



HAL
open science

Basinga: A cell-by-cell GIS toolbox for computing basin average scaling factors, cosmogenic production rates and denudation rates

Julien Charreau, Pierre-Henri Blard, Jena Zumaque, L.C.P. Martin, Tony Delobel, L. Szafran

► To cite this version:

Julien Charreau, Pierre-Henri Blard, Jena Zumaque, L.C.P. Martin, Tony Delobel, et al.. Basinga: A cell-by-cell GIS toolbox for computing basin average scaling factors, cosmogenic production rates and denudation rates. *Earth Surface Processes and Landforms*, 2019, 44 (12), pp.2349-2365. 10.1002/esp.4649 . hal-02377535

HAL Id: hal-02377535

<https://hal.science/hal-02377535>

Submitted on 4 Jan 2021

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

BASINGA: a cell-by-cell GIS toolbox for computing BASIN average scaling factors, cosmogenic production rates and denudation rates

Journal:	<i>Earth Surface Processes and Landforms</i>
Manuscript ID	ESP-18-0325.R1
Wiley - Manuscript type:	Research Article
Date Submitted by the Author:	n/a
Complete List of Authors:	CHARREAU, Julien; Université de Lorraine, CRPG Blard, Pierre-Henri; Université de Lorraine, CRPG Zumaque, Jéna; Université du Québec à Montréal Geotop, Geotop Martin, Léo; University of Oslo, Department of Geosciences Delobel, Tony; Université de Lorraine, CRPG Szafran, Lucas; Université de Lorraine, CRPG
Keywords:	Scaling factors, Cosmogenic production rates, Basin average denudation rates, ArcGIS and QGIS

SCHOLARONE™
Manuscripts

1
2
3 1 **BASINGA: a cell-by-cell GIS toolbox for computing BASIN average scaling factors,**
4 **cosmogenic production rates and denudation rates**
5 2
6 3
7 3

8 4 Julien Charreau^{1**}, Pierre-Henri Blard¹, Jéna Zumaque^{1,2}, Léo C.P. Martin^{1,3}, Tony Delobel¹ and Lucas Szafran¹
9 5

11 6 1. CRPG, UMR 7358, CNRS, Université de Lorraine, 54501 Vandoeuvre-lès-Nancy, France, charreau@univ-lorraine.fr, blard@univ-lorraine.fr, tony-delobel@laposte.net, lucas.szafran@gmail.com
12 7
13 7

14 8 2. Geotop, Université de Québec à Montréal, CP 8888, Succ. Centre Ville Montréal, Québec, Canada, zumaque.jena@courrier.uqam.ca
15 9
16 9

17 10 3. Department of Geosciences, University of Oslo, P.O. Box 1047, Blindern, 0316 Oslo, Norway, leo.martin@geo.uio.no
18 11
19 11
20 12

21 13 **corresponding author: Julien Charreau (charreau@crpg.cnrs-nancy.fr)
22 14
23 14

24 15 **Abstract**
25 15

26 16 The calculation of denudation rates from the measured cosmogenic nuclide concentrations
27 17 in river sediments requires assumptions and approximations. Several different approaches and
28 18 numerical tools are available in the literature. A widely used analytical approach represents the
29 19 muogenic production with one or two exponentials, assumes the attenuation length of muons to
30 20 be constant and also neglects temporal variations in the Earth magnetic field. The denudation
31 21 rates are then directly and analytically calculated from the measured concentrations. A second
32 22 numerical and iterative approach was more recently proposed and considers a more rigorous
33 23 muogenic production laws based on pre-calculated variable attenuation length of muons and
34 24 accounts for temporal changes of the magnetic field. It also assumes a specific distribution of
35 25 denudation rates throughout the basin and uses an iterative approach to calculate the basin
36 26 average denudation rates.
37 26
38 26
39 26
40 26
41 26
42 26
43 26
44 26

45 27 We tested the two approaches across several natural basins and we found that both
46 28 approaches provide similar denudation results. Hence, assuming exponential muogenic
47 29 production and constant attenuation length of muons in the rock has little impact on the derived
48 30 denudation rates. Therefore, unless *a priori* known distributions of denudation rates are to be
49 31 tested, there does not appear to be any particular gain from using the second iterative method
50 32 which is computationally less effective.
51 32
52 32
53 32
54 32
55 32
56 32
57 32
58 32
59 32
60 32

1
2
3 33 Based on these findings, we developed and describe here **Basinga**, a new ArcGIS® and
4 34 QGIS toolbox which computes the basin average scaling factors, cosmogenic production rates
5 35 and denudation rates for several tens of drainage basins together. **Basinga** follows either the
6 36 Lal/Stone or the LSD scaling schemes and includes several optional tools for correcting for
7 37 topographic shielding, ice cover and lithology. We have also developed an original method for
8 38 correcting the cosmogenic production rates for past variations in the Earth's magnetic field.
9
10
11
12
13
14

15 40 key words: scaling factors, cosmogenic production rates, denudation rates, ArcGIS and QGIS
16
17
18

19 42 1. Introduction

20 43 Denudation is a critical parameter controlling the landscape evolution. It can be
21 44 determined at the scale of an entire watershed from the cosmogenic nuclides concentration
22 45 measured in one river sediment sample (e.g. Brown et al., 1995). This method has consequently
23 46 been widely used in a variety of geological settings (Portenga and Bierman, 2011). The
24 47 calculation of denudation rates from measured concentrations in sediments relies on specific
25 48 assumptions and requires computation of several parameters, notably the cosmogenic production
26 49 rates at the surface of the drainage basin. The physical characteristics of these production rates
27 50 can be estimated from a number of analytical, empirical or physical formulations. Consequently,
28 51 in the literature, the approaches adopted vary between authors and studies, leading to potential
29 52 discrepancies (Table 1) (e.g. Brown et al., 1995; Fox et al., 2015; Godard et al., 2012; Lupker et
30 53 al., 2012; Mudd et al., 2016; Portenga and Bierman, 2011; Scherler et al., 2014). In this paper,
31 54 we first review the different approaches, the associated assumptions and the formulae used to
32 55 calculate the basin average denudation rates, and we test their sensitivity. From these results, we
33 56 define a strategy to estimate the true basin average denudation rates and find the best balance
34 57 between the computational time of the methods and their accuracy. Accordingly, we have
35 58 developed and present here a free, simple and open-source tool that provides an accurate and
36 59 efficient means for computing the basin average denudation rates under different assumptions
37 60 and scaling models. It is named **Basinga** (**B**ASIN-avera**G**e scaling factors, cosmogenic
38 61 production and denudation r**A**tes) and includes two Python-script-based geoprocessing tools that
39 62 can calculate both the cosmogenic production rates and the denudation rates. These tools use two
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

63 simple and user-friendly graphical interfaces that can be installed and run on two widely used
64 GIS systems: ArcGIS® and QGIS.

66 2. Denudation rates from the cosmogenic concentration

67 2.1 General formulation

68 At any location, the concentration N (atoms.g⁻¹) of a cosmogenic nuclide i in a surface
69 rock ($z=0$) can be related to the exposure duration t (a) (present is 0 and positive toward the past)
70 and the local denudation rate ε (cm.a⁻¹) following this general equation (e.g. Balco, 2017):

$$71 \quad N_{z=0, i} = \sum_{x=sp, \mu} \int_0^{\infty} P_{x, i}(\varepsilon t) e^{-\lambda_i t} dt \quad (1)$$

72 where the subscript i and x indicate the studied cosmogenic nuclide (e.g. ¹⁰Be, ²⁶Al, ³He, ²¹Ne)
73 and the cosmogenic production pathway (sp for production by spallation; μ for slow muon
74 capture and fast muon processes), respectively. λ_i is the decay constant of the studied nuclide
75 ($4.9975 \times 10^{-7} \text{a}^{-1}$ for ¹⁰Be; (Chmeleff et al., 2010)). $P_{x, i}$ is the local *in situ* cosmogenic production
76 rates at the surface (at.g⁻¹.a⁻¹) of the production mechanism associated with each pathway x . The
77 depth production due to spallation follows an exponential (Lal, 1991), then the equation (1) can
78 be rewritten as follow:

$$79 \quad N_{z=0, i} = \frac{P_{sp, i}}{\frac{\rho \varepsilon}{\Lambda_{sp, i}} + \lambda_i} e^{-\left(\frac{\rho \varepsilon}{\Lambda_{sp, i}} + \lambda_i\right)t} + \int_0^{\infty} P_{\mu, i}(\varepsilon t) e^{-\lambda_i t} dt \quad (2)$$

80 where ρ and $\Lambda_{sp, i}$ are the rock density (g.cm⁻³) and the attenuation length of fast neutron
81 production (g.cm⁻²), respectively. This later theoretically varies with latitude and elevation, and
82 more specifically with atmospheric depth and cut-off rigidity (Gosse and Phillips, 2001; Lal,
83 1991; Marrero et al., 2015; Sato et al., 2008; Stone, 2000). It is however difficult to constrain
84 with accuracy, and therefore it is often convenient to assume a constant value of 160 g.cm⁻² for
85 $\Lambda_{sp, i}$ (e.g. Braucher et al., 2011).

86 The first term of this equation (2) that represents the spallogenic production is generally
87 simplified in $\frac{P_{sp, i}}{\frac{\rho \varepsilon}{\Lambda_{sp, i}} + \lambda_i}$, assuming that there is no inherited cosmogenic nuclide before exposure
88 initiation and that the cosmogenic nuclide concentration has reached steady state (i.e. $t \gg 1/(\lambda +$
89 $\varepsilon \rho / \Lambda)$ (Brown et al., 1995; Lal, 1991). In some conditions, the denudation may not be at steady
90 state and hence the denudation rates derived from this assumption can be biased (e.g. Bierman
91 and Steig, 1996). However, the potential inaccuracy due to the violation of this assumption is

1
2
3 92 significant (30 to 50%) only in very slowly eroding landscapes ($<10^{-3}$ cm/a) but remain below
4
5 93 few percent in most of the other geological contexts (Bierman and Steig, 1996; Schaller and
6
7 94 Ehlers, 2006).

8 95 The second term of equation (2) represents the muogenic contribution, which includes two
9
10 96 different production pathways (slow muon capture and fast muon processes). Rigorously, the
11
12 97 depth-dependence production rates of these particles do not follow a simple exponential
13
14 98 attenuation (Heisinger et al., 2002a, 2002b). Equation (2) should include a rigorous calculation of
15
16 99 the muogenic contribution following the Heisinger's equations (Heisinger et al., 2002a, 2002b)
17 100 (see for example equations 5 and 6 in Balco, 2017).

18
19 101 Assuming that a river mixes the sediments eroded across the whole drainage basin well,
20
21 102 the concentration measured at the river outlet represents the basin average of all local
22
23 103 concentrations (Brown et al., 1995; Lal, 1991). By solving and integrating equation (2) over the
24
25 104 basin surface, it is therefore possible to derive the average denudation rate at the basin scale from
26
27 105 a measured cosmogenic nuclide concentration in a river sediment (Brown et al., 1995; Lal, 1991),
28
29 106 provided that the cosmogenic production rates of the nuclide at the surface ($P_{x,i}$) are known at
30
31 107 each point of the basin.

32 108

33 109 2.2 The cosmogenic production rates and scaling factors

34 110 The *in situ* spallogenic production of cosmogenic nuclides at the surface is a function of
35
36 111 the longitude, but more importantly of the latitude L ($^{\circ}$), since it is primarily controlled by the
37
38 112 quantity of cosmic flux that reaches the high atmosphere and is therefore driven by the strength
39
40 113 of the geomagnetic field and the cut-off rigidity of the incoming particles (Lal, 1991). Moreover,
41
42 114 temporal variations in the Earth's magnetic field (e.g. Valet et al., 2005) are responsible for
43
44 115 changes in the cosmic flux (Dunai, 2001; Nishiizumi et al., 1989; Pigati and Lifton, 2004) and
45
46 116 hence in the spallogenic production rates. The cosmogenic nuclide concentration measured at the
47
48 117 surface is integrated over an equivalent exposure time, which-represents the time needed by the
49
50 118 grain to reach the surface while it is subjected to cosmic ray bombardment. This duration depends
51
52 119 on the denudation rate and the attenuation length: $t_{eq} = 1/(\lambda + \rho\varepsilon/\Lambda)$. However, the Earth's
53
54 120 magnetic field has negligible impact on muon fluxes and hence on muogenic production (e.g.
55
56 121 Balco et al., 2008; Braucher et al., 2011; Lifton et al., 2014). Both production pathways are a
57
58 122 function of the elevation since the secondary fluxes produced in the high atmosphere are

1
2
3 123 attenuated both in flux and energy by the atmosphere (Lal, 1991). In the calculations, elevation is
4
5 124 usually converted to the equivalent atmospheric depth h ($\text{g}\cdot\text{cm}^{-2}$) (Stone, 2000), which can be
6
7 125 calculated either using the hydrostatic standard atmosphere model specific to mid-latitude and the
8
9 126 northern hemisphere (see Equation (1) in Stone (2000)) or can be interpolated from the
10
11 127 atmospheric 2D ERA-40 database (Uppala et al., 2005).

12 128 The rate of cosmogenic production at the surface ($\text{at}\cdot\text{g}^{-1}\cdot\text{a}^{-1}$) at any location within a given
13
14 129 watershed can be scaled to the latitude, elevation and time as follows:

15 130
$$P_{i,x} = P_{i,x,SLHL} \cdot S_{i,x}(h,L,t(\varepsilon)) \quad (3)$$

17 131 where $P_{i,x,SLHL}$ is the surface production at Sea Level and High Latitude (SLHL) ($\text{at}\cdot\text{g}^{-1}\cdot\text{a}^{-1}$) for
18
19 132 each nuclide i and production pathway x . Global average values for the SLHL production rates of
20
21 133 different nuclides have recently been constrained by Martin et al. (2017) (see table 7), taking into
22
23 134 account all published calibration studies, notably the most recent ones (Balco et al., 2009;
24
25 135 Kaplan et al., 2011; Kelly et al., 2015; Lifton et al., 2014; Martin et al., 2015; Stroeven et al.,
26
27 136 2015). These worldwide averages were computed using the CREp program (Martin et al., 2017)
28
29 137 and include a time-integration correction based on the VDM reconstructed by Muscheler et al.
30
31 138 (2005).

32
33 139 In equation (3), $S_{i,x}$ represents the scaling factor for each production pathway x and each
34
35 140 studied nuclide i . Several empirical scaling models have been proposed in the literature. Some of
36
37 141 them were calibrated from the counting of spallation events by either photo-emulsion (e.g. Lal,
38
39 142 1991; Stone, 2000) or neutron-monitor (Desilets et al., 2006; Dunai, 2001; Lifton et al., 2005).
40
41 143 However, more recently, a purely theoretical and physical *ab initio* model was developed by
42
43 144 Lifton/Sato/Dunai (LSD) to describe the temporal and spatial variability in cosmogenic
44
45 145 production (Lifton et al., 2014).

46
47 146 For computational efficiency, previous studies (e.g. Fox et al., 2015; Godard et al., 2014;
48
49 147 Scherler et al., 2014; Wittmann and von Blanckenburg, 2009) have often calculated the
50
51 148 production rates using the widely used and accessible empirical scaling scheme of Lal/Stone (Lal,
52
53 149 1991; Stone, 2000). Considering the worldwide calibration dataset, statistical analyses show that
54
55 150 the Lal/Stone model has a better accuracy than the neutron-monitor-based schemes (Balco, 2017;
56
57 151 Borchers et al., 2015; Phillips et al., 2016). These analyses also show that, despite regional
58
59 152 differences, the Lal/Stone model has a similar efficiency than the LSD model (Borchers et al.,
60
153 2015; Lifton et al., 2014).

1
2
3 154 However, calibration sites remain too sparse to accurately unravel the full differences
4
5 155 between these two models at the global scale (Figs. 1 and 2). To estimate the spatial variability
6
7 156 and the agreement between the two models, we calculated the difference between the two scaling
8
9 157 models for the entire world, using as inputs the 2D ERA atmosphere database (Uppala et al.,
10
11 158 2005) and the Global Multi-resolution Terrain Elevation Data 2010 (GMTED2010) (Danielson
12
13 159 and Gesch, 2011). In most regions the two models differ by less than 10% on average, especially
14
15 160 at mid-latitude and moderate elevation (1-4 km) (Figs. 1 and 2). At high altitude/high latitude and
16
17 161 low altitude/low latitude the discrepancy between the two models may reach ~20-30% (Figs. 1
18
19 162 and 2) (Phillips et al., 2016). The difference also varies strongly with altitude (**Fig. 1**).
20
21 163

22 164 **3. Approaches and assumptions for computing basin average denudation rates**

23 165 The equations (1) and (2), that link the denudation rate to the cosmogenic concentration at
24
25 166 the surface, **are rigorously implicit in ε** . To calculate the basin average denudation rate from the
26
27 167 cosmogenic concentration measured at the outlet, assumptions and approximations must therefore
28
29 168 be made and two sorts of approach (analytical or numerical) have been developed for this (Table
30
31 169 1) (Balco et al., 2008; Brown et al., 1995; Mudd et al., 2016).
32
33 170

34 171 3.1 Analytical approaches

35 172 The first type of approach, which are traditionally used in the literature, either neglects the
36
37 173 muogenic production (method 1 in Table 1) or approximates, similarly to the spallogenic
38
39 174 production, the two muogenic production rates at depth with either one or two different
40
41 175 exponential laws (methods 2 and 3 in Table 1) (e.g. Braucher et al., 2011; Lupker et al., 2012).
42
43 176 Then, the equation (2) can be simplified as follow:

$$44 177 N_{z=0, i} = \sum_{x=sp, \mu_{sm}, \mu_{fm}} \frac{P_{x,i}}{\frac{\rho \varepsilon}{\Lambda_{x,i}} + \lambda_i} \quad (4)$$

45
46 178 where μ_{sm} and μ_{fm} indicate the two muogenic production pathways. This approach may use the
47
48 179 constant attenuation lengths of 4320 g/cm² and 1500 g/cm² determined by Braucher et al. (2011)
49
50 180 using the experimental data of Heisinger et al. (2002a,b) for fast muons capture and slow muons
51
52 181 processes, respectively (method 2). If only one family of muons is considered with a single
53
54 182 exponential then one single constant attenuation length in the rocks can be used (method 3) (see
55
56 183 table 2 in Braucher et al., 2013).
57
58
59
60

1
2
3 184 This first type of approach (methods 1,2 and 3) also assumes no temporal variation in the
4
5 185 Earth's magnetic field. In such a case, equation (4) can be directly solved analytically (Brown et
6
7 186 al., 1995). The basin average denudation rate is only a function of the concentration measured at
8
9 187 the outlet and the present average cosmogenic production rate of the basin (e.g. Brown et al.,
10
11 188 1995). In the literature, the latter is sometimes estimated from the mean altitude and latitude of
12
13 189 the studied catchment area (method 1) (Brown et al., 1995). However, because the production
14
15 190 rate vs. elevation relationship is non-linear, such an approximation may induce significant
16
17 191 uncertainties (>30%), especially in high elevation regions with high relief in the drainage basins.
18
19 192 To avoid these inaccuracies, it is critical to consider the whole basin topography (Balco et al.,
20
21 193 2008). A more accurate method scales the factors and hence the production rates on a pixel basis
22
23 194 using a Digital Elevation Model (DEM) and a cell-by-cell approach (methods 2 and 3) (e.g. Fox
24
25 195 et al., 2015; Godard et al., 2012; Lupker et al., 2012). The average production at the basin scale
26
27 196 can then be easily calculated to derive the basin average denudation rate.
28

27 198 3. 2 Iterative numerical approaches

29 199 The second type of approach solves the equation (2) numerically in order to provide the
30
31 200 denudation rates (e.g. Balco et al., 2008) (methods 4,5 and 6 in Table 1). Indeed, based on this
32
33 201 equation and using the Heisinger's formulation of the muogenic production (Heisinger et al.,
34
35 202 2002a, 2002b), it is possible to compute a theoretical cosmogenic concentration only if the
36
37 203 denudation is *a priori* known. Then, the denudation rate can be adjusted iteratively in order to
38
39 204 minimize the discrepancy between the measured and calculated concentrations (method 4). This
40
41 205 iterative methodology is available in the updated online calculator of Balco et al. (2008)
42
43 206 (<http://hess.ess.washington.edu/>). One advantage of this method is that the exposure duration can
44
45 207 be calculated from the input denudation at each iteration and, thus, the cosmogenic production
46
47 208 rate can be corrected for temporal variations in the Earth's magnetic field (Balco et al., 2008).
48
49 209 However, the initial code of Balco et al. (2008) was designed for the calculation of local
50
51 210 denudation rates only (method 4).

