Method article

Two MATLAB programs for computing paleo-elevations and burial ages from paired-cosmogenic nuclides

Pierre-Henri Blard\textsuperscript{a,b,*}, Maarten Lupker\textsuperscript{c}, Moïse Rousseau\textsuperscript{d}, Jim Tesson\textsuperscript{e}

\textsuperscript{a}Centre de Recherches Pétrographiques et Géochimiques (CRPG), UMR 7358, CNRS - Université de Lorraine, 15 rue Notre Dame des Pauvres, 54500 Vandoeuvre-lès-Nancy, France
\textsuperscript{b}Laboratoire de Glaciologie, DGES-IGEOS, Université Libre de Bruxelles, 1050 Bruxelles, Belgium
\textsuperscript{c}ETH Zürich - Geological Institute, Sonneggstrasse 5, 8092 Zürich, Switzerland
\textsuperscript{d}Research Institute on Mines and Environment (RIME) UQAT-Polytechnique, Montréal, Canada

\textbf{A B S T R A C T}

Methods based on cosmic-ray produced nuclides are key to improve our understanding of the Earth surface dynamic. Measuring multiple cosmogenic nuclides in the same rock sample has a great potential, but data interpretation requires rigorous and often complex mathematical treatments. In order to make progress on this topic, this paper presents two easy-to-use MATLAB\textsuperscript{©} programs permitting to derive information from pairs of cosmogenic nuclides ($^{26}$Al-$^{10}$Be or $^{10}$Be-$^{21}$Ne) measured in rock samples that have been exposed to cosmic rays in the past: "Paleoaltitude.m" and "Burial.m".

- "Paleoaltitude.m" computes paleoelevations from a sample whose burial age is known. This new paleoaltimetry method is presented in detail in Blard et al. [1]. The present article also develops the mathematical approach.
- Since the elevation of exposure may affect the accuracy of a burial age [1], the second MATLAB\textsuperscript{©} script "Burial.m" is designed to compute burial ages from $^{26}$Al-$^{10}$Be or $^{10}$Be-$^{21}$Ne pairs, taking into account the position of a sample (elevation and latitude) during its preburial exposure history.

© 2019 Published by Elsevier B.V. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).

\textbf{A R T I C L E  I N F O}

Method name: Cosmogenic nuclides, Paleoaltimetry, Burial age.

Keywords: Cosmogenic nuclides, $^{10}$Be, $^{26}$Al, $^{21}$Ne, MATLAB, Paleoelavation, Continuous exposure, Steady erosion, Burial ages.

Article history: Received 19 March 2019; Accepted 16 May 2019; Available online 25 June 2019.

* Corresponding author at: Centre de Recherches Pétrographiques et Géochimiques (CRPG), UMR 7358, CNRS - Université de Lorraine, 15 rue Notre Dame des Pauvres, 54500 Vandoeuvre-lès-Nancy, France.

E-mail address: pierre-henri.blard@univ-lorraine.fr (P.-H. Blard).

https://doi.org/10.1016/j.mex.2019.05.017
2215-0161 © 2019 Published by Elsevier B.V. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).
Method details

This article presents two Matlab© programs, “Paleoaltitude.m” and “Burial.m”, and their mathematical descriptions. These two geological applications are based on the measurement of a cosmogenic nuclides pair (26Al–10Be or 10Be–21Ne) in rocks that have been exposed to cosmic rays in the geological past (up to > 10 million years ago) (Fig. 1). The paleoaltimetry method is new and described in [1]. The burial age method is already widely used (e.g. [2]); the main novelty of the script “Burial.m” is to take into account the spatial position of the sample (latitude and elevation) in the calculation of the burial age [1].

Program 1 - “Paleoaltitude.m”: This script computes the elevation of a rock samples in which a pair of cosmogenic nuclides with different half-lives (26Al–10Be and 10Be–21Ne) was measured. In the case of ancient exposures, the burial age has to be known and be accounted for radioactive decay.

Program 2 - “Burial.m”: This code computes the duration since a rock was buried from cosmic-rays. Altitude and latitude at which the paleo-exposure occurred have to be known. Both are necessary input of the program.

By default, the code includes sea level high latitude production rates computed from the worldwide database available in the CREp calculator (crep.crpg.cnrs-nancy.fr, ICE-D database; [3]) and the production parameters summarized in [1].

