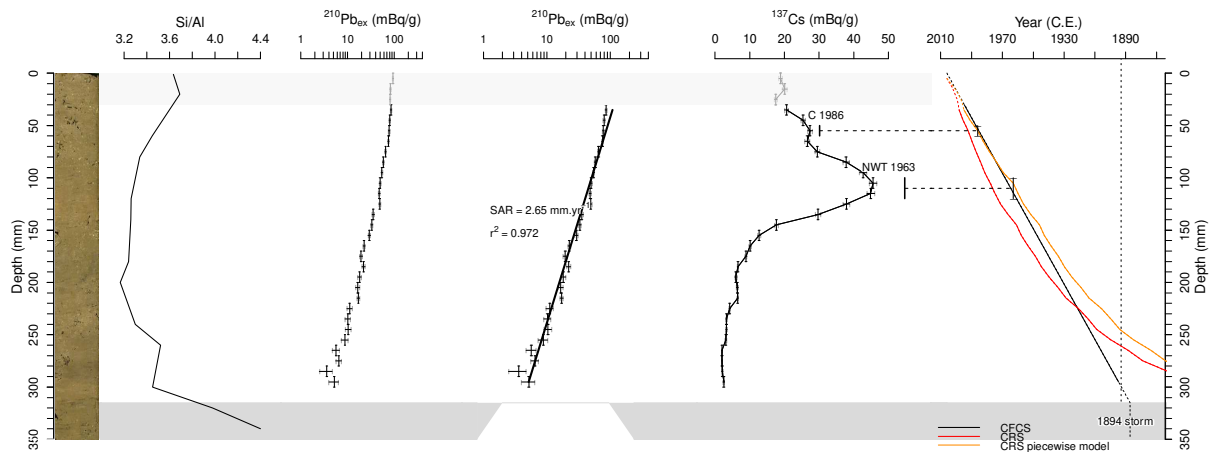
416 **Figure 6.** Descriptors, short-lived radionuclides measures, and age-depth model for Lake Allos sequence. From left to right:
 417 core photograph, Ca/Fe ratio and raw Fe, $^{210}\text{Pb}_{\text{ex}}$ activity with and without instantaneous deposit events, ^{137}Cs activity and
 418 ^{241}Am activity, and the CFCS, CRS and CRS_pw age model for the Lake Allos sequence. The horizontal grey lines indicate
 419 layers that were identified as instantaneous events.

420 4.6. Pierre Blanche lagoon – An example of a sediment sequence with a surface mixed layer

421 The PB06 core (7.9 m) was collected in the Pierre Blanche Lagoon (PBL), in the southern
 422 part of the Palavasian lagoonal complex (France) in 2006 (Sabatier et al., 2010b). This coastal
 423 shallow water environment contains many organisms that induce bioturbation, with
 424 advection-diffusion in the upper first centimetres in the deepest regions caused by mollusc
 425 and gallery-diffusion by worms (François et al., 2002). This second process is difficult to
 426 identify and to correct for (Sabatier et al., 2010a). The resolution of the advection-diffusion
 427 model (Sharma et al., 1987) by Lacroart *et al.* (2007) applied to $^{210}\text{Pb}_{\text{ex}}$ allows the estimation
 428 of SARs and the biodiffusion coefficient (D_b). We can thus define a surface mixed layer
 429 (SML) within which $^{210}\text{Pb}_{\text{ex}}$ activities are perturbed; PB06 has almost constant activities in the
 430 first 3 cm (Fig. 7). The $^{210}\text{Pb}_{\text{ex}}$ activities profile is thus composed of a bioturbated upper part,
 431 characterised by a combination of sedimentation and bioturbation (SAR, D_b) and below which
 432 a non-perturbed profile exists where $D_b = 0$. To solve this model, we calculated a mean
 433 sedimentation rate for the non-bioturbated part and, making the hypothesis the sedimentation
 434 rate remained constant, we extrapolated this estimate to the upper part. The SML is defined in
 435 *serac* by its upper and lower depth. In the presence of SML, CIC model cannot be applied
 436 because the initial activity is perturbed. The age model for PB06 is also constrained by the
 437 ^{137}Cs peaks and a historical storm event identified by geochemical data (Fig. 7); for more
 438 details see Sabatier et al. (2010c). The full *serac* code is:

```
439 | serac(name = "PB06", coring_yr = 2006, model = c("CFCS", "CRS", "CRS_pw"), plotphoto =
440 | TRUE, minphoto = c(0), maxphoto = c(350), plot_Pb = T, plot_Pb_inst_deposit = T,
```