52
53 211 To extrapolate this iterative technique at the basin scale one must assume that the
54
55 212 denudation is homogenous (Mudd et al., 2016; Scherler et al., 2014) or specify a known
56
57 213 distribution of denudation throughout the basin. Otherwise, there would be an infinite number of
58
59 214 denudation distribution solutions throughout the basin that could be possible. Based on this *a*

1
2
3 215 *priori* known denudation distribution (homogenous or specified) the production rates can be
4
5 216 corrected for temporal variations in the Earth's magnetic field. Again, as for the previous
6
7 217 approaches (methods 1,2 and 3), this method requires calculation of the cosmogenic production
8
9 218 rates for both production pathways (spallogenic and muogenic) at each location in the basin, and
10
11 219 this must also be made on a pixel basis using a DEM. The concentration of a cosmogenic nuclide
12
13 220 at each location and the basin average concentration could then be calculated accordingly. The
14
15 221 denudation rate of the basin could then be adjusted iteratively in order to minimize the
16
17 222 discrepancy between the measured and calculated concentrations at the outlet. To use this
18
19 223 iterative methodology at the basin scale one would need to calculate the muogenic production
20
21 224 using Heisinger's equations at each point of the basin, which is a time-consuming computation.
22
23 225 Therefore, such an approach still needs to be fully developed for the calculation of basin average
24
25 226 denudation rates. Indeed, though Mudd et al. (2016) have developed an iterative methodology,
26
27 227 they assumed a constant attenuation length for muons and considered only present-day
28
29 228 production rates derived from the Lal/Stone model, without any correction for temporal
30
31 229 variations (method 5 in Table 1).

32
33 230 Alternatively, the right muogenic production can be calculated using Heisinger's
34
35 231 formulations (Heisinger et al., 2002a, 2002b) for a reasonable range of denudation rates and
36
37 232 atmospheric depth values and, hence, the attenuation length of muons can be derived accordingly
38
39 233 assuming a single exponential law (see equation 12 of Balco, 2017) (**Fig. 3**). Based on these pre-
40
41 234 calculated values, the attenuation length of muons can be interpolated at each point of a given
42
43 235 drainage basin using elevations and denudations grids. The cosmogenic concentration can be then
44
45 236 more quickly but relatively accurately estimated at each point of the studied basin. The denudation
46
47 237 rate can be then derived using the same iterative technic than in method 4 and 5 (method 6).

48
49 238

50 239 **4. Sensitivity analysis**

51
52 240 It is worth testing and comparing the accuracies of the two types of approach. Moreover,
53
54 241 it is still unclear if the new LSD model would yield any significant differences when calculating
55
56 242 basin average denudation rates.

57
58 243

59 244 4.1 Approach

1
2
3 245 To discriminate between the two types of approach and the two scaling models, we
4
5 246 considered several natural catchments across the world, notably in regions where the two scaling
6
7 247 schemes differ strongly (Table 2), in particular at high latitude/high elevation (i.e. the Susitna
8
9 248 basin in Alaska) and at low latitude/low elevation (the Maroni basin in the French Guyana, 0-
10
11 249 900m at $\sim 4^\circ\text{N}$) (Fig. 1). We also tested several basins that exhibit a wide elevation range (i.e.
12
13 250 Marshyangdi, Kuitun). At each cell in a basin, we assumed that denudation was a linear function
14
15 251 of the local slope. We then arbitrarily set the maximum denudation rate so that the basin average
16
17 252 denudation rate roughly equaled the rates reported in the literature, which were derived from
18
19 253 thermochronology, sediment gauging and/or TCN analysis (see the complete list of references
20
21 254 given in Table 2) (Fig. 4).

22
23 255 Based on these *a priori* known denudation rate distributions, we applied a forward model
24
25 256 to calculate the theoretical "true" *in situ* ^{10}Be concentrations at each cell in the basins. We used
26
27 257 both the LSD (Lifton, 2015) and Lal/Stone (Lal, 1991; Stone, 2000) schemes to estimate the
28
29 258 scaling factors and production rates in each cell based on the cell's latitude, longitude and
30
31 259 elevation. For the LSD model, we used the Matlab[®] functions of Lifton et al. (2015), which were
32
33 260 amended by Martin et al. (2017) to test for different dipolar geomagnetic corrections. When using
34
35 261 the Lal/Stone scheme the time was not integrated and we used only the present-day scaling
36
37 262 factors. For LSD, we considered both the present-day factors and factors corrected for variations
38
39 263 in the Earth's magnetic field. In such a case, the time was integrated for each cell based on the
40
41 264 equivalent time derived from the denudation itself. Atmospheric depth was always calculated
42
43 265 using the data from the 2D ERA-40 database (Uppala et al., 2005). ^{10}Be cosmogenic production
44
45 266 rates were calculated based on the SLHL rate of 4.11 of Martin et al. (2017) (see their Table 7).
46
47 267 We followed the approach and database proposed by Balco (2017) to accurately estimate the
48
49 268 attenuation length of muons in the rocks as a function of the denudation and elevation (Fig. 4).
50
51 269 Next, we calculated the basin average "true" concentration using equation (4). These values were
52
53 270 then inverted using the two types of approach (method 3 vs. 5) to estimate the basin average
54
55 271 denudation rates for each basin accordingly. For consistency, the inversions considered the same
56
57 272 scaling as that used during the calculation of the theoretical concentration. For the iterative
58
59 273 approach, the distribution of the denudation was assumed to be homogenous throughout the
60
274 basin. Since the attenuation length of muons as a function of denudation and elevation can only
275 be calculated for all muons together, in the analytical approach we therefore considered only one

1
2
3 276 single family of muons and used the method 3 with constant attenuation length in the rocks. We
4
5 277 used the value of 4814 g.cm^{-2} which represents the mean of the attenuation lengths given in
6
7 278 Braucher et al. (2013). Finally, we compared the inverted average denudation results to the input
8
9 279 theoretical values.

10 280

11 281 4.2 Results

12
13 282 The complete results are given in table 2 and figures 5, 6 and 7 show the results for
14
15 283 representative basins. For most of the studied basins, we found that the analytical approach
16
17 284 (method 3) (which assumes the attenuation length of muons to be constant) provided denudation
18
19 285 rate estimates that were on average better than or similar to those of the iterative approach,
20
21 286 whatever the scaling model used. Adding the temporal modulation of the production rates led to
22
23 287 larger misfits between the denudation rates calculated using the analytical approach (which uses
24
25 288 the present rates) and the theoretical denudation rates. However, the iterative approach, which
26
27 289 can account for these modulations, did not provide better results (Table 2) and for several basins
28
29 290 it yielded large differences (10-20%)(Fig. 5). When we used the scaling models for inversion
30
31 291 without time integration ahead, meaning that only the attenuation length of muons differed
32
33 292 between the theoretical calculation and the inversion, the differences between the theoretical and
34
35 293 inverted denudation rates were on average negligible except for basins with very low denudation
36
37 294 rates (i.e. Maroni and Chambal), where the differences were significant (<10%).

36 295

37 296 **5. Discussion and implementation in Basinga**

38 297 5.1 Goals of Basinga

39
40
41 298 The first aim of **Basinga** (**BASIN**-averaGe scaling factors, cosmogenic production and
42
43 299 denudation rates) was to provide a tool, named "*Production rate*", for computing cosmogenic
44
45 300 production rates for different nuclides (^3He , ^{21}Ne and ^{10}Be). The second goal of **Basinga** was to
46
47 301 calculate, for a large number of drainage basins together, the mean denudation rates from the
48
49 302 cosmogenic concentrations measured at their outlet. Hence, a second tool named "*Denudation*
50
51 303 *rates*" was designed. Our main objective was to provide, for both tools, simple and user-friendly
52
53 304 graphical interfaces that could be installed on GIS systems and run using simple Digital Elevation
54
55 305 Model (DEM) raster and shape files of the drainage basins. Based on the above methodological
56
57 306 analysis, we therefore developed Python-script-based geoprocessing tools that can be run and

1
2
3 307 installed on two widely used and/or free GIS systems, ArcGIS® and QGIS. These tools calculate
4
5 308 the cosmogenic production and denudation rates for several nuclides, based on two possible
6
7 309 scaling models and using several corrective options that were built to improve the accuracy of the
8
9 310 estimates. However, all of these methodological improvements and associated potential gain in
10
11 311 accuracy must be handled with caution, given the uncertainties associated to the cosmogenic
12
13 312 method itself, especially in low eroding landscape (<0.001 cm/a) (Bierman and Steig, 1996). A
14
15 313 detailed description of **Basinga**, its interfaces and how they can be used are given in the
16
17 314 Supplementary information.
18

19 316 5.2 Choice of the scaling model

20 317 At moderate altitudes (1000-6000m), the differences between the two scaling models are
21
22 318 in general quite low ($<10\%$). Hence, for basins of high relief at moderate elevation (e.g.
23
24 319 Marshyangdi, Susitna, Kuitun), the weights of the extreme scaling values are likely negligible
25
26 320 and the higher production rates at lower elevations derived using Lal/Stone are compensated for
27
28 321 by the lower production rates at high elevation (Figs. 6 and 7). Moreover, the true difference
29
30 322 between the two scaling models is likely lower than our modeling suggests because at high
31
32 323 elevation, where the discrepancies between the models are greater, cosmogenic production is
33
34 324 partially canceled out by ice cover that shields surficial rocks from cosmic rays. The other
35
36 325 sources of random uncertainty associated with the cosmogenic measurements are equivalent to
37
38 326 the bias computed in our simulation (ca. 5 to 10%). Therefore, given the other geological
39
40 327 uncertainties such as those related to the steady state assumption (Bierman and Steig, 1996;
41
42 328 Schaller and Ehlers, 2006), for most natural cases, the choice of the scaling model will have little
43
44 329 impact. Since it is computationally more efficient to follow the Lal/Stone model for calculating
45
46 330 the cosmogenic production rates, we would encourage use of this model in most of the cases.

47 331 Nevertheless, precautions must be taken when studying drainage basins or sub-catchments
48
49 332 of low relief in regions where the difference between the two scaling models is rather high (15-
50
51 333 30%). For example, in the Maroni and Chambal basins, because of the low relief (0-1000m) and
52
53 334 low latitude, the difference between the scaling models is significant everywhere and the extreme
54
55 335 values are not compensated by each other. The resulting difference in denudation rates remains
56
57 336 significant ($\sim 15\%$). Unfortunately, the calibration data remain too sparse in these particular
58
59 337 regions to determine which of the two models is more accurate (Phillips et al., 2016; Martin et al.,
60

1
2
3 338 2017). In such cases, and until new discriminant calibration data are provided, both scaling
4
5 339 models should be used to provide a realistic range of possible denudation values. However, if the
6
7 340 expected denudation rates of the studied low relief region are low (<0.001 cm/a), the difference
8
9 341 between the two estimates will likely be in the range of the uncertainties associated to the
10
11 342 precision of the cosmogenic method itself (Bierman and Steig, 1996).

12 343 The Basinga tool *Production rates* thus allows the user to calculate the scaling factors and
13
14 344 the production rates using either the LSD or the Lal/stone model. The LSD model was
15
16 345 implemented in Python using the Matlab functions of Lifton et al. (2014) modified by Martin et
17
18 346 al. (2017). The *Production rates* tool calculates the basin average production rates based on the
19
20 347 SLHL rates provided in Martin et al. (2017) (see their table 7) as a function of the studied nuclide
21
22 348 and the scaling model and derived from the ERA40 atmosphere database. For ^{21}Ne the SLHL is
23
24 349 calculated from the ^{10}Be SLHL rate and a $^{10}\text{Be}/^{21}\text{Ne}$ ratio of 4.12 (Kober et al., 2011). The SLHL
25
26 350 for each particles are calculated based on their relative production rate to the total production at
27
28 351 sea level high latitude with values of 98.86%, 0.27% and 0.87% for spallation, slow muon
29
30 352 capture and fast muon processes, respectively (see table Table 1 of Martin et al., 2017 and
31
32 353 Braucher et al., 2011).

33
34 354 Nevertheless, the SLHL values can be easily updated and modified in the program file if
35
36 355 needed using a simple text editor (see Online supplementary information and the section "Getting
37
38 356 Started" for the procedure and which lines to change). For example, local or regional SLHL
39
40 357 values can be used, as derived from the CREp program and using a compilation of local
41
42 358 calibration sites (Martin et al., 2017).

43
44 359 However, calculation of the production rates using LSD may take several hours for an
45
46 360 average sized drainage basin of few thousand km^2 (Fig. 8). For large catchments, for example the
47
48 361 Gangese (9.0×10^5 km^2), the Amazon (6.9×10^6 km^2) or the Rhône (9.7×10^4 km^2), the computing
49
50 362 time can be very long (Fig. 8) and the computation may be difficult to perform on a simple laptop
51
52 363 computer. The same is true if a large number of basins are analyzed together. In such cases, the
53
54 364 resolution of the analyzed DEM needs to be increased, which could generate a potential source of
55
56 365 inaccuracy. Use of the LSD model is therefore for now limited to basins of small size.

57
58
59
60

366 367 5.3 An alternative approach for estimating the LSD scaling factors

1
2
3 368 To overcome this issue and to reduce the computing time when using the LSD model, we
4
5 369 can lean on the simple relationship that exists, at the basin scale, between the Lal/Stone and the
6
7 370 LSD scaling factors (Figs. 2, 6 and 7). If time is not integrated to correct for past changes in the
8
9 371 Earth's magnetic field, the relationship between the two models can be approximated by a simple
10
11 372 polynomial law for each basin (Figs. 6 and 7). The spallogenic and muogenic factors for both
12
13 373 models can be calculated together over a small number of cells that are randomly sampled within
14
15 374 the studied basin. These data can then be used to find the best fit relationship between the two
16
17 375 models for each production pathway. The LSD factors on the other cells are then calculated using
18
19 376 these conversion laws and the previous Lal/Stone factors that had been quickly estimated for each
20
21 377 cell. Our tests show that a 4 degree polynomial fit derived from 1000 sampled cells provides an
22
23 378 accurate law for estimating the LSD factors of the whole basin (the average bias is lower than
24
25 379 1%, and never exceeds 3%) (Fig. 9). This alternative approach significantly reduces the
26
27 380 computing time needed to calculate the LSD scaling factors when time is not integrated (Fig. 8).
28
29 381 A similar approximation of the LSD factors based on a pre-calculated table is also used in the
30
31 382 updated online calculator of Balco et al. (2008) (<http://hess.ess.washington.edu/>). When using the
32
33 383 LSD model in Basinga, this simplification can be activated if desired.

34 384 35 385 5.4 Chosen methodology for denudation inversion

36 386 Though we analyzed ten natural basins in different settings, because the controlling
37
38 387 factors are multiple (denudation, hypsometry, reliefs, latitude, longitude etc) our results cannot
39
40 388 easily be generalized. Since the calculations are relatively long for each basin, especially when
41
42 389 using the iterative approach, it is difficult to multiply the studied cases to encompass all possible
43
44 390 variations in all of these factors. To discriminate between the two methods, the net influence of
45
46 391 the attenuation length of muons in the rocks is critical. However, the sensitivity of the denudation
47
48 392 rate to this parameter can be tested more systematically using the Lal/Stone model, which is
49
50 393 computationally more efficient. In such a case, it is computationally possible to vary the
51
52 394 maximum altitude (hence its relief), the mean latitude and the denudation distribution of a given
53
54 395 basin of relatively small size. We considered here a smaller sub-basin of the Marshyangdi and
55
56 396 fixed its hypsometry while the other parameters were varied. We tested about 300 different cases
57
58 397 with mean latitudes, reliefs and denudation rates ranging from 5 ° to 55°, 450 to 4500m and 0.01
59
60 398 to 0.4 cm/a, respectively. The differences between the inverted and theoretical denudation are on

1
2
3 399 average less than 1% (**Fig. 10**). These results also suggest that assuming a constant attenuation
4
5 400 length of 4814 g.cm^{-2} (Braucher et al., 2013) has negligible impact on the final denudation results
6
7 401 in a wide range of settings. However, for very low denudation rates ($<0.01 \text{ cm/a}$) at low altitude
8
9 402 ($<1000\text{m}$), as for example in the Maroni and Chambal basins, the effective attenuation length
10
11 403 derived by Balco (2017) is significantly lower than Braucher's value (**Fig. 1**), resulting in larger
12
13 404 discrepancies between theoretical and inverted denudation rates. The discrepancy still remains
14
15 405 lower than $<10\%$ however (**Fig. 10**). These results reinforce the conclusion that the analytical
16
17 406 approach provides relatively accurate results even if variations in the attenuation length of muons
18
19 407 are neglected.

20
21 408 Moreover, the analytical approach has the advantage of being straightforward and
22
23 409 computationally faster even when using the LSD model. In contrast, the numerical and iterative
24
25 410 approach requires, at each step, the attenuation length of muons from the tested denudation to be
26
27 411 re-computed for each cell. If the temporal fluctuations in the production rates are integrated, the
28
29 412 associated computation must also be performed at each step as function of the tested denudation
30
31 413 rates. The time needed to compute the scaling factors is hence significantly increased and the
32
33 414 calculation may take several tens of hours for a basin of average size when using the time-
34
35 415 dependent version of the LSD model (**Fig. 8**).

