

UThwgl - an R package for closed- and open-system uranium-thorium dating

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Abstract

For several decades, uranium-thorium (U-Th) dating has allowed geochronologists to precisely date geological materials, providing invaluable geochronological constraints on Quaternary processes. Open-system dating of bones and teeth has also provided ages of human and faunal remains of archaeological significance.

To facilitate access to closed- and open-system U-Th dating to the broad scientific community, here we provide an R package, named *UThwgl*. Description of input and output parameters is given, as well as a guide for running the model. The package can be used three different ways: (i) as a web application, (ii) through a web browser with an internet connection, or (iii) in R (most efficiently with RStudio). Examples of application of the model are also provided, showing that it yields ages within error of previously published values.

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1 Introduction

2 Uranium-thorium (U-Th) dating has revolutionised Quaternary science and
3 archaeology. Dating uses the decay of ^{238}U into ^{230}Th , with ^{234}U and a few
4 short-lived nuclides as intermediary products. It is based on the principle that
5 the age of formation of a material can be dated as it incorporates U and no or
6 little Th at the time of formation, so all the ^{230}Th in the sample comes from
7 decay of ^{238}U . If detrital Th is incorporated into the sample, a correction must
8 be included to account for the fraction of ^{230}Th which is detrital and not derived
9 from ^{238}U decay. Another requirement is that there is no gain or loss of ^{230}Th ,
10 ^{234}U or ^{238}U after formation of the material (*closed system*).

11 Closed-system U-Th dating has been successfully applied to a range of
12 carbonates, from corals (Edwards, Gallup, and Cheng 2003) to speleothems
13 (Richards and Dorale 2003). In corals and most speleothems, detrital correction
14 is minimal; however, it can be significant when dating pedogenic carbonates,
15 for instance (Ludwig and Paces 2002). In this case, detrital correction can be
16 performed using the measured or assumed composition of the detrital fraction
17 (e.g. Ludwig 2003a). Alternatively, isochron techniques can be applied (Ludwig
18 and Titterton 1994); the latter are beyond the scope of this article but IsoPlot
19 is a commonly used software for isochron calculations and other geochronologi-
20 cal applications (Ludwig 2003b), now also available as a R package (Vermeesch
21 2018).

22 Closed-system conditions are seldom met in teeth and bones (although enamel
23 can sometimes be quite impervious to isotope gain or loss). Thus, U-Th dating
24 requires to take into account open system behaviour. The diffusion-adsorption
25 model of Pike and Hedges (2002) and the diffusion-adsorption-decay (DAD)
26 model of Sambridge et al. (2012) were instrumental to implement successfully
27 open-system U-Th dating. They allow for advective and diffusive transport
28 of uranium and thorium isotopes, while include synchronous radioactive decay.
29 Software implementation for the DAD model was written in Fortran and is
30 available as a Java GUI (<http://www.earth.org.au/codes/iDaD/>).

31 Open-system U-Th dating of teeth and bones, while challenging, has pro-
32 vided quantitative ages for human and faunal remains (Eggins et al. 2005;
33 Grün et al. 2014; Sambridge, Grün, and Eggins 2012; Pike and Hedges 2002;
34 Hoffmann et al. 2018). Thus, this approach has significantly improved our un-
35 derstanding of human evolution (e.g. Dirks et al. 2017; Sutikna et al. 2016;
36 Hoffmann et al. 2018).

37 In this article, we propose a R package, *UThwgl*, which offers functions to
38 perform closed-system, `csUTh()`, and open-system, `osUTh()`, U-Th age calcula-
39 tions. The former implements formulations given in Ludwig (2003a) while the
40 latter applies the DAD model of Sambridge et al. (2012). The R package *Iso-*
41 *PlotR* provides a more extensive tool for closed-system U-Th dating (Vermeesch
42 2018), and *UThwgl* only includes closed-system U-Th age calculations for the
43 sake of offering both closed- and open-system calculations.

44 The motivation for providing an R package is to increase the transparency, re-
45 producibility, and flexibility of the analytical workflow for computing U-Th ages.

For instance, with open-system dating, it is difficult to include the Java GUI in a fully scripted data analysis so the method for computing the DAD model is not highly transparent. This can obscure steps where key decisions are made that are important for others to see to verify the reliability of the analysis. Enabling a scripted workflow for computational analysis of geoscience data is important for improving the reproducibility of results. Reproducibility refers the ability to recreate the results or retest the hypotheses leading to a scientific claim, either by rerunning the same code used by the original authors, or by writing new code. High rates of irreproducibility of research results have been estimated in several fields and disciplines (Medical Sciences 2015; Freedman, Cockburn, and Simcoe 2015; Institute 2013; Ioannidis 2005; Collaboration and others 2015; Camerer et al. 2018, 2016). Consequently, the transparency, openness, and reproducibility of results and methods are receiving increased attention, and the norms of research in many fields are changing (Nosek et al. 2015; Miguel et al. 2014; Marwick 2016).

There is strong interest in open, transparent, and reusable research in the geoscience community (Gil et al. 2016) and substantial progress toward open data has been made in the geosciences with the widespread use of data services of NASA, USGS, NOAA and community-built data portals such as OneGeology, EarthChem, RRUFF, PANGAEA, PaleoBioDB, and others (Kattge, Díaz, and Wirth 2014; Ma 2018). However, the use of open source software such as R (Pebesma, Nüst, and Bivand 2012), and sharing of scripted data analysis workflows with research publications is not yet widespread (Hutton et al. 2016). With this R package our goal is to make scripted and reproducible data analysis easy for open-system uranium-thorium dating. This will improve the transparency of geochronology research, and provide a more credible and robust foundation for scientific advancement (Hutton et al. 2016).

To enable re-use of our materials and improve reproducibility and transparency, all the results and visualisations in this paper can be reproduced using the RMarkdown vignette document included with the UThwgl package. We have archived these files at <http://doi.org/10.17605/OSF.IO/D5P7S> to ensure long-term accessibility. Our code is released under the MIT licence, our data as CC-0, and our figures as CC-BY, to enable maximum re-use (for more details, see Marwick 2016).

Methods

For U-Th dating, two types of analysis are possible: bulk or in-situ. For bulk analysis, a fraction of the samples is dissolved and the solution processed through ion exchange chromatography to separate U and Th (e.g. Luo et al. 1997). Each element is then analysed separately for their isotope ratios by mass spectrometry. For in-situ analysis, laser ablation is commonly used (Eggins et al. 2005). In this case, a laser with a spot size ranging from a few μm to several hundreds of μm produces an aerosol which is carried using a gas (helium or preferably a mixture of helium and nitrogen; Eggins, Kinsley, and Shelley (1998)). While laser ablation offers a better spatial resolution and is less time

90 consuming than bulk analysis, the precision of the data is inferior because of
91 the much smaller amount of material sampled.

92 Uranium and thorium isotope ratios are then analysed by multi-collector
93 inductively-coupled plasma mass spectrometry (e.g. Luo et al. (1997); although
94 bulk analysis can also be performed by thermal ionisation mass spectrometry).
95 A plasma ionise U and Th atoms, their isotopes are separated through a mag-
96 netic field and each are collected in a different collector (Faraday cups or ion
97 counters). If using laser ablation, it is best to have two ion counters so ^{230}Th
98 and ^{234}U can be collected simultaneously.

99 *Closed-system dating*

100 Pending closed-system behaviour can be assessed, it is possible to derive an
101 age for each U-Th analysis. The closed-system function `csUTh()` requires that
102 for each analysis to yield an age, $(^{234}\text{U}/^{238}\text{U})$, $(^{230}\text{Th}/^{238}\text{U})$ and $(^{232}\text{Th}/^{238}\text{U})$
103 activity ratios are measured (parentheses denote activity ratios throughout this
104 article). The $(^{232}\text{Th}/^{238}\text{U})$ activity ratio is required for detrital correction (note
105 it is needed to use `csUTh()` whether the detrital correction is performed or not).