441 inst_deposit = c(315, 350), SML = 30, plot-Cs = T, Cher = c(50, 60), Hemisphere = c("NH"),
 442 NWT = c(100, 120), suppdSCRIPTOR = T, descriptor_lab = c("Si/Al"), historic_d = c(315, 350),
 443 historic_a = c(1893), historic_n = c("1894 storm"), min_yr = 1870, dmax = c(350), plotpdf =
 444 TRUE, depth_forced_CRs = c(55, 105), age_forced_CRs = c(1986, 1963))
 445



446
 447 **Figure 7.** Descriptor, short-lived radionuclides measurements, and age-depth model for Pierre-Blanche lagoon sediment core.
 448 From left to right: core photograph, Si/Al content, $^{210}\text{Pb}_{\text{ex}}$ activities, ^{137}Cs activities, and the age model (CFCS, CRS and
 449 CRS_pw), the surface mixed layer is in light grey and the 1894 AD storm event in dark grey.

450
 451 The comparison among historical events (storms), artificial radionuclides and the
 452 $^{210}\text{Pb}_{\text{ex}}$ model results in the CFCS model being preferable to the CRS and CRS_pw for this
 453 core and evidence of the “too-old” age error described by Binford (1990) for the CRS models
 454 in the deeper core sections, resulting from the identified 1894 storm event.
 455

456 5. Metadata

457 Every time the code is run, a metadata file is automatically generated in the folder. The
 458 metadata file summarises the main decisions made by the user (e.g., presence/absence of
 459 instantaneous deposit, type of model chosen) but also other general information on the user
 460 (ORCID, affiliation, email) and the core (ISGN: International Geo Sample Number
 461 (IGSN)/System for Earth Sample Registration Database (www.geosamples.org, measurement
 462 laboratory, measurement method, date of measurement). These data are entered independently
 463 from the exploration phase of the model through the function `user_infos()` and
 464 `core_metadata()`. The former function theoretically needs to be used only once by each new
 465 user the first time the library *serac* is used. The new user will be required to answer several
 466 questions (affiliation, ORCID number, etc.). The user information are then integrated into the
 467 metadata file associated with the age modelling, in text format. The `core_metadata()` function

468 ask more details about the core itself and the analytical data, summarised in Table 4 and will
 469 be enter according to the following lines:

470 | `core_metadata(name = "Mycore")`

471 These data can also be directly implemented during the age modelling phase by adding
 472 `archive_metadata=T` in the *serac* function. The metadata listed in Table 5 emerges from both
 473 data reports of radioactivity detections from the CNRS in France (Centre National de la
 474 Recherche Scientifique) and a recent international survey (literature review and questionnaire)
 475 about ²¹⁰Pb metadata (Courtney Mustaphi et al., 2019). The French initiative coordinated the
 476 development of a common way to present short-lived radionuclides data through the ROZA
 477 (Rétro-observatoire Archives sédimentaires des Zones Ateliers) experience and produced a
 478 document guiding the information needed to store data in a repository. The review by
 479 Courtney Mustaphi et al. (2019) also suggests a set of minimum reporting guidelines for ²¹⁰Pb
 480 metadata and data needed to improve data archiving standards to facilitate data reutilisation.

481

482 **Table 5. Example of metadata associated with the SAN core (Sabatier et al., 2014)**

Parameters	Example
ISGN	EDYSAN001
sample date	2011-12-01
coring coordinates y	45.494980
coring coordinates x	5.985720
coring method	gravity corer
laboratory subsampling method	calibrated volumetric sampler
measurement laboratory	LSM/EDYTEM, FR
instrument type	well-type germanium detector
measurement startdate	2012-01-15
measurement enddate	2012-04-05
additional comments	²¹⁰ Pb background reached

483

484 These two functions and all parameters inside are optional but we encourage the users
 485 to use these functionalities as they help generate a more exhaustive background for the core.