36
37 416 At last, the potential gain in accuracy that could results from considering variations in the
38
39 417 attenuation length of muons is likely negligible compared to the natural geological uncertainties.

40
41 418 Nevertheless, the iterative approach merits consideration if an *a priori* known distribution
42
43 419 of denudation is available, derived for example from shear stress, lithology data or output from
44
45 420 numerical landscape models. In such a case, the tool developed by Mudd et al. (2016), which is
46
47 421 freely available online, may be used. However, this tool is based on the Lal/stone model only and
48
49 422 also assumes a constant attenuation length of muons. A complete iterative tool, with a variable
50
51 423 attenuation length of muons and based on the LSD model including time integration, has yet to be
52
53 424 developed.

54
55 425 If the distribution of denudation is a priori unknown, the use of the analytical approach is,
56
57 426 in our opinion, sufficient and more efficient. Unfortunately, no simple and freely available tool
58
59 427 has been provided for this approach. Consequently, our second Python script, *Denudation rates*,
60
428 follows the analytical approach and uses the method 2 (Table 1) with the muogenic production
429 represented by two exponentials. To calculate the denudation rates for each basin studied,

1
2
3 430 *Denudation rates* requires the measured concentration of the in situ cosmogenic nuclide at the
4
5 431 outlet and the calculation of the basin average production rates before. These basin averages are
6
7 432 provided by the *Production rates* tool using a DEM projected in a geographical system with the
8
9 433 area of each individual cells of the DEM corrected for latitudinal effects.

10 434
11
12 435 5.5 An approach for integrating time and changes in the Earth's magnetic field using the
13
14 436 analytical approach

15 437 Theoretically, the analytical approach precludes any accounting for past changes in the
16
17 438 Earth's magnetic field because the production rates are calculated for the present time only. In
18
19 439 many mountain ranges, such as in Taiwan, the Himalayas or the New Zealand Alps, denudation
20
21 440 rates are usually high and exceed 0.1-0.2 cm/a (Derrioux et al., 2014; Herman et al., 2010;
22
23 441 Lupker et al., 2012). In such cases, the equivalent exposure times are low (<400 a) and the
24
25 442 associated biases likely negligible (Fig. 11). However, for regions of lower denudation, such as in
26
27 443 the Tianshan mountains (i.e < 0.05 cm/a) (e.g. Charreau et al., 2011), where typical equivalent
28
29 444 exposure times are on the order of several ka, ignoring changes in the Earth's magnetic field may
30
31 445 induce biases of up to 20% (e.g. Lifton, 2016; Martin et al., 2016) (Fig. 11). Such biases are
32
33 446 significantly higher than the potential errors associated to the geological uncertainties, especially
34
35 447 than those associated to the violation of the steady state assumption (Bierman and Steig, 1996;
36
37 448 Schaller and Ehlers, 2006). If overlooked, this may lead to significant inaccuracies in the derived
38
39 449 denudation rates.

40
41 450 Temporal variations in the Earth magnetic field can be theoretically integrated using the
42
43 451 LSD model and the iterative approach. However, the inverted denudation rates still differ from
44
45 452 the theoretical values and are not significantly better than those derived from the analytical
46
47 453 approach without time integration (Table 2). Therefore, to account for the past changes in the
48
49 454 Earth's magnetic field when using the analytical approach (method 2) in Basinga, we have
50
51 455 developed a simplified approach. Based on equation 4, the equivalent exposure time at the basin
52
53 456 scale can be approximated by dividing the nuclide concentration measured at the outlet by the
54
55 457 basin average production rates calculated without paleomagnetic correction. The production rates
56
57 458 can then be corrected for the paleomagnetic changes by integration during this so-computed
58
59 459 equivalent exposure time. We followed the approach developed in the online CREp program
60
460 (Martin et al., 2017), where the fundamental equations of the Lal/Stone model have been

1
2
3 461 modified to use the cut-off rigidity rather than the latitude (see paragraph 2.2 of Martin et al.,
4 462 2017). Based on a Virtual Dipole Moment (VDM) database, the rigidity is integrated during the
5 463 equivalent exposure time and the new production rates calculated accordingly whatever the
6 464 scaling model used. During the calculation we consider only the Muscheler's VDM database
7 465 (Muscheler et al., 2005) as use of other VDMs would yield negligible differences (<5%)
8 466 compared to the other random analytical uncertainties (~10%). In addition, the Muscheler
9 467 geomagnetic database is effective in reducing the dispersion in the data set of the world wide
10 468 SHLH production rates when coupled with the Lal/Stone or LSD model (Martin et al. 2017).

11 469 However, the integration time should in theory be different for each cell of the basin since
12 470 each is affected by a different denudation rate while equation 4 requires a uniform denudation
13 471 rate throughout the basin. This time correction is thus a simplification that may introduce some
14 472 bias. This approach can therefore only provide a first order estimate of the paleomagnetic
15 473 correction and must be handled with caution.

16 474

17 475 5.6 Additional corrective options

18 476 Basinga also includes several other corrections and options (see the Supplementary
19 477 Information for a technical description of these options). First, several authors have highlighted
20 478 the importance of the geometry of the exposed surface (e.g. Lal, 1991; Dunne et al., 1999; Gosse
21 479 and Phillips, 2001). The quantity of the incoming cosmic ray flux received at a geographic point
22 480 strongly depends on topographic shielding by both the surrounding relief and the local slope. An
23 481 option was therefore built to correct for this topographic shielding. However, this optional
24 482 correction must be used with caution. Indeed, DiBiase (2018) suggests that the topographic
25 483 shielding correction is inappropriate in many settings. According to this author this correction is
26 484 only needed for steep catchments with non-uniform distribution of quartz and/or erosion rate.

27 485 Second, the TCN approach assumes a uniform concentration of quartz throughout the
28 486 catchment area which may bias the results toward the quartz-bearing locations. If instead the
29 487 quartz content of eroded lithologies varies across the studied basin, equation (4) is no longer
30 488 valid. However, though it remains relatively difficult to quantify the concentration of quartz from
31 489 each eroded lithology, we can at least exclude any lithology without quartz from the calculation
32 490 (e.g. Delunel et al., 2010). We therefore integrated and built an additional option that allows the
33 491 corresponding area to be removed from the studied watershed.

1
2
3 492 Third, the presence of an ice cap may shield the ground surface from incoming cosmic
4 rays, thereby reducing or preventing cosmogenic *in situ* production. **Basinga** also allows a
5 493 correction for ice cover when computing the scaling factor and cosmogenic production rate. We
6 494 assume that the ice cover is sufficiently thick to fully shield the surface and thus that no
7 495 cosmogenic isotopes are produced below the ice (Wittmann et al., 2007). However, because ice
8 496 erosion remains efficient, the area covered by ice may still deliver sediment to the main stream
9 497 (Wittmann et al., 2007). As they have previously been shielded by ice, in **Basinga** these
10 498 sediments are presumed to be free of cosmogenic isotopes. However, in nature, processes of
11 499 glacial erosion are far more complex, with notably, supra-glacial hillslopes providing sediments
12 500 whose cosmogenic concentration may differ from 0 (e.g. Godard et al., 2012; Guillon et al.,
13 501 2015). Moreover, the ice cover may have varied during time with periods of retreat and hence
14 502 cosmic exposition and periods of advance and shielding. Accounting for all these glacial
15 503 complexities in order to calculate more accurate denudation rates is likely vain. Therefore, the
16 504 goal of this new option is not to improve the precision of the denudation rates but to provide end-
17 505 member values of the denudation rates. Indeed, because glaciers are located at high elevations,
18 506 assuming a zero production under the ice could result in an underestimation of production rates
19 507 and thus an underestimation of the true denudation rates. Conversely, assuming full production
20 508 by ignoring the ice cap would lead to overestimation of the production and denudation rates. The
21 509 two scenarios can be easily tested using **Basinga** to bracket the true denudation rates.
22 510

23
24
25
26
27
28
29
30
31
32
33
34
35
36 511 Like glacial cover, snow cover can also partially shield the rocks and should be accounted
37 512 for when estimating the production rates. This effect is particularly significant in high elevation
38 513 mountain ranges, and may induce a reduction of the overall production rate by 5 to 10% (Scherler
39 514 et al., 2014; Schildgen et al., 2005). Schildgen et al. (2005) attempted to correct for snow cover
40 515 using a complex physical model coupled with remote sensing monitoring of snow cover spanning
41 516 several years, which required calibration from ground-based records and measurements. Snow
42 517 thickness can also be estimated from Precipitation Daily Data (PDD) derived from Global
43 518 Climate Models (GCM). Such calculations are far beyond the goal of **Basinga**. However, this
44 519 correction can be computed independently and integrated into **Basinga** by multiplying it by the
45 520 topographic shielding factor. In such a case, the snow correction will be included in the overall
46 521 calculation if the correction for topographic shielding is selected during the process.
47
48
49
50
51
52
53
54

55 522

5.7 Estimation of the denudation uncertainties

Basinga also provides an estimation of the denudation uncertainties. However, errors in the cosmogenic production rates and the measured concentrations are only propagated as follows:

$$\delta\bar{\varepsilon} = \sqrt{\left[\frac{\delta N}{N^2} \left(\frac{P_{spal}}{\Lambda_{n,rock}} + \frac{P_{sm}}{\Lambda_{\mu sm,rock}} + \frac{P_{fm}}{\Lambda_{\mu fm,rock}} \right) \right]^2 + \left(\frac{P_{spal} \cdot \delta P_{spal}}{N\rho \Lambda_{n,rock}} \right)^2 + \left(\frac{P_{sm} \cdot \delta P_{sm}}{N\rho \Lambda_{\mu sm,rock}} \right)^2 + \left(\frac{P_{fm} \cdot \delta P_{fm}}{N\rho \Lambda_{\mu fm,rock}} \right)^2}$$

(13)

where N , δN and $\delta\bar{\varepsilon}$ are the measured concentration of the studied nuclide, its 1σ uncertainty, and the error in the denudation rates, respectively. δP_i represents the uncertainty in the cosmogenic production rates for spallation and muons. **Basinga** attaches, to the spallogenic production parameters, the uncertainties provided in Martin et al. (2017) as a function of the studied nuclide, the scaling model and the ERA40 database (see table 7 of Martin et al. (2017)). This represents, on average, an uncertainty of less than 10%, consistent with the value proposed in Balco et al. (2008). This uncertainty accounts for variability resulting from both these production rate calibrations and from the spatial scaling (Balco et al., 2008). We attached a value of 20% for both muogenic production uncertainties based on the standard deviation of the surficial SLHL estimate of Braucher et al. (2013). All these values can be easily changed and updated if needed (see online supplementary information).

A more rigorous approach would consider all of the parameters in equation 4 and their related uncertainties but would require a laborious partial derivation. This error propagation could also be performed using a numerical approach based on a Monte Carlo simulation that explores the range of all the input parameters (Puchol et al., 2017). Such an approach would require further developments that are beyond the scope of the present tool.

7. Conclusion

Our sensitivity analysis suggests that inverting denudation rates from the cosmogenic concentration measured at the basin outlet using the analytical approach, which assumes constant attenuation lengths of muons in the rocks and spatially variable denudation rates, remains as accurate as the second, more sophisticated, iterative approach. The attenuation lengths of muons have little impact on the final denudation rates determined whatever the latitude, denudation and

1
2
3 553 relief of the studied basin. The analytical approach is moreover computationally more rapid and
4
5 554 does not require the relatively unrealistic hypothesis that denudation rates are homogenous
6
7 555 throughout the studied basins.

8 556 Consequently, **Basinga** is based on these results and calculates the denudation rates using
9
10 557 the analytical approach (method 2). However, this method neglects past variations in the Earth's
11
12 558 magnetic field. To address this issue, through Basinga we developed a new simplified approach
13
14 559 for correcting for paleomagnetic changes. This approach is based on integration of the production
15
16 560 rates during the equivalent exposure time, which is approximated at the basin scale by dividing
17
18 561 the present-day basin-average production rates by the cosmogenic concentration measured at the
19
20 562 outlet.

21 563 Our analysis also shows that the choice of the scaling model may be critical in some
22
23 564 regions where the Lal/Stone and LSD factors can differ by up to 30% leading to large
24
25 565 discrepancies in the denudation results. Because calibration data are sparse in many regions of the
26
27 566 world, it is difficult to determine which of the two models is the most accurate. New calibration
28
29 567 data sites are therefore needed, especially in regions where the scaling factors determined by two
30
31 568 schemes differ strongly. Until such data are made available, in regions of low relief with a strong
32
33 569 difference between the two models, both models should be used in the calculation to provide a
34
35 570 range of possible denudation values. Consequently, the two models are available in **Basinga**.
36
37 571 However, calculation of scaling factors using the LSD model is computationally longer, which
38
39 572 precludes application of this model to a large dataset. To overcome this limitation, we developed
40
41 573 in Basinga an alternative approach in which the LSD factors are interpolated for the whole basin
42
43 574 from the Lal/Stone factors. This interpolation is based on a polynomial law that is fitted using a
44
45 575 limited number of cells in which both models have been used to calculate scaling factors.

46 576 **Basinga** is a freely available GIS toolbox that provides two independent tools for
47
48 577 computing basin average cosmogenic scaling factors, cosmogenic ^{10}Be , ^3He and ^{21}Ne production
49
50 578 rates, and associated denudation rates, from the cosmogenic concentrations. It presents several
51
52 579 significant improvements with respect to the literature:

53
54
55
56
57
58
59
60 580 (1) it is based on user-friendly interfaces, for which comprehensive instructions and help are
61
62 581 provided. Its use does not require any particular skills in programming.

1
2
3 582 (2) it can be run on either ArcGIS or QGIS. It is therefore the first existing tool which couples a
4
5 583 code-based program to calculate the cosmogenic production and denudation rates with the
6
7 584 powerful skills of a GIS system.

8 585 (3) it computes the scaling factors and cosmogenic rates in a few minutes for several catchments
9
10 586 together and allows quick processing of large datasets.

11 587 (4) it is the first existing tool which calculates the LSD scaling factors at the basin scale

12 588 (5) it is the first tool that provides, at the basin scale, a correction for paleomagnetic changes, ice
13
14 589 cover and geology.

15
16
17 590 **Basinga** can be easily downloaded from the Online Supplementary Information and installed
18
19 591 following the instructions "Getting Started" document, also provided online. The
20
21 592 parameterization can be easily updated or changed if needed following the instructions given in
22
23 593 the "Getting Started" document.

24 594

25 595 **Acknowledgements**

26
27 596 We thank Jérôme Lavé and Maarten Lupker for fruitful discussions about cosmogenic nuclides
28
29 597 and denudation rates. We also thank Pauline Collon and Christine Fay-Varnier for their
30
31 598 assistance and help with programming in Python. We are also thankful to the associate editor and
32
33 599 two anonymous reviewers for their reading and comments which greatly improved the quality of
34
35 600 this manuscript. We dedicate this work to the fictional, but Nobel-Prize-worthy Sheldon Cooper,
36
37 601 from Caltech, who greatly inspired the name of our tool. This is CRPG contribution 2692.

38 602

39 603

40 604 **References**

- 41
42
43 605 Balco, G., 2017. Production rate calculations for cosmic-ray-muon-produced ^{10}Be and ^{26}Al
44
45 606 benchmarked against geological calibration data. *Quat. Geochronol.* 39, 150–173.
46
47 607 doi:10.1016/j.quageo.2017.02.001
- 48 608 Balco, G., Briner, J., Finkel, R.C., Rayburn, J.A., Ridge, J.C., Schaefer, J.M., 2009. Regional
49
50 609 beryllium-10 production rate calibration for late-glacial northeastern North America. *Quat.*
51
52 610 *Geochronol.* 4, 93–107. doi:10.1016/j.quageo.2008.09.001
- 53 611 Balco, G., Stone, J.O., Lifton, N.A., Dunai, T.J., 2008. A complete and easily accessible means of
54
55 612 calculating surface exposure ages or erosion rates from ^{10}Be and ^{26}Al measurements. *Quat.*

- 1
2
3 613 Geochronol. 3, 174–195. doi:10.1016/j.quageo.2007.12.001
4
5 614 Bierman, P., Steig, E.J., 1996. ESTIMATING RATES OF DENUDATION USING
6 615 COSMOGENIC ISOTOPE ABUNDANCES IN SEDIMENT. *Earth Surf. Process.*
7 616 *Landforms* 21, 125–139.
8
9
10 617 Borchers, B., Marrero, S., Balco, G., Caffee, M., 2015. Geological Calibration of Spallation
11 618 Production Rates in the CRONUS-Earth Project.
12
13 619 Braucher, R., Bourlès, D., Merchel, S., Vidal Romani, J., Fernandez-Mosquera, D., Marti, K.,
14 620 Léanni, L., Chauvet, F., Arnold, M., Auma??tre, G., Keddadouche, K., 2013. Determination
15 621 of muon attenuation lengths in depth profiles from in situ produced cosmogenic nuclides.
16 622 *Nucl. Instruments Methods Phys. Res. Sect. B Beam Interact. with Mater. Atoms* 294, 484–
17 623 490. doi:10.1016/j.nimb.2012.05.023
18
19 624 Braucher, R., Merchel, S., Borgomano, J., Bourlès, D.L., 2011. Production of cosmogenic
20 625 radionuclides at great depth : A multi element approach. *Earth Planet. Sci. Lett.* 309, 1–9.
21 626 doi:10.1016/j.epsl.2011.06.036
22
23 627 Brown, E.T., Stallard, R.F., Larsen, M.C., Raisbeck, G.M., Yiou, F., 1995. Denudation rates
24 628 determined from the accumulation of in situ-produced ^{10}Be in the Luquillo Experimental
25 629 Forest, Puerto Rico. *Earth Planet. Sci. Lett.* 129, 193–202.
26
27 630 Carretier, S., Regard, V., Vassallo, R., Aguilar, G., Martinod, J., Riquelme, R., Christophoul, F.,
28 631 Charrier, R., Gayer, E., Fariás, M., Audin, L., Lagane, C., 2015. Differences in ^{10}Be
29 632 concentrations between river sand, gravel and pebbles along the western side of the central
30 633 Andes. *Quat. Geochronol.* 27, 33–51. doi:10.1016/j.quageo.2014.12.002
31
32 634 Charreau, J., Blard, P.H., Puchol, N., Avouac, J.P., Lallier-Vergès, E., Bourlès, D., Braucher, R.,
33 635 Gallaud, A., Finkel, R., Jolivet, M., Chen, Y., Roy, P., 2011. Paleo-erosion rates in Central
34 636 Asia since 9Ma: A transient increase at the onset of Quaternary glaciations? *Earth Planet.*
35 637 *Sci. Lett.* 304, 85–92. doi:10.1016/j.epsl.2011.01.018
36
37 638 Chmeleff, J., von Blanckenburg, F., Kossert, K., Jakob, D., 2010. Determination of the ^{10}Be
38 639 half-life by multicollector ICP-MS and liquid scintillation counting. *Nucl. Instruments*
39 640 *Methods Phys. Res. Sect. B Beam Interact. with Mater. Atoms* 268, 192–199.
40
41 641 Danielson, J.J., Gesch, D.B., 2011. Global Multi-resolution Terrain Elevation Data 2010. U.S.
42 642 *Geol. Surv. Open-File Rep.* 2011 1073, 26 p.
43
44 643 Delunel, R., van der Beek, P.A., Carcaillet, J., Bourlès, D.L., Valla, P.G., 2010. Frost-cracking
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