106 *Open-system dating*

107 Data required for the DAD model are $(^{230}\text{Th}/^{238}\text{U})$ and $(^{234}\text{U}/^{238}\text{U})$ activity
108 ratios collected along a transect perpendicular to the surface of the tooth or bone.
109 Sampling for analysis can be done by micro-drilling or laser ablation.

110 The distance of each analysis location from the inner and outer surfaces of
111 the sample needs to be recorded. One surface is given a coordinate of 1 and the
112 other one -1, thus coordinates of analyses take values in between (Figure 1).



Figure 1: Modern human femur (132A/LB/27D/03) from Liang Bua, Flores, Indonesia. Two analysis transects can be seen. For a given transect, the outer and inner surface of the bone are given 1 and -1 reference coordinates, and the position of each analysis is calculated accordingly. Modified from Sutikna et al. (2016).

113 Working with the package

114 We provide three methods for using this package to suit different levels of
 115 familiarity with the R programming language. The simplest way to use the pack-
 116 age is our web applications, online at <https://ben-marwick.shinyapps.io/csUTh/>
 117 and <https://ben-marwick.shinyapps.io/osUTh/> (Figure 2). Using the web ap-
 118 plication requires no familiarity with R. To use the web application we upload
 119 a CSV file, then click through a series of tabs to inspect the data, adjust the
 120 model parameters, run the model, and inspect the output. The interface is
 121 mouse-driven and requires no programming. In the web application we upload
 122 the data file on the *Load the data* tab, set parameters from the *Set model pa-*
 123 *rameters* tab, run the model by clicking the button *Run Simulation* on the same
 124 tab, and observe the results on the *Visualise the model* and *Inspect the model*
 125 tabs. We can change the parameters and re-run the model by click the button
 126 *Run Simulation*. Once done, close the window.

127 The second way to use the package is with Binder, a browser-based instance
 128 of R and RStudio that includes our package ready to work with. Binder is a
 129 server technology that turns computational material, such as an R package, into
 130 interactive computational environments in the cloud. Using Binder requires a
 131 novice level of familiarity with R, for example to use the code in this paper and
 132 adapt it to work with a different CSV file. Because Binder provides a complete
 133 R environment, custom R code can be written during a Binder instance to
 134 further explore the model's output in the browser. These two methods, the

A UThwgl::osUth : compute open-system Uranium-Thorium ages using the diffusion-adsorption-decay (DAD) model

Load the data Inspect the data Set model parameters

Visualise the model Inspect the model

Before uploading, check that your CSV file contains columns with these names:

- idAD.position**: coordinates of the ($^{234}\text{U}/^{238}\text{U}$) analyses, which take values between -1 and 1 (0: center of the bone; -1 and 1: inner and outer surfaces of the bone, respectively)
- U234_U238_CORR**: activity ratios
- U234_U238_CORR_1m2SE**: the 2 sigma errors of the activity ratios
- idAD.position.1**: coordinates of the ($^{230}\text{Th}/^{232}\text{Th}$) analyses, which take values between -1 and 1 (can be the same or different values from those of the ($^{234}\text{U}/^{238}\text{U}$) analyses)
- Th230_U238_CORR**: activity ratios
- Th230_U238_CORR_1m2SE**: the 2 sigma errors of the activity ratios
- U_ppm**: calculated uranium concentrations (in ppm)
- U_ppm_1m2SE**: the 2 sigma errors of the uranium concentrations

Choose CSV file

Browse... **Hobbit_MHRTT_for_idAD.csv**

Upload complete

Go to inspect the data

C UThwgl::osUth : compute open-system Uranium-Thorium ages using the diffusion-adsorption-decay (DAD) model

Load the data Inspect the data Set model parameters

Visualise the model Inspect the model

Number of iterations: 100

Value of squared sum: 0.01

Thickness of sample (cm): 5.35

Uranium concentration at the sample surface (ppm): 25

Min U diffusion coefficient: 0.000000000001

Max U diffusion coefficient: 0.000000000001

Run simulation and visualise the output

E UThwgl::osUth : compute open-system Uranium-Thorium ages using the diffusion-adsorption-decay (DAD) model

Load the data Inspect the data Set model parameters

Visualise the model Inspect the model

Age (ka)	Age 67% quantile (ka)	Age 33% quantile (ka)	U234_U238_0	U234_U238_0 67% quantile	U234_U238_0 33% quantile
6.82	0.58	0.53	1.27	0.01	0.00

diff	T_final	K_final	T_sol
695.89	6817.35	0.00	7492.41
-1149.35	6817.35	0.00	5647.17
1898.93	6817.35	0.00	8695.46
-1123.74	6817.35	0.00	5672.78
1370.91	6817.35	0.00	8167.43
-1634.21	6817.35	0.00	5162.31
-20.83	6817.35	0.00	6775.70
1051.79	6817.35	0.00	7848.31
-1489.97	6817.35	0.00	5333.55

B UThwgl::osUth : compute open-system Uranium-Thorium ages using the diffusion-adsorption-decay (DAD) model

Load the data Inspect the data Set model parameters

Visualise the model Inspect the model

Here is the raw data from the CSV file

Show 10 entries Search:

idAD.position	U234_U238_CORR	U234_U238_CORR_1m2SE	idAD.position.1
1	-0.95588237	1.2696216	0.00421
2	-0.85681117	1.2729341	0.00424
3	-0.75773996	1.2654235	0.00372
4	-0.85866876	1.2673451	0.00454
5	-0.55859755	1.2691554	0.00291
6	-0.48052632	1.2655151	0.00284
7	-0.36145511	1.268979	0.00255
8	-0.26238391	1.2760185	0.00231
9	-0.16331269	1.265514	0.00228
10	-0.0642	1.2766815	0.0021

Showing 1 to 10 of 20 entries Previous 1 2 Next

Go to set the model parameters

D UThwgl::osUth : compute open-system Uranium-Thorium ages using the diffusion-adsorption-decay (DAD) model

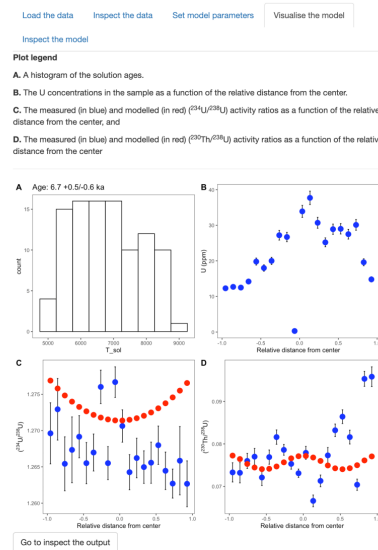


Figure 2: Screenshots of the web application for using the UThwgl package. A: Upload a CSV file of the data to model, B: Inspect a table of the uploaded data. C: Set the model parameters and run the model. D: Inspect visualisations of the model's output. E: Inspect and download the numeric output from the model.

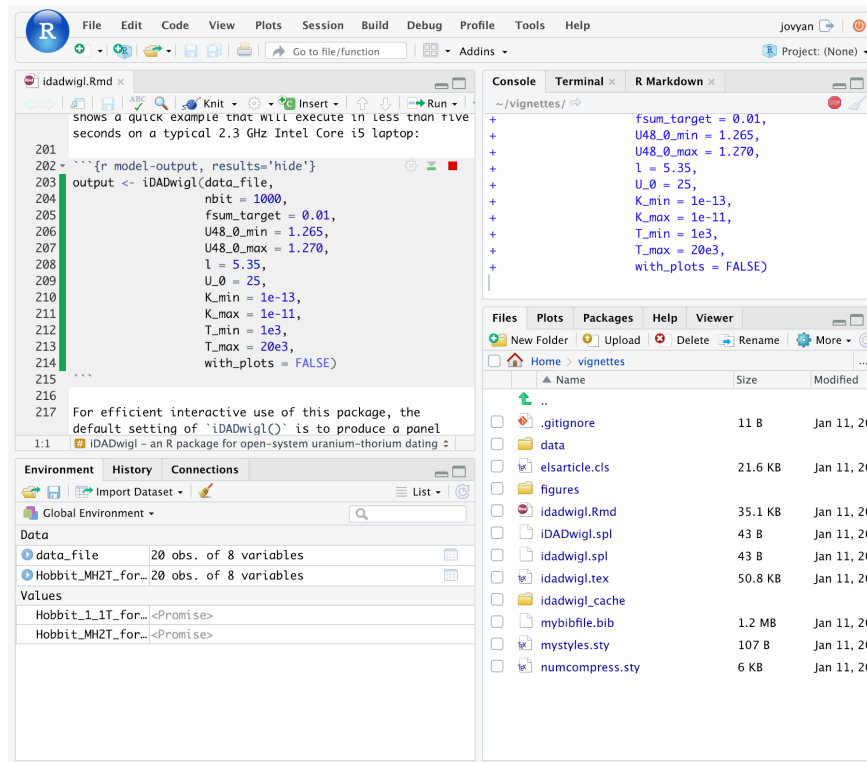


Figure 3: Screenshot of Binder running R and RStudio in a web browser window.

web application and Binder, do not require any software to be downloaded and installed on the user's computer, all computation occurs in the browser. The web application and Binder are suitable for getting a quick start on working with the package, but they require a connection to the internet, and they have limited memory and compute time available per instance.