These programs were designed and optimized with the 2018a version of Matlab©. Some functions could be unavailable if the programs are run with an older version of Matlab©. All default parameters used in the codes are those defined in the Table 1 of Blard et al. [1].

Program 1: “Paleoaltitude.m” – Computation of paleoaltitude of exposure

The physical principles of this new paleoaltimetry method are presented in the main article [1].

Tutorial of the Matlab© script: “Paleoaltitude.m”

To use the program, users must load the function file in their Matlab© workspace and run the "Paleoaltitude.m" script. A window with clickable buttons is then displayed. Necessary input data (in the form of .csv or .xlsx spreadsheets) are:

Column 1: Sample name
Column 2: Latitude (°)
Column 3: Present altitude (m)
Column 4: Burial age (Ma)
Columns 5 and 6: Nuclide 1 ± 1σ (at. g⁻¹)
Columns 7 and 8: Nuclide 2 ± 1σ (at. g⁻¹)

Types of nuclides (10Be, 26Al or 21Ne) must be defined using the interactive box. It is important to check that the correct nuclides are loaded below the corresponding headers. Once data are correctly uploaded, users may push the "1 - Calculate elevations" button to start the calculations. It is also possible to push the "2 - Plot" button to display the data in a two cosmogenic nuclides diagram (26Al/10Be vs 10Be or 10Be/21Ne vs 21Ne). Once the figure is displayed, specific samples or sub-dataset may be selected and plotted. Fig. 2 shows an example of such a plot that permits to compare data with
theoretical exposure curves at various elevations (by default, the program plots surface exposure curves for 0, 2000 and 4000 m elevations).

Output results (in. csv):

Column 1: Sample name.
Columns 2 to 4: H(m), H_min(m), H_max(m) - Mean, minimum and maximum elevation computed assuming continuous exposure (no erosion). See Blard et al. [1] for complementary information.
Columns 5 and 6: T int ± 1σ (Ma) - Integration time over which altitude is computed assuming continuous exposure (no erosion). T int is computed from Eq. (7) in Blard et al. [1], using the nuclide having the shortest half-life (26Al or 10Be) and the scaling factor of the computed elevation.
Columns 7 to 9: H_erosion(m), H_min_Erosion(m), H_max_Erosion(m) - Mean, minimum and maximum elevation computed assuming steady state erosion. See Blard et al. [1] for complementary information.
Columns 10 and 11: Erosion ± 1σ (m.Ma⁻¹). Erosion is here computed considering the spallogenic production only and the preburial 10Be concentration, using Eq. (14) in Lal [4].
Columns 12 and 13: T int ± 1σ (Ma) - Integration time over which altitude is computed assuming steady state erosion. T int is computed from Eq. (7) in Blard et al. [1], using the nuclide having the shortest half-life (26Al or 10Be) and the spatial scaling factor of the computed elevation.
Results may be exported in the form of a. csv spreadsheet by clicking the button “Export”.

Mathematical description of the program used in “Paleoaltitude.m” to compute paleo-elevations and their associated uncertainties

For a nuclide X, λ_X is the radioactive decay constant (yr⁻¹), P_X (at. g⁻¹.yr⁻¹) the SLHL production rate, N_X and ΔN_X (at. g⁻¹) the measured concentration with its uncertainty. λ_XP_X, N_Y and ΔN_Y are the variables specific to the nuclide Y.

In the case of paleo-exposed material, N_X and N_Y are first corrected for radioactive decay since the burial initiation (t_burial):

\[ N_X = N_X^{\text{present}} e^{\lambda_X t_{\text{burial}}} \]  \hspace{1cm} (1a)

\[ N_Y = N_Y^{\text{present}} e^{\lambda_Y t_{\text{burial}}} \]  \hspace{1cm} (1b)

Here, it is assumed that there is no inheritance due to pre-exposure and that altitude has remained constant during exposure.

For two cosmogenic radioactive nuclides X and Y with different half-lives λ_X and λ_Y, such as λ_X<λ_Y:

\[ N_X = \frac{f \cdot P_X}{\lambda_X + \mu \varepsilon} \left( 1 - e^{-(\lambda_X + \mu \varepsilon) t} \right) \]  \hspace{1cm} (2a)

\[ N_Y = \frac{f \cdot P_Y}{\lambda_Y + \mu \varepsilon} \left( 1 - e^{-(\lambda_Y + \mu \varepsilon) t} \right) \]  \hspace{1cm} (2b)

In Eqs. (2a) and (2b), t (yr) is the preburial exposure duration, f (dimensionless) the spatial production rate scaling factor, μ (cm⁻¹) the rock absorption coefficient (μ = ρ/λ, with ρ the density in g/cm³ and λ the attenuation length in g/cm²) and ε (cm.yr⁻¹) the erosion rate.