- 1
2
3 644 control on catchment denudation rates: Insights from in situ produced ^{10}Be concentrations
4 645 in stream sediments (Ecrins–Pelvoux massif, French Western Alps). *Earth Planet. Sci. Lett.*
5 646 293, 72–83. doi:10.1016/j.epsl.2010.02.020
6
7
8 647 Derrieux, F., Siame, L.L., Bourlès, D.L., Chen, R., Braucher, R., Léanni, L., Lee, J., Chu, H.,
9 648 Byrne, T.B., 2014. How fast is the denudation of the Taiwan mountain belt ? Perspectives
10 649 from in situ cosmogenic ^{10}Be . *J. Asian Earth Sci.* 88, 230–245.
11 650 doi:10.1016/j.jseaes.2014.03.012
12
13 651 Desilets, D., Zreda, M., Prabu, T., 2006. Extended scaling factors for in situ cosmogenic
14 652 nuclides: New measurements at low latitude. *Earth Planet. Sci. Lett.* 246, 265–276.
15
16 653 Dibiase, R.A., 2018. Increasing vertical attenuation length of cosmogenic nuclide production on
17 654 steep slopes negates topographic shielding corrections for catchment erosion rates. *Earth*
18 655 *Surf. Dyn. Discuss.* 1–17.
19
20 656 Dunai, T.J., 2001. Influence of secular variation of the geomagnetic field on production rates of
21 657 in situ produced cosmogenic nuclides. *Earth Planet. Sci. Lett.* 193, 197–212.
22
23 658 Dymond, J.R., Betts, H.D., Schierlitz, C.S., 2010. An erosion model for evaluating regional land-
24 659 use scenarios. *Environ. Model. Softw.* 25, 289–298. doi:10.1016/j.envsoft.2009.09.011
25
26 660 Fox, M., Leith, K., Bodin, T., Balco, G., Shuster, D.L., 2015. Rate of fluvial incision in the
27 661 Central Alps constrained through joint inversion of detrital ^{10}Be and thermochronometric
28 662 data. *Earth Planet. Sci. Lett.* 411, 27–36. doi:10.1016/j.epsl.2014.11.038
29
30 663 Godard, V., Bourles, D.L., Spinabella, F., Burbank, D.W., Bookhagen, B., Fisher, G.B., Moulin,
31 664 A., Leanni, L., 2014. Dominance of tectonics over climate in Himalayan denudation.
32 665 *Geology* 42, 243–246. doi:10.1130/G35342.1
33
34 666 Godard, V., Burbank, D.W., Bourlès, D.L., Bookhagen, B., Braucher, R., Fisher, G.B., 2012.
35 667 Impact of glacial erosion on ^{10}Be concentrations in fluvial sediments of the Marsyandi
36 668 catchment, central Nepal. *J. Geophys. Res.* 117, F03013. doi:10.1029/2011JF002230
37
38 669 Gosse, J.C., Phillips, F.M., 2001. Terrestrial in situ cosmogenic nuclides: theory and application.
39 670 *Quat. Sci. Rev.* 20, 1475–1560.
40
41 671 Guillon, H., Mugnier, J., Buoncristiani, J., Carcaillet, J., Godon, C., Beek, P. Van Der, Vassallo,
42 672 R., 2015. Improved discrimination of subglacial and periglacial erosion using ^{10}Be
43 673 concentration measurements in subglacial and supraglacial sediment load of the Bossons
44 674 glacier (Mont Blanc massif , France) 1215, 1202–1215. doi:10.1002/esp.3713
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

- 1
2
3 675 Heisinger, B., Lal, D., Jull, A.J.T., Kubik, P., Ivy-Ochs, S., Knie, K., Nolte, E., 2002a. Production
4 of selected cosmogenic radionuclides by muons; 2. Capture of negative muons. *Earth Planet.*
5 676 *Sci. Lett.* 200 , 357–369.
6
7 677
8 678 Heisinger, B., Lal, D., Jull, A.J.T., Kubik, P., Ivy-Ochs, S., Neumaier, S., Knie, K., Lazarev, V.,
9 679 Nolte, E., 2002b. Production of selected cosmogenic radionuclides by muons; 1. Fast
10 680 muons. *Earth Planet. Sci. Lett.* 200, 345–355.
11
12 681 Herman, F., Rhodes, E.J., Braun, J., Heiniger, L., 2010. Uniform erosion rates and relief
13 682 amplitude during glacial cycles in the Southern Alps of New Zealand , as revealed from
14 683 OSL-thermochronology. *Earth Planet. Sci. Lett.* doi:10.1016/j.epsl.2010.06.019
15
16 684 Hippe, K., Kober, F., Zeilinger, G., Ivy-Ochs, S., Maden, C., Wacker, L., Kubik, P.W., Wieler,
17 685 R., 2012. Quantifying denudation rates and sediment storage on the eastern Altiplano,
18 686 Bolivia, using cosmogenic ^{10}Be , ^{26}Al , and in situ ^{14}C . *Geomorphology* 179, 58–70.
19 687 doi:10.1016/j.geomorph.2012.07.031
20
21 688 Kaplan, M.R., Strelin, J.A., Schaefer, J.M., Denton, G.H., Finkel, R.C., Schwartz, R., Putnam,
22 689 A.E., Vandergoes, M.J., Goehring, B.M., Travis, S.G., 2011. In-situ cosmogenic ^{10}Be
23 690 production rate at Lago Argentino , Patagonia : Implications for late-glacial climate
24 691 chronology. *Earth Planet. Sci. Lett.* doi:10.1016/j.epsl.2011.06.018
25
26 692 Kelly, M.A., Lowell, T.V., Applegate, P.J., Phillips, F.M., Schaefer, J.M., Smith, C.A., Kim, H.,
27 693 Leonard, K.C., Hudson, A.M., 2015. A locally calibrated, late glacial ^{10}Be production rate
28 694 from a low-latitude, high-altitude site in the Peruvian Andes. *Quat. Geochronol.* 26, 70–85.
29
30 695 Kober, F., Al, V., Ivy-ochs, S., Kubik, P.W., Wieler, R., 2011. The cosmogenic Ne – ^{10}Be data
31 696 Ne production rate in quartz evaluated on a large set of existing 302, 163–171.
32 697 doi:10.1016/j.epsl.2010.12.008
33
34 698 Lal, D., 1991. Cosmic ray labeling of erosion surfaces: in situ nuclide production rates and
35 699 erosion models. *Earth Planet. Sci. Lett.* 104, 424–439.
36
37 700 Lifton, N., 2015. Implications of two Holocene time-dependent geomagnetic models for
38 701 cosmogenic nuclide production rate scaling. *Earth Planet. Sci. Lett.* 433, 257–268.
39 702 doi:10.1016/j.epsl.2015.11.006
40
41 703 Lifton, N., Sato, T., Dunai, T.J., 2014. Scaling in situ cosmogenic nuclide production rates using
42 704 analytical approximations to atmospheric cosmic-ray fluxes. *Earth Planet. Sci. Lett.* 386,
43 705 149–160. doi:10.1016/j.epsl.2013.10.052
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

- 1
2
3 706 Lifton, N.A., Bieber, J.W., Clem, J.M., Duldig, M.L., Evenson, P., Humble, J.E., Pyle, R., 2005.
4
5 707 Addressing solar modulation and long-term uncertainties in scaling secondary cosmic rays
6
7 708 for in situ cosmogenic nuclide applications. *Earth Planet. Sci. Lett.* 239, 140–161.
- 8
9 709 Lupker, M., Blard, P.H., Lavé, J., France-Lanord, C., Leanni, L., Puchol, N., Charreau, J.,
10
11 710 Bourlès, D., 2012. ^{10}Be -derived Himalayan denudation rates and sediment budgets in the
12
13 711 Ganga basin. *Earth Planet. Sci. Lett.* 333-334, 146–156. doi:10.1016/j.epsl.2012.04.020
- 14
15 712 Marrero, S.M., Phillips, F.M., Borchers, B., Lifton, N., Aumer, R., Balco, G., 2015. Cosmogenic
16
17 713 Nuclide Systematics and the CRONUScale Program. *Quat. Geochronol.* 31, 160–187.
18
19 714 doi:10.1016/j.quageo.2015.09.005
- 20
21 715 Martin, L.C.P., Blard, P.H., Balco, G., Lavé, J., Delunel, R., Lifton, N., Laurent, V., 2017. The
22
23 716 CREp program and the ICE-D production rate calibration database : A fully parameterizable
24
25 717 and updated online tool to compute cosmic- ray exposure ages. *Quat. Geochronol.* 38, 25–
26
27 718 49. doi:10.1016/j.quageo.2016.11.006
- 28
29 719 Martin, L.C.P., Blard, P.-H., Lavé, J., Braucher, R., Lupker, M., Condom, T., Charreau, J.,
30
31 720 Mariotti, V., Davy, E., 2015. In situ cosmogenic ^{10}Be production rate in the High Tropical
32
33 721 Andes. *Quat. Geochronol.* 30, 54–68. doi:10.1016/j.quageo.2015.06.012
- 34
35 722 Molliex, S., Rabineau, M., Leroux, E., Bourlès, D.L., Authemayou, C., Aslanian, D., Chauvet, F.,
36
37 723 Civet, F., Jouët, G., 2016. Multi-approach quantification of denudation rates in the Gulf of
38
39 724 Lion source-to-sink system (SE France). *Earth Planet. Sci. Lett.* 444, 101–115.
40
41 725 doi:10.1016/j.epsl.2016.03.043
- 42
43 726 Mudd, M.S., Harel, M.A., Hurst, M.D., Grieve, S.W.D., Marrero, S.M., 2016. The CAIRN
44
45 727 method: Automated, reproducible calculation of catchment-averaged denudation rates from
46
47 728 cosmogenic nuclide concentrations. *Earth Surf. Dyn.* 4, 655–674. doi:10.5194/esurf-4-655-
48
49 729 2016
- 50
51 730 Muscheler, R., Beer, J., Kubik, P.W., Synal, H. a., 2005. Geomagnetic field intensity during the
52
53 731 last 60,000 years based on ^{10}Be and ^{36}Cl from the Summit ice cores and ^{14}C . *Quat. Sci.*
54
55 732 *Rev.* 24, 1849–1860. doi:10.1016/j.quascirev.2005.01.012
- 56
57 733 Nishiizumi, K., Kohl, C.P., Winterer, E.L., Klein, J., Middleton, R., 1989. Cosmic ray production
58
59 734 rates of ^{10}Be and ^{26}Al in quartz from glacially polished rocks. *J. Geophys. Res.* 94, 907–
60
735 917. doi:10.1029/JB094iB12p17907
- 736
Phillips, F.M., Argento, D.C., Balco, G., Caffee, M.W., Clem, J., Dunai, T.J., Finkel, R.,

- 1
2
3 737 Goehring, B., Gosse, J.C., Hudson, A.M., Jull, A.J.T., Kelly, M.A., Kurz, M., Lal, D.,
4 738 Lifton, N., Marrero, S.M., Nishiizumi, K., Reedy, R.C., Schaefer, J., Stone, J.O.H.,
5 739 Swanson, T., Zreda, M.G., 2016. Quaternary Geochronology The CRONUS-Earth Project :
6 740 A synthesis. *Quat. Geochronol.* 31, 119–154. doi:10.1016/j.quageo.2015.09.006
7
8 741 Pigati, J.S., Lifton, N.A., 2004. Geomagnetic effects on time-integrated cosmogenic nuclide
9 742 production with emphasis on in situ ^{14}C and ^{10}Be . *Earth Planet. Sci. Lett.* 226, 193–205.
10 743 Portenga, E.W., Bierman, P.R., 2011. Understanding Earth's eroding surface with ^{10}Be . *GSA*
11 744 *Today* 21, 4–10. doi:10.1130/G1111A.1
12 745 Puchol, N., Charreau, J., Blard, P., Lavé, J., Dominguez, S., Pik, R., Saint-carlier, D., ASTER
13 746 Team, 2017. Limited impact of Quaternary glaciations on denudation rates in central Asia.
14 747 *Geol. Soc. Am. Bull.* 129, 479–499.
15 748 Riccio, S.J., Fitzgerald, P.G., Benowitz, J.A., Roeske, S.M., 2014. The role of thrust faulting in
16 749 the formation of the eastern Alaska Range : Thermochronological constraints from the ...
17 750 *Geochemistry Geophys. Geosystems* 1–23. doi:10.1002/2014TC003646
18 751 Sato, T., Yasuda, H., Niita, K., Sihver, L., 2008. Development of PARMA : PHITS-based
19 752 Analytical Radiation Model in the Atmosphere Development of PARMA : PHITS-based
20 753 Analytical Radiation Model in the Atmosphere 170, 244–259.
21 754 Schaller, M., Ehlers, T.A., 2006. Limits to quantifying climate driven changes in denudation rates
22 755 with cosmogenic radionuclides 248, 153–167. doi:10.1016/j.epsl.2006.05.027
23 756 Scherler, D., Bookhagen, B., Strecker, M.R., 2014. Tectonic control on ^{10}Be -derived erosion
24 757 rates in the Garhwal Himalaya, India. *J. Geophys. Res. Earth Surf.* 119, 83–105.
25 758 doi:10.1002/2013JF002955
26 759 Schildgen, T.F., Phillips, W.M., Purves, R.S., 2005. Simulation of snow shielding corrections for
27 760 cosmogenic nuclide surface exposure studies. *Geomorphology* 64, 67–85.
28 761 doi:10.1016/j.geomorph.2004.05.003
29 762 Siame, L., Angelier, J., Chen, R., Godard, V., Derrieux, F., Bourlès, D.L., Braucher, R., 2011.
30 763 Erosion rates in an active orogen (NE-Taiwan): A confrontation of cosmogenic
31 764 measurements with river suspended loads. *Quat. Geochronol.* 6, 246–260.
32 765 doi:10.1016/j.quageo.2010.11.003
33 766 Stone, J.O., 2000. Air pressure and cosmogenic isotope production. *J. Geophysical Res.* 105,
34 767 753–759.
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

- 1
2
3 768 Stroeven, A.P., Heyman, J., Fabel, D., Björck, S., Caffee, M.W., Fredin, O., Harbor, J.M., 2015.
4
5 769 A new Scandinavian reference 10Be production rate. *Quat. Geochronol.* 29, 104–115.
6
7 770 doi:10.1016/j.quageo.2015.06.011
- 8
9 771 Uppala, S.M., KÅllberg, P.W., Simmons, A.J., Andrae, U., Bechtold, V.D.C., Fiorino, M.,
10 772 Gibson, J.K., Haseler, J., Hernandez, A., Kelly, G.A., Li, X., Onogi, K., Saarinen, S., Sokka,
11 773 N., Allan, R.P., Andersson, E., Arpe, K., Balmaseda, M.A., Beljaars, A.C.M., Berg, L. Van
12 774 De, Bidlot, J., Bormann, N., Caires, S., Chevallier, F., Dethof, A., Dragosavac, M., Fisher,
13 775 M., Fuentes, M., Hagemann, S., Hólm, E., Hoskins, B.J., Isaksen, L., Janssen, P.A.E.M.,
14 776 Jenne, R., McNally, A.P., Mahfouf, J.-F., Morcrette, J.-J., Rayner, N.A., Saunders, R.W.,
15 777 Simon, P., Sterl, A., Trenberth, K.E., Untch, A., Vasiljevic, D., Viterbo, P., Woollen, J.,
16 778 2005. The ERA-40 re-analysis. *Q. J. R. Meteorol. Soc.* 131, 2961–3012.
17 779 doi:10.1256/qj.04.176
- 18
19 780 Valet, J., Meynadier, L., Guyodo, Y., 2005. Geomagnetic dipole strength and reversal rate over
20 781 the past two million years 435, 5–8. doi:10.1038/nature03674
- 21
22 782 Whipp, D.M., Ehlers, T.A., Blythe, A.E., Huntington, K.W., Hodges, K. V, Burbank, D.W.,
23 783 2007. Plio-Quaternary exhumation history of the central Nepalese Himalaya : 2 .
24 784 Thermokinematic and thermochronometer age prediction model 26, 1–23.
25 785 doi:10.1029/2006TC001991
- 26
27 786 Wittmann, H., Blanckenburg, F. Von, Kruesmann, T., Norton, K.P., Kubik, P.W., 2007. Relation
28 787 between rock uplift and denudation from cosmogenic nuclides in river sediment in the
29 788 Central Alps of Switzerland 112, 1–20. doi:10.1029/2006JF000729
- 30
31 789 Wittmann, H., Blanckenburg, F. Von, Maurice, L., Guyot, J., Filizola, N., Kubik, P.W., 2011.
32 790 Sediment production and delivery in the Amazon River basin quantified by in situ –
33 791 produced cosmogenic nuclides and recent river loads. doi:10.1130/B30317.1
- 34
35 792 Wittmann, H., von Blanckenburg, F., 2009. Cosmogenic nuclide budgeting of floodplain
36 793 sediment transfer. *Geomorphology* 109, 246–256. doi:10.1016/j.geomorph.2009.03.006
37
38
39
40
41
42
43
44
45
46
47
48
49

795 **Figure captions and tables:**

50 796 **Fig. 1:** Worldwide comparison of the LSD and Lal/Stone models. The map at the top shows the
51
52
53 797 difference (in %) between scaling factors calculated using the Lal/Stone and the LSD models,
54
55 798 based on data from the ERA40 and the GMTED2010 databases (Danielson and Gesch, 2011;
56
57
58
59
60

1
2
3 799 Uppala et al., 2005). The white circles indicate the locations of several vertical profiles where we
4
5 800 also calculated the difference between the two models, as shown in the figures below the map.
6
7 801 The red circles show the locations of the calibration data sites according to the ICE-D database
8
9 802 (Martin et al., 2017). The yellow stars show the location of the drainage basins that are studied
10
11 803 for the sensitivity analyze.

12 804
13
14 805 **Fig. 2:** a. Maximum elevation against latitude calculated using a 1° interval. The red circles
15
16 806 indicate the positions of the calibration data sites; b. possible ranges for the difference between
17
18 807 the LSD and Lal/Stone scaling model against latitude using a 10° interval.