486 Note that another text file is automatically generated and incremented with all new tests. The
 487 file is found in the core folder (`~/Cores/MyCore/serac_model_history_MyCore.txt`). It (1)
 488 provides a history of attempts and (2) displays a message in R if a code has been tested
 489 previously. A vigilant user can then compare and trace back the logical thinking that led to the
 490 final model.

491

492 6. Discussion

493 *serac* provides a rapid yet exhaustive tool for testing sedimentation hypotheses and creating
494 age models for the last century. Several functions (Table 2) guide the user in building age-
495 depth models for a given core. To choose the best chronology for the studied sequence, *serac*
496 allows the comparison of different age models to be computed against depth or mass depth,
497 but also to be compared with other independent markers such as artificial radionuclides
498 fallout or historic events. In most cases, we recommend users to plot $^{210}\text{Pb}_{\text{ex}}$ activities versus
499 mass depth as this representation take into account both natural and coring compactions
500 which remain invariant under the previous processes (Fig. 4). Note that the identification of
501 independent time marker such as artificial radionuclides (Fig. 2-6) or historical events (Fig. 2,
502 5, 6) is often necessary to validate the age model choice (Baskaran et al., 2014; Kirchner,
503 2011). However, users have to be aware of potential wrong identification of i) the first ^{137}Cs
504 atmospheric fallout when non-ideal deposition is relevant with diffusion (Delaval et al., 2020)
505 or mixing (Sabatier et al., 2010a) and ii) ^{137}Cs -peaks when translocational and/or incomplete
506 mixing occur (Abril, 2004; Sabatier et al., 2010a).

507 $^{210}\text{Pb}_{\text{ex}}$ models are sometime used incorrectly. For instance, CIC model cannot be used
508 for a core that has instantaneous deposits with lower $^{210}\text{Pb}_{\text{ex}}$ activities or a surface mixed layer
509 linked to bioturbation processes. Furthermore, the CRS model cannot be used when the
510 $^{210}\text{Pb}_{\text{ex}}$ inventory is not the total (activities were not measured until secular equilibrium
511 existed between ^{210}Pb and ^{226}Ra). Note that *serac* will display warnings when sedimentation
512 hypotheses are not satisfied. In that respect, *serac* is also a pedagogic tool.

513 Other parameters non-related to sedimentation hypotheses are automatically computed
514 in *serac*. If the density is present in the input data, ^{210}Pb and ^{137}Cs inventories of sediment
515 cores are generated. These data can be interesting to compare across systems to map the
516 trajectory of radionuclide fallouts. For instance, ^{137}Cs inventories of Lake Iseo (1390 ± 100
517 Bq.m^{-2}) and Lake Bourget ($975 \pm 19 \text{ Bq.m}^{-2}$) reported the same age of 2020, but present
518 significant differences related to the higher Chernobyl accident fallout in Italy relative to that
519 in France. Inventories can also indicate allochthonous inputs variations, and comparisons
520 across sites can yield valuable insights into catchment sediment dynamics (Pulley et al.,
521 2018). Finally, radionuclides inventories of multiples cores in different part of the same lake
522 allow to identify sediment redistribution from shallow to deep zone by waves and water
523 currents through sediment focusing (Crusius and Anderson, 1995).

524 Using *serac* easily allows reproducibility of the main hypotheses behind any age-depth
525 model (such as changes in sedimentation rates or the presence of instantaneous deposits). We
526 believe that the availability of a user-friendly code on an open source platform to visualise

527 and test sedimentation hypotheses is an important step towards reproducibility. *serac* allows
528 users customisation of parameters to include, as well as cross-platform support (Windows,
529 Linux, Macs). The R code of *serac* can be understood relatively easily by a beginner R user,
530 and its open source nature means it can be adapted to fit an advanced user's preferences.
531 Output files (age model, metadata, figure) could be used (1) in the current form or integrated
532 in a larger age model such as *clam* (2) to create a figure for publication and (3) in data saving
533 platforms with general information on data, metadata, the age modeller, and the age model
534 parameters, which would allow data tractability and reproducibility. It is hoped that *serac*
535 could help the palaeoscience community standardise and enhance future age depth models
536 that use short-lived radionuclides and allow the extension of the data lifecycle (Wilkinson et
537 al., 2016).