Continuous exposure case (ε = 0 m.Ma⁻¹)

In the following, the variables A, B, ΔA, ΔB and r are defined as:

\[ A = \frac{\lambda_Y N_Y}{\mu \varepsilon} \]  \hspace{1cm} \[ B = \frac{\lambda_X N_X}{\mu \varepsilon} \]  \hspace{1cm} \[ \Delta A = \frac{\lambda_Y \Delta N_Y}{\mu \varepsilon} \]  \hspace{1cm} \[ \Delta B = \frac{\lambda_X \Delta N_X}{\mu \varepsilon} \]  \hspace{1cm} and \[ r = \frac{\lambda_X}{\lambda_Y} \text{ with } r < 1 \]
Fig. 1. Synoptic description of the two methods for the $^{26}$Al-$^{10}$Be pair.
Case 1: Burial age is known and paleoaltitudes can be computed.
Case 2: Paleoelevation of exposure is known and burial ages can be computed.
Exact solution. Solving the $Y$ nuclide Eq. (2b) for $t$ and substitute it in $X$ Eq. (2a) leads to:

$$0 = f - f \left(1 - \frac{A}{T}\right)^T - B$$  \hspace{1cm} (3a)
\[ t = \frac{-1}{\lambda Y} \ln \left( 1 - \frac{A}{f} \right) \]  \hspace{1cm} (3b)

(3b) can also be written with the X nuclide. Both equations need to satisfy the condition \( f > \text{max}(A,B) \). Eq. (3a) has no analytical solution for \( f \) and must be numerically solved. For this, the function \( g \) that is decreasing on the interval \([A, \infty]\) can be defined as follow:

\[ g(x) = x - x \left( 1 - \frac{A}{x} \right)^r - B \]  \hspace{1cm} (4a)

\[ g(f) = 0 \]  \hspace{1cm} (4b)

To ensure the existence of the solution \( f \), the following conditions need to be satisfied:

\[ \lim_{A} g = A - B > 0 \]  \hspace{1cm} (5a)

\[ \lim_{\infty} g = rA - B < 0 \]  \hspace{1cm} (5b)

(5a) and (5b) conditions are satisfied when the sample does not plot in the lower or upper forbidden areas (Fig. 3).

**Uncertainty propagation.** Since Eqs. (4a) and (4b) cannot be analytically solved, the confidence interval \([f^- , f^+]\) can be determined by defining the function \( \Delta g \) that describes the uncertainty attached to the \( g \) function. \( \Delta g \) is a monotone decreasing function. Thus, \( f^- \) and \( f^+ \), the negative and positive boundaries of \( f \), can be computed by finding the roots of \( g - \Delta g \) and \( g + \Delta g \):

\[ \Delta g(x) = \sqrt{\left( \frac{\partial g(x)}{\partial A} \Delta A \right)^2 + \left( \frac{\partial g(x)}{\partial B} \Delta B \right)^2} = \sqrt{\left[ rA \left( 1 - \frac{A}{x} \right)^{r-1} \right]^2 + \Delta B^2} \]  \hspace{1cm} (6a)

\[ (g - \Delta g)(f_-) = 0 \]  \hspace{1cm} (6b)

\[ (g + \Delta g)(f_+) = 0 \]  \hspace{1cm} (6c)

Maximum elevation and upper forbidden zone

\( f_+ \) exists when the following condition is satisfied. This condition requires that the upper value of the solution range remains below the upper forbidden area (Fig. 3):

\[ \lim_{\infty} (g + \Delta g) = rA - B + \sqrt{r^2 \Delta A^2 + \Delta B^2} < 0 \]  \hspace{1cm} (7)

Minimum elevation and lower forbidden zone

The minimum elevation \( f_- \) can be computed if the condition (5b) is satisfied, which leads to the following condition:

\[ \lim_{\infty} (g - \Delta g) = rA - B - \sqrt{r^2 \Delta A^2 + \Delta B^2} < 0 \]  \hspace{1cm} (8a)