19 808
20
21 809 **Fig. 3:** Variation in the attenuation length of muons in rock for ^{10}Be against the denudation rates
22
23 810 and atmospheric pressures if a single exponential is assumed (modified after Balco, 2017).

24
25 811
26
27 812 **Fig. 4:** Flow chart showing the process used to compute and invert the theoretical basin
28
29 813 average cosmogenic concentration of the studied basins in order to test the sensitivity of the
30
31 814 methods and scaling model.

32 815
33
34 816 **Fig. 5:** Differences between the theoretical and inverted denudation rates as a function of the
35
36 817 theoretical denudation for the two methods. The theoretical concentrations were calculated
37
38 818 either without (top) or with (bottom) time integration.

39
40 819
41
42 820 **Fig. 6:** Results of inversion using the analytical approach (method 3) and the Lal/Stone model
43
44 821 for (a) the Marshyangdi basin and (b) the Susitna basin (see figure 1 for location). The frequency
45
46 822 diagrams show the distribution of elevation and denudation rates throughout the basin. The
47
48 823 vertical bars indicate the theoretical mean (red) and the results of the inversion if the time is
49
50 824 integrated or not. The other diagrams show the Stone factors against the LSD factor and the
51
52 825 difference between the two as a function of elevation for 10000 cells throughout the basin. The
53
54 826 red and blue dots were calculated without and with time integration, respectively.

55
56
57
58
59
60

1
2
3 828 **Fig. 7:** Results of inversion with time integration using the analytical approach (method 3) and
4 the Lal/Stone model for the Maroni basin (see figure 1 for location). See figure 5 for more
5 829 information.
6
7 830
8
9 831

10 832 **Fig. 8:** Computing time using Basinga. (a) Computing time needed to calculate the LSD scaling
11 833 factors with time integration as a function of the number of cells and the surface area of the
12 834 basin (cell size = 90m). (b) Computing time needed to calculate the Lal/Stone factors and the
13 835 LSD using a polynomial fit without time integration. All calculations were performed on a laptop
14 836 with a 2.6GHz processor.
15
16
17
18
19 837

20
21 838 **Fig. 9:** Mean and maximum difference between the theoretical, true LSD scaling factors and the
22 839 LSD factors calculated from the Lal/stone factors and a polynomial law fitted using a limited
23 840 number of cells. The differences are plotted against the number of cells used for the fit and are
24 841 shown for different polynomial degrees.
25
26
27
28 842

29
30 843 **Fig. 10:** Differences in % between the "true" basin average denudation and the inverted
31 844 denudation rate when the attenuation length of muons in the rocks is assumed to be constant
32 845 with a value of 4814 g/cm^2 (Braucher et al., 2013). The difference is plotted as a function of the
33 846 relief of the basin and the distribution of the denudation within the basin. For computational
34 847 efficiency and simplicity, the true rates were calculated using the Lal/Stone factors. The results
35 848 were determined for 5° latitude but are very similar for the other latitudes. The differences are
36 849 always negative because the constant value of the attenuation length that is used for the
37 850 inversion is higher than the pre-calculated values of Balco (2017) (**Fig. 3**).
38
39
40
41
42
43
44
45 851

46 852 **Fig. 11:** Contour diagrams showing the biases (in %) of the scaling factors if the time is not
47 853 integrated to account for past changes in the Earth's magnetic field. The biases were calculated
48 854 using the LSD model and the Muscheler ^{10}Be atmospheric geomagnetic database (Muscheler et
49 855 al., 2005) for different denudation rates (i.e. characteristic integration time), at different
50 856 elevations and latitudes. The ranges of elevation respect the maximum possible altitude
51
52
53
54
55
56
57
58
59
60

1
2
3 857 observed at each latitude in the GMTED2010 database (Danielson and Gesch, 2011). The
4
5 858 integration times were calculated based on the attenuation length of neutrons in the rocks.
6
7 859

8
9 860 **Table 1** -possible methods used to calculate denudation rates from the cosmogenic concentration
10 861 measured in river sediments.
11
12 862

13
14 863 **Table 2: Results of the sensitivity analysis**

15 864 Inverted denudation rates for the studied basins, calculated using either the Lal/Stone or the LSD
16 865 scaling model and based on either method 1 or 2. The theoretical cosmogenic concentrations
17 866 were calculated throughout the basin either with or without time integration as a function of the
18 867 local denudation, which is a simple linear function of the slope. ϵ_{lit} , $\epsilon_{min}/\epsilon_{max}$ and $\epsilon_{mean\ theo.}$ indicate
19 868 the denudation rates reported in the literature, the minimum and maximum denudation rates
20 869 specified for the calculation, and the theoretical basin average denudation rates obtained based on
21 870 this range of values, respectively.
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

Table 1 -possible methods used to calculate denudation rates from the cosmogenic concentration in river sediments

Method number	Muon production	Attenuation lengths	Time	Watershed topography	Resolution method	Relevant references
1	No	-	No	Single point	Analytical	Brown et al. (1995)
2	Two exponentials	Constant	No	Pixel array	Analytical	This study, Lupker et al. (2012), Fox et al. (2015)
3	Single exponential	Constant	No	Pixel array	Analytical	This study
4	Heisinger's equations	Constant	Yes	Single point	Iterative	Portenga et al. (2011); Balco et al. (2008)
5	Two exponentials	Constant	No	Pixel array	Iterative	Mudd et al., (2017)
6	Single exponential	Effective and interpolated	Yes	Pixel array	Iterative	This study

Table 2: Results of the sensitivity analysis

Inverted denudation rates for the studied basins, calculated using either the Lal/Stone or the LSD scaling model and based on either method 1 or 2. The theoretical cosmogenic concentrations were calculated throughout the basin either with or without time integration as a function of the local denudation, which is a simple linear function of the slope. ϵ_{lit} , $\epsilon_{min}/\epsilon_{max}$ and $\epsilon_{mean\ theo.}$ indicate the denudation rates reported in the literature, the minimum and maximum denudation rates specified for the calculation, and the theoretical basin average denudation rates obtained based on this range of values, respectively.

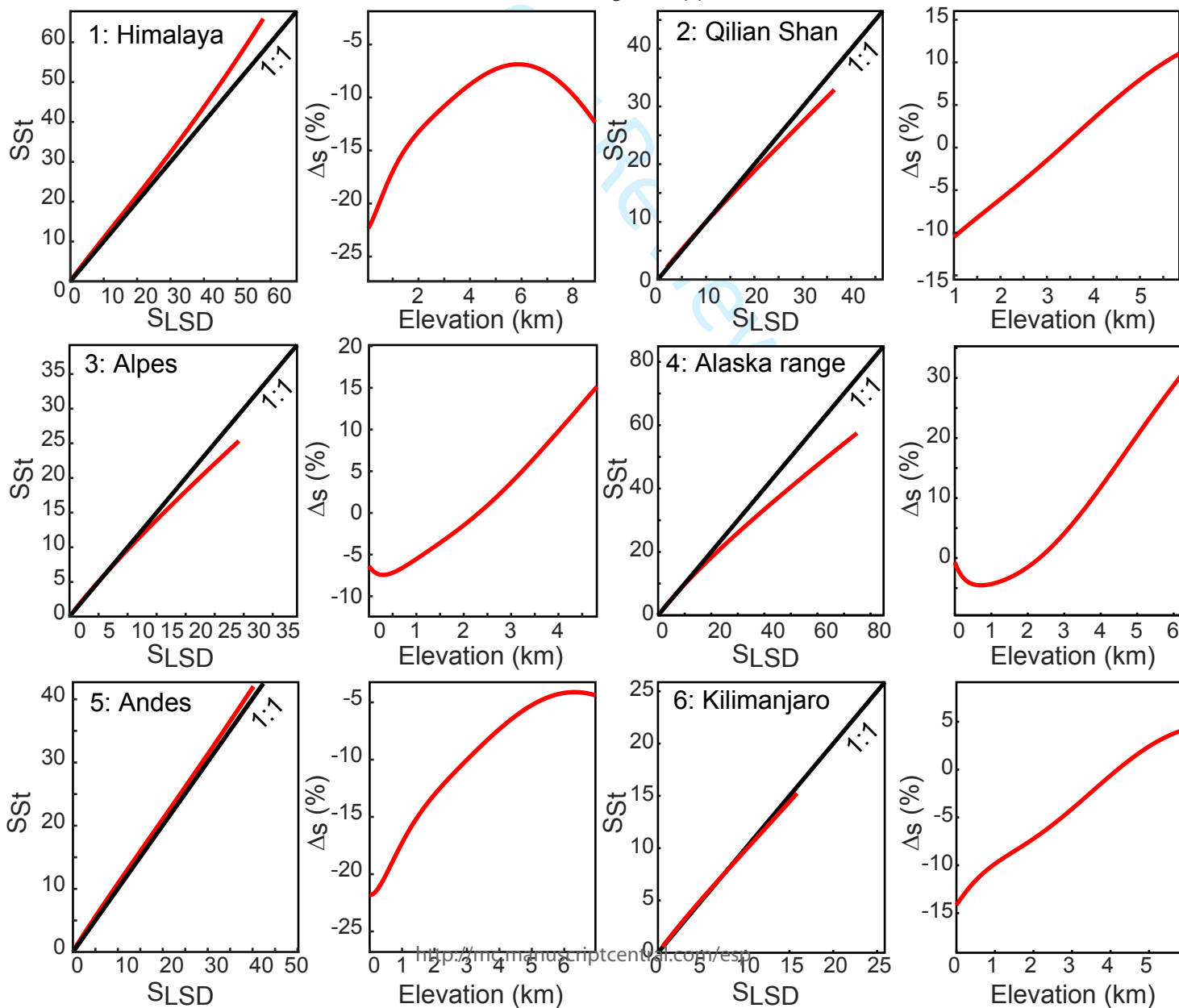
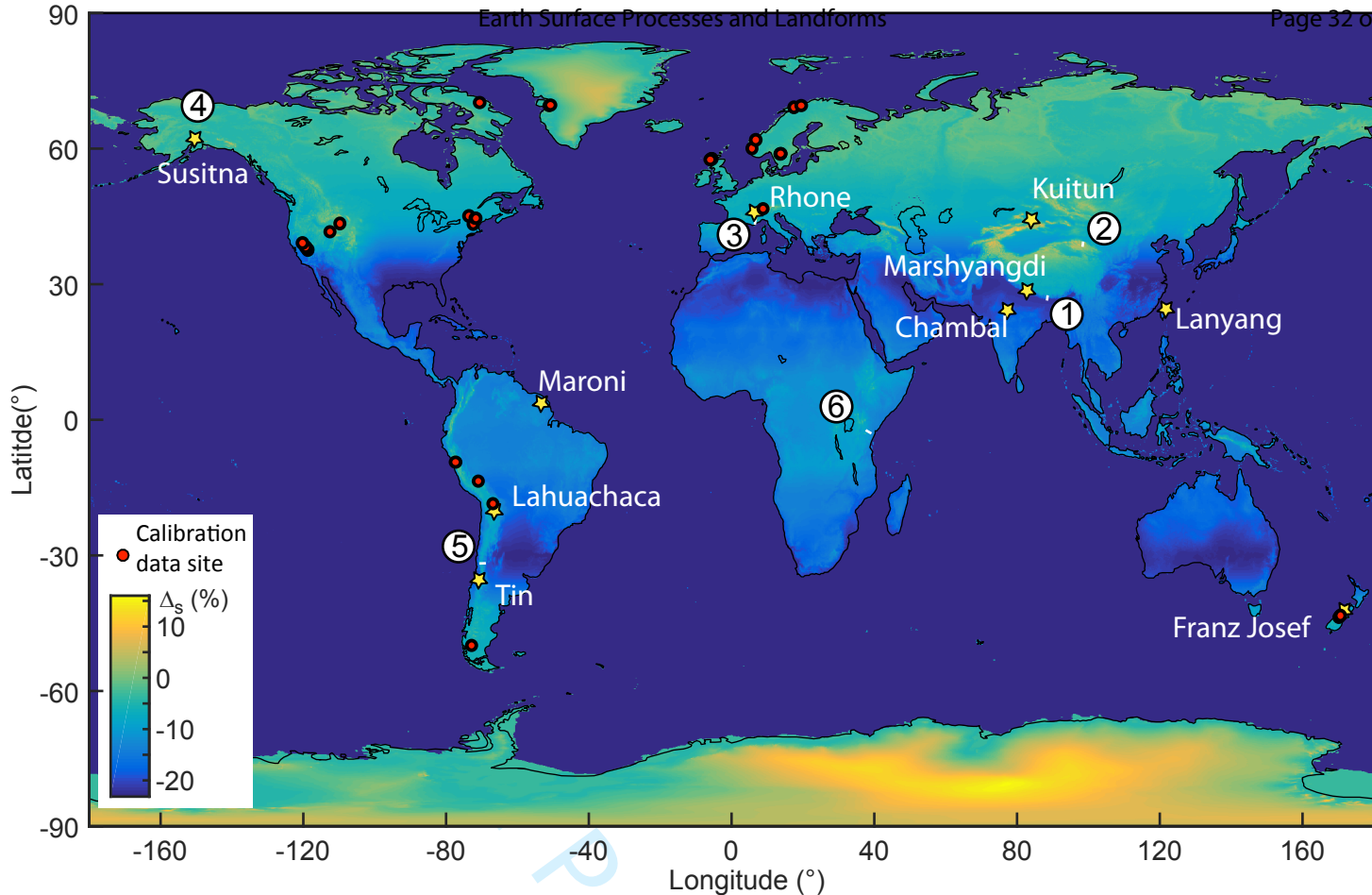
Name of basin	Region	Elevation (m)	ϵ_{lit} (m/Ma)	$\epsilon_{min}/\epsilon_{max}$ (m/Ma)	$\epsilon_{mean\ theo.}$ (m/Ma)	$\epsilon_{inverted}$ (m/Ma) ^a				$\epsilon_{inverted}$ (m/Ma) ^b	
						Method 1		Method 2 (no time)		Method 1	Method 2(time)
						Lal/St	LSD(t=0)	Lal/St	LSD (t=0)	LSD(t=0)	LSD
Marsyangdi	Himalaya	240-7920	100-5000 ¹	0-8000	3058	3063	3060	3337	3330	3110	3337
Susitna	Alaska	30-5350	60-1000 ²	0-3000	423	426	426	526	520	380	539
Maroni	French Guyana	0-900	10 ³	0-100	11	12	11	12	n.a	11	n.a
Kuitun	Tianshan	750-4820	400 ⁴	0-1200	453	454	454	462	463	461	478
Rhône	French Alps	20-4440	118 ⁵	0-800	123	124	124	191	195	124	183
Lahuachaca	Altiplano	3800-4500	3-29 ⁶	0-600	14	14	14	15	15	13	10
Tin	Andies	470-4990	160 ⁷	0-500	164	165	165	173	168	195	164
Chambal	India	120-1240	7 ⁸	0-170	8	9	9	8	n.a	8	n.a
Lanyang	Taiwan	90-3520	2000 ⁹	0-4800	2093	2095	2095	2207	2230	2153	2230
Franz Josef	New Zealand Alps	10-3090	1800-7000 ¹⁰	0-8000	2977	2982	2982	3419	3430	2934	3430

^aTheoretical concentration calculated without time integration and using either the Lal/Stone or the LSD model

^bTheoretical concentration calculated with time integration using the LSD model only

¹(Godard et al., 2012; Whipp et al., 2007); ²(Riccio et al., 2014); ³(Wittmann et al., 2011); ⁴(Puchol et al., 2017); ⁵(Molliex et al., 2016); ⁶(Hippe et al., 2012); ⁷(Carretier et al., 2015); ⁸(Lupker et al., 2012); ⁹(Siame et al., 2011); ¹⁰(Dymond et al., 2010)

n.a : Because of the size of the basins and their low denudation rates, the calculation using iterative method 2 based on LSD took too long to compute and was not possible



1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

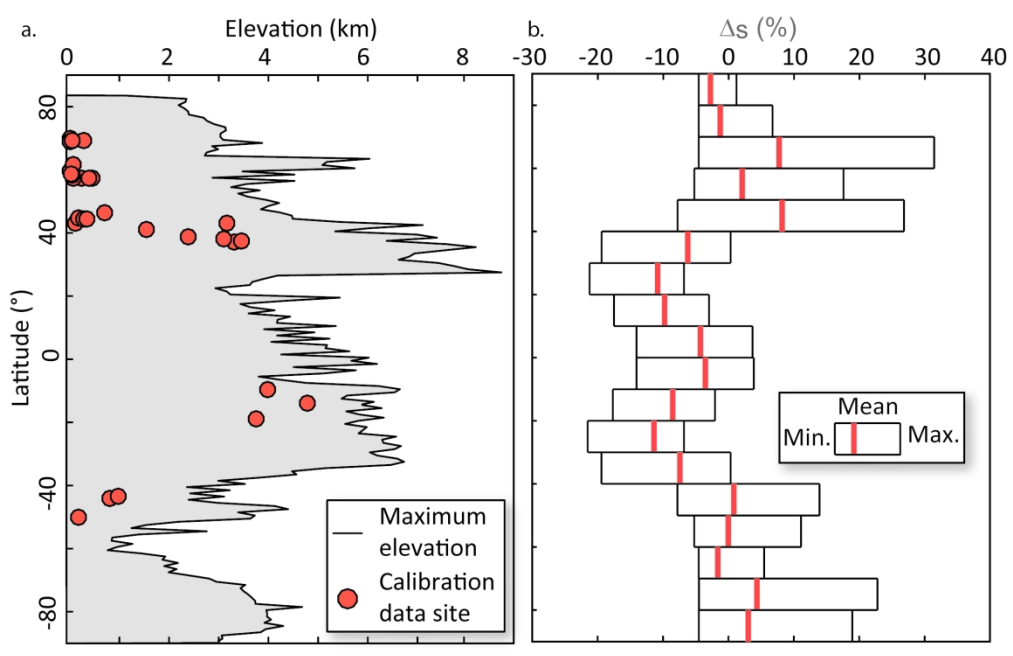


Fig. 2

188x155mm (300 x 300 DPI)