538

539 **7. Conclusion**

540 The past century is characterized by rapid environmental socio-ecological changes, as
541 showcased by the few case studies we presented before (e.g., Sabatier et al., 2014).
542 Consequences of environmental modifications and critical ecosystem thresholds can be
543 informed resorting to historical reconstructions. Shortlived radionuclides are essential for
544 developing ages models for the past 100 years and setting a convincing chronology for
545 changes unveiled by proxies.

546 *serac* complement other tools by offering a method to produce age-depth model using
547 radionuclides data with classic model applications (CFCS, CIC, CRS) and piecewise versions.
548 The automation allows to try different sedimentation hypothesis, makes unlikely calculation
549 errors and saves computational time that can now be allocated to comparing different
550 chronological models or further analyses.

551 An important feature of *serac* is the generation of metadata. Good report of metadata
552 relative to the core or the model is not common yet (Courtney Mustaphi et al., 2019), but is
553 decisive to extend the data life cycle and promote knowledge integration by the community
554 (Courtney Mustaphi et al., 2019; Wilkinson et al., 2016).

555

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562

563 **Data Availability**

564 Data to reproduce the example for Lake Allos (Fig. 6) are accessible through the package.
565 Other data are available upon request.

566

567 **References**

- 568 Abril Hernández, J.-M., 2016. A ^{210}Pb -based chronological model for recent sediments with
569 random entries of mass and activities: Model development. *J. Environ. Radioact.* 151,
570 64–74. <https://doi.org/10.1016/j.jenvrad.2015.09.018>
- 571 Abril, J.M., 2020. Multimodal-TERESA, a ^{210}Pb -based radiometric dating model for recent
572 sediments under largely varying rates of supply. *Quat. Geochronol.* 55, 101032.
573 <https://doi.org/10.1016/j.quageo.2019.101032>
- 574 Abril, J.M., 2019. Radiometric dating of recent sediments: On the performance of ^{210}Pb -
575 based CRS chronologies under varying rates of supply. *Quaternary Geochronology* 51,
576 1–14. <https://doi.org/10.1016/j.quageo.2018.12.003>
- 577 Abril, J.M., 2004. Constraints on the use of ^{137}Cs as a time-marker to support CRS and SIT
578 chronologies. *Environ. Pollut.* 129, 31–37.
579 <https://doi.org/10.1016/j.envpol.2003.10.004>
- 580 Abril, J.-M., Gharbi, F., 2012. Radiometric dating of recent sediments: beyond the boundary
581 conditions. *J. Paleolimnol.* 48, 449–460. <https://doi.org/10.1007/s10933-012-9622-5>
- 582 Andrews, A., Stone, R., Lundstrom, C., DeVogelaere, A., 2009. Growth rate and age
583 determination of bamboo corals from the northeastern Pacific Ocean using refined
584 ^{210}Pb dating. *Marine Ecology Progress Series* 397, 173–185.
585 <https://doi.org/10.3354/meps08193>
- 586 Appleby, P.G., 2008. Three decades of dating recent sediments by fallout radionuclides: a
587 review. *The Holocene* 18, 83–93. <https://doi.org/10.1177/0959683607085598>
- 588 Appleby, P.G., 2001. Chronostratigraphic Techniques in Recent Sediments, in: Last, W.M.,
589 Smol, J.P. (Eds.), *Tracking Environmental Change Using Lake Sediments, Basin*
590 *Analysis, Coring, and Chronological Techniques. Developments in*
591 *Paleoenvironmental Research Series*. Dordrecht, pp. 171–203.
- 592 Appleby, P.G., Oldfield, F., 1992. Applications of lead-210 to sedimentation studies, in:
593 *Uranium-Series Disequilibrium: Applications to Earth, Marine, and Environmental*
594 *Sciences*. Clarendon Press ; Oxford University Press, Oxford : Oxford ; New York.
- 595 Appleby, P.G., Oldfield, F., 1978. The calculation of lead-210 dates assuming a constant rate
596 of supply of unsupported ^{210}Pb to the sediment. *CATENA* 5, 1–8.
597 [https://doi.org/10.1016/S0341-8162\(78\)80002-2](https://doi.org/10.1016/S0341-8162(78)80002-2)
- 598 Appleby, P.G., Richardson, N., Nolan, P.J., 1991. ^{241}Am dating of lake sediments.
599 *Hydrobiologia* 214, 35–42. <https://doi.org/10.1007/BF00050929>
- 600 Aquino-López, M.A., Blaauw, M., Christen, J.A., Sanderson, N.K., 2018. Bayesian Analysis
601 of ^{210}Pb Dating. *JABES* 23, 317–333. <https://doi.org/10.1007/s13253-018-0328-7>
- 602 Arias-Ortiz, A., Masqué, P., Garcia-Orellana, J., Serrano, O., Mazarrasa, I., Marbà, N.,
603 Lovelock, C.E., Lavery, P., Duarte, C.M., 2018. Reviews and syntheses: ^{210}Pb -derived
604 sediment and carbon accumulation rates in vegetated coastal ecosystems: setting the
605 record straight. *Biogeosciences Discussions* 1–47. <https://doi.org/10.5194/bg-2018-78>