Moreover \( \lim_{A} (g - \Delta g) = -\infty \). Thus, \( (g - \Delta g) \) need to be not monotonic to ensure the existence of \( f \):

\[ \exists x_0 \in A, \infty. \ g(x_0) > 0 \text{ and } \forall x > x_0: \frac{\partial (g - \Delta g)}{\partial x}(x) < 0 \]  \hspace{1cm} (8b)
When a sample is close to the lower forbidden area, reaching the limits of conditions (8a) and (8b), it is still possible to define a limit value for \( f_- \), corresponding to a sample that stands just above the forbidden area. This limit value is determined by the equilibrium between production and radioactive decay, and it is here computed as:

\[
f_- = \max(A, B)
\]

**Steady-state erosion case ( \( t \to \infty \))**

**Normal case.** For long exposure durations ( \( t \gg 1/(\lambda + \mu, \varepsilon) \)), Eqs. (2a) and (2b) become time-independent. Solving Eq. (2b) for \( \mu, \varepsilon \) and substitute it in Eq. (2a) then leads to:

\[
f = \frac{N_XN_Y(\lambda_X\lambda_Y)}{P_XN_Y - P_YN_X}
\]

(10a)

\[
\mu, \varepsilon = f \cdot \frac{P_Y}{N_Y} - \lambda_Y
\]

(10b)

Because \( f > 0 \) and \( \mu, \varepsilon > 0 \), Eqs. (10a) and (10b) lead to the three following conditions, where (11a) and (11b) are equivalent to the (5a) and (5b) conditions:

\[
\frac{N_Y}{N_X} \geq \frac{P_Y\lambda_X}{P_X\lambda_Y}
\]

(11a)

\[
P_XN_Y - P_YN_X < 0
\]

(11b)

\[
f > \max(A, B)
\]

(11c)

The classical uncertainty propagation formula can here be used to compute analytical solutions for \( f_- \) and \( f_+ \), \([f_-, f_+]\) being the one-sigma confidence interval:

\[
\Delta f = \frac{\lambda_Y - \lambda_X}{(P_XN_Y - P_YN_X)^2}
\]

(12a)

\[
f_+ = f + \Delta f
\]

(12b)

\[
f_- = f - \Delta f
\]

(12c)

**Particular case of large erosion.** \( f_+ \) and \( f_- \) should be considered carefully when erosion is large because \( \Delta f \) tends to infinity in this case. Therefore \( \Delta f \) can be larger than \( f_- \), resulting in a negative \( f_- \). Since it is required that \( f > \max(A, B) \), \( f_- \) can however be defined in any case by:

\[
f_- = \max(A, B, f - \Delta f)
\]

(13)

**Note on samples lying in the forbidden zone.** When a sample is in the upper forbidden zone, the upper uncertainty \( f_+ \) does not exist, \( f < 0 \), and \( f_- \) can be estimated as follow:

\[
f_- = \max(A, B)
\]

(14)
When a sample is in the lower forbidden zone, \( f_+ \) does not exist and \( \mu \varepsilon < 0, f_+ \) could thus be defined as the minimum elevation which ensure a positive erosion:

\[
f_+ = \max(A, B)
\]  

(15)

**Program 2: “Burial.m” – Calculation of burial ages**

**Tutorial of the Matlab© script: “Burial.m”**

To use the program, users must load the function file in their Matlab© workspace and run the "Burial.m" script. A window with clickable buttons is then displayed.

Necessary input data (in the form of .csv or .xlsx spreadsheet) are:

| Column 1: Sample name |
|-----------------------|
| Column 2: Latitude (°) |
| Column 3: Altitude (m) |
| Columns 4 and 5: Nuclide 1 ± 1σ (at. g⁻¹) |
| Columns 6 and 7: Nuclide 2 ± 1σ (at. g⁻¹). |

Nuclides \(^{10}\text{Be}, ^{26}\text{Al} \) or \(^{21}\text{Ne} \) must be defined using the interactive box. It is important to check that the correct nuclides are loaded below the corresponding headers. Once data are correctly uploaded, users may push the “1 - Calculate burial ages” button to start calculations. It is also possible to push the “2 - Plot” button to display the data in a two cosmogenic nuclides diagram \(^{26}\text{Al}/^{10}\text{Be} \) vs \(^{10}\text{Be} \) or \(^{10}\text{Be}/^{21}\text{Ne} \) vs \(^{21}\text{Ne} \). Note that the plot function becomes functional only after the calculation of burial ages. Once the figure is displayed, it is possible to select specific samples and plot a sub-dataset only. Fig. 4 shows an example of such a plot.