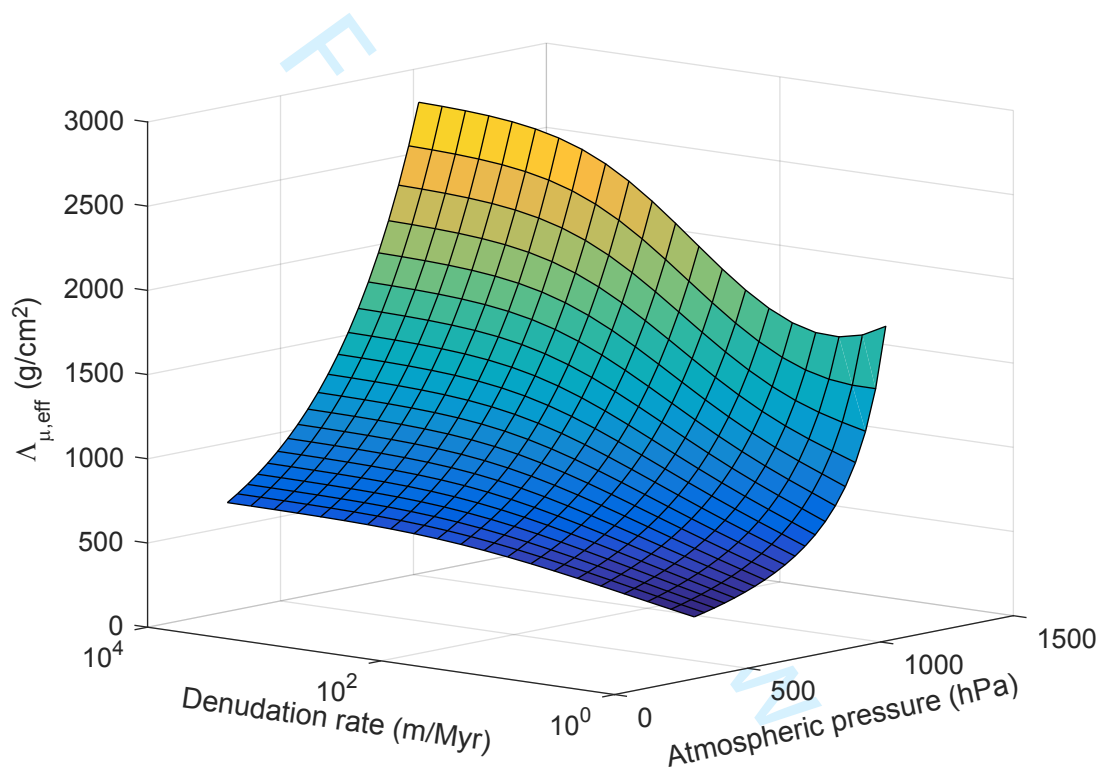


Fig. 3

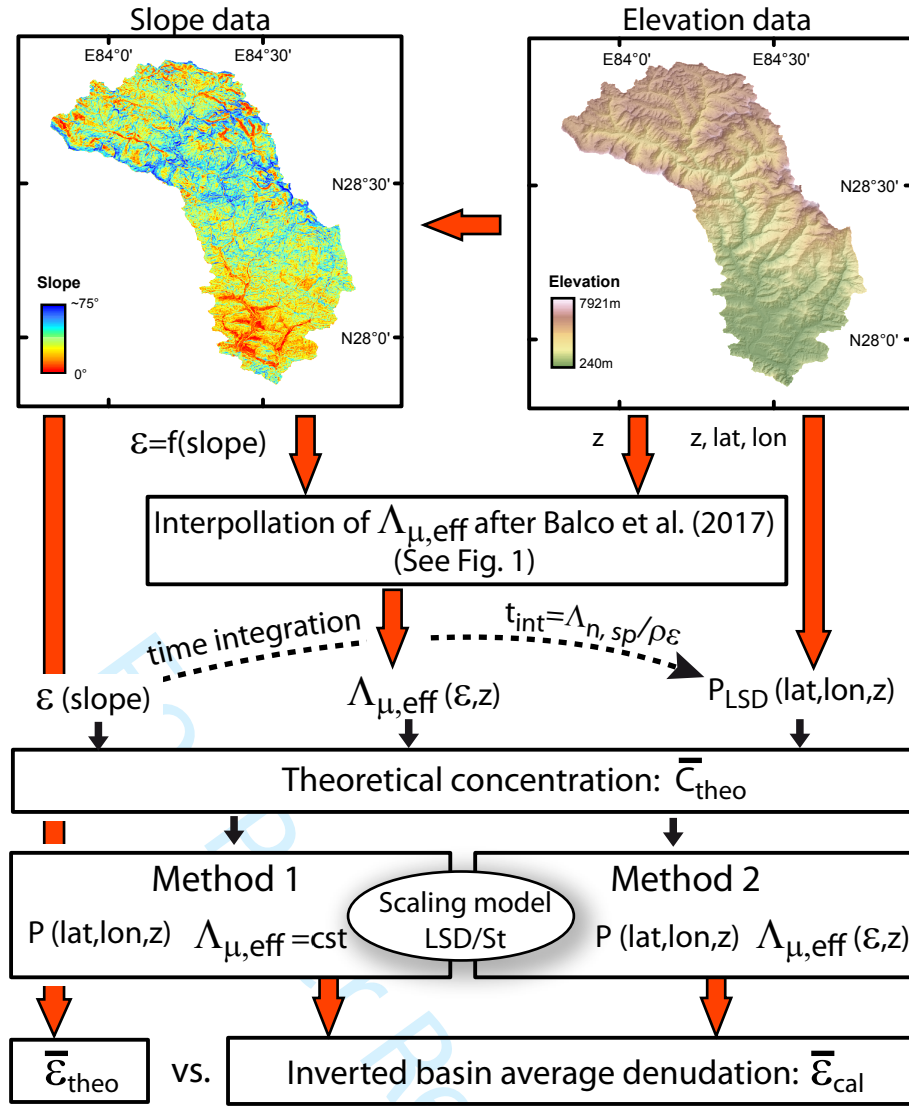


Fig. 4

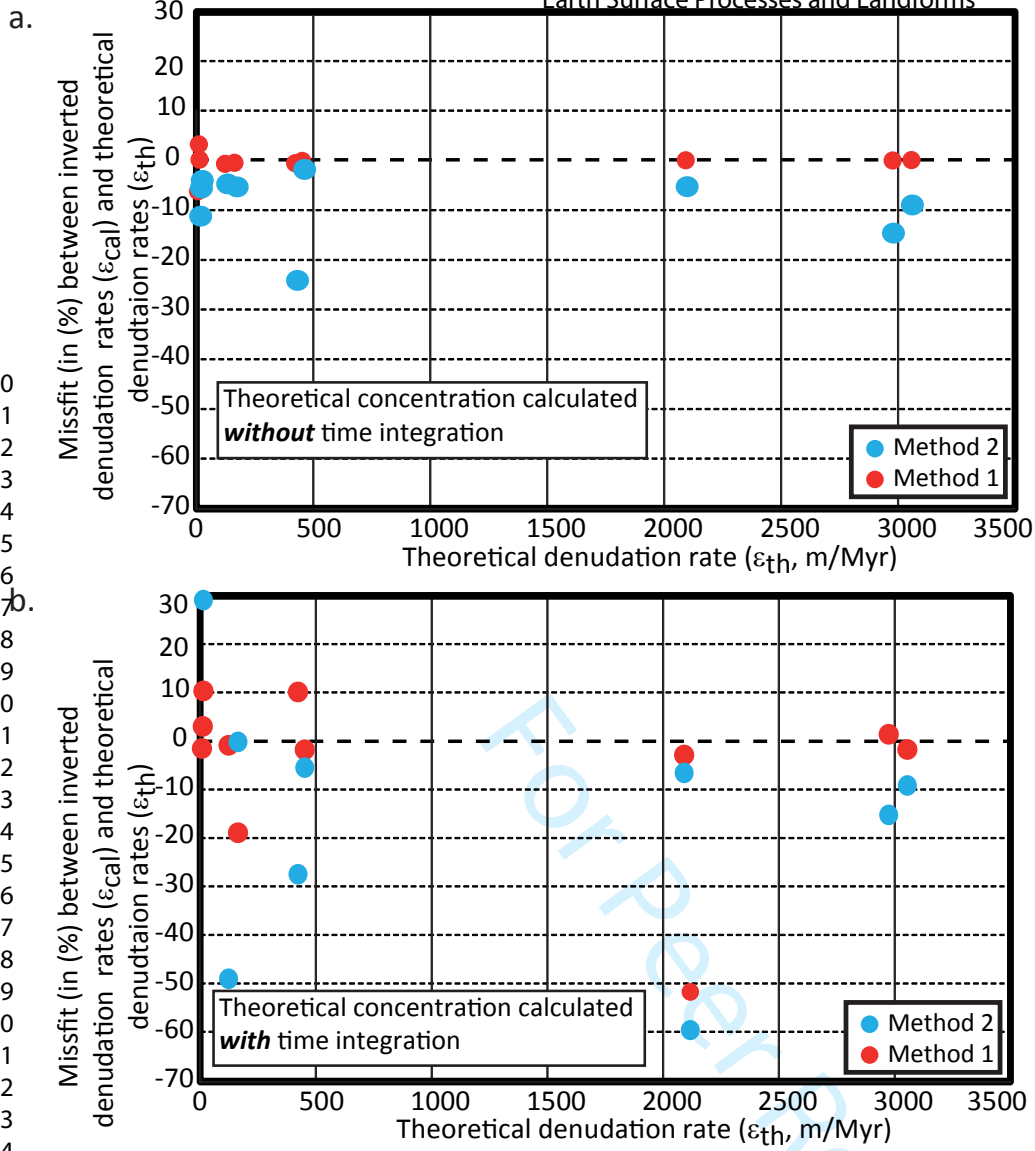
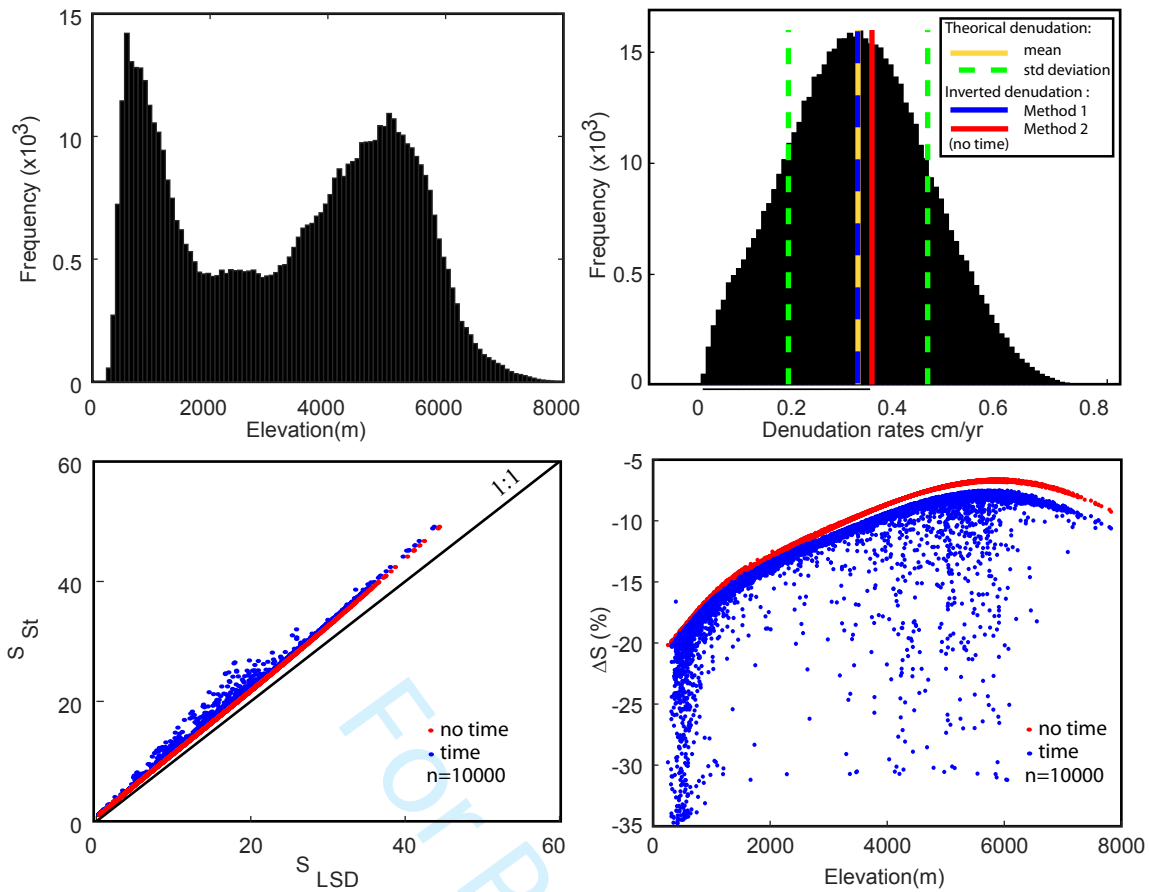


Fig. 5



b. Susitna basin (lat: N62.7330°, lon: E211.3822°)