- 606 Baskaran, M., Iliffe, T.M., 1993. Age determination of recent cave deposits using excess ²¹⁰Pb - A new technique. *Geophysical Research Letters* 20, 603–606.
607 <https://doi.org/10.1029/93GL00531>
608
- 609 Baskaran, M., Nix, J., Kuyper, C., Karunakara, N., 2014. Problems with the dating of
610 sediment core using excess ²¹⁰Pb in a freshwater system impacted by large scale
611 watershed changes. *J. Environ. Radioact* 138, 355–363.
612 <https://doi.org/10.1016/j.jenvrad.2014.07.006>
- 613 Binford, M.W., 1990. Calculation and uncertainty analysis of ²¹⁰Pb dates for PIRLA project
614 lake sediment cores. *J Paleolimnol* 3, 253–267.
- 615 Blaauw, M., 2010. Methods and code for ‘classical’ age-modelling of radiocarbon sequences.
616 *Quat. Geochronol.* 5, 512–518. <https://doi.org/10.1016/j.quageo.2010.01.002>
- 617 Blais, J.M., Kalff, J., Cornett, R.J., Evans, R.D., 1995. Evaluation of ²¹⁰Pb dating in lake
618 sediments using stable Pb, Ambrosia pollen, and ¹³⁷Cs. *J. Paleolimnol.* 13, 169–178.
- 619 Carroll, J., Lerche, I., 2003. *Sedimentary processes: quantification using radionuclides.*
620 Elsevier, Amsterdam; Boston.
- 621 Condomines, M., Rihs, S., 2006. First ²²⁶Ra–²¹⁰Pb dating of a young speleothem. *Earth and*
622 *Planetary Science Letters* 250, 4–10. <https://doi.org/10.1016/j.epsl.2006.06.012>
- 623 Cooke, C.A., Hobbs, W.O., Michelutti, N., Wolfe, A.P., 2010. Reliance on ²¹⁰Pb Chronology
624 Can Compromise the Inference of Preindustrial Hg Flux to Lake Sediments.
625 *Environmental Science & Technology* 44, 1998–2003.
626 <https://doi.org/10.1021/es9027925>
- 627 Courtney Mustaphi, C.J., Brahney, J., Aquino-López, M.A., Goring, S., Orton, K., Noronha,
628 A., Czaplewski, J., Asena, Q., Paton, S.C., Panga Brushworth, J., 2019. Guidelines for
629 reporting and archiving ²¹⁰Pb sediment chronologies to improve fidelity and extend
630 data lifecycle. *Quat. Geochronol.* 52, 77–87.
- 631 Crusius, J., Anderson, R.F., 1995. Sediment focusing in six small lakes inferred from
632 radionuclide profiles. *J Paleolimnol* 13, 143–155. <https://doi.org/10.1007/BF00678103>
- 633 Delaval, A., Duffa, C., Radakovitch, O., 2020. A review on cesium desorption at the
634 freshwater-seawater interface. *J. Environ. Radioact.* 218, 106255.
635 <https://doi.org/10.1016/j.jenvrad.2020.106255>
- 636 Druffel, E.R.M., King, L.L., Belastock, R.A., Buesseler, K.O., 1990. Growth rate of a deep-
637 sea coral using ²¹⁰Pb and other isotopes. *Geochimica et Cosmochimica Acta* 54,
638 1493–1499. [https://doi.org/10.1016/0016-7037\(90\)90174-J](https://doi.org/10.1016/0016-7037(90)90174-J)
- 639 François, F., Gerino, M., Stora, G., Durbec, J.-P., Poggiale, J.-C., 2002. Functional approach
640 to sediment reworking by gallery-forming macrobenthic organisms: modeling and
641 application with the polychaete *Nereis diversicolor*. *Mar. Ecol. Prog. Ser.* 229, 127–
642 136. <https://doi.org/10.3354/meps229127>
- 643 Giguet-Covex, C., Arnaud, F., Poulenard, J., Enters, D., Reyss, J.-L., Millet, L., Lazzaroto, J.,
644 Vidal, O., 2010. Sedimentological and geochemical records of past trophic state and
645 hypolimnetic anoxia in large, hard-water Lake Bourget, French Alps. *J. Paleolimnol.*
646 43, 171–190. <https://doi.org/10.1007/s10933-009-9324-9>
- 647 Goldberg, E.D., 1963. Geochronology with ²¹⁰Pb in radioactive dating. *International Atomic*
648 *Energy Contribution* 1510, 121–131.
- 649 Guédron, S., Amouroux, D., Sabatier, P., Desplanque, C., Develle, A.-L., Barre, J., Feng, C.,
650 Guiter, F., Arnaud, F., Reyss, J.L., Charlet, L., 2016. A hundred year record of
651 industrial and urban development in French Alps combining Hg accumulation rates
652 and isotope composition in sediment archives from Lake Luitel. *Chemical Geology*
653 431, 10–19. <https://doi.org/10.1016/j.chemgeo.2016.03.016>
- 654 Jenny, J.-P., Arnaud, F., Dorioz, J.-M., Giguet-Covex, C., Frossard, V., Sabatier, P., Millet,
655 L., Reyss, J.-L., Tachikawa, K., Bard, E., Pignol, C., Soufi, F., Romeyer, O., Perga,