The third method is to download and install the package locally to the user's computer, and work with it in the user's local installation of R and RStudio. This method requires some familiarity with R, but gives the most flexibility when working with the model because we are not limited by the memory and compute time of the cloud services. Our recommendation is to use Binder or a local installation of UThwgl because then the user can save an R script file that includes the name of the input file, the specific parameters used to generate the model output, and any downstream processing and visualisation. This script file and the CSV file can then be archived in a data repository to ensure long-term accessibility for other researchers. In the following sections we demonstrate the use of UThwgl with a local installation of R and RStudio.

151 Installing and attaching the package

152 First the user will need to download and install R, and we also recommend
153 downloading and installing RStudio. To run the model, start `RStudio` and
154 install the package from GitHub. There are many ways to do this, one simple
155 method is shown in the line below. This only needs to be done once per
156 computer.

```
if(!require("remotes")) install.packages("remotes")  
remotes::install_github("tonydoss/UThwgl")
```

157 For routine data analysis, R scripts need to contain the following line to
158 attach the package to the current working environment. This line needs to be
159 run at the start of each analysis:

```
# attach the package  
library(UThwgl)
```


160 Closed-system U-Th dating

161 *Input data format*

162 Our package provides the function `csUTh()` for closed-system U-Th dating.
163 Data for this function needs to be in a data frame (a form of table in R) with
164 the following column names:

- 165 • `Sample_ID`
- 166 • `U234_U238_CORR`
- 167 • `U234_U238_CORR_Int2SE`
- 168 • `Th230_U238_CORR`
- 169 • `Th230_U238_CORR_Int2SE`
- 170 • `Th232_U238_CORR`
- 171 • `Th232_U238_CORR_Int2SE`

172 To help with preparing data for input into our function, we have included an
173 example of an input file, taken from Pan et al. (2018). Inspecting the included
174 data sets will be helpful for understanding how to prepare new data to prepare
175 for use with this package. After attaching the package, we can access the built-in
176 datasets with the `data()` function, like this:

```
# access the data included in the UThwgl package
data("Pan2018")
```

177 This will make the built-in data available in the R environment to inspect
178 and explore how to use the `csUTh()` function. To use new data with this pack-
179 age, the user needs to import a CSV or Excel file with the U-Th data into the
180 R environment. This can be done using a generic function such as `read.csv`
181 or `read_excel` from the `readxl` package (Wickham and Bryan 2018). Before
182 reading in the data file, the user needs to set the working directory to the folder
183 containing the data file. This can be done in RStudio using the menu item
184 ‘Session’ > ‘Set Working Directory’ > ‘To Source File Location’. Alternatively,
185 the working directory can be defined interactively at the R prompt in the Con-
186 sole panel using `setwd()`. However, we do not recommend including `setwd()`
187 in script files because it is bad for reproducibility, since the path to one user’s
188 working directory will not exist on another user’s computer.

189 To download the built-in data to the user’s computer so it can be inspected
190 and modified in a spreadsheet program, use `write.csv()`

```
# download the data included in the package
write.csv(Pan2018, "Pan2018.csv")
```

191 The code chunk below shows how to read one of the CSV files included in the
192 package into the R environment. We assume that the user’s working directory
193 contains a directory called `data` and the CSV file is in this `data` directory, and
194 so the data can be imported as follows:

```
# read in one of the example CSV files included in the package
input_data_cs <-
  read.csv('data/Pan2018.csv')
```

Table 1 shows the data contained in the Pan2018.csv file included in the package.

Sample_ID	U234_U238_CORR	U234_U238_CORR_Int2SE	Th230_U238_CORR	Th230_U238_CORR_Int2SE	Th232_U238_CORR	Th232_U238_CORR_Int2SE
YP002A	1.150	0.005	0.794	0.007	0.010	0.00005
YP002B	1.120	0.004	0.788	0.006	0.004	0.00002
YP003-1_1	1.125	0.004	0.752	0.010	0.000	0.00001
YP003-1_2	1.113	0.007	0.761	0.011	0.000	0.00000
YP003-1_3	1.122	0.005	0.748	0.008	0.001	0.00001
YP003-1_4	1.122	0.005	0.726	0.007	0.001	0.00001
YP003-1_5	1.119	0.006	0.757	0.006	0.002	0.00001
YP002-1_1	1.129	0.006	0.722	0.008	0.001	0.00001
YP002-1_2	1.137	0.005	0.767	0.008	0.001	0.00001
YP002-1_3	1.118	0.008	0.739	0.009	0.002	0.00002
YP002-1_4	1.114	0.006	0.749	0.008	0.003	0.00003
YP002-1_5	1.105	0.007	0.764	0.011	0.003	0.00004

Table 1: Data contained in the example CSV file Pan2018.csv included in the package

The columns Sample_ID, U234_U238_CORR, U234_U238_CORR_Int2SE, Th230_U238_CORR, Th230_U238_CORR_Int2SE, Th232_U238_CORR and Th232_U238_CORR_Int2SE must be present in the input data frame with these exact names for the model to function. The csUTh() function will check if the input data frame has these columns, and will stop with an error message if it does not find these columns. The names() function can be used to update column names of a data frame to ensure they match the names that the model function requires. Alternatively the user can edit the column names in a spreadsheet program such as Microsoft Excel. The order of the columns in the data frame is not important.

Columns U234_U238_CORR and U234_U238_CORR_Int2SE are the ($^{234}\text{U}/^{238}\text{U}$) activity ratios and their 2σ errors. Columns Th230_U238_CORR and Th230_U238_CORR_Int2SE are the ($^{230}\text{Th}/^{238}\text{U}$) activity ratios and their 2σ errors. Columns Th232_U238_CORR

209 and `Th232_U238_CORR_Int2SE` are the ($^{232}\text{Th}/^{238}\text{U}$) activity ratios and their 2σ
210 errors.

211 *Details of the input parameters of closed-system analysis*

212 `sample_name` is the name of the sample to calculate closed-system ages for.
213 The function will partially match by sample prefix. For example in Table 1 one
214 sample is indicated by the Sample ID ‘YP003’. If the user inputs ‘YP003’ for
215 the `sample_name`, then this will match rows where the Sample ID is ‘YP003-1’,
216 ‘YP003-2’, ‘YP003-3’, and so on.

217 `nbitchoice` is the number of iterations in the model (it is recommended to
218 have at least 100). `detcorrectionchoice` is a parameter for choosing whether
219 or not to apply a detrital correction to the calculation.

220 `R28det` (0.8) and `R28det_err` (0.08) are the values for the ($^{232}\text{Th}/^{238}\text{U}$)
221 activity ratio of the detritus and its standard error (default values in paren-
222 theses). Similarly, `R08det` (1) and `R08det_err` (0.05) are the values for the
223 ($^{230}\text{Th}/^{238}\text{U}$) activity ratio of the detritus and its standard error, and `R48det`
224 (1) and `R48det_err` (0.02) are the corresponding values for ($^{234}\text{U}/^{238}\text{U}$) activity
225 ratio of the detritus.