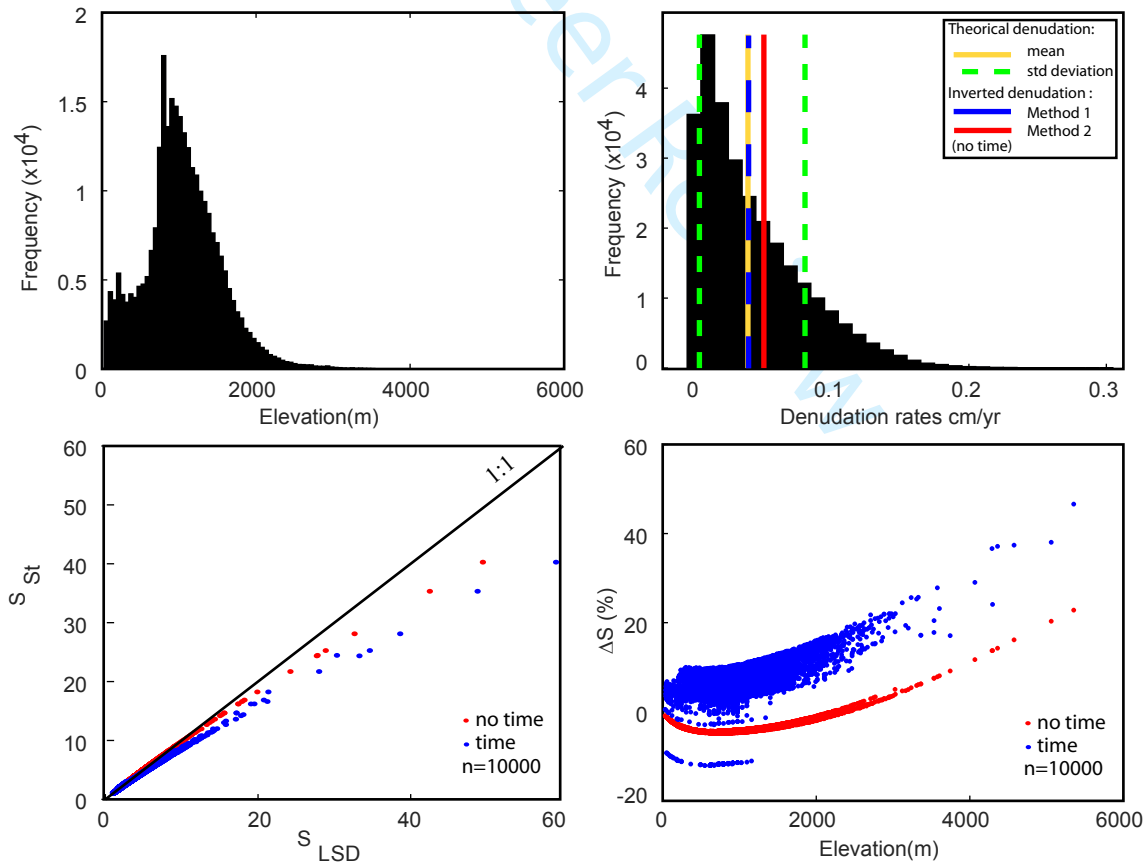


Fig. 6

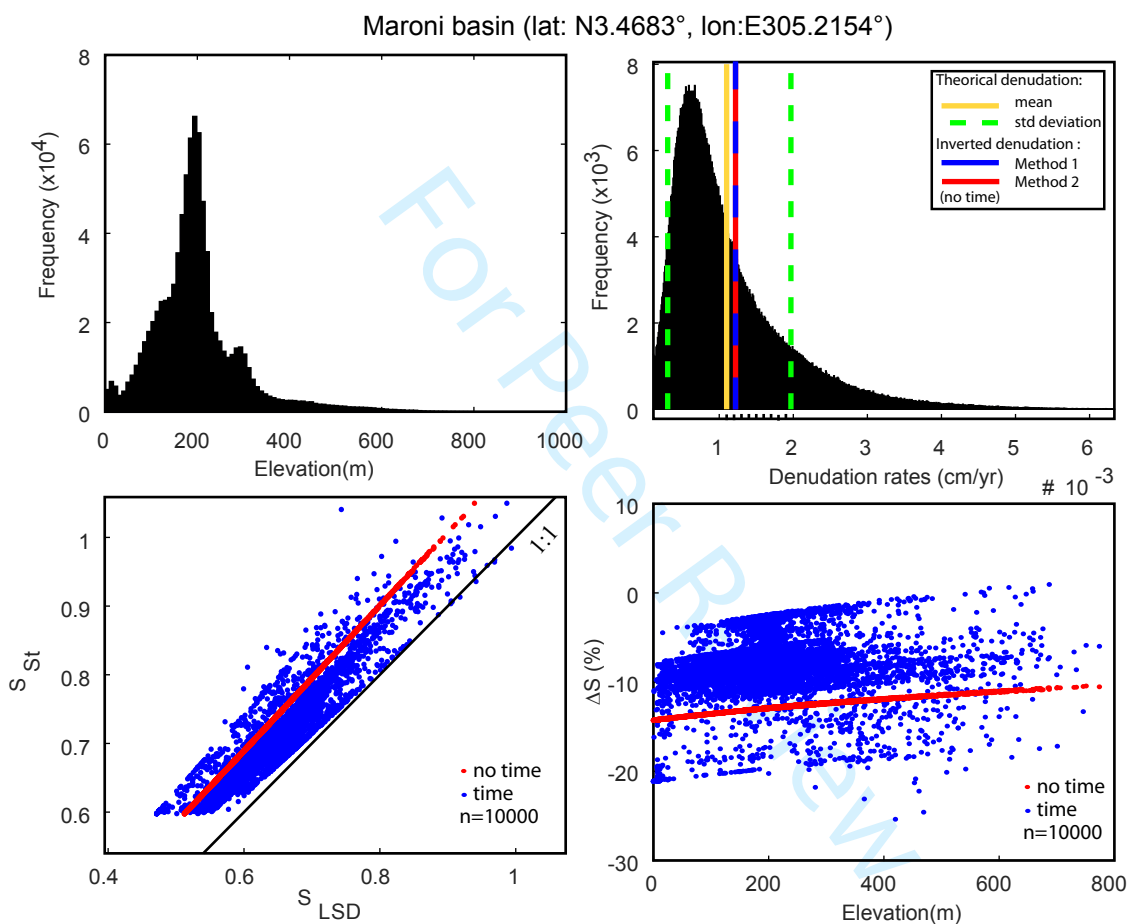


Fig. 7

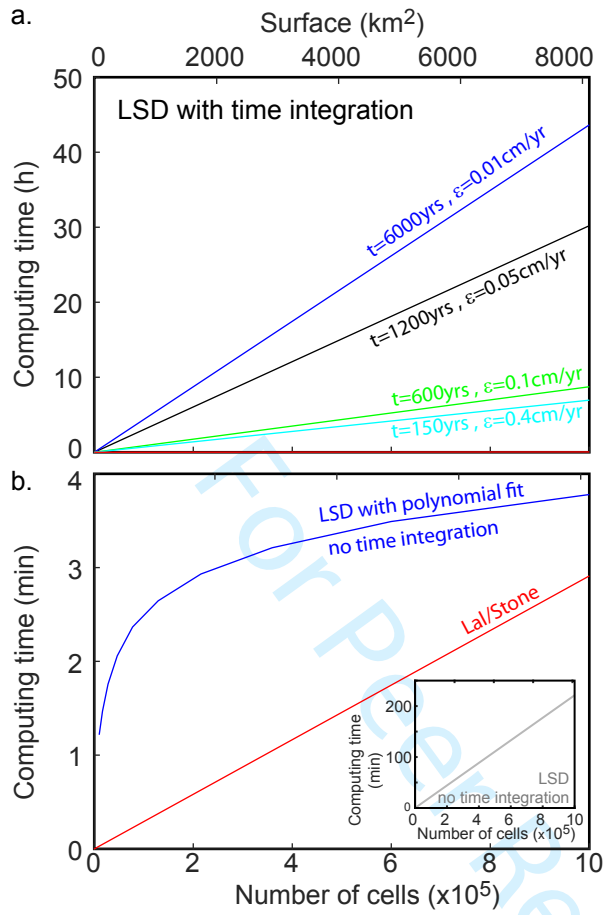


Fig. 8

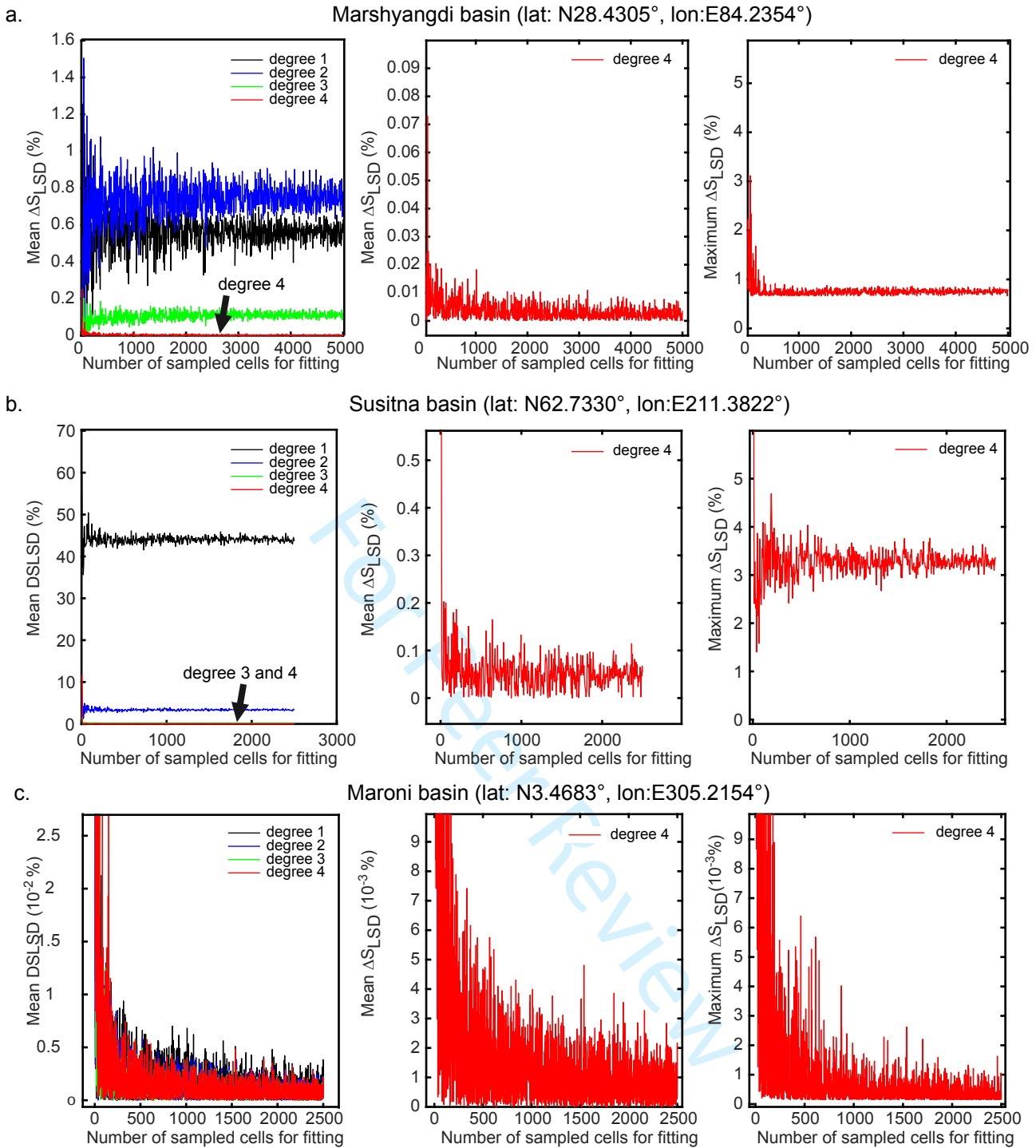


Fig. 9

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

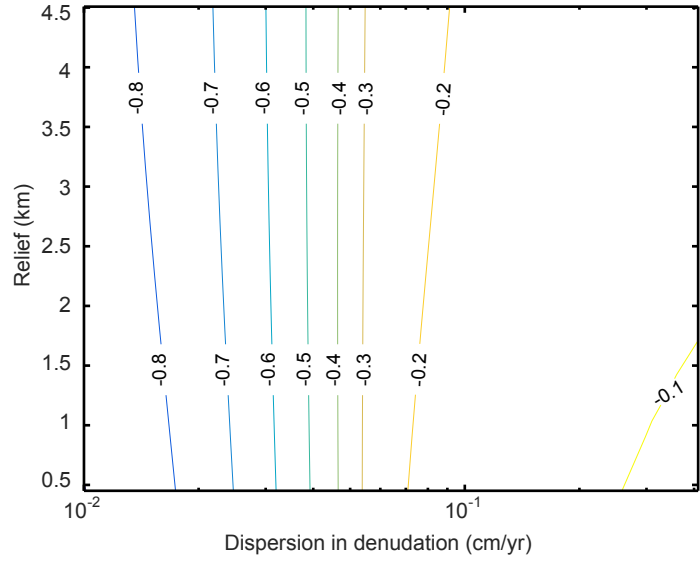


Fig. 10

For Peer Review

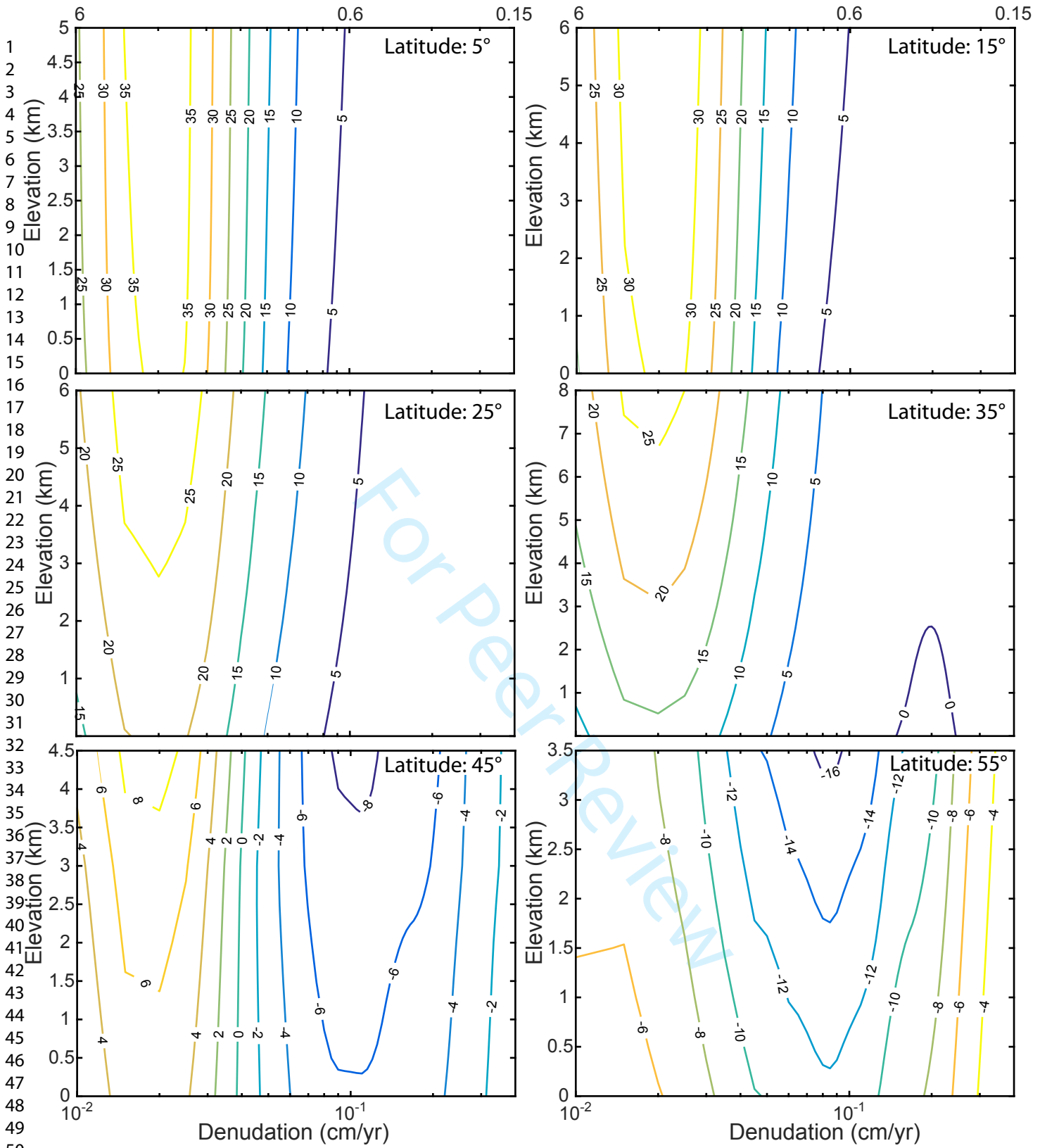


Fig. 11

Online repository of " BASINGA: a cell-by-cell GIS toolbox for computing BASIN average scaling factors, cosmogenic production rates and denudation rates "

Julien Charreau, Pierre-Henri Blard, Jéna Zumaque, Léo C.P. Martin, Tony Delobel and Lucas Szafran

I- Technical description of Basinga

1. General overview of Basinga

Basinga comprises two tools and their associated interfaces (Figs. A and B). The *Production rates* tool (Fig. A) calculates the basin average production rates based on the latitude and altitude of each cell of the studied basins (Fig. C). The minimum requirements are a raster file of the DEM and a shape file of the studied drainage basin (Fig. C).

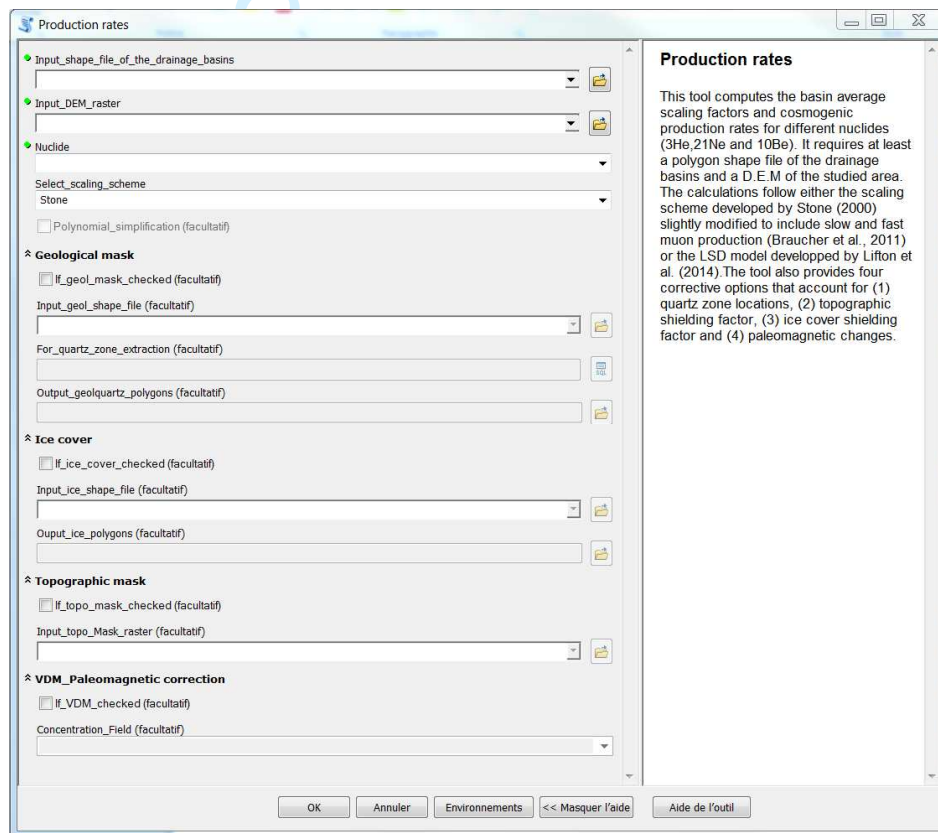


Fig. A: *Production rates* tool interface in ArcMap. This is the main interface where the user must specify at least the shape file of the drainage basin and the DEM. The other fields remain optional and can be activated if required by checking the corresponding boxes. A detailed help file is provided for each of the fields and is displayed on the right-hand side of the tool by clicking the "Show Help" button in the bottom right corner.

The results of the calculations are stored in the attribute table of the basin shape file (Fig. C) following the nomenclature described in Table A. The *Production rates* tool can also correct the basin average value for paleomagnetic variations if the cosmogenic concentration at the outlet is known. The *Denudation rates tool* (Fig. B) calculates the denudation rates according to method 1, the basin average production rates previously calculated using the *Production rates* tool and the cosmogenic concentration measured at the outlet. The latter must be already stored in the attribute table of the basins' shape file. The results are also returned in the attribute table of this input file.

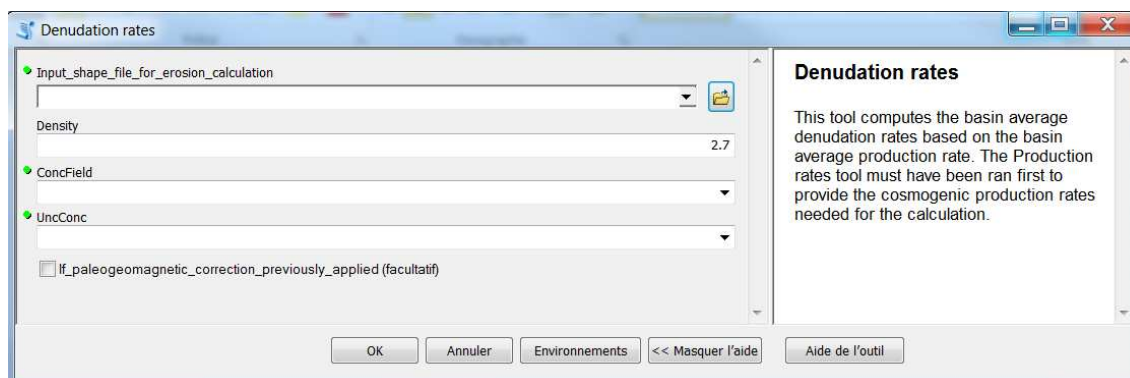


Fig. B: *Denudation rates* tool interface. The user must specify the path to the shape file where the concentrations in ^{10}Be and their uncertainties are stored. This file must include the cosmogenic production rates calculated using the *Production rates* tool. The fields for the ^{10}Be concentrations and their uncertainties must be specified and the box underneath the fields must be checked if the correction for paleomagnetism was carried out during the previous calculations.

2. Topographic shielding

This option requires an additional raster that provides the shielding factor (from 0 to 1) for each cell of the studied region. This correction can be applied either to the entire watershed or only to restricted regions (see below). The shielding factor raster can be independently computed in ArcGIS® using the approach developed by Codilean (2006), which is available upon request from these authors and can thus be easily integrated in **Basinga** without any further work. Their tool is based on the Relief Shadow Modeling method, which accounts for both Self-shadows and Cast-shadows (Codilean, 2006). The user is however free to choose any other topographic shielding computation as long as it can be converted into a raster file. It must strictly share the same coordinate system (i.e. geographic), resolution and shape of the original DEM.

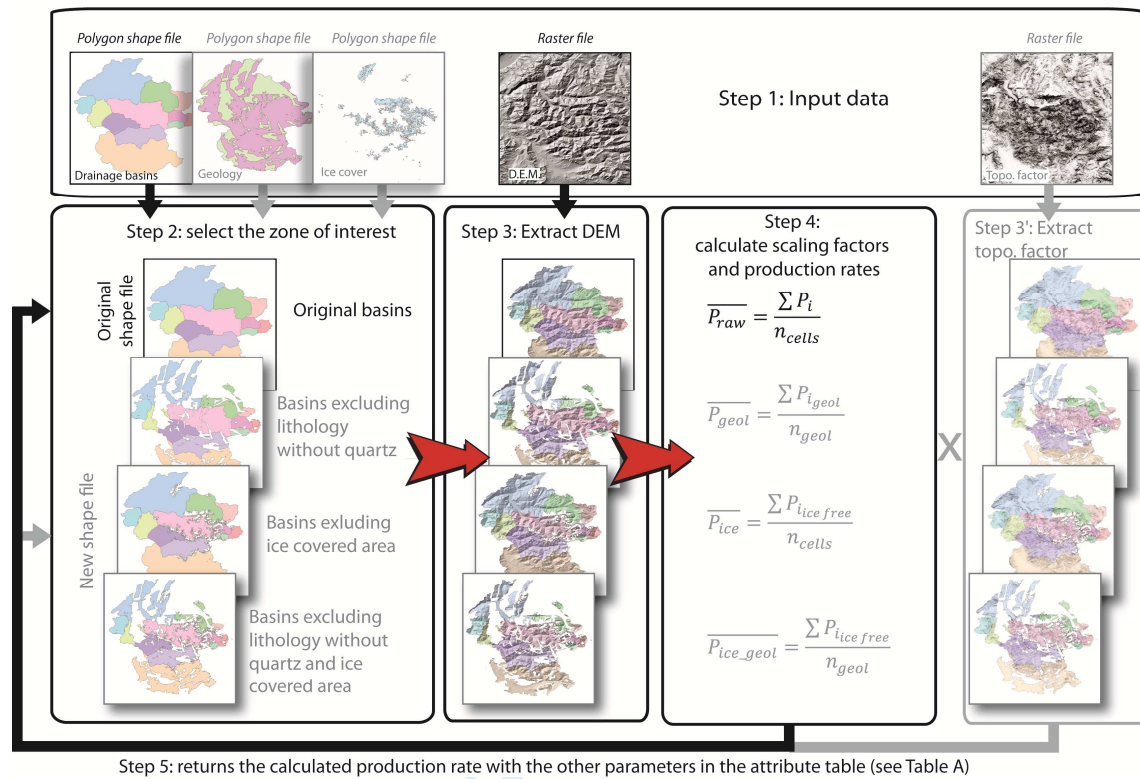


Fig. C: Work flow of the *Production rates* tool. The tool mainly works in 5 steps. The user must first provide the input data corresponding to the corrective options chosen (Step 1). The tool then first selects and extracts the corresponding zone of interest (Steps 2 and 3). At this point, it may create a new shape file if the corrections for geology and ice have been selected. It then calculates the cosmogenic scaling factors and cosmogenic production rates for each individual cell and averages the values over the basins. Finally, it returns the calculated values to the attribute table of either the original shape file or of a new shape file created when the region of interest was selected.

3. Lithology

The user may exclude a region of undesired lithology using a SQL interface and expression (Fig. D) from an independent polygon shape file of the geology, which includes, in the attribute table, the necessary lithological information. Once selected, the desired geological regions are cut out from the original polygon of the basins and the tool creates a newly polygon shape file of the studied watershed in which it calculates the cosmogenic production rates. The production rates are therefore calculated and averaged only in this restricted region and may also include a correction for topographic shielding if the former option has been checked. The calculated parameters are stored in the attribute table of this newly created shape file (Fig. C and Table A).

Table A. List and description of the different fields generated by the *Production rates* and *Denudation rates* tools.

Fields	Description	Units
Pixels	Number of cells encountered in the area of the original catchment ^a	-
Alt_ave	Catchment-averaged altitude	(m)
LAT_ave	Catchment-averaged latitude	Decimal degrees ^b
H_ave	Catchment-averaged atmospheric pressure	hPa
Time	Equivalent time of exposure	yr
Topo_fc*	Catchment-averaged topographic shielding factor	-
Pneu_ ¹	Catchment-averaged ¹⁰ Be nuclides produced by spallation ^b	atoms.g ⁻¹ .yr ⁻¹
Psm_ ¹	Catchment-averaged ¹⁰ Be nuclides produced by slow muon capture ^b	atoms.g ⁻¹ .yr ⁻¹
Pfm_ ¹	Catchment-averaged ¹⁰ Be nuclides produced by fast muon capture ^b	atoms.g ⁻¹ .yr ⁻¹
SFn_ ¹	Catchment-averaged scaling factor for spallation	-
SFf_ ¹	Catchment-averaged scaling factor for fast muogenic production	-
SFs_ ¹	Catchment-averaged scaling factor for slow muogenic production	-
Nuclide ²	Number that records the nuclide selected for the last calculation	-
Option ³	Number that records the options selected for the last calculation	-
Scaling ⁴	Number that records the scaling selected for the last calculation	-

*These fields are directly related to two different corrective options and may not appear if not requested.

^a If the correction for lithology has been activated, this number excludes the zones without quartz.

^b Negative values represent southern latitudes.

¹ May be followed by one or more indicative letters according to any optional corrections selected by the user (G: Geology (lithology); T: Topographic shielding factor; I: Ice cover shielding factor; P: Paleomagnetic changes). Of note, as the paleomagnetic results are computed independently (see section 4.6), any time this option is selected, these fields will appear twice: first referred to with all options except paleomagnetic changes activated, and second with a "P" at the end indicating the rate corrected for past variations in the Earth's magnetic field.

² 3 (³He), 10 (¹⁰Be) or 21 (²¹Ne)

³ 0: Lal/Stone, 1: LSD.

⁴ 1: GTI, 2: GI, 3:TI, 4: I, 5:GT, 6: G, 7: T and 8: no option selected

4. Ice cap

To run this optional tool, the ice cover must be entered as a polygon shape file (Figure 3). The modern ice cover can be downloaded as a shape file free of charge from the Global Land Ice Measurements from Space (GLIMS) website (<http://www.glims.org>), which provides a thorough and frequently updated glacier database (Armstrong *et al.*, 2005; Raup *et al.*, 2007). Nevertheless, cosmogenic nuclides may average out denudation rates over long time scales (10²-10⁵ years) especially in slowly eroding areas. However, glacial coverage has changed over time, which may induce a significant bias in the calculated production rate. Delunel *et al.* (2010) for example found it more relevant to consider ancient glacial extent reconstruction rather than modern glacial coverage and built a polygon shape file accordingly.

Once the paleoglacial cover shape file has been selected, the tool will first execute the main process to provide the total number of cells of the entire drainage basin, and it will then recalculate the mean production rate excluding the glacial zones. A new shape file of the

drainage basin is created, including an attribute table that provides the results of the calculation (**Error! Reference source not found.**). Even if the ice cover correction box has been checked, the uncorrected raw production rate and scaling factors remain stored in the attribute table as before, along with the corrected values for ice cover. Note that, again, this correction for ice can be applied independently from the other options. If the quartz-free areas were excluded, the correction for ice is applied to this restricted area only.



Fig. D: a. Example of an attribute table providing lithological information and specifying the presence or absence of quartz in an independent field (e.g. the field named 'Quartz'); b. Example of a shape file showing the polygons associated with the attribute table where the lithological information is given (after Delunel et al. (2010)); c. SQL interface open once the correction for lithology is selected. To compute the production rate in the region with quartz only (e.g. 'Crystalline basement') the user must specify a SQL expression (e.g. 'Quartz' = 'yes') which selects the correct polygons from the shape file accordingly.

II- Getting started with Basinga

ArcGIS

System requirements

Basinga requires Windows 7 version or later and ArcGIS 10.1 or later. The extensions *Spatial Analyst* and *3D Analyst* must also be installed and activated. Python 2.7 or later must be installed and include the *NumPy* and *SciPy* libraries. The latter are two open source libraries for scientific calculation and are provided in the online files or can be freely downloaded from the web (see for example: <http://www.scipy.org/scipylib/download.html>). The computer must be configured with the point as a decimal symbol (Start button → Control Panel → Clock, Language and Region → Region and Language → Format → Additional settings → Decimal symbol).

Installation

The downloaded folder provides the two Python scripts and the **Basinga** toolbox ('Basinga.tbx'), which was configured to include both the *Production rates* and *Denudation rates* tools. First, add the Basinga toolbox to the ArcToolbox (Open ArcToolbox → right click → Add Toolbox). More details can be found in the ArcGIS online resources, which provide documentation, help and tutorials. See for example:

http://webhelp.esri.com/arcgisdesktop/9.3/tutorials/gp/GP_1_4.htm

The links to the Python Scripts must be specified before starting any process (click on the added Basinga toolbox → right click on *Production rates* → Properties → Source → script file, repeat the operation for the *Denudation rates* tool).

Changing the main cosmogenic parameterization

SLHL parameters

The normalized surface production rates at Sea Level and High Latitude (SLHL) can be easily changed if needed by editing the script "Prod_rates.py" as follows: right click on "Prod_rates.py" → Edit with IDLE (editing can be performed by opening the file with MS-Word or any simple text editor such as Notepad or Wordpad). Then modify the parameters from line 68:

```
# Definition of the SLHLP : Sea Level High Latitude Production rate (at/g/a):
##10Be:
if Input_nuclide == "10Be":
    if Input_scaling_scheme == "Stone":
        ##Lal/Stone + ERA40 atmosphere + Muscheler:
        SLHLP_Be=4.18 #Table 7 Martin et al. (2017) : cREP
    elif Input_scaling_scheme == "LSD":
```

```

1
2
3   ##LSD + ERA40 atmosphere + Muscheler:
4   SLHLP_Be=4.14 #Table 7 Martin et al. (2017) : cREP
5   nuclide=10
6
7
8   elif Input_nuclide == "3He":
9   ##Please note that the code was originally written for 10Be only, for simplicity we keep the
10  same for the parameters with "_Be" but it does consider different nuclide
11  if Input_scaling_scheme == "Stone":
12  ##Lal/Stone + ERA40 atmosphere + Muscheler:
13  SLHLP_Be=122 #Table 7 Martin et al. (2017) : cREP
14
15
16  elif Input_scaling_scheme == "LSD":
17  ##LSD + ERA40 atmosphere + Muscheler:
18  SLHLP_Be=125 #Table 7 Martin et al. (2017) : cREP
19  nuclide=3
20
21
22
23  elif Input_nuclide == "21Ne":
24  ##Please note that the code was originally written for 10Be only, for simplicity we keep the
25  same for the parameters with "_Be" but it does consider different nuclide
26  if Input_scaling_scheme == "Stone":
27  ##Lal/Stone + ERA40 atmosphere + Muscheler:
28  SLHLP_Be=4.18/4.12 #10Be/21Ne=4.12 +/- 0.17 see Kober et al., EPSL 2011 and
29  Table 7 Martin et al. (2017) : cREP
30
31
32
33  elif Input_scaling_scheme == "LSD":
34  ##LSD + ERA40 atmosphere + Muscheler:
35  SLHLP_Be=4.14/4.12 #10Be/21Ne=4.12 +/- 0.17 see Kober et al., EPSL 2011 and
36  Table 7 Martin et al. (2017) : cREP
37  nuclide=10
38
39
40  SLHLP_Be_neutron = fsp*SLHLP_Be
41  SLHLP_Be_fastmuon=fmu_fastmuon*SLHLP_Be
42  SLHLP_Be_slowmuon=fmu_slowmuon*SLHLP_Be

```

A complete list of the references used to set these parameters is given in the main text. The SLHL values also depend on the production rate between the different particles, which can be changed if needed in lines 34 to 37:

```

51  #production rate between the different particles at SLHL:
52  fsp = 0.9886 #Braucher et al.
53  fmu_slowmuon=0.0027# Braucher et al.
54  fmu_fastmuon=0.0087# Braucher et al.

```

Atmospheric attenuation lengths

The atmospheric attenuation lengths were specified after Braucher et al. (2011). These can easily be changed by editing "Prod_rates.py" to modify the values in lines 39 to 41 of the code as needed:

```
#Atmospheric attenuation (g.cm-2)(Braucher et al., EPSL 2011):
at_attenuation_fastmuon=510
at_attenuation_slowmuon=260
```

Attenuation lengths in rocks

The cosmogenic attenuation lengths in the rocks required to calculate the denudation rates are given lines 25 to 31 of the "Denudation.py" script as follows:

```
#Attenuation length (g.cm-2)(Braucher et al., EPSL 2011):
lght_att_n=160.0
lght_att_n=float(lght_att_n)
lght_att_fm=4320.0
lght_att_fm=float(lght_att_fm)
lght_att_sm=1500.0
lght_att_sm=float(lght_att_sm)
```

"n" refers to neutrons, "fm" to fast muons and "sm" to slow muons. These values may be changed if needed.

Uncertainties in ¹⁰Be cosmogenic production rates

The *uncertainties in ¹⁰Be cosmogenic production rates* are specified in the Denudation.py script, for the nucleogenic production:

```
#Uncertainties on the 10Be nucleogenic production rates:
U_sm=0.5
U_fm=0.5
```

and for spallation:

```
def nuclideSelected(nuclide,scaling):
#Table 7Martin et al. (2017) : cREP
    if scaling == 1:#Lal/St scaling + ERA40 atmosphere + Muscheler:
        if nuclide == 10:
            U_spal= 0.048
        elif nuclide == 3:
            U_spal= 0.0103
        elif nuclide == 21:
            U_spal=0.048
```

```

elif scaling == 0:##LSD scaling + ERA40 atmosphere + Muscheler:
    if nuclide == 10:
        U_spal= 0.063
    elif nuclide == 3:
        U_spal= 0.048
    elif nuclide == 21:
        U_spal=0.063

return U_spal

```

QGIS

System requirements

Basinga is fully functional on Windows and Mac OS with QGIS versions 2.8 and 2.14. It should also work on Linux systems but it has not yet been tested. All versions of QGIS can be downloaded from the QGIS website (<https://www.qgis.org/fr/site/forusers/download.html>).

Basinga requires the NumPy and SciPy libraries to be installed for the 2.7 python interpreter of QGIS. Both are open source and available online:

<https://www.scipy.org/>

<http://www.numpy.org/>

Follow the installation instructions given online or use pip to perform the task. Make sure that both libraries are installed for the python interpreter of QGIS and not for other software. Basinga requires the GDAL/OGR processing scripts so it is necessary to ensure that the GdalTools extension is installed and activated. The default installation of QGIS usually performs this.

To install Basinga follow these instructions:

- Close QGIS if necessary, and copy and paste the Basinga folder into the plugins directory of QGIS. The default path for Windows users is:
"C:\Users\YourUserAccount\.qgis2\python\plugins"
For OSX users: "/Applications/QGIS.app/Contents/Resources/python/plugins"
If the "plugins" folder does not exist, create it.
- Launch QGIS. Go to Plugins > Manage and Install Plugins...
First ensure to check the box "Show also experimental plugins" in the Settings tab.
Then look for Basinga and activate it.
That's it! Basinga is now installed.

For more details on plugins visit the QGIS online documentation:

http://docs.qgis.org/2.8/en/docs/training_manual/qgis_plugins/index.html

If the plugin cannot be loaded, make sure that the Basinga folder contains the following files :
"__init__.py" , "Denudation_process.py", "icon.png", "metadata.txt", "P_E_process.py",
"P_E_process_dialog.py", "P_E_process_dialog_base.ui", "P_E_process_dialog_help.ui",

"P_E_process_dialog_sql.ui", "parameters_definition.py", "PR_processes.py",
 "prod_rate_functions.py", "resources.py", "ressources.qrc".

Changing the main cosmogenic parameterization

All cosmogenic parameters used can be accessed and changed if needed. In order to do so, open the python file "parameters_definition.py" with any text editor (as Notepad or with python IDLE).

The normalized surface production rates at Sea Level and High Latitude (SLHL) can be found starting at lines 2075 of the code. If the cosmogenic production rates for nuclides other than ^{10}Be are needed, these values may be changed accordingly.

```

if Input_nuclide == "10Be":
    if Input_scaling_scheme == "ls":
        ##Lal/Stone + ERA40 atmosphere + Muscheler:
        SLHLP_Be=4.18 #Table 7 Martin et al. (2017) : cREP
        nuclide=10
    else:
        ##LSD + ERA40 atmosphere + Muscheler:
        SLHLP_Be=4.14 #Table 7 Martin et al. (2017) : cREP
        nuclide=10

elif Input_nuclide == "3He":
    ##Please note that the code was originally written for 10Be only, for simplicity we keep the
    same for the parameters with "_Be" but it does consider different nuclide
    if Input_scaling_scheme == "ls":
        ##Lal/Stone + ERA40 atmosphere + Muscheler:
        SLHLP_Be=122 #Table 7 Martin et al. (2017) : cREP
        nuclide=3
    else:
        ##LSD + ERA40 atmosphere + Muscheler:
        SLHLP_Be=125 #Table 7 Martin et al. (2017) : cREP
        nuclide=3

elif Input_nuclide == "21Ne":
    ##Please note that the code was originally written for 10Be only, for simplicity we keep the
    same for the parameters with "_Be" but it does consider different nuclide
    if Input_scaling_scheme == "ls":
        ##Lal/Stone + ERA40 atmosphere + Muscheler:
        SLHLP_Be=4.18/4.12 #10Be/21Ne=4.12 +/- 0.17 see Kober et al., EPSL 2011 and
        Table 7 Martin et al. (2017) : cREP
        nuclide=10
    else:
        ##LSD + ERA40 atmosphere + Muscheler:

```

```

SLHLP_Be=4.14/4.12 #10Be/21Ne=4.12 +/- 0.17 see Kober et al., EPSL 2011 and
Table 7 Martin et al. (2017) : cREP
nuclide=10

```

```

SLHLP_Be_neutron = fsp*SLHLP_Be
SLHLP_Be_fastmuon=fmu_fastmuon*SLHLP_Be
SLHLP_Be_slowmuon=fmu_slowmuon*SLHLP_Be

```

The values of the SLHL also depend on the production rate between the different particles, which can be changed if needed in the file "Parmaters_definition.py":

```

#production rate between the different particles at SLHL:
fsp = 0.9886 #Braucher et al.
fmu_slowmuon=0.0027# Braucher et al.
fmu_fastmuon=0.0087# Braucher et al.

```

The atmospheric attenuation lengths were specified after Braucher et al. (2011). They can easily be changed in "Parmaters_definition.py":

```

#Attenuation lenght (g.cm-2)(Braucher et al., EPSL 2011):
lght_att_n=160.0
lght_att_n=float(lght_att_n)
lght_att_fm=4320.0
lght_att_fm=float(lght_att_fm)
lght_att_sm=1500.0
lght_att_sm=float(lght_att_sm)

```

"n" refer to neutrons, "fm" to fast muons and "sm" to slow muons.

The cosmogenic attenuation lengths in the rocks required to calculate the denudation rates are given in the same file:

```

# Atmospheric attenuation (g.cm-2)(Braucher et al., EPSL 2011):
at_attenuation_fastmuon = 510
at_attenuation_slowmuon = 260

```

The uncertainties in the cosmogenic production rates are specified in the Denudation_process.py script, for the nucleogenic production:

```

#Uncertainties on the 10Be cosmogenic production rates:
#U_spal=0.09 #Balco et al. (2008) - we used instead the uncertianties given in Table 7 of
Martin et al. (2017)
U_sm=0.5
U_fm=0.5

```

and for spallation:

```
def nuclideSelected(nuclide,scaling):
#Table 7Martin et al. (2017) : cREP
    if scaling == 1:#Lal/St scaling + ERA40 atmosphere + Muscheler:
        if nuclide == 10:
            U_spal= 0.048
        elif nuclide == 3:
            U_spal= 0.0103
        elif nuclide == 21:
            U_spal=0.048
    elif scaling == 0:##LSD scaling + ERA40 atmosphere + Muscheler:
        if nuclide == 10:
            U_spal= 0.063
        elif nuclide == 3:
            U_spal= 0.048
        elif nuclide == 21:
            U_spal=0.063

    return U_spal
```

Changing the source code of Basinga

If you wish to change the source code of Basinga, we recommend using python IDE and Qt Creator. The GUI was created with PyQt. We also recommend use of the plugins reloader plugin to gain time while testing.