656 M.-E., 2013. A spatiotemporal investigation of varved sediments highlights the
657 dynamics of hypolimnetic hypoxia in a large hard-water lake over the last 150 years.
658 *Limnol. Oceanogr.* 58, 1395–1408. <https://doi.org/10.4319/lo.2013.58.4.1395>

659 Kirchner, G., 2011. ²¹⁰Pb as a tool for establishing sediment chronologies: examples of
660 potentials and limitations of conventional dating models. *J. Environ. Radioact.*
661 *International Topical Meeting on Polonium and Radioactive Lead Isotopes* 102, 490–
662 494. <https://doi.org/10.1016/j.jenvrad.2010.11.010>

663 Krishnaswamy, S., Lal, D., Martin, J.M., Meybeck, M., 1971. Geochronology of lake
664 sediments. *Earth Planet. Sci. Lett.* 11, 407–414. [https://doi.org/10.1016/0012-821X\(71\)90202-0](https://doi.org/10.1016/0012-821X(71)90202-0)

665 Lecroart, P., Schmidt, S., Anschutz, P., Jouanneau, J.-M., 2007. Modeling sensitivity of
666 biodiffusion coefficient to seasonal bioturbation. *J. Mar. Res.* 65, 417–440.
667 <https://doi.org/10.1357/002224007781567630>

668 Moore, W.S., Krishnaswami, S., 1972. Coral growth rates using ²²⁸Ra and ²¹⁰Pb. *Earth and*
669 *Planetary Science Letters* 15, 187–190. [https://doi.org/10.1016/0012-821X\(72\)90059-3](https://doi.org/10.1016/0012-821X(72)90059-3)