226 *How to run the model*

227 Assuming that the package is attached with `library(UThwig1)`, as shown
228 above, and the data have been imported to the working environment as noted
229 above, run `csUTh()`, specifying the input data frame and the input parameters
230 as described above. The code block below shows a typical example that will
231 execute in less than five seconds on a typical 2.3 GHz Intel Core i5 laptop:

```
# Solve for sample YP003
output_cs <-
  csUTh(
    input_data_cs,
    sample_name = 'YP003',
    nbitchoice = 100,
    detcorrectionchoice = TRUE,
    R28det = 0.8,
    R28det_err = 0.08,
    R08det = 1,
    R08det_err = 0.05,
    R48det = 1,
    R48det_err = 0.02,
    keepfiltereddata = FALSE,
    print_summary = TRUE,
    with_plots = TRUE,
    save_plots = FALSE,
    save_output = FALSE
  )
```

For efficient interactive use of this package, the default setting of `csUTh()` is to produce a panel plot as seen in Figure 4. The setting `with_plots = FALSE` prevents plots from being generated which is more useful when the function is part of a longer sequence of code. The function runs faster when not producing plots, which is helpful when replicating many runs. The setting `save_output = TRUE` will save a csv file to the current working directory so the output data can be used in other contexts. The csv file that is created when `save_output = TRUE` will be given a name that includes a date and time stamp so that the output of each time the function is run can be saved to a unique file.

When run on the R console, this function will print a confirmation that the input data frame has the required columns. If `print_summary` is set to `TRUE`, it will also the resulting mean age value of several analyses on a single sample, with an error reported as 2 Standard Error, for example:

```
All required columns are present in the input data
[1] "Mean age: 117.1 +/- 3.7 ka"
```

`print_summary` should be set to `FALSE` if ages computed are not for analyses of the same sample, since this mean age would be meaningless.

Inspecting and visualizing the models' output

The function returns a data frame with the age, error and summary output for each measurement, as shown in Table 2. This includes calculated ages (with or without detrital correction, depending how `detcorrectionchoice` was set), initial ($^{234}\text{U}/^{238}\text{U}$) activity ratios, along with their uncertainties.

Sample ID	Age (ka)	Age 2se	($^{234}\text{U}/^{238}\text{U}$)i	Ratio 2se
YP003-1_1	117.317	0.3480	1.1730	0.0010
YP003-1_2	122.424	0.4120	1.1590	0.0010
YP003-1_3	116.081	0.2630	1.1710	0.0010
YP003-1_4	111.187	0.2410	1.1660	0.0010
YP003-1_5	119.658	0.2610	1.1670	0.0010

Table 2: Output produced by the `csUTh` function used with data from Pan et al. 2018

The plots produced by the `csUTh()` function are stored as list objects in the output from the function. We can show the plots by accessing the list like this:

```
output_cs$plots
```

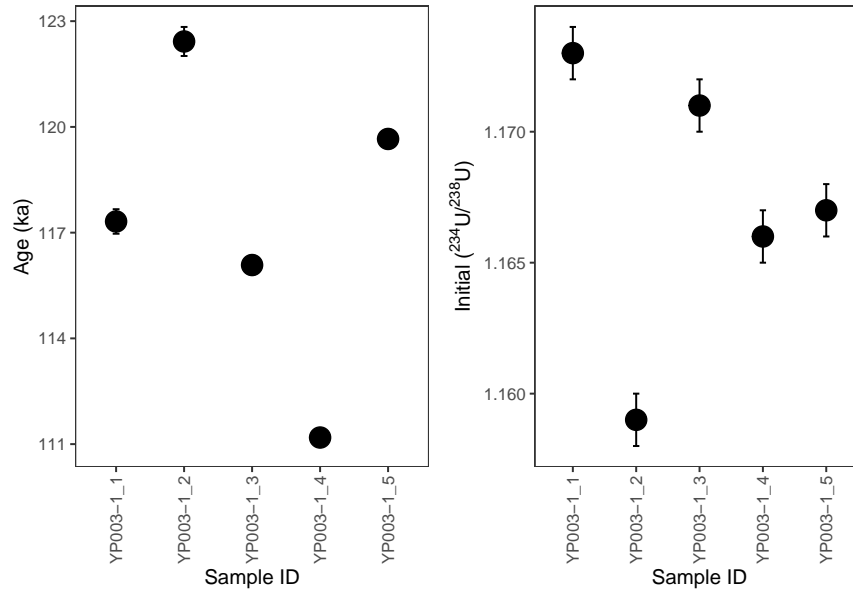


Figure 4: Example of the visualisations produced by the `csUTh()` function, using the demonstration run described above, and five in-situ analyses by laser ablation of coral sample YP003. A: closed-system ages and B: initial ($^{234}\text{U}/^{238}\text{U}$) activity ratios for each sample analysis

Open-system U-Th dating

Input data format

For open-system U-Th dating we provide the function `osUTh()`, which requires a data frame with the following column names:

- `iDAD.position`
- `U234_U238_CORR`
- `U234_U238_CORR_Int2SE`
- `iDAD.position.1`
- `Th230_U238_CORR`
- `Th230_U238_CORR_Int2SE`
- `U_ppm`
- `U_ppm_Int2SE`

We have included two examples of input files. After attaching the package, we can access the built-in datasets with the `data()` function, like this:

```
# access the data included in the UThwigl package
data("Hobbit_1_1T_for_iDAD")
data("Hobbit_MH2T_for_iDAD")
```

As above, these datasets can be downloaded from the package with `write.csv()`:

```
# download the data included in the package  
write.csv(Hobbit_1_1T_for_iDAD, "Hobbit_1_1T_for_iDAD.csv")  
write.csv(Hobbit_MH2T_for_iDAD, "HHobbit_MH2T_for_iDAD.csv")
```

271 The code chunk below shows how to read one of the CSV files included
272 in the package into the R environment. As above, we assume that the user's
273 working directory contains a directory called **data** and the CSV file is in this
274 **data** directory, and so the data can be imported as follows (Table 3):

```
# read in one of the example CSV files included in the package  
input_data_os <-  
  read.csv('data/Hobbit_MH2T_for_iDAD.csv')
```

iDAD.position	U234_U238_CORR	U234_U238_CORR_Int2SE	iDAD.position.1	Th230_U238_CORR	Th230_U238_CORR_Int2SE	U_ppm	U_ppm_Int2SE
-0.956	1.270	0.004	-0.956	0.073	0.002	12.3	0.6
-0.857	1.273	0.004	-0.857	0.073	0.002	12.7	0.6
-0.758	1.265	0.004	-0.758	0.076	0.002	12.5	0.6
-0.659	1.267	0.005	-0.659	0.077	0.002	14.2	0.7
-0.560	1.269	0.003	-0.560	0.072	0.002	19.8	1.0
-0.461	1.266	0.003	-0.461	0.077	0.002	18.0	0.9
-0.361	1.267	0.003	-0.361	0.082	0.002	20.0	1.0
-0.262	1.276	0.002	-0.262	0.079	0.001	27.2	1.4
-0.163	1.266	0.002	-0.163	0.075	0.001	26.7	1.3
-0.064	1.277	0.002	-0.064	0.073	0.001	0.3	0.0
0.035	1.271	0.002	0.035	0.078	0.002	33.9	1.7
0.134	1.264	0.002	0.134	0.067	0.001	37.7	1.9
0.233	1.266	0.003	0.233	0.071	0.001	30.7	1.5
0.332	1.265	0.002	0.332	0.077	0.002	25.2	1.3
0.431	1.266	0.003	0.431	0.083	0.001	28.9	1.4
0.530	1.268	0.003	0.530	0.086	0.002	29.0	1.4
0.629	1.264	0.003	0.629	0.082	0.002	27.5	1.4
0.728	1.263	0.002	0.728	0.070	0.001	30.1	1.5
0.827	1.266	0.005	0.827	0.095	0.002	19.6	1.0
0.926	1.263	0.003	0.926	0.096	0.002	14.8	0.7

Table 3: Data contained in the example CSV file `Hobbit_MH2T_for_iDAD.csv` included in the package

As for the closed-system function, the columns `iDAD.position`, `U234_U238_CORR`, `U234_U238_CORR_Int2SE`, `Th230_U238_CORR` and `Th230_U238_CORR_Int2SE` must be present in the input data frame with these exact names for the model to function. The `osUTh()` function will check if the input data frame has these columns, and will stop with an error message if it does not find these columns.