After calculations, results may be exported in the form of a .csv spreadsheet by clicking the button "Export".

| Column 1: Sample name |
|-----------------------|
| Columns 2, 3 and 4: \( T\text{Burial (Ma)}, -1\sigma (\text{Ma}), +1\sigma (\text{Ma}) \). Burial age is computed solving Eq. (16) for the \(^{26}\text{Al}/^{10}\text{Be} \) pair and Eq. (17) for the \(^{10}\text{Be}/^{21}\text{Ne} \) pair. The one sigma confidence interval [\(-1\sigma, +1\sigma\)] is computed from the statistical distribution of the solutions obtained from a Monte Carlo simulation \((10^4 \text{ draws})\). |
| Columns 5 and 6: Preburial erosion \( ± 1\sigma \) (m.Ma⁻¹). Erosion is calculated using Eq. (14) in [4], considering only the spallogenic production and the preburial \(^{10}\text{Be} \) concentration. |
| Columns 7 and 8: Preburial exposure duration \( ± 1\sigma \) (ka). Equivalent surface exposure time is computed assuming no erosion, using Eqs. (8a) and (8b) in [1]. Calculation uses the \(^{21}\text{Ne} \) concentration in the case of the \(^{10}\text{Be}/^{21}\text{Ne} \) pair and \(^{10}\text{Be} \) in the case of the \(^{26}\text{Al}/^{10}\text{Be} \) pair. |

**Mathematical description of the algorithm used in the “Burial.m” code**

In this version, the “Burial.m” program assumes that two geological conditions are satisfied: 1) before burial, the material had reached steady-state erosion and 2) the burial was instantaneous and deep enough to ensure the absence of post-burial production. In this case, the equation linking the burial age \( t\text{burial} \) and the measured cosmogenic nuclide concentrations \( N_1 \) and \( N_2 \) is:

\[
\frac{P_1}{N_1} e^{-\lambda_1 \cdot t\text{burial}} - \frac{P_2}{N_2} e^{-\lambda_2 \cdot t\text{burial}} = \frac{\lambda_1 - \lambda_2}{f}
\]  

(16)

Since Eq. (16) has no analytical solution, it has to be numerically solved to determine \( t\text{burial} \). In practice, the “Burial.m” program calls the “Burial26Al_10Ne.m” function that solves Eq. (16) using a Monte Carlo approach. By default, \( 10^4 \) random draws are realized, assuming \(^{10}\text{Be} \) and \(^{26}\text{Al} \) follow the normal distributions \( (N_{10}, \sigma_{10}) \) and \( (N_{26}, \sigma_{26}) \), where \( N_{10} \) and \( N_{26} \) (at. g⁻¹) are the measured concentrations, \( \sigma_{10} \) and \( \sigma_{26} \) (at. g⁻¹) their one sigma analytical uncertainties. This equation is here applied in the case of the \(^{26}\text{Al}/^{10}\text{Be} \) pair.
For the particular case of the $^{10}$Be-$^{21}$Ne pair, Eq. (16) simplifies and can be analytically solved:

$$t_{\text{burial}} = -\frac{1}{\lambda} \ln \left[ \frac{N_{10}}{P_{10}} \left( \frac{P_{21}}{N_{21}} + \frac{\lambda_{10}}{\lambda} \right) \right]$$  \hspace{1cm} (17)

The function “Burial$^{10}$Be$_{-21}$Ne.m” uses Eq. (17) to compute $t_{\text{burial}}$.

To keep calculations simple, pre-burial erosion (Columns 4 and 5) is here computed considering the spallogenic production only. Note however that the neglect of muogenic production may underestimate the correct erosion rates by up to 30% (e.g. [5,6]). If preburial erosion is faster than 100 m.Ma$^{-1}$, neglecting the muogenic production may lead to underestimate the computed burial ages by 100 to 200 ka.

Acknowledgements

We are grateful to Greg Balco, Derek Fabel and two anonymous reviewers for their constructive comments that permitted to improve the Matlab® scripts and the earlier version of the manuscript. This is CRPG contribution n°2690.