670 Pennington, W., Cambray, R.S., Eakins, J.D., Harkness, D.D., 1976. Radionuclide dating of
671 the recent sediments of Blelham Tarn. *Freshw. Biol.* 6, 317–331.
672 <https://doi.org/10.1111/j.1365-2427.1976.tb01617.x>

673 Pulley, S., Foster, I.D.L., Collins, A.L., Zhang, Y., Evans, J., 2018. An analysis of potential
674 controls on long-term ¹³⁷Cs accumulation in the sediments of UK lakes. *J.*
675 *Paleolimnol.* 60, 1–30. <https://doi.org/10.1007/s10933-017-0016-6>

676 Putyrskaya, V., Klemm, E., Röllin, S., Corcho-Alvarado, J.A., Sahli, H., 2020. Dating of recent
677 sediments from Lago Maggiore and Lago di Lugano (Switzerland/Italy) using ¹³⁷Cs
678 and ²¹⁰Pb. *Journal of Environmental Radioactivity* 212, 106135.
679 <https://doi.org/10.1016/j.jenvrad.2019.106135>

680 R Core Team, 2020. R: A language and environment for statistical computing. R Foundation
681 for Statistical Computing, Vienna, Austria. R Foundation for Statistical Computing.

682 Rapuc, W., Sabatier, P., Andrič, M., Crouzet, C., Arnaud, F., Chapron, E., Šmuc, A., Develle,
683 A.-L., Wilhelm, B., Demory, F., Reyss, J.-L., Régnier, E., Daut, G., Von Grafenstein,
684 U., 2018. 6600 years of earthquake record in the Julian Alps (Lake Bohinj, Slovenia).
685 *Sedimentology* 65, 1777–1799. <https://doi.org/10.1111/sed.12446>

686 Robbins, J., Krezoski, J., Mozley, S., 1977. Radioactivity in sediments of the Great Lakes:
687 Post-depositional redistribution by deposit-feeding organisms. *Earth Planet. Sci. Lett.*
688 36, 325–333. [https://doi.org/10.1016/0012-821X\(77\)90217-5](https://doi.org/10.1016/0012-821X(77)90217-5)

689 RStudio Team, 2016. RStudio: Integrated Development for R. RStudio, Inc., Boston, MA.

690 Sabatier, P., Dezileau, L., Barbier, M., Raynal, O., Lofi, J., Briquieu, L., Condomines, M.,
691 Bouchette, F., Certain, R., Grafenstein, U.V., Jorda, C., Blanchemanche, P., 2010a.
692 Late-Holocene evolution of a coastal lagoon in the Gulf of Lions (South of France).
693 *Bulletin de la Société Géologique de France* 181, 27–36.
694 <https://doi.org/10.2113/gssgfbull.181.1.27>

695 Sabatier, P., Dezileau, L., Blanchemanche, P., Siani, G., Condomines, M., Bentaleb, I.,
696 Piquès, G., 2010b. Holocene Variations of Radiocarbon Reservoir Ages in a
697 Mediterranean Lagoonal System. *Radiocarbon* 52, 91–102.

698 Sabatier, P., Dezileau, L., Briquieu, L., Colin, C., Siani, G., 2010c. Clay minerals and
699 geochemistry record from northwest Mediterranean coastal lagoon sequence:
700 Implications for paleostorm reconstruction. *Sedimentary Geology* 228, 205–217.
701 <https://doi.org/10.1016/j.sedgeo.2010.04.012>

702 Sabatier, P., Poulenard, J., Fanget, B., Reyss, J.-L., Develle, A.-L., Wilhelm, B., Ployon, E.,
703 Pignol, C., Naffrechoux, E., Dorioz, J.-M., Montuelle, B., Arnaud, F., 2014. Long-

706 term relationships among pesticide applications, mobility, and soil erosion in a
707 vineyard watershed. *Proc. Natl. Acad. Sci.* 111, 15647–15652.
708 <https://doi.org/10.1073/pnas.1411512111>

709 Sabatier, P., Reyss, J.-L., Hall-Spencer, J.M., Colin, C., Frank, N., Tisnérat-Laborde, N.,
710 Bordier, L., Douville, E., 2012. ^{210}Pb chronology reveals rapid growth rate of
711 *Madrepora oculata* and *Lophelia pertusa* on
712 world's largest cold-water coral reef. *Biogeosciences* 9, 1253–1265.
713 <https://doi.org/10.5194/bg-9-1253-2012>

714 Sanchez-Cabeza, J.A., Ruiz-Fernández, A.C., 2012. ^{210}Pb sediment radiochronology: An
715 integrated formulation and classification of dating models. *Geochim. Cosmochim.*
716 *Acta, Environmental Records of Anthropogenic Impacts* 82, 183–200.
717 <https://doi.org/10.1016/j.gca.2010.12.024>

718 Sharma, P., Gardner, L.R., Moore, W.S., Bollinger, M.S., 1987. Sedimentation and
719 bioturbation in a salt marsh as revealed by ^{210}Pb , ^{137}Cs , and ^7Be studies: Sedimentation
720 and bioturbation. *Limnol. Oceanogr.* 32, 313–326.
721 <https://doi.org/10.4319/lo.1987.32.2.0313>

722 Tylmann, W., Bonk, A., Goslar, T., Wulf, S., Grosjean, M., 2016. Calibrating ^{210}Pb dating
723 results with varve chronology and independent chronostratigraphic markers: Problems
724 and implications. *Quat. Geochronol.* 32, 1–10.

725 Tylmann, W., Enters, D., Kinder, M., Moska, P., Ohlendorf, C., Poręba, G., Zolitschka, B.,
726 2013. Multiple dating of varved sediments from Lake Łazduny, northern Poland:
727 Toward an improved chronology for the last 150 years. *Quaternary Geochronology*
728 15, 98–107. <https://doi.org/10.1016/j.quageo.2012.10.001>

729 Wickham, H., Hester, J., Chang, W., RStudio, R), R.C. team (Some namespace and vignette
730 code extracted from base, 2018. devtools: Tools to Make Developing R Packages
731 Easier.

732 Wilhelm, B., Arnaud, F., Sabatier, P., Crouzet, C., Brisset, E., Chaumillon, E., Disnar, J.-R.,
733 Guiter, F., Malet, E., Reyss, J.-L., Tachikawa, K., Bard, E., Delannoy, J.-J., 2012.
734 1400 years of extreme precipitation patterns over the Mediterranean French Alps and
735 possible forcing mechanisms. *Quat. Res.* 78, 1–12.

736 Wilhelm, B., Sabatier, P., Arnaud, F., 2015. Is a regional flood signal reproducible from lake
737 sediments? *Sedimentology* 62, 1103–1117. <https://doi.org/10.1111/sed.12180>

738 Wilkinson, M.D., Dumontier, M., Aalbersberg, I.J., Appleton, G., Axton, M., Baak, A.,
739 Blomberg, N., Boiten, J.-W., da Silva Santos, L.B., Bourne, P.E., Bouwman, J.,
740 Brookes, A.J., Clark, T., Crosas, M., Dillo, I., Dumon, O., Edmunds, S., Evelo, C.T.,
741 Finkers, R., Gonzalez-Beltran, A., Gray, A.J.G., Groth, P., Goble, C., Grethe, J.S.,
742 Heringa, J., 't Hoen, P.A.C., Hooft, R., Kuhn, T., Kok, R., Kok, J., Lusher, S.J.,
743 Martone, M.E., Mons, A., Packer, A.L., Persson, B., Rocca-Serra, P., Roos, M., van
744 Schaik, R., Sansone, S.-A., Schultes, E., Sengstag, T., Slater, T., Strawn, G., Swertz,
745 M.A., Thompson, M., van der Lei, J., van Mulligen, E., Velterop, J., Waagmeester, A.,
746 Wittenburg, P., Wolstencroft, K., Zhao, J., Mons, B., 2016. The FAIR Guiding
747 Principles for scientific data management and stewardship. *Scientific Data* 3, 160018.
748 <https://doi.org/10.1038/sdata.2016.18>

749
750