



HAL
open science

Control of geomorphic processes on ^{10}Be concentrations in individual clasts: Complexity of the exposure history in Gobi-Altay range (Mongolia)

Riccardo Vassallo, Jean-François Ritz, Sébastien Carretier

► To cite this version:

Riccardo Vassallo, Jean-François Ritz, Sébastien Carretier. Control of geomorphic processes on ^{10}Be concentrations in individual clasts: Complexity of the exposure history in Gobi-Altay range (Mongolia). *Geomorphology*, 2011, 135 (1-2), pp.35-47. 10.1016/j.geomorph.2011.07.023 . hal-00626702

HAL Id: hal-00626702

<https://hal.science/hal-00626702>

Submitted on 6 Oct 2011

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.

1 **Control of geomorphic processes on ¹⁰Be concentrations in**
2 **individual clasts: complexity of the exposure history in Gobi-Altay**
3 **range (Mongolia)**

4
5 Riccardo Vassallo¹, Jean-François Ritz² and Sébastien Carretier³

6
7 1 : ISTERre, CNRS, Université de Savoie, 73376 Le Bourget du Lac, France

8 2 : Géosciences Montpellier, CNRS, Université Montpellier 2, 34095 Montpellier, France

9 3 : Géosciences Environnement Toulouse, IRD, 31400 Toulouse, France

10
11 **Abstract**

12 The dating of alluvial landforms by cosmogenic nuclides requires distinguishing the
13 pre-deposition inheritance from the post-deposition history of the clasts in the studied marker.
14 Moreover, estimating catchment-scale erosion rates from the concentrations of cosmogenic
15 nuclides in active alluvia requires a good knowledge of the local/regional relationships
16 between rock exhumation and transport through space and time. This is still poorly known for
17 timescales of tens of thousand years. In order to document the evolution of clast exhumation
18 and transport rates through time, we analyze in situ ¹⁰Be concentrations in boulders and
19 cobbles from hillslopes to outlet of an arid mountainous catchment located in Gobi-Altay,
20 Mongolia, strongly affected by global climatic changes during the Pleistocene-Holocene
21 period. Samples were collected on bedrock, abandoned alluvial deposits, active colluvia and
22 alluvia. Our results show a large ¹⁰Be scattering in the active river bed, consistent with a low
23 and discontinuous catchment erosion rate dominated by mass wasting and fluvial incision. On

24 the contrary, pre-exposure signal within abandoned terraces is much more homogeneous,
25 consistent with climatic pulses responsible of strong erosional events on hillslopes and rapid
26 fluvial transport. These results show that exhumation/transport processes at the catchment
27 scale vary in style and intensity through time as a consequence of climatic oscillations. The
28 occurrence of abrupt climatic changes during short periods of time recorded by ^{10}Be
29 concentrations in abandoned alluvia raise questions about the temporal applicability of
30 catchment erosion rates derived from cosmogenic nuclide concentrations measured in
31 sediments of active rivers. On the other hand, strong and short erosion events limit and
32 homogenize the pre-exposure ^{10}Be signal in associated deposits like debris-flows, making
33 them particularly suitable markers for dating in active tectonic and paleoclimatic studies.

34

35 Keywords: Cosmogenic radionuclides; River terraces; Hillslopes; Dating; Catchment
36 erosion; Mongolia

37

38 **I. Introduction**

39 During the last two decades, thanks to the development of the geochronological
40 methods and improvement in the accuracy of analytical measurements, many studies have
41 focused on the determination of rates and frequencies of geomorphic processes in various
42 tectonic/climatic contexts (e.g. Anderson et al., 1996; Burbank et al., 1996; Granger et al.,
43 1997; Heimsath et al., 2001; Dunai et al., 2005; Von Blanckenburg; 2006, Belmont et al.,
44 2007; Palumbo et al., 2009; Delunel et al., 2010; Matmon et al., 2010). However, further
45 improvement in the understanding and quantification of these processes requires a close
46 collaboration between geomorphologists and Quaternary geochronologists. To establish
47 natural laws that explain the mechanisms and the characteristic timescales of the landscape
48 evolution (bedrock exhumation, sediment dynamics, landform preservation),

49 geomorphologists need more precise chronological data for reconstructing the history of
50 geomorphic markers. In parallel, to improve the precision on landforms dating, Quaternary
51 geochronologists need better knowledge of surface processes controlling the pre- and post-
52 depositional histories of sediments.

53 Methods based on cosmogenic radionuclides (CRN) for dating the exposure of
54 landforms or for quantifying catchment-scale erosion rates are based on simplified models of
55 exhumation, transport and deposition of sediments. In many cases, these models are too
56 simplistic. For example, dating of alluvial markers using a limited set of clasts along a depth-
57 profile is strongly limited if inheritance varies a lot from one clast to another (Repka et al.,
58 1997; Ritz et al., 2006; Le Dorz et al., 2009) or if denudation rate is not well-constrained
59 (Gillespie and Bierman, 1995). Further, , to estimate the catchment-scale erosion rates, we
60 assume that CRN concentrations are at steady-state on the hillslopes and that CRN acquisition
61 during fluvial transport is negligible (Brown et al., 1995; Granger et al., 1996). However, the
62 significant scattering of CRN observed in distinct clasts of alluvial fans (e.g. Ritz et al., 2006;
63 Owen et al., 2011; Schmidt et al., 2011) and along the fluvial system (Belmont et al., 2007)
64 suggests that fluvial processes can contribute significantly and perturb the CRN signal in
65 sediments.

66 Theoretical models have recently emphasized that the evolution of CRN in distinct
67 clasts through the fluvial system could allow exhumation-transport rates to be quantified
68 (Codilean et al., 2008; Gayer et al., 2008; Carretier et al., 2009a; Yanites et al., 2009).
69 Nevertheless, there is a crucial lack of systematic analysis of CRN concentrations in clasts
70 through a catchment.

71 Measuring CRN concentration in distinct clasts could provide a tool to analyse how
72 spatial and temporal variations of the hillslope erosion rate are recorded in the cosmogenic
73 signal, or, on the contrary buffered, along the fluvial system (Repka et al., 1997). A critical

74 issue is the potential of CRN to document past variations in erosion rate. Inversely, it is
75 difficult to determine the period of time over which the CRN-derived erosion rate applies.
76 Schaller et al. (2004) reconstructed paleo-erosion rates from ^{10}Be concentrations in abandoned
77 terraces of the River Meuse since 1.3Ma. These authors concluded that the CRN-derived
78 hillslope erosion rate has a long response time after the tectonic and climatic perturbations.
79 Braucher et al. (2003) modelled the effect of varying climates on ^{10}Be concentration evolution
80 on hillslopes. They showed that ^{10}Be -derived erosion rates can be significantly shifted and
81 attenuated, compared to true erosion rate variations for long periods of times (16-100 ka).
82 Niemi et al. (2005) also found that complete equilibration of CRN concentrations to new
83 erosional conditions may take tens of thousands of years. On the other hand, landslides can
84 generate stochastic variations in ^{10}Be concentrations in river channels (Small et al., 1997;
85 Niemi et al., 2005; Reinhardt et al., 2007; Binnie et al., 2007; Densmore et al., 2009; Ouimet
86 et al., 2009; Yanites et al., 2009; Palumbo et al., 2011). Models suggest that these variations
87 can be averaged in large catchments, and that a good estimation of catchment-average erosion
88 rate can be obtained if the catchment area is sufficiently large (Yanites et al., 2009). However,
89 other complexities may arise from large catchments, like long fluvial transport, sediment
90 storage and recycling (e.g. Matmon et al., 2005; Kober et al., 2007).

91 Overall, the capacity of fluvial system to buffer short-term (landslides) and long-term
92 (global climatic change) variations of hillslope erosion rates remains to be documented. A
93 suitable field case to study this phenomenon requires strong temporal erosion rate variations,
94 and well preserved river terraces formed cyclically during transitions of global climatic cycle.