The `iDAD.position` column corresponds to the coordinates of the ($^{234}\text{U}/^{238}\text{U}$) analyses, which as indicated above take values between -1 and 1 (Figure 1). The second `iDAD.position.1` column is used if the coordinates of the ($^{230}\text{Th}/^{238}\text{U}$) analyses are different from those of the ($^{234}\text{U}/^{238}\text{U}$) analyses.

Columns `U_ppm` and `U_ppm_Int2SE` are the calculated uranium concentrations (in ppm) and their 2σ errors. Uranium concentrations are not necessary

286 for the model calculations but needed to display the U concentration profile in
287 a figure.

288 *Details of the input parameters of open-system analysis*

289 Our key function, `osUTh()` has several arguments that need to be set before
290 meaningful results can be obtained:

291 `nbit` is the number of iterations. For the first run, set to 1.

292 `fsum_target` is the sum of the squared differences between the calculated
293 and observed activity ratios. Give it a low value to start with (e.g. 0.01). If
294 script takes too long, try a higher value for `fsum_target`.

295 `U48_0_min` and `U48_0_max` are the minimum and maximum values allowed
296 for the ($^{234}\text{U}/^{238}\text{U}$) activity ratio at the surface of the sample. Since ($^{234}\text{U}/^{238}\text{U}$)
297 does not vary greatly over the time period generally studied, the values mea-
298 sured near the surface of the sample can be used as a guide. These values
299 can be adjusted if the model fit to the data is not optimal. For `Hobbit_1-1T`
300 they are taken to be 1.360 and 1.375, and for `Hobbit_MH2T`, 1.265 and 1.270,
301 respectively.

302 `l` is the thickness of the sample in centimeters. For `Hobbit_1-1T` it is 3.5
303 cm, for `Hobbit_MH2T` it is 5.35 cm

304 `U_0` is the uranium concentration at the surface in ppm. This value does
305 not significantly affect the model results and values from analyses near either
306 surface of the sample can be used as a guide. For `Hobbit_1-1T` it is taken to
307 be 15 ppm; for `Hobbit_MH2T`, 25 ppm.

308 `K_min` and `K_max` are the minimum and maximum values allowed for the
309 uranium diffusion coefficient (in cm^2/s). Values between 10^{-13} and 10^{-11} cm^2/s
310 are generally appropriate.

311 `T_min` and `T_max` are the minimum and maximum values for the age of the
312 specimen (yr). If there is no estimated knowledge of the sample age, the range
313 of values can be 1,000 to 500,000 yr and adjusted later. For `Hobbit_1-1T`,
314 in the final model run, they are taken to be 50,000 and 100,000 yr, and for
315 `Hobbit_MH2T`, 1,000 and 20,000 yr, respectively.

316 *How to run the model*

317 Attach the package as shown above and then run `osUTh()`, specifying the
318 input data frame and the input parameters as described above. The code block
319 below shows a quick example that will execute in less than five seconds on a
320 typical 2.3 GHz Intel Core i5 laptop:

```
output_os <- osUTh(input_data_os,  
  nbit = 1000,  
  fsum_target = 0.01,  
  U48_0_min = 1.265,  
  U48_0_max = 1.270,  
  l = 5.35,  
  U_0 = 25,
```



```

K_min = 1e-13,
K_max = 1e-11,
T_min = 1e3,
T_max = 20e3,
with_plots = TRUE,
save_plots = FALSE,
save_output = FALSE)

```

321 The default setting of `osUTh()` is to produce a panel plot as seen in Figure 5.
322 The setting `with_plots = FALSE` prevents plots from being generated which is
323 more useful when the function is part of a longer sequence of code. The function
324 runs faster when not producing pots, which is helpful when replicating many
325 runs.

326 Similar to the `csUTh()` function, when `osUTh()` is run on the R console, it
327 will print a confirmation that the input data frame has the required columns,
328 and print the resulting age value with an error reported as the 67% and 33%
329 quantiles, for example:

```

330 All required columns are present in the input data
331 [1] "Age: 7 +0.6/-0.7 ka"

```

332 The model computes a Monte Carlo simulation where age of the sample,
333 U diffusion coefficient and ($^{234}\text{U}/^{238}\text{U}$) ratio at the surface of the sample are
334 taken randomly within the range of values allowed. Results are only kept if the
335 calculated sum of the squared differences between the calculated and observed
336 activity ratios is less than the value set in `fsum_target`. If this is the case,
337 the calculated ratios and the set of solutions for age of the sample, U diffusion
338 coefficient and ($^{234}\text{U}/^{238}\text{U}$) ratio at the surface of the sample are saved. The
339 model stops once the number of sets of solutions reaches `nbit`.

340 The final calculated age `T_final` (in yr), U diffusion coefficient `K_final` (in
341 cm^2/s) and ($^{234}\text{U}/^{238}\text{U}$) ratio at the surface of the sample `U48_0_final` are the
342 set of solutions where the solution age is the closest to the median age of the
343 population of solutions. The uncertainty on each output parameter is calculated
344 as the 67% and 33% quantiles of the population of solution sets.

345 In a typical analysis, the user explores the model fit by first running the
346 model with a single iteration `nbit` and a value for `fsum_target` low enough to
347 allow for an acceptable fit, but large enough such that computing time is not
348 too long. Once this is done, the user should adjust `T_min` and `T_max` using first
349 estimates of the age, as well as `U48_0_min` and `U48_0_max` to obtain the best
350 fit of the calculated ($^{234}\text{U}/^{238}\text{U}$) to the observed values. Then, `fsum_target`
351 should be adjusted again to find the lowest value with an acceptable computing
352 time. Finally, the model should be run one last time with `nbit` set to a larger
353 value (at least 100) to reduce the uncertainty of the calculated age and initial
354 ($^{234}\text{U}/^{238}\text{U}$) activity ratios.

355 *Inspecting the model's output*

356 `T_final`, `K_final` and `U48_0_final` are included in the model's output,
 357 along with their uncertainties. The function also includes a one-row data frame
 358 summarising the age:

Age (ka)	Age 67% quantile (ka)	Age 33% quantile (ka)	U234_ U238_0	U234_ U238_0 67% quantile	U234_ U238_0 33% quantile
6.92	0.67	0.64	1.2672	0.0028	0.0022

Table 4: Summary table of the computed age and error values

359 The last item in the output is a copy of the input data with two additional
 360 columns, the modelled activity ratios, ($^{234}\text{U}/^{238}\text{U}$) and ($^{230}\text{Th}/^{238}\text{U}$), for each
 361 measurement location on the sample.

362 *Visualising the models' output*

363 `osUTh()` returns several figures useful for visualisation of the model results
 364 along with the data:

- 365 1. a histogram of the solution ages (Figure 5 A)
- 366 2. the measured U concentrations in the sample as a function of the relative
 367 distance from the center (Figure 5 B)
- 368 3. the measured and modelled ($^{234}\text{U}/^{238}\text{U}$) activity ratios as a function of
 369 the relative distance from the center (Figure 5 C), and
- 370 4. the measured and modelled ($^{230}\text{Th}/^{238}\text{U}$) activity ratios as a function of
 371 the relative distance from the center (Figure 5 D).

372 We can show the plots produced by `osUTh()` by accessing the list as follows:

```
output_os$plots
```

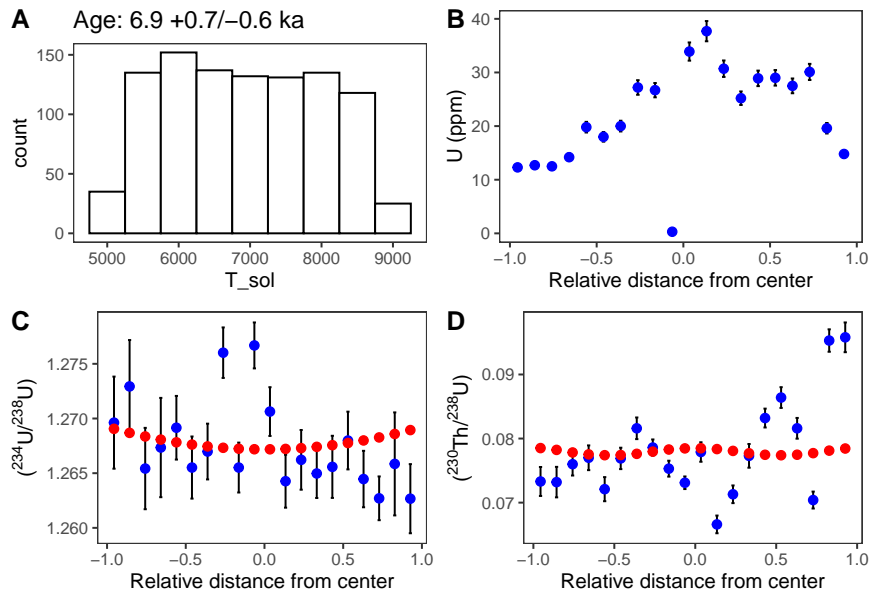


Figure 5: Example of the visualisations produced by the `osUTh()` function, using the demonstration run described above. A: Histogram of the solution ages, B: measured uranium concentration profile for transect 2 of modern human femur 132A/LB/27D/03. C: Measured (blue) and modelled (red) $(^{234}U/^{238}U)$ activity ratios for transect 2 of modern human femur 132A/LB/27D/03. D: Measured (blue) and modelled (red) $(^{230}Th/^{238}U)$ activity ratios for transect 2 of modern human femur 132A/LB/27D/03.

iDAD.position	U234_U238_CORR	U234_U238_CORR_Int2SE	iDAD.position.1	Th230_U238_CORR	Th230_U238_CORR_Int2SE	U_ppm	U_ppm_Int2SE	U234_U238_CALC	Th230_U238_CALC
-0.956	1.270	0.004	-0.956	0.073	0.002	12.3	0.6	1.269	0.079
-0.857	1.273	0.004	-0.857	0.073	0.002	12.7	0.6	1.269	0.078
-0.758	1.265	0.004	-0.758	0.076	0.002	12.5	0.6	1.268	0.078
-0.659	1.267	0.005	-0.659	0.077	0.002	14.2	0.7	1.268	0.078
-0.560	1.269	0.003	-0.560	0.072	0.002	19.8	1.0	1.268	0.077
-0.461	1.266	0.003	-0.461	0.077	0.002	18.0	0.9	1.268	0.077
-0.361	1.267	0.003	-0.361	0.082	0.002	20.0	1.0	1.267	0.078
-0.262	1.276	0.002	-0.262	0.079	0.001	27.2	1.4	1.267	0.078
-0.163	1.266	0.002	-0.163	0.075	0.001	26.7	1.3	1.267	0.078
-0.064	1.277	0.002	-0.064	0.073	0.001	0.3	0.0	1.267	0.078
0.035	1.271	0.002	0.035	0.078	0.002	33.9	1.7	1.267	0.078
0.134	1.264	0.002	0.134	0.067	0.001	37.7	1.9	1.267	0.078
0.233	1.266	0.003	0.233	0.071	0.001	30.7	1.5	1.267	0.078
0.332	1.265	0.002	0.332	0.077	0.002	25.2	1.3	1.267	0.078
0.431	1.266	0.003	0.431	0.083	0.001	28.9	1.4	1.268	0.077
0.530	1.268	0.003	0.530	0.086	0.002	29.0	1.4	1.268	0.077
0.629	1.264	0.003	0.629	0.082	0.002	27.5	1.4	1.268	0.077
0.728	1.263	0.002	0.728	0.070	0.001	30.1	1.5	1.268	0.078
0.827	1.266	0.005	0.827	0.095	0.002	19.6	1.0	1.269	0.078
0.926	1.263	0.003	0.926	0.096	0.002	14.8	0.7	1.269	0.078

Table 5: Example of output table including the input data described above, and two new columns showing the modelled activity ratios

373 Case studies

374 *Closed-system dating - Case study from Pan et al. 2018*

375 The package includes sample data from Marine Isotope Stage 5 corals from
376 Pan et al. (2018) (Table 1). Two *Plesiastrea versipora* coral samples were
377 analysed: YP002 and YP003. The first two rows in Table 1 are bulk analyses
378 while the rest are in-situ analyses produced by laser ablation (hence the lower
379 precision compared to the first two rows). In Pan et al. (2018), closed-system
380 ages were calculated using IsoPlot 4.15 (Ludwig 2003b). For bulk analyses, Pan
381 et al. (2018) reported detrital-corrected ages of 121.4 ± 2.4 ka and $127.3 \pm$
382 2.1 ka for YP002A and YP002B, respectively. For in-situ analyses, Pan et al.
383 (2018) reported mean detrital-corrected ages of five analyses for each sample:
384 117.5 ± 4.5 ka for YP002 and 115.0 ± 5.4 ka for YP003.

385 Here we solve the closed-system model for all samples by simply entering 'YP'
386 against `sample_name` since all analyses in the table contain these two characters
387 in their `Sample_ID` column. `print_summary` is set to `FALSE` since we are solving
388 for different samples and a mean age would have no significance.

```
# Solve for all samples
output_cs_all <-
  csUTh(
    input_data_cs,
    sample_name = 'YP',
    nbitchoice = 100,
    detcorrectionchoice = TRUE,
    keepfiltereddata = FALSE,
    print_summary = FALSE,
    with_plots = TRUE,
    save_plots = FALSE
  )
```

389 We obtain detrital-corrected ages of 122.9 ± 0.2 ka and 128.5 ± 0.2 ka for
390 bulk analyses of YP002 and YP003, respectively. This is within error of values
391 reported in Pan et al. (2018).

392 Solving in-situ analyses of YP002-1 is done by setting `sample_name` to 'YP002-
393 1' and `print_summary` to `TRUE`:

```
# Solve for YP002 in-situ analyses
output_cs_YP002insitu <-
  csUTh(
    input_data_cs,
    sample_name = 'YP002-1',
    nbitchoice = 100,
    detcorrectionchoice = TRUE,
    keepfiltereddata = FALSE,
    print_summary = TRUE,
  )
```

```

with_plots = TRUE,
save_plots = FALSE
)

```

394 We obtain a mean detrital-corrected age for the five analyses of 117.1 ± 5.3
395 ka, within error of the value reported in Pan et al. (2018). Similarly, solving
396 in-situ analyses for YP003-1 yields a mean detrital-corrected age for the five
397 analyses of 117.1 ± 3.7 ka, also within error of the value reported in Pan et al.
398 (2018).

399 *Open-system dating - Case study of two ages from Sutikna et al. 2016*

400 The package includes two sample datasets derived from Sutikna et al. (2016)
401 : “Hobbit_MH2T_for_iDAD.csv” is the dataset for transect 2 from mod-
402 ern human femur 132A/LB/27D/03 (shown above in Table 3). “Hobbit_1-
403 1T_for_iDAD.csv” is the dataset for transect 1 from *Homo floresiensis* ulna
404 LB1/52 (Table 6). For the latter, six analyses were removed from the set as in
405 Sutikna et al. (2016).

iDAD.position	U234_U238_CORR	U234_U238_CORR_Int2SE	iDAD.position.1	Th230_U238_CORR	Th230_U238_CORR_Int2SE	U_ppm	U_ppm_Int2SE
-0.143	1.369	0.002	-0.143	0.699	0.006	32.0	1.6
0.165	1.370	0.002	0.165	0.733	0.008	41.1	2.1
0.319	1.364	0.002	0.319	0.672	0.006	35.8	1.8
0.472	1.362	0.003	0.472	0.636	0.006	27.6	1.4
0.626	1.365	0.003	0.626	0.641	0.006	31.0	1.6
0.780	1.374	0.003	0.780	0.712	0.005	27.9	1.4

Table 6: Data contained in the example CSV file Hobbit_11T_for_iDAD.csv included in the package

406 *Age of the modern human remains from Sutikna et al. 2016*

407 For transect 2 of 132A/LB/27D/03, Sutikna et al. (2016) reported an age
408 of 7.4 ± 0.5 ka (thousand years before 2014). With osUTh, we first run the
409 model with `nbit = 1`, `fsum_target = 0.05`, `U48_0_min` and `U48_0_max = 1.25`
410 and 1.3, respectively, `l = 5.35` cm, `U_0 = 25` ppm, `K_min` and `K_max = 10-13`

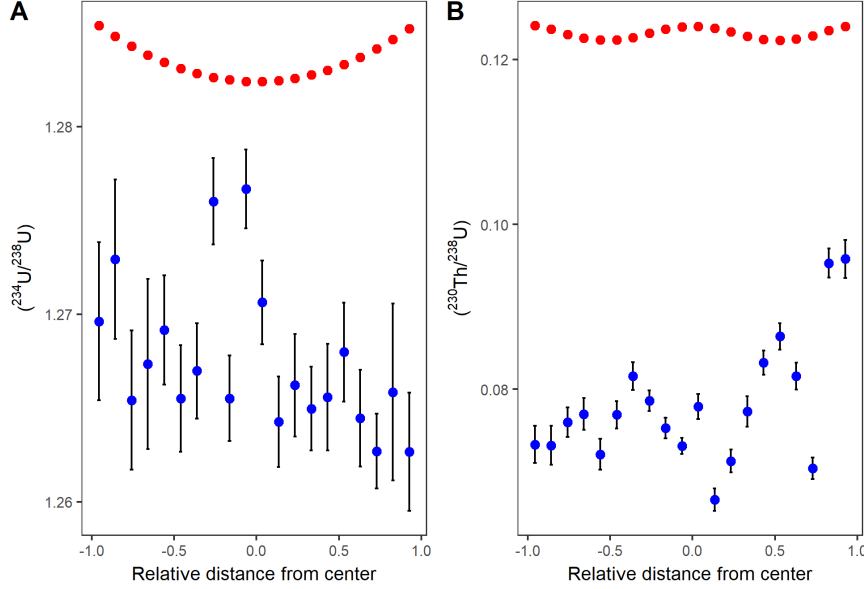


Figure 6: Results from the model's first run for the modern human femur. A: Measured (blue) and modelled (red) $(^{234}\text{U}/^{238}\text{U})$ activity ratios for transect 2 of modern human femur 132A/LB/27D/03. B: Measured (blue) and modelled (red) $(^{230}\text{Th}/^{238}\text{U})$ activity ratios for transect 2 of modern human femur 132A/LB/27D/03.

411 and 10^{-11} cm^2/s , respectively, T_{\min} and $T_{\max} = 10^3$ and 500×10^3 yr, respec-
 412 tively. $U48_0_min$ and $U48_0_max$ are determined by considering the measured
 413 $(^{234}\text{U}/^{238}\text{U})$ values near the surfaces of the sample. T_{\min} and T_{\max} values
 414 were chosen such that no a priori knowledge of the age biases the results.

415 With this first run, we obtain an age of 11 ka. There is no calculated error
 416 on the age since there is only one iteration. In this case, we can see that the
 417 calculated $(^{234}\text{U}/^{238}\text{U})$ and $(^{230}\text{Th}/^{238}\text{U})$ ratios are too high (Figure 7). For the
 418 $(^{234}\text{U}/^{238}\text{U})$, it makes sense to thus use a lower value for $U48_0_max$. Calculated
 419 $(^{230}\text{Th}/^{238}\text{U})$ ratios are too high compared to observed values suggest that the
 420 calculated age is too old (since this ratio increases with age). Thus, we should
 421 adjust T_{\max} accordingly.

422 Since the first run suggests a Holocene age for the sample, the measured
 423 $(^{234}\text{U}/^{238}\text{U})$ at the surfaces must be similar to the calculated values, thus the
 424 chosen values for the range above. Once $U48_0_min$, $U48_0_min$, T_{\min} and
 425 T_{\max} parameters have been adjusted, the model is run again. $fsum_target$
 426 can also be decreased to 0.01 in order to get a better fit and error, but it is at
 427 the expense of computing time. This operation is repeated until a satisfying
 428 fit is obtained (by visual inspection of the figures). Finally, the model is run
 429 once more, increasing the number of iterations to 1000 (or more). Following this
 430 method, we obtain an age of $6.2 \pm 1.2/-1.3$ ka (Figure 7). Note $(^{234}\text{U}/^{238}\text{U})$ and
 431 $(^{230}\text{Th}/^{238}\text{U})$ are still too high and low, respectively, so $U48_0_min$, $U48_0_min$,

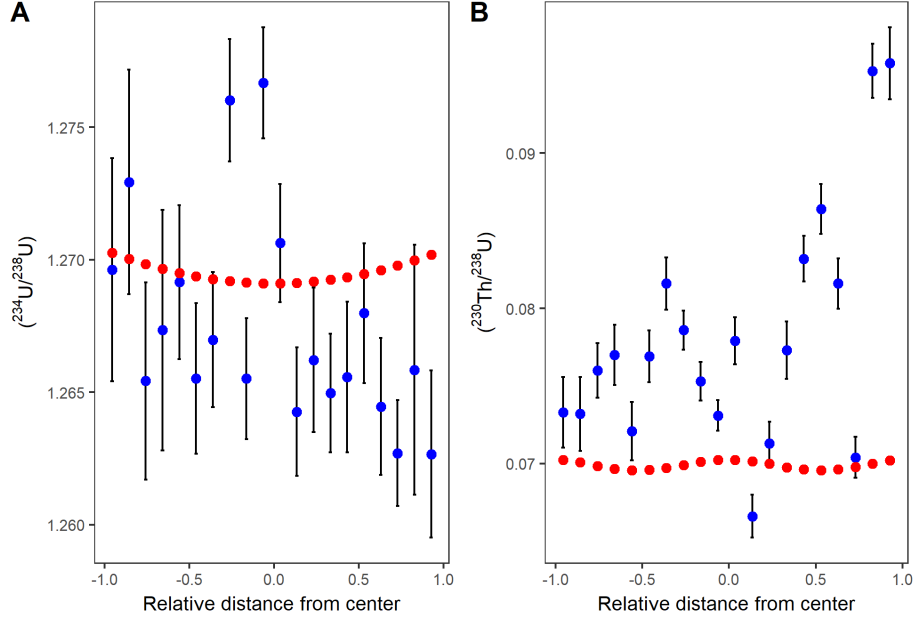


Figure 7: Results from the model's second run for the modern human femur. A: Measured (blue) and modelled (red) $(^{234}\text{U}/^{238}\text{U})$ activity ratios for transect 2 of modern human femur 132A/LB/27D/03. B: Measured (blue) and modelled (red) $(^{230}\text{Th}/^{238}\text{U})$ activity ratios for transect 2 of modern human femur 132A/LB/27D/03.

432 T_{\min} and T_{\max} parameters should be adjusted and the model run again.

433 *Age of the Homo floresiensis remains from Sutikna et al. 2016*

434 For transect 1 of LB1/52, Sutikna et al. (2016) reported an age of 79.0 ± 3.7
 435 ka. With osUTh, using data in the file `Hobbit_1-1T_for_iDAD.csv` provided
 436 in the package, and following the same method as above, we obtain an age of
 437 $75.4 +1.0/-0.9$ ka (Figure 8). Note that results and errors vary slightly for each
 438 run since populations of solution sets are randomly generated.

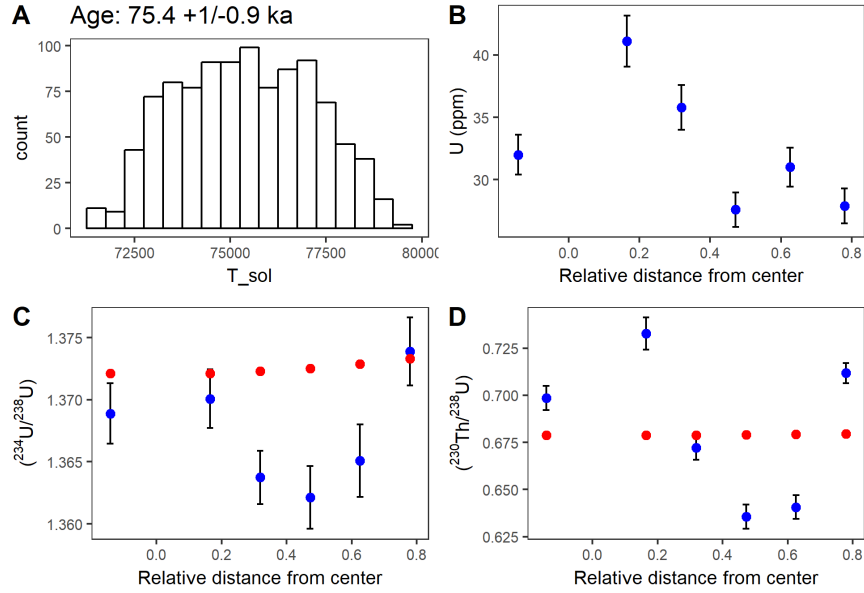


Figure 8: Results from running the model with *Homo floresiensis* ulna LB1/52 data from Sutikna et al. (2016). A: Histogram of the solution ages, B: Uranium concentration profile for transect 1 of *Homo floresiensis* ulna LB1/52. C: Measured (blue) and modelled (red) $(^{234}U/^{238}U)$ activity ratios for transect 1 of *Homo floresiensis* ulna LB1/52. D: Measured (blue) and modelled (red) $(^{230}Th/^{238}U)$ activity ratios for transect 1 of *Homo floresiensis* ulna LB1/52.

Conclusions

In this paper we have described `UThwig1`, an open source R package for computation of closed- and open-system U-Th ages. This helps to enable transparency, reproducibility, and flexibility of the analytical workflow for computing U-Th ages. The examples above show that results from our model are within error of previously published ages.

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Colophon

This report was generated on 2020-10-29 00:15:32 using the following computational environment and dependencies:

```
# which R packages and versions?
devtools::session_info()
```

```
## - Session info -----
## setting value
## version R version 4.0.2 (2020-06-22)
## os      macOS Catalina 10.15.6
## system  x86_64, darwin17.0
## ui      X11
## language (EN)
## collate en_US.UTF-8
## ctype   en_US.UTF-8
## tz      America/Los_Angeles
## date    2020-10-29
##
## - Packages -----
## package      * version date      lib source
## assertthat    0.2.1   2019-03-21 [2] CRAN (R 4.0.0)
## backports     1.1.10  2020-09-15 [2] CRAN (R 4.0.2)
## bookdown      0.21    2020-10-13 [2] CRAN (R 4.0.2)
## callr         3.5.1   2020-10-13 [2] CRAN (R 4.0.2)
## cli           2.1.0   2020-10-12 [2] CRAN (R 4.0.2)
## colorspace    1.4-1   2019-03-18 [2] CRAN (R 4.0.0)
## cowplot       1.1.0   2020-09-08 [2] CRAN (R 4.0.2)
## crayon        1.3.4   2017-09-16 [2] CRAN (R 4.0.0)
## desc          1.2.0   2018-05-01 [2] CRAN (R 4.0.0)
## deSolve       1.28    2020-03-08 [2] CRAN (R 4.0.0)
## devtools      2.3.2   2020-09-18 [2] CRAN (R 4.0.2)
## digest        0.6.27  2020-10-24 [2] CRAN (R 4.0.2)
## dplyr         * 1.0.2   2020-08-18 [2] CRAN (R 4.0.2)
## ellipsis      0.3.1   2020-05-15 [2] CRAN (R 4.0.0)
## evaluate      0.14    2019-05-28 [2] CRAN (R 4.0.0)
## fansi         0.4.1   2020-01-08 [2] CRAN (R 4.0.0)
## farver        2.0.3   2020-01-16 [2] CRAN (R 4.0.0)
## fs            1.5.0   2020-07-31 [2] CRAN (R 4.0.2)
## generics      0.0.2   2018-11-29 [2] CRAN (R 4.0.0)
## ggplot2       * 3.3.2   2020-06-19 [2] CRAN (R 4.0.0)
## glue          1.4.2   2020-08-27 [2] CRAN (R 4.0.2)
## gtable        0.3.0   2019-03-25 [2] CRAN (R 4.0.0)
## htmltools     0.5.0   2020-06-16 [2] CRAN (R 4.0.0)
## knitr         * 1.30    2020-09-22 [2] CRAN (R 4.0.2)
## labeling      0.4.2   2020-10-20 [2] CRAN (R 4.0.2)
```

```

## lifecycle      0.2.0    2020-03-06 [2] CRAN (R 4.0.0)
## magrittr       1.5      2014-11-22 [2] CRAN (R 4.0.0)
## memoise        1.1.0    2017-04-21 [2] CRAN (R 4.0.0)
## munsell         0.5.0    2018-06-12 [2] CRAN (R 4.0.0)
## pillar         1.4.6    2020-07-10 [2] CRAN (R 4.0.0)
## pkgbuild       1.1.0    2020-07-13 [2] CRAN (R 4.0.0)
## pkgconfig      2.0.3    2019-09-22 [2] CRAN (R 4.0.0)
## pkgload        1.1.0    2020-05-29 [2] CRAN (R 4.0.0)
## prettyunits    1.1.1    2020-01-24 [2] CRAN (R 4.0.0)
## processx       3.4.4    2020-09-03 [2] CRAN (R 4.0.2)
## ps             1.4.0    2020-10-07 [2] CRAN (R 4.0.2)
## purrr          0.3.4    2020-04-17 [2] CRAN (R 4.0.0)
## R6             2.5.0    2020-10-28 [2] CRAN (R 4.0.2)
## remotes        2.2.0    2020-07-21 [2] CRAN (R 4.0.2)
## rlang          0.4.8    2020-10-08 [2] CRAN (R 4.0.2)
## rmarkdown      2.4.6    2020-10-19 [2] Github (rstudio/rmarkdown@7239cea)
## rprojroot      1.3-2    2018-01-03 [2] CRAN (R 4.0.0)
## rticles        0.16     2020-09-22 [2] CRAN (R 4.0.2)
## scales        1.1.1    2020-05-11 [2] CRAN (R 4.0.0)
## sessioninfo    1.1.1    2018-11-05 [2] CRAN (R 4.0.0)
## stringi        1.5.3    2020-09-09 [2] CRAN (R 4.0.2)
## stringr        1.4.0    2019-02-10 [2] CRAN (R 4.0.0)
## testthat       2.3.2    2020-03-02 [2] CRAN (R 4.0.0)
## tibble         3.0.4    2020-10-12 [2] CRAN (R 4.0.2)
## tidyselect     1.1.0    2020-05-11 [2] CRAN (R 4.0.0)
## usethis        1.6.3    2020-09-17 [2] CRAN (R 4.0.2)
## UThwgl         * 0.1.0    2020-10-29 [1] local
## vctrs          0.3.4    2020-08-29 [2] CRAN (R 4.0.2)
## withr          2.3.0    2020-09-22 [2] CRAN (R 4.0.2)
## xfun           0.18     2020-09-29 [2] CRAN (R 4.0.2)
## xtable         * 1.8-4    2019-04-21 [2] CRAN (R 4.0.2)
## yaml           2.2.1    2020-02-01 [2] CRAN (R 4.0.0)
##
## [1] /private/var/folders/mz/6nn330m17_37ck5hhz2p24100000gn/T/Rtmpx0h6q0/temp_libpathfd17a
## [2] /Library/Frameworks/R.framework/Versions/4.0/Resources/library

```

The current Git commit details are:

```
# git2r::repository(here::here())
```