References

[1] P.-H. Blard, M. Lupker, M. Rousseau, Paired-cosmogenic nuclide paleoaltimetry, Earth Planet. Sci. Lett. 515 (2019) 271–282, doi:http://dx.doi.org/10.1016/j.epsl.2019.03.005.
[2] D.E. Granger, P.F. Muzikar, Dating sediment burial with in situ-produced cosmogenic nuclides: Theory, techniques, and limitations, Earth Planet. Sci. Lett. 188 (2001) 269–281, doi:http://dx.doi.org/10.1016/S0012-821X(01)00309-0.
[3] L. Martin, P.-H. Blard, G. Balco, J. Lave, R. Delunel, N. Lifton, V. Laurent, The CREp program and the ICE-D production rate calibration database: a fully parameterizable and updated online tool to compute cosmic-ray exposure ages, Quat. Geochronol. 38 (2017) 25–49, doi:http://dx.doi.org/10.1016/j.quageo.2016.11.006.
[4] D. Lal, Cosmic ray labeling of erosion surfaces: in situ nuclide production rates and erosion models, Earth Planet. Sci. Lett. 104 (1991) 424–439, doi:http://dx.doi.org/10.1016/0012-821X(91)90220-C.
[5] M. Lupker, P.H. Blard, J. Lavé, C. France-Lanord, L. Leanni, N. Puchol, J. Charreau, D. Bourlès, 10. Earth Planet. Sci. Lett. 333 (2012) 146–156, doi:http://dx.doi.org/10.1016/j.epsl.2012.04.020.

Fig. 4. Example of a paired nuclides plot realized using the “Plot” function of the “Burial.m” program. Shown is the $^{26}$Al-$^{10}$Be dataset from cave silico-clastic sediments buried in the caves of the Ariège region, Pyrénées, France (Sartégou [12], PhD Thesis).
[6] G. Balco, Production rate calculations for cosmic-ray-muon-produced $^{10}$Be and $^{26}$Al benchmarked against geological calibration data, Quat. Geochronol. 39 (2017) 150–173, doi:http://dx.doi.org/10.1016/j.quageo.2017.02.001.
[7] F. Kober, S. Ivy-Ochs, F. Schlunegger, H. Baur, P.W. Kubik, R. Wieler, Denudation rates and a topography-driven rainfall threshold in northern Chile: multiple cosmogenic nuclide data and sediment yield budgets, Geomorphology 83 (2007) 97–120, doi:http://dx.doi.org/10.1016/j.geomorph.2006.06.029.
[8] K. Nishizumi, M.W. Caffee, R.C. Finkel, G. Brimhall, T. Mote, Remnants of a fossil alluvial fan landscape of Miocene age in the Atacama desert of northern Chile using cosmogenic nuclide exposure age dating, Earth Planet. Sci. Lett. 237 (2005) 499–507, doi:http://dx.doi.org/10.1016/j.epsl.2005.05.032.
[9] C.J. Placzek, A. Matmon, D.E. Granger, J. Quade, S. Niedermann, Evidence for active landscape evolution in the hyperarid Atacama from multiple terrestrial cosmogenic nuclides, Earth Planet. Sci. Lett. 295 (2010) 12–20, doi:http://dx.doi.org/10.1016/j.epsl.2010.03.006.
[10] B. Ritter, S.A. Binnie, F.M. Stuart, V. Wennrich, T.J. Dunai, Evidence for multiple Plio-Pleistocene lake episodes in the hyperarid Atacama desert, Quat. Geochronol. 44 (2018) 1–12, doi:http://dx.doi.org/10.1016/j.quageo.2017.11.002.
[11] B. Ritter, F.M. Stuart, S.A. Binnie, A. Gerdes, V. Wennrich, T.J. Dunai, Neogene fluvial landscape evolution in the hyperarid core of the Atacama desert, Sci. Rep. 8 (2018) 13952, doi:http://dx.doi.org/10.1038/s41598-018-32339-9.
[12] A. Sartégou, - Évolution Morphogénique Des Pyrénées Orientales : Apports Des Datations De Systèmes Karstiques Étagés Par Les Nucléides Cosmogènes Et La RPE. PhD Thesis, Université de Perpignan, 2017 NNT: 2017PERP0044.