95 The Ih Bogd massif, located in the Gobi-Altay mountain range in southwestern
96 Mongolia, is a favorable site to understand the dynamics of catchment surface processes
97 under an arid climate (**Fig. 1**). Situated in a desert region, this massif presents outstanding
98 geomorphic features like a large preserved flat summit plateau, the absence of Quaternary

99 glacial landforms, and the presence of abandoned strath terraces along the rivers. A localized
100 granitic source (corresponding to the summit plateau) located above 3000 m allows tracing of
101 the path of the alluvial sediments that compose the terraces cover and the present river bed.

102 The Ih Bogd massif belongs to the Gurvan Bulag mountain range, the easternmost part
103 of the Gobi-Altay, where the great M8 Gobi-Altay earthquake occurred in 1957 (Florensov
104 and Solonenko, 1965). Since the early 90's, several studies provided an important set of
105 morpho-structural data (Baljinnyam et al., 1993; Cunningham et al., 1996; Kurushin et al.,
106 1997; Bayasgalan et al., 1999a and b; Carretier et al., 2002; Vassallo et al., 2007a) and
107 geochronological data (Ritz et al., 1995; Hanks et al., 1997; Ritz et al., 2003, 2006; Vassallo
108 et al., 2005, 2007a and 2007b; Jolivet et al., 2007).

109 The Bitut catchment, the larger of Ih Bogd massif, is the best-studied one in terms of
110 morphology, tectonics and geochronology (**Figs. 1, 2**). There, Vassallo et al. (2007a) carried
111 out a topographic survey, a detailed mapping and a ^{10}Be analysis of the alluvial markers to
112 study the activity of the Quaternary faulting bounding the massif. To quantify the surface
113 processes that sculpted the catchment's topography, and analyze their rates and frequencies,
114 from the long-term (10^3 - 10^5 yrs) to the Present, we supplemented the existing database of
115 Vassallo et al. (2007a) with a detailed analysis of landforms, with 13 new ^{10}Be data on
116 bedrock, colluvia and alluvia.

117 Analyzing the distribution of ^{10}Be concentrations from the watersheds to the outlet, we
118 address three main questions. 1) What are the differences in style and magnitude of present
119 and ancient surface processes (bedrock exhumation, stocking of colluvia on the hillslopes,
120 remobilization and transport within the drainage network)?. 2) What are the main processes
121 controlling the erosion of a catchment in an arid landscape? Analyzing abandoned and active
122 landforms at different settings along the catchment, we compare geomorphic rates as a
123 function of altitude, local slope, surface roughness, proximity to the drainage network. 3)

124 What is the impact of inherited ^{10}Be on the dating of “young” and “old” terraces? We discuss
125 the errors in the age calculation that can be generated by an incorrect interpretation of the pre-
126 exposure history of the sediments of the alluvial landforms.

127

128 **II. Morpho-structural setting of Ih Bogd massif**

129 The Ih Bogd massif, culminating at 3957 m, is the highest mountain of the Gobi-Altay
130 range, in southwestern Mongolia (**Fig. 1**). The massif is 50 km long, 25 km wide, and forms a
131 relief of ~2 km between its flat summit surface and the surrounding piedmont. Located in one
132 of the restraining bends of the 600-kmlong Gobi-Altay strike-slip fault, this massif is uplifted
133 by oblique and reverse faults on both of its northern and southern sides (Cunningham et al.,
134 1996; Bayasgalan et al., 1999b). Morpho-structural analysis (Vassallo et al., 2007a) and
135 thermochronological data (Vassallo, 2006; Vassallo et al., 2007b) show that the massif built
136 up during an in-sequence migration of fault activity from its central part towards its external
137 boundaries. Upper Pleistocene–Holocene vertical slip rates along the active bounding faults
138 are identical on both sides and of the order 0.1-0.2 mm/yr (Ritz et al., 2006), which is
139 consistent with the horizontal summit plateau feature, interpreted as a remnant of a large
140 Jurassic peneplain surface (Jolivet et al., 2007) that has been uplifted during the late Cenozoic
141 (Vassallo et al., 2007b). The summit surface experienced very small runoff erosion, as shown
142 by the absence of tracks of ancient transverse drainage. Catchment erosion processes are
143 dominated by mass wasting and fluvial incision, creating the formation of deep canyons and a
144 series of natural dams in the narrow parts of the valleys (**Fig. 3**).

145 The preservation of the summit plateau from the erosion associated with the
146 catchment’s growth is due both to the young age of the massif and to the aridity of the
147 regional climate during the Late Cenozoic. The permanence of an arid climate over this period
148 is proven by the absence of relevant Quaternary glacial morphologies and deposits, implying

149 that glacial stages must be particularly dry. Thus, fluvial incision is limited to the short
150 interglacial stages (a few thousand years over ~100 ka cycles), associated with changing
151 hydrological conditions, resulting in the periodical formation and abandonment of alluvial
152 fans in the piedmont and alluvial terraces within the massif (Ritz et al., 1995; Carretier et al.,
153 1998; Vassallo et al., 2005). Owen et al. (1999) provided a similar model based on climate
154 variability for sediment production and transfer through another mountain in Gobi-Altay. The
155 present climate is arid with less than 200 mm/yr of precipitation (Hilbig, 1995), usually
156 concentrated in intense summer rainstorms. As a consequence, vegetation is rare and
157 dominated by sparse low grass, while trees grow only around small spring areas.

158 Alluvial surfaces are mainly formed by debris-flows constituted of rounded meter-size
159 boulders encased in a sandy-silty, matrix-supported deposit. Cover thicknesses vary from one
160 surface to another, ranging from a few meters up to a dozen meters. Most of the outcropping
161 boulders have a desert varnish at the surface, gradually vanishing from their tops towards the
162 ground, revealing a gradient of weathering due to the progressive lowering of the surrounding
163 matrix by wind deflation (Ritz et al., 2006). Some boulders have a more complex patina
164 distribution, indicating some remobilization during their exposure history at the surface
165 (Vassallo et al., 2007a).

166 Stepped strath terraces inside the massif are connected with large alluvial fans within
167 catchment outlets. In some catchments, strath terraces are preserved for several kilometers
168 along rivers, and their width can reach a hundred meters. Strath levels of different age diverge
169 along a vertical axis from the outlet to the middle reaches. In the downstream direction,
170 terrace treads have generally the same gentle slope of the strath levels that they cover. In a
171 cross-valley direction, terrace tread slopes become steeper due to the enhanced erosion
172 associated with the runoff coming from the above hillslopes.

173 Alluvial fans are located within the piedmont at the outlet of the main catchments. The
174 surface area of each fan increases with the size of the source catchment, with an average of a
175 few tens of km² and a maximum of the order of a hundred km². Each catchment yields a
176 series of stepped alluvial fans of different ages (Carretier et al., 1998; Vassallo et al., 2005).
177 Their total thickness within the sedimentary basins is unknown, but it is reasonably of the
178 order of several hundred meters (Florensov and Solonenko, 1965). Younger alluvial fans
179 show a typical higher frequency/lower amplitude incision pattern with respect to the older
180 ones. The abundance of meter-size boulders at the surface is well correlated to the age of the
181 fans, diminishing on older ones, suggesting a progressive disintegration by weathering
182 processes (Ritz et al., 2006).

183

184 **III. Morphology of Bitut catchment**

185 The Bitut catchment has a surface of about 80 km², and extends from the northern
186 mountainous front at 1600 m to the edges of the summit plateau at 4000 m (**Fig. 2**). The Bitut
187 river, the main river draining the massif, is 18km long, with a main bend toward the middle
188 reaches from a N0°E to a N100°E direction. This river system is associated with a Quaternary
189 alluvial fan of 120 km² in the piedmont. The active riverbed is 150m wide at the lower
190 reaches, narrowing up to a few tens of meters at the middle reaches when it flows in a steep
191 canyon carved in the bedrock (**Figs. 3a, 3b**). Alluvia are composed of coarse sand and
192 rounded boulders with a maximum diameter of 2-3 m. Within the higher part of the
193 catchment, a huge landslide triggered by the earthquake of 1957 (Florensov and Solonenko,
194 1965) affects an entire flank of the valley over a length of more than 8 km. The frontal part of
195 this landslide dammed the river leading to an abrupt change in the morphology of the valley
196 and the formation of two lakes (**Fig. 3c**).

197 The morphology of the interfluves is dominated by landslides and mass wasting
198 processes, determining characteristic slopes of $\sim 30^\circ$. However, spatial variability of bedrock
199 lithology and fracturing results in locally enhanced or lowered erosion of the topography.
200 Colluvial material covering hillslopes is relatively finer (pebbles and cobbles) at low
201 altitudes, and coarse-grained (boulders up to few meters) at high altitudes. Within the summit
202 region of the massif, large blocks of bedrock at the edge of the plateau are exhumed by
203 differential erosion and become unstable. Once these blocks collapse on to the slopes beneath,
204 they form long corridors – about 10 to 50 m in width – whose genesis is likely to be
205 controlled by gravitational movements associated with the freezing-unfreezing of the first few
206 meters of the surface. Along the hillslopes, these boulders corridors laterally alternate with
207 screes and outcropping parts of bedrock (**Fig. 4**).

208 At the outlet of the catchment we observed four stepped strath terraces (T1 to T4, from
209 the oldest to the youngest) (**Fig. 5 and Fig. 14 in Vassallo et al. (2007a)**). Downstream, the
210 surfaces of the two younger terraces (T4 and T3) connect with alluvial fan surfaces. The four
211 terraces are vertically spaced out over a height of ~ 80 m above the river bed. T4 is the only
212 terrace that is found on both sides of the river. It is formed by meter-size rounded granitic
213 boulders encased in an unconsolidated sand matrix, and shows well preserved bar-and-swale
214 morphology. The thickness of the alluvial cover is unknown at this site, because the strath
215 level is hidden by the present river deposits, but it is likely to be of the order of a few meters.
216 Terraces T3 and T2 look similar to one another in terms of geometry and composition. They
217 form two clear steps in the topography of the left-bank, with large planar surfaces sloping
218 gently ($3-4^\circ$) downstream. They are constituted by large boulders, similar to those of terrace
219 T4, encased in a consolidated sandy-silty matrix. The alluvial cover of terrace T3 is a few
220 meters thick, while that of terrace T2 varies between 10 and 12 m. Terrace T1, the oldest
221 observed, is much less preserved than T2 and T3 and appears discontinuously on the left

222 bank. Boulders still outcrop from the matrix, but their aerial part is largely reduced with
223 respect to the boulders of the younger terraces. The sedimentary cover is a few meters thick.
224 Its tread surface has a relatively high downstream slope (6°). Well above these terraces, a
225 wide sub-planar surface containing weathered boulders corresponds to the remnant of an
226 ancient piedmont (P0) of the massif. This perched piedmont is several hundred meters above
227 the present one due to the movement on the frontal reverse fault, and is limited by a thrust
228 fault to the south.

229 Upstream of the outlet area, terrace T1 is not preserved, while the three younger
230 terraces can be followed for several kilometers along the river. However, only the youngest
231 terrace T4 shows a continuous pattern on both banks, keeping a planar geometry all along.
232 The sediment charge of the active river bed progressively decreases toward the middle
233 reaches. This corresponds to the downstream filling of a canyon carved between the base of
234 the river bed and terrace T4. The canyon is 25m deep at about 7 km from the outlet, where it is
235 almost sediment-free (**Fig. 3b**). Upstream of this point, the canyon is dammed by a small
236 landslide causing its partial filling by alluvia.

237

238 **IV. ^{10}Be results**

239 For the ^{10}Be analysis of the Bitut catchment, we combine data collected on the alluvial
240 terraces (indicated by letter T in figures) and along a vertical profile in the bedrock (BT) at the
241 canyon site (Vassallo et al., 2007a), with a new set of thirteen rock samples (**Figs. 2 and 6,**
242 **Table 1**). This new set of samples includes bedrock (B) from the summit plateau and its
243 edges, colluvial boulders (C) on the hillslopes, and alluvial boulders and cobbles on the
244 perched piedmont (P0) and in the active river (A). With the exception of colluvia on the
245 hillslope, which are gneisses, all the new and old samples are granites coming from the
246 highest part (> 3000 m) of the left flank of the main Bitut valley (**Fig. 2**). Samples were

247 prepared following the chemical procedures described by Brown et al. (1991). ^{10}Be analyses
248 were performed at the Tandétron Accelerator Mass Spectrometry Facility, Gif-sur-Yvette
249 (INSU-CNRS, France) (Raisbeck et al., 1987). The ^{10}Be analyses were calibrated against
250 NIST Standard Reference Material 4325 using its certified $^{10}\text{Be}/^9\text{Be}$ ratio of $(2.68 \pm 0.14) \times 10^{-11}$.
251 ¹¹. Production rates have been calculated following Stone (2000) using the modified scaling
252 functions of Lal (1991) and a ^{10}Be production rate in quartz of 4.5 ± 0.3 at/g/yr at sea level
253 and high altitude owing to the revaluated ^{10}Be half-life of 1.36 Ma (Nishiizumi et al., 2007).
254 Where surrounding topography partially shields incoming cosmic rays, geomorphic scaling
255 factors have been calculated following Dunne et al. (1999). ^{10}Be data are presented as pre-
256 and post-deposit, in order to distinguish the respective contributions to the final ^{10}Be signal.

257

258 **IV.1 Pre-deposit ^{10}Be**

259 *IV.1.1 Summit plateau*

260 Two granitic bedrock samples have been collected on the summit plateau, one within
261 its central part (IB001) and one on its northern edge (MO-03-75) (**Fig. 7a, 7b**). The two
262 samples show different ^{10}Be concentrations: 1.74 ± 0.19 Mat/g for the first and 0.02 ± 0.01
263 Mat/g for the second. Although we only consider two samples in this zone, the difference in
264 concentrations is qualitatively consistent with the intensities of the erosional processes that we
265 describe. Indeed, it is obvious that a strong gradient of denudation rates exists between the
266 edges of the plateau, constantly rejuvenated by the lateral growth of the catchments, and its
267 central region, preserved from significant runoff and gravitational processes. Therefore, rock
268 exhumation on the edges is rapid and variable in time at the scale of Quaternary climatic
269 cycles, while in the central part of the plateau it is much slower and constant, and dominated
270 by cryoturbation processes, as suggested by the polygonal soil pattern observed within the
271 summit surface (**Fig. 7b**).

272 Even though the stochasticity of the processes on the edge of the plateau does not
273 allow us to generalize a precise rate for the rest of the watershed, we consider that sample
274 MO-03-75 is representative of a relatively fast rock exhumation at the slope break. On the
275 contrary, given the central position of sample IB001 on the plateau and the flatness of this
276 area, we believe that its concentration reflects an average rate that can be applied to the entire
277 flat surface. Considering a constant vertical denudation rate, at an altitude of 3900 m, this
278 concentration yields a long-term exhumation rate of the summit surface of 23.6 ± 3 m/Ma.
279 The lowering of this flat surface by exhumation is, therefore, extremely slow with respect to
280 the surface uplift produced by tectonics, which is 600-700 m/Ma on average since the Mio-
281 Pliocene (Vassallo et al., 2007b).

282

283 *IV.1.2 Colluvia*

284 On the northern flank of the higher part of the Bitut valley, within the first hundreds of
285 meters below the summit plateau, three angular meter-size granitic boulders have been
286 sampled (**Fig. 7a**). They are situated in one of the boulders corridors – many others
287 characterize the hillslopes at this altitude - going from the plateau to the main drainage
288 system. Their ^{10}Be concentrations increase downslope with the distance from the edge of the
289 plateau. The highest boulder (MO03-59, 3620 m) has a concentration of 0.46 ± 0.07 Mat/g,
290 while the lowest (MO03-63, 3340 m) has a concentration of 0.91 ± 0.09 Mat/g. We only refer
291 to three samples and we are aware that more measurements would be necessary to have a
292 better statistics. Nevertheless, two main arguments strongly suggest that the downstream ^{10}Be
293 increase corresponds to transport time: 1- all the boulders have the same source – which is
294 almost ^{10}Be free as shown by sample MO03-75 situated on the edge of the plateau at 3860 m;
295 and 2- they have followed the same path along the slope. For an average ^{10}Be surface
296 production rate of 57.4 ± 3.8 at/g/yr at 3600 m on a 30° slope, and considering that the

297 production rate in the sample varies between this maximum value (when the boulder is in the
298 present relative position) and about 10 times less (when the boulder is upside-down), and for a
299 constant rolling movement, we estimate a travel time of the order of 20-30 ka for a vertical
300 displacement of 0.5 km. This yields a downslope transport rate of 15-25 m/ka.

301

302 *IV.1.3 Abandoned alluvia*

303 Two arguments concerning the sediments covering the youngest strath terrace T4
304 confirm the presence of inherited ^{10}Be in the boulders. Firstly, boulders of the alluvial cover
305 have concentrations 10 times higher than the bedrock exposed just below them in the vertical
306 canyon walls (weighted means of 0.189 Mat/g and 0.013 Mat/g, respectively) (**Fig. 8**).
307 Nevertheless, it cannot be excluded that a rejuvenation of the steep canyon by lateral collapse
308 contributes to accentuate this difference. Secondly, for 3 boulders among 4 (2m diameter
309 boulders), samples collected on the top and at the bottom show that the bottoms have similar
310 or even higher concentrations than tops (**Figs. 2, 6a**). In this case, the only possibility to
311 explain such a concentration distribution is to admit that the boulders have a complex pre-
312 exposure history. This pre-exposure signal is also observed within the cobbles that were
313 sampled along the depth-profiles within terraces T3 and T2, and more generally within the 8
314 depth-profiles carried out within the alluvial deposits of the mountain range (see Ritz et al.,
315 2006). Indeed, even at 2 m depth, ^{10}Be concentrations are very similar for deposits of different
316 ages (~20 ka, ~100 ka, ~200 ka) and too large to be explained by in situ production by muons
317 (**Table 1**). Moreover, since concentrations decrease exponentially at depth with little
318 scattering, the quantity of inherited ^{10}Be must be relatively uniform for all the samples. Its
319 approximate value is given by the asymptotic concentration towards which the exponential
320 curves tend at depth (around 0.1-0.3 Mat/g, taking into account all the profiles).

321 In the same way, looking at the distribution of surface concentrations within the four
322 strath terraces at the outlet of Bitut river, we observe that only two boulders on terrace T4,
323 over the 30 sampled boulders, have much higher – more than 3 times higher – concentrations
324 than the mean (**Fig. 6b, Table 1**). Therefore, high inherited ^{10}Be concentrations are very rare
325 for granulometric classes comprised between 0.1 and 2 m diameter. On the other hand, three
326 samples on terraces T3 and T2 have lower concentrations than the mean. We interpret these
327 lower concentrations as an effect of shielding (see next section).

328 All these results show that pre-exposure histories of abandoned alluvial deposits of the
329 Ih Bogd major catchment are similar. Moreover, the inherited concentration in alluvial
330 deposits is significantly lower – up to 9 times lower – than that of the hillslope active colluvia
331 situated at high altitude. This means that the hillslope erosional processes at the origin of main
332 debris-flow events mobilize locally more than a few meters of material, bringing detrital
333 sediments with low ^{10}Be concentration into the drainage network. In addition, similar
334 transport time and similar exposure history seem to be characterizing transport dynamics for
335 all granulometric classes between 0.1 and 2 m diameter.

336

337 *IV.1.3 Active alluvia*

338 Alluvia in the river bed have been collected between the middle reaches, downstream
339 of the region disturbed by landslides, and the outlet of the Bitut valley (**Figs. 2, 6**). Five
340 cobbles and boulders, ranging from 30 cm to 1 m diameter, show ^{10}Be concentrations between
341 0.03 Mat/g and 1 Mat/g. These concentrations are neither correlated with the size of the
342 samples nor with their position along the longitudinal profile of the river, nor with the
343 lithology. Three samples show minimum values very close to the concentrations obtained for
344 the bedrock at the edge of the plateau, while two samples show maximum values approaching
345 the hillslope colluvium with the highest concentration. These similarities suggest that river

346 sediments are derived from two main types of dynamics on hillslopes: after bedrock
347 exhumation to surface, boulders that fall rapidly in the river after their detachment; and
348 boulders that remain trapped longer within the hillslope colluvia. We could observe directly
349 the first mechanism during a strong summer rainstorm during the fieldwork, when large
350 boulders came off the heights of the mountain and rolled downslope to the bottom part of the
351 valley situated nearly 1 km below. Therefore, these two dynamics (leading to opposite
352 tendencies in terms of inherited ^{10}Be concentrations) induce a more stochastic pre-exposure
353 history at Present than during the past major aggradation events recorded within the alluvial
354 landforms.

355

356 **IV.2 Post-deposit ^{10}Be**

357 Within the strath terraces, at the outlet, mean surface ^{10}Be concentrations increase with
358 the age of the terraces, except for T1 that shows lower concentrations than those of terraces
359 T2 and T3 (**Fig. 5**). For all terraces, ^{10}Be concentrations are relatively clustered around an
360 average value, with few outliers showing much higher (T4) or lower values (T2 and T3) (**Fig.**
361 **6**). Samples with high concentration were interpreted as boulders that remained exposed much
362 more time than the others on the hillslopes. Samples with low concentration can be correlated
363 to the fact that they were outcropping closer to the ground surface than the other samples. The
364 denudation of the depositional surface, estimated at ~ 1 m/100 ka (Vassallo et al., 2007a),
365 exhumes and assembles at the surface clasts that were initially at different depths (**Fig. 9**).
366 This phenomenon has also been described on alluvial fans in Southern California, confirming
367 that the local denudation rate is partly determined by the initial lateral position in the alluvial
368 deposit – bar or swale – and by the dimensions of the aerial part of the clast (Matmon et al.,
369 2006; Behr et al., 2010).

370 While concentrations on terrace T4 do not show significant variations along the river,
371 terrace T3 is characterized by lower values toward the middle reaches, where its surface is
372 steeper (**Figs. 2, 6, 10**). As shown by the absence of varnished patina over a larger band at the
373 outcropping base of the boulders (**Fig. 10**), the denudation of the surface at this site is higher
374 in comparison with the flat surface of the same terrace at the outlet. This leads to a faster
375 exhumation of the boulders within the terrace, and consequently to their shorter exposure at
376 surface. If this longitudinal variability of the denudation rate were not taken into account, the
377 analysis of the measured concentrations on this steeper portion would underestimate the age
378 of terrace T3 by a factor 3. The enhanced denudation rate on terrace T1 for the same
379 topographic reasons explains an average concentration lower than that of the younger terrace
380 T2.

381 The abandoned alluvial piedmont P0, much higher, older and steeper than all the other
382 alluvial surfaces, has one sample in the range of the average concentration of terrace T1, and
383 one that is half of this value. Since the production rate on P0 is 20-25% higher than the
384 younger terraces at the outlet, even the sample with the highest concentration yields a lower
385 apparent exposure age than terrace T1. This implies that, as expected given its relative age
386 and tread slope, this surface has reached a steady state concentration for a denudation rate that
387 is higher than that of terrace T1. The difference in steady-state concentrations between the
388 two samples on P0 also suggests that development of a more organized runoff pattern on a no-
389 longer planar surface creates zones of enhanced denudation rates that can locally be much
390 faster than the average on the same surface.

391 Thus, in such an alluvial context, two physical parameters have a main impact on the
392 post-deposit shielding and the subsequent calculation of the exposure age of an alluvial
393 landform: 1) the elevation of the top of the boulders over the ground level; and 2) the local

394 slope of the topographic surface. These two parameters should be considered critically when
395 sampling boulders on the surface.

396

397 **V. Discussion**

398 *V.1 Geomorphic processes and exposure*

399 A synthesis of different works in the Bitut catchment converges toward a scenario in
400 which erosion processes in the Ih Bogd massif are characterized by different rates and paces
401 depending on the spatial and temporal scale. Watershed retreat is determined by the drainage
402 network growth, constantly active but particularly fast – several m/ka – at the transition
403 between glacial and interglacial periods when hydrological conditions change and flash
404 flooding becomes dominant (Owen et al., 1998). River incision is mostly controlled by this
405 phenomenon (more than mountain uplift), leading to a cyclic intense beveling of river bed in
406 the middle reaches with lateral retreat of 100 m at the catchment head and bedrock canyons of
407 more than 25m depth created in less than 5 ka (cf. Vassallo et al., 2007a; Carretier et al.,
408 2009b) (**Figs. 3b, 8**). During the interglacial stages, the enhanced river incision rate triggers
409 periods of hillslope instability expressed by large landslides, up to 8km long when the
410 geological structures are favorably oriented with respect to the axis of the valley – for
411 example a parallel bedding/foliation dipping downslope (**Fig. 3c**), or local collapses. The style
412 and intensity of present geomorphic processes at catchment scale are, therefore, a
413 consequence of the recent Holocene incision.

414 Concerning sediment production and transport, on the basis of the geomorphic and
415 CRN analysis we propose the following scenario. Recent (last 4-5 ka) exhumation rates are
416 slow on average. Hillslope residence time and river transport rate vary considerably from one
417 clast to another because of the strong climatic variability between long dry seasons and
418 episodic summer storms, and because of a high number of “sinks” along the catchment –

419 boulder corridors, dams, ephemeral basins created by landslides and collapses - where
420 sediments can be trapped for long periods. On the contrary, alluvial covers on strath terraces
421 are associated with strong erosion events that remove a thick layer on hillslopes – locally
422 several meters – and quickly transport these sediments in the river. Consequently, during
423 these periods, the clast-to-clast inheritance and variance is smaller on hillslopes and in river
424 sediments.

425 Denudation processes on the abandoned alluvial terraces appear much slower and
426 stable through time. These processes are dominated by wind deflation and runoff, as shown
427 by the distribution of the desert varnish at the top of the outcropping boulders. The
428 consequent lowering of the silty-sandy matrix leads to the progressive exhumation of
429 originally deeper encased boulders characterized by lower ^{10}Be concentrations. For sub-
430 horizontal terraces ($< 5^\circ$ slope) having experienced one or more climatic cycles, denudation
431 rates are of the same order (0.6-0.7 m/100 ka). On the other hand, steeper terraces – or steeper
432 parts of them – undergo denudation rates of more than 1 m/ 100 ka, and their dating by CRN
433 is problematic if this value cannot be constrained with precision.

434 The superficial processes leading to the formation of the strath terraces are
435 characterized by localized strong erosion of the hillslopes and rapid transport of the sediments
436 through the drainage network. These processes produce minimum pre-exposure CRN
437 concentration before abandonment, and make the alluvial landforms suitable geomorphic
438 markers for dating. Inherited CRN concentrations in old alluvial landforms (>100 ka) show
439 constant values that are smaller than 10% of the total concentrations. Young terraces and fans
440 (<20 ka) contain alluvia with significant quantities of inheritance – sometimes more than 50%
441 of the total concentration - but since their genesis dynamics is the same as the older ones, one
442 can expect that the average inheritance should be also similar. If this value can be estimated
443 from the old alluvial landforms by the analysis of the distribution of the concentration at

444 depth, it can eventually be subtracted from the total ^{10}Be concentration for dating the young
445 alluvial landforms.

446 On the other hand, the high variability in the ^{10}Be concentrations in sediments of the
447 active channel raises questions about their representativeness of the long-term hillslope
448 erosion. Assuming a simple local constant denudation rate model, ^{10}Be concentration in river
449 sediments would theoretically allow estimation of the Bitut catchment mean erosion rate over
450 the last several thousands years (Brown et al., 1995; Granger et al., 1996). The numerical
451 calculation derived from the mean concentration of the active alluvia yields a rate of ~ 0.61
452 m/ka for an apparent age of ~ 10 ka. However, our observations and data show that this
453 approach does not apply in Bitut catchment at least for the present day, where sediment
454 production and transport are very discontinuous and where sediments exhumed at different
455 periods of time could be mixed in the active river. Consequently, the mean ^{10}Be concentration
456 is not easily linked to a mean catchment-average erosion rate, nor to a well defined averaging
457 period.

458 Since alluvia covering strath terraces have more homogeneous pre-exposure histories,
459 we tested this approach to estimate a mean paleo-erosion rate of the catchment associated to
460 the last significant debris-flow event (5 ka). To calculate this rate, we used the mean inherited
461 ^{10}Be estimated from terrace T4. We calculate a paleo-erosion rate of ~ 0.22 m/ka for an
462 apparent age of ~ 3 kyr, i.e. since 8 to 5 ka. This means that the theoretical interval concerned
463 is probably larger than the “instantaneous” event of 5 ka, including periods of different
464 erosion intensity. Nevertheless, the impact of this strong erosion is likely to be of the first
465 order on the inherited ^{10}Be of the abandoned alluvia.

466 The difference in pre-exposure concentrations between active and abandoned alluvia
467 could be interpreted in two different ways. The first interpretation is that active alluvia have,
468 on average, higher concentrations resulting from slow erosion and transport in the catchment.

469 The large scattering in concentrations would therefore be related to episodic transport and
470 residence on hillslopes and in the channel, as suggested by the concentrations pattern in the
471 active colluvia. In this case, CRN concentrations in channel sediments would not give an
472 accurate estimate of hillslope erosion rate because a large part of CRN concentrations would
473 be acquired during transport.

474 The second interpretation is that CRN concentrations in the active channel include
475 clasts eroded on hillslopes during the last significant erosion event and clasts exhumed during
476 a previous period of slow hillslope erosion. In this case large differences in CRN
477 concentrations would result from a mix between two erosion periods on hillslopes of different
478 intensities rather than from stochastic transport in the channel. If true, the average CRN
479 concentration would give an estimate of the long-term hillslopes erosion rate over a period of
480 ~10 ka, integrating variations over periods of low and high erosion rates. In parallel, average
481 inheritance determined in the abandoned alluvia would allow estimation of a stronger
482 catchment erosion rate integrating a shorter period of time (~3 kyr) before and during the
483 Holocene climatic pulse. In other words, a combined analysis on active and abandoned alluvia
484 should enable us to reconstruct the evolution of the erosion rate.

485

486 *V.II Inherited ¹⁰Be impact on young and old terraces dating*

487 As discussed above, the inherited part of the total ¹⁰Be concentration in a deposit can
488 be estimated by the analysis of the distribution of the concentrations at depth (Anderson et al.,
489 1996). The presence of inherited ¹⁰Be, if neglected, can induce significant errors on the dating
490 of “young” terraces – less than few tens of thousands years – but also “old” terraces
491 approaching the steady state concentration.

492 When the pre-exposure time of the sediments is of the same order or longer than the
493 post-deposit exposure, young terraces can contain high fractions of inherited ¹⁰Be (e.g. Le

494 Dortz et al., 2009). This is the case for boulders of T4 in Bitut valley, or for young alluvial
495 fans on the southern side of Ih Bogd (Vassallo et al., 2005). If one does not take into account
496 the inheritance factor, the calculated age of the alluvial surface can overestimate, by more
497 than 100% the real age. Two cases are possible: if the inheritance is quite homogeneous and
498 can be precisely estimated, one can calculate the age by simply subtracting this quantity from
499 the total concentration (Anderson et al., 1996); or, if the inheritance is high but cannot be
500 precisely determined (scattering in the concentrations) it is possible to calculate a maximum
501 age by choosing the lower concentration sample (Vassallo et al., 2007a).

502 Inheritance is also a perturbing element for the dating of old alluvial deposits, where it
503 represents only a small part of the total concentration. The concentration of a sample, for a
504 given production and denudation rate, tends sooner or later to a steady-state determined by the
505 equilibrium between ^{10}Be gains (cosmogenic production) and losses (radioactive decay and
506 surface denudation). An initial quantity of inherited ^{10}Be implies that the CRN concentration
507 increases through time, passes by a maximum and then tends very slowly toward the steady-
508 state value. During the growth phase, the CRN concentration evolution is about the same as in
509 the case without inheritance, but offset by a quantity equal to the inherited CRN (**Fig. 11**).
510 Therefore, by neglecting inheritance, the risk is to consider a sample at the steady-state while
511 actually its concentration is still increasing. Such a misinterpretation will induce an over-
512 estimation of the in-situ denudation rate and, consequently, an even more important over-
513 estimation of the minimum age of the surface. It is important to note that, if steady-state is
514 assumed for interpreting CRN concentrations, an error of less than 10% on the estimation of
515 the inheritance value or of the denudation rate yields considerable changes in the theoretical
516 curves of concentration evolution for ages older than ~ 100 ka (**Fig. 11**). Therefore, in absence
517 of other independent ages or concentrations of other CRNs (^{26}Al or ^{21}Ne , for example), the
518 only way to establish if the CRN concentration of a surface has reached a steady-state or not

519 is to compare it with that of younger or older surfaces, and analyze the relationships between
520 the relative morphological ages and the respective concentrations.

521

522 **VI. Conclusion**

523 The Ih Bogd massif in the Gobi-Altay range is a particularly well-suited site to study
524 the dynamics of catchment surface processes under an arid climate and to evaluate
525 potentialities and limits of cosmogenic nuclides to quantify geomorphic processes. Erosion
526 and transport processes in this massif vary in style and magnitude under the control of
527 Quaternary climatic fluctuations. At present and during most of the time, the exhumation rate
528 of rocks is slow and constant on average, while the transport of sediments is highly stochastic
529 because of the numerous potential traps on hillslopes and in the drainage network. During
530 past climatic pulses occurring in the interglacial periods, associated with different
531 hydrological conditions, erosional events were much more intense and localized in time, and
532 exhumation and transport were rapid. This variability in the landscape dynamics through time
533 results in different pre-exposure histories for sediments in abandoned alluvial landforms –
534 produced by the main erosional events – and for active alluvia. Do the differences in CRN
535 concentrations reflect the evolution of the catchment erosion rate during different periods,
536 during climatic pulses and over a longer time-span? Or are they the result of different rates of
537 transport on hillslopes and in the drainage network? Our results do not enable definite
538 discrimination between these scenarios, even though the comparison with present processes
539 and the concentration pattern in the active colluvia seems more consistent with the latter one.
540 Quantifying past erosion and transport processes in catchments requires further investigations
541 combining other CRNs on different alluvial systems.

542 Considering our results in the perspective of the dating of the abandoned alluvial
543 landforms, we insist on the importance of a detailed

544 geomorphic/stratigraphic/sedimentological analysis at the catchment and at the local scale. A
545 good knowledge of the pre-deposit processes (exhumation, transport dynamics) and of the
546 post-deposit processes (surface denudation, burying, sediment remobilization, soil processes)
547 is required for a correct sampling and interpretation of the cosmogenic data, prior to
548 mathematical inversions of the data. For “young” deposits, ^{10}Be inheritance can cause
549 apparent exposure ages to be several times higher than true ones. For “old” deposits, small
550 errors on the estimation of the inheritance or the denudation rate can lead to considerable age
551 over-estimation or under-estimation. For suitable deposits, sampling both at surface and at
552 depth – or at the bottom of the boulders – is therefore fundamental for a better quantification
553 of the complex exposure history of the sediments, and thus for correct interpretation of the
554 concentrations in terms of ages.

555

556 **Acknowledgments**

557 We would like to acknowledge R. Braucher and D. Bourlès for fruitful discussions and
558 for the help in preparation and measurements of the samples, and all the Mongolian team for
559 their assistance during the fieldwork. We are also thankful to L. Palumbo and L. Owen for
560 their constructive reviews that helped to improve the manuscript.

561

562 **References**

563 Anderson, R.S., Repka, J.L., Dick, G.S., 1996. Dating depositional surfaces using in
564 situ produced cosmogenic radionuclides. *Geology* 24, 47-51.

565

566 Baljinnyam, I., Bayasgalan, A., Borisov, B.A., Cisternas, A., Dem'yanovich, M.G.,
567 Ganbaatar, L., Kochetkov, V.M., Kurushin, R.A., Molnar, P., Philip, H., Vashchilov, Yu.Ya.,

568 1993. Ruptures of major earthquakes and active deformation in Mongolia and its
569 surroundings. *Geol. Soc. Am., Memoir* 181, p. 62.

570

571 Bayasgalan, A., Jackson, J., Ritz, J-F., Carretier, S., 1999a. 'Forebergs', flowers
572 structures, and the development of large intra-continental strike-slip fault: the Gurvan Bogd
573 fault system in Mongolia. *J. Struct. Geol.* 21, 1285 – 1302.

574

575 Bayasgalan, A., Jackson, J., Ritz, J-F., Carretier, S., 1999b. Field examples of strike-
576 slip fault terminations in Mongolia and their tectonic significance. *Tectonics* 18, 394-411.

577

578 Belmont, P., Pazzaglia, F.J., Gosse, J.C., 2007. Cosmogenic ¹⁰Be as a tracer for
579 hillslope and channel sediment dynamics in the Clearwater River, western Washington State.
580 *Earth Planet. Sci. Lett.* 264, 123-135.

581

582 Behr, W.M., Rood, D.H., Fletcher, K.E., Guzman, N., Finkel, R., Hanks, T.C.,
583 Hudnut, K.W., Kendrick, K.J., Platt, J.P., Sharp, W.D., Weldon, R.J., Yule, J.D., 2010.
584 Uncertainties in slip-rate estimates for the Mission Creek strand of the southern San Andreas
585 fault at Biskra Palms Oasis, southern California. *GSA Bulletin* 122,1360–1377, doi:
586 10.1130/B30020.1

587

588 Binnie, S.A., Phillips, W.M., Summerfield, M.A., Fifield, L.K., 2007. Tectonic uplift,
589 threshold hillslopes, and denudation rates in a developing mountain range. *Geology* 35, 743–
590 746.

591

592 Braucher R., Brown, E.T, Bourlès, D.L., Colin, F., 2003. In situ-produced ^{10}Be
593 measurements at great depths : implications for production rates by fast muons. Earth Planet.
594 Sci. Lett. 211, 251-258.

595

596 Brown, E.T., Edmond, J.M., Raisbeck, G.M., Yiou, F., Kurz, M.D., Brook, E.J., 1991.
597 Examination of surface exposure ages of Antarctic moraines using in situ produced ^{10}Be et
598 ^{26}Al . Geochim. et Cosmochim. Acta 55, 2699-2703.

599

600 Brown, E.T., Stallard, R.F., Larsen, M.C., Raisbeck, G.M., Yiou, F., 1995. Denudation
601 rates determined from the accumulation of in situ-produced ^{10}Be in the Luquillo experimental
602 forest, Puerto Rico. Earth Planet. Sci. Lett. 129, 193-202.

603

604 Burbank, D.W., Leland, J., Fielding, E., Anderson, R.S., Brozovic, N., Reid, M.E.,
605 Duncan, C., 1996. Bedrock incision, uplift, and threshold hillslopes in the northwest
606 Himalaya. Nature 379, 505-510.

607

608 Carretier, S., Lucazeau, F., Ritz, J-F., 1998. Approche numérique des interactions
609 entre climat, tectonique et érosion. Exemple de la faille de Bogd, Mongolie. Comptes Rendus
610 de l'Académie des Sciences 326, 1-7.

611

612 Carretier, S., Ritz, J-F., Bayasgalan, A., Jackson, J., 2002. Morphologic dating of
613 cumulative reverse fault scarp, example of the Gurvan Bogd Range, Mongolia. Geophys. J.
614 Int. 148, 256-277.

615

616 Carretier, S., Regard, V., Soual, C., 2009a. Theoretical cosmogenic nuclide
617 concentration in river bed load clasts: Does it depend on clast size? *Quaternary*
618 *Geochronology* 4, 108-123.

619

620 Carretier, S., Poisson, B., Vassallo, R., Pepin, E., Farias, M., 2009b. Tectonic
621 interpretation of transient stage erosion rates at different spatial scales in an uplifting block. *J.*
622 *Geophys. Res.*, 114, F02003, doi:10.1029/2008JF001080.

623

624 Codilean, A.T., Bishop, P., Stuart, F.M., Hoey, T.B., Fabel, D. Freeman, S.P.H.T.,
625 2008. Single-grain cosmogenic Ne-21 concentrations in fluvial sediment reveal spatially
626 variable erosion rates. *Geology* 36, 159-162, doi: 10.1130/g24360a.1.

627

628 Cunningham, W.D., Windley, B.F., Dorjnamjaa, D., Badamgarov, J., Saandar, M.,
629 1996. Late Cenozoic transpression in southwestern Mongolia and the Gobi Altai-Tien Shan
630 connection. *Earth Planet. Sci. Lett.* 140, 67-81.

631

632 Delunel, R., Van der Beek, P.A., Carcaillet, J., Bourlès, D.L., Valla, P.G., 2010. Frost-
633 cracking control on catchment denudation rates: insights from in situ produced ¹⁰Be
634 concentrations in stream sediments (Ecrins–Pelvoux massif, French Western Alps). *Earth*
635 *Planet. Sci. Lett.* 293, 72–83.

636

637 Densmore, A.L., Hetzel, R., Ivy-Ochs, S., Krugh, W.C., Dawers, N., Kubik., P., 2009.
638 Spatial variations in catchment averaged denudation rates from normal fault footwalls.
639 *Geology* 37, 1139–1142, doi:10.1130/G30164A.1.

640

641 Dunai, J.T., Gonzalez Lopez, G.A., Juez-Larré, J., 2005. Oligocene–Miocene age of
642 aridity in the Atacama Desert revealed by exposure dating of erosion-sensitive landforms.
643 *Geology* 33, 321-324.

644

645 Dunne, J., Elmore, D., Muzikar, P., 1999. Scaling factors for the rates of production of
646 cosmogenic nuclides for geometric shielding and attenuation at depth on sloped surfaces.
647 *Geomorphology* 27, 3-11.

648

649 Florensov, N.A., Solonenko, V.P. (Eds.), 1965. The Gobi-Altay Earthquake. U.S. Dep.
650 of Commer., Washington D.C., 424p.

651

652 Gillespie, A.R., Bierman, P.R., 1995. Precision of terrestrial exposure ages and erosion
653 rates estimated from analysis of cosmogenic isotopes produced in situ. *J. Geophys. Res.*, 100,
654 B12, 24637-24649.

655

656 Gayer, E., Mukhopadhyay, S., Meade, B. J., 2008. Spatial variability of erosion rates
657 inferred from the frequency distribution of cosmogenic He-3 in olivines from Hawaiian river
658 sediments. *Earth Planet. Sci. Lett.* 266,303-315.

659

660 Granger, D.E., Kirchner, J.W., Finkel, R.C., 1996. Spatially averaged long-term
661 erosion rates measured from in situ-produced cosmogenic nuclides in alluvial sediment. *The*
662 *Journal of Geology* 104, 249-257.

663

664 Granger, D.E., Kirchner, J.W., Finkel, R.C., 1997. Quaternary downcutting rate of the
665 New River, Virginia, measured from differential decay of cosmogenic ^{26}Al and ^{10}Be in cave-
666 deposited alluvium. *Geology* 25, 107-110.

667

668 Hanks, T., Ritz, J-F., Kendrick, K., Finkel, R.C., Garvin, C., 1997. Uplift rates in a
669 continental interior: faulting offsets of a ~100 Ka abandoned fan along the Bogd fault,
670 southern Mongolia. Proceedings of the Penrose Conference on the Tectonics of Continental
671 Interiors. 23-28 September 1997, Brian Head Resort, Cedar City, Utah.

672

673 Heimsath, A.M., Dietrich, W.E., Nishiizumi, K., Finkel, R.C., 2001. Stochastic
674 processes of soil production and transport: erosion rates, topographic variation and
675 cosmogenic nuclides in the Oregon Coast Range. *Earth Planet. Sci. Lett.* 26, 531-552.

676

677 Hilbig, W., 1995. Introduction to the country: The Vegetation in Mongolia. SPB
678 Academic Publishing, Amsterdam, pp.13-32.

679

680 Jolivet, M., Ritz, J-F., Vassallo, R., Larroque, C., Braucher, R., Todbileg, M.,
681 Chauvet, A., Sue, C., Arnaud, N., De Vicente, R., Arzhannikova, A., Arzhannikov, S., 2007.
682 The Mongolian summits: An uplifted, flat, old but still preserved erosion surface. *Geology* 35,
683 871-874. doi: 10.1130/G23758A.1.

684

685 Kober, F., Ivy-Ochs, S., Schlunegger, F., Baur, H., Kubik, P.W., Wieler R., 2007.
686 Denudation rates and a topography-driven rainfall threshold in northern Chile: Multiple
687 cosmogenic nuclide data and sediment yield budgets. *Geomorphology* 83, 97-120.

688

689 Kurushin, R.A., Bayasgalan, A., Ölziybat, M., Enkhtuvshin, B., Molnar, P.,
690 Bayarsayhan, C., Hudnut, K.W., Lin, J., 1997. The surfaces rupture of the 1957 Gobi-Altay,
691 Mongolia, earthquake. *Geol. Soc. Am. Spec. Pap.*, 320 143p.

692

693 Lal, D., 1991. Cosmic ray labeling of erosion surfaces : in situ nuclide production rates
694 and erosion models. *Earth Planet. Sci. Lett.* 104, 424-439.

695

696 Le Dortz, K., Meyer, B., Sébrier, M., Nazari, H., Braucher, R., Fattahi, M., Benedetti,
697 L., Foroutan, M., Siame, L., Bourlès, D., Talebian, M., Bateman, M.D., Ghoraiishi, M., 2009.
698 Holocene right-slip rate determined by cosmogenic and OSL dating on the Anar fault, Central
699 Iran. *Geophys. Journ. Int.* 179, doi :10.1111/j.1365-246X.2009.04309.x

700

701 Matmon, A., Shaked, Y., Porat, N., Enzel, Y., Finkel, R., Lifton, N., Boaretto, E.,
702 Agnon, A., 2005. Landscape development in an hyperarid sandstone environment along the
703 margins of the Dead Sea fault: Implications from dated rock falls. *Earth Planet. Sci. Lett.* 240,
704 803-817.

705

706 Matmon, A., Nichols, K., Finkel, R., 2006. Isotopic insights into smoothening of
707 abandoned fan surfaces, Southern California. *Quaternary Research* 66, 109–118.

708

709 Matmon, A., Briner, J.P., Carver, G., Bierman, P., Finkel, R.C., 2010. Moraine
710 chronosequence of the Donnelly Dome region, Alaska. *Quaternary Research* 74, 63-72.
711 doi:10.1016/j.yqres.2010.04.007.

712

713 Niemi, N.A., Oskin, M., Burbank, D.W., Heimsath, A.M., Gabet, E.J., 2005. Effects of
714 bedrock landslides on cosmogenically determined erosion rates, *Earth Planet. Sci. Lett.* v.
715 237, 480–498.

716

717 Nishiizumi, K., Imamura, M., Caffee, M.W., Southon, J.R., Finkel, R.C., McAninch,
718 J., 2007. Absolute calibration of ^{10}Be AMS standards. *Nucl. Instrum. Methods B258*, 403–
719 413.

720

721 Ouimet, W.B., Whipple, K.W., Granger, D.E., 2009. Beyond threshold hillslopes:
722 Channel adjustment to base-level fall in tectonically active mountain ranges. *Geology* 37,
723 579–582, doi:10.1130/G30013A.1.

724

725 Owen, L.A., Richards, B., Rhodes, E.J., Cunningham, W.D., Windley, B.F.,
726 Badamgarav, J., Dorjnamjaa, D., 1998. Relic permafrost structures in the Gobi of Mongolia:
727 age and significance. *Journal of Quaternary Science* 13, 539-548.

728

729 Owen, L.A., Cunningham, D., Windley, B.F., Badamgarov, J., Dorjnamjaa, D., 1999.
730 The landscape evolution of Nemegt Uul: a late Cenozoic transpressional uplift in the Gobi
731 Altai, southern Mongolia. In: Smith, B. J., Whalley, W.B., Warke, P.A. (eds.) *Uplift, Erosion
732 and Stability: Perspectives on Long-term Landscape Development*, Geological Society,
733 London, Special Publications, 162, pp. 1-18.

734

735 Owen, L.A., Frankel, K.L., Knott, J.R., Reynhout, S., Finkel, R.C., Dolan, J.F., Lee, J.,
736 2011. Beryllium-10 terrestrial cosmogenic nuclide surface exposure dating of Quaternary

737 landforms in Death Valley. *Geomorphology* 125, 541-557,
738 doi:10.1016/j.geomorph.2010.10.024

739

740 Palumbo, L., Hetzel, R., Tao, M., Li, X., 2009. Topographic and lithologic control on
741 catchment-wide denudation rates derived from cosmogenic ^{10}Be in two mountain ranges at
742 the margin of NE Tibet. *Geomorphology* 117, 130-142,
743 doi:10.1016/j.geomorph.2009.11.019.

744

745 Palumbo, L., Hetzel, R., Tao, M., Li, X., 2011. Catchment-wide denudation rates at
746 the margin of NE Tibet from in situ-produced cosmogenic ^{10}Be . *Terra Nova* 23, 42-48.

747

748 Raisbeck, G.M., Yiou, F., Bouchès, D.L., Lestringuez, J., Deboffe, D., 1987.
749 Measurements of ^{10}Be and ^{26}Al with a Tandem AMS facility. *Nuclear Instruments and*
750 *Methods* 29, 22-27.

751

752 Reinhardt, L.J., Hoey, T.B., Barrows, T.T., Dempster, T.J., Bishop, P., Fifield, L.K.,
753 2007. Interpreting erosion rates from cosmogenic radionuclide concentrations measured in
754 rapidly eroding terrain. *Earth Surf. Process. Landforms* 32, 390–406.

755

756 Repka, J.L., Anderson, R.S., Finkel, R.C., 1997. Cosmogenic dating of fluvial
757 terraces, Fremont River, Utah. *Earth Planet. Sci. Lett.* 152, 59-73.

758

759 Ritz, J-F., Brown, E.T., Bouchès, D.L., Philip, H., Schlupp, A., Raisbeck, G.M., Yiou,
760 F., Enkhtuvshin, B., 1995. Slip rates along active faults estimated with cosmic-ray-exposure
761 dates: Application to the Bogd fault, Gobi-Altaï, Mongolia. *Geology* 23, 1019– 1022.

762

763 Ritz, J-F., Bourlès, D., Brown, E.T., Carretier, S., Chery, J., Enhtuvushin, B., Galsan,
764 P., Finkel, R.C., Hanks, T.C., Kendrick, K.J., Philip, H., Raisbeck, G., Schlupp, A., Schwartz,
765 D.P., Yiou, F., 2003. Late Pleistocene to Holocene slip rates for the Gurvan Bulag thrust fault
766 (Gobi-Altay, Mongolia) estimated with ^{10}Be dates. *J. Geophys. Res.* 108(B3), 2162,
767 doi :10.1029/2001JB000553.

768

769 Ritz, J-F., Vassallo, R., Braucher, R., Brown, E.T., Carretier, S., Bourlès, D.L., 2006.
770 Using In Situ-Produced ^{10}Be to Quantify Active Tectonics in the Gurvan Bogd Mountain
771 Range (Gobi-Altay, Mongolia). In Geological Soc. of America Special Paper 415 “In Situ-
772 Produced Cosmogenic Nuclides and Quantification of Geological Processes”, edited by
773 Siame, L., Bourlès, D.L., Brown, E.T. pp. 87– 110.

774

775 Schaller, M., Von Blanckenburg, F., Veldkamp, A., Van den Berg, M.W., Hovius, N.,
776 Kubik, P.W., 2004. Paleo-erosion rates from cosmogenic ^{10}Be in a 1.3 Ma terrace sequence:
777 River Meuse, the Netherlands. *Journal of Geology* 112, 127-144.

778

779 Schmidt, S., Hetzel, R., Kuhlmann, J., Mingorance, F., Ramos, V.A., 2011. A note of
780 caution on the use of boulders for exposure dating of depositional surfaces. *Earth Planet. Sci.*
781 *Lett.* 302, 60-70.

782

783 Small, E.E., Anderson, R.S., Repka, J.L., Finkel, R., 1997. Erosion rates of alpine
784 bedrock summit surfaces deduced from in situ ^{10}Be and ^{26}Al . *Earth Planet. Sci. Lett.* 150,
785 413–425.

786

787 Stone, J.O., 2000. Air pressure and cosmogenic isotope production. *J Geophys. Res.*
788 105(B10), 23753-13759.

789

790 Vassallo, R., Ritz, J-F., Braucher, R., Carretier, S., 2005. Dating faulted alluvial fans
791 with cosmogenic ^{10}Be in the Gurvan Bogd mountain (Gobi-Altay, Mongolia): climatic and
792 tectonic implications. *Terra Nova* 17, 278-285, doi: 10.1111/j.1365-3121.2005.00612.x.

793

794 Vassallo, R., 2006. Chronologie et évolution des reliefs dans la région Mongolie-
795 Sibérie : Approche Morphotectonique et géochronologique. PhD thesis, Université
796 Montpellier 2, 260 p.

797

798 Vassallo, R., Ritz, J-F., Braucher, R., Jolivet, M., Chauvet, A., Larroque, C., Carretier,
799 S., Bourlès, D., Sue, C., Todbileg, M., Arzhannikova, N., Arzhannikov, S., 2007a.
800 Transpressional tectonics and stream terraces of the Gobi-Altay, Mongolia. *Tectonics* 26,
801 TC5013, doi:10.1029/2006TC002081.

802

803 Vassallo, R., Jolivet, M., Ritz, J-F., Braucher, R., Larroque, C., Sue, C., Todbileg, M.,
804 Javkhlanbold, D., 2007b. Uplift age and rates of the Gurvan Bogd system (Gobi-Altay) by
805 apatite fission track analysis. *Earth Planet. Sci. Lett.* 259, 333-346,
806 doi:10.1016/j.epsl.2007.04.047.

807

808 Von Blanckenburg, F., 2006. The control mechanisms of erosion and weathering at
809 basin scale from cosmogenic nuclides in river sediment. *Earth Planet. Sci. Lett.* 242, 224-239.

810

811 Yanites, B.J., Tucker, G.E., Anderson, R.S., 2009. Numerical and analytical models of
812 cosmogenic radionuclide dynamics in landslide-dominated drainage basins. *J. Geophys. Res.*
813 114, F01007, doi:10.1029/2008JF001088.

814

815

816 **Figure captions**

817 **Figure 1:** A) Sketch map of the Asian continent with the main tectonic lineations and
818 localization of Ih Bogd massif (black rectangle) in the Gobi-Altay range. B) 3D view of the Ih
819 Bogd massif on a Landsat image. Main active faults and Bitut catchment/fan system are
820 shown.

821

822 **Figure 2:** 3D view of the Bitut catchment on a SPOT image. Colored circles (squares for
823 bedrock) represent the measured ^{10}Be concentrations corresponding to the different landforms
824 or single clasts (this study and Vassallo et al., 2007). Values for piedmont P0 and for terraces
825 T1, T2 and T3 at the outlet are weighted means.

826

827 **Figure 3:** Bitut catchment geomorphology is dominated by river incision and mass wasting.
828 This leads to the formation of stepped strath terraces (A and B), canyons (B) and landslides of
829 different sizes that dam the river creating small lakes or ephemeral basins along the valley
830 (C). Dashed zone in figure C corresponds to the topography before the last landslide occurred
831 (pictures by R. Vassallo).

832

833 **Figure 4:** Picture of boulder corridors starting from the edges of the summit plateau (picture
834 by R. Braucher).

835

836 **Figure 5:** Stepped strath terraces at the outlet of the catchment with their mean ^{10}Be
837 concentrations (picture by C. Larroque). Note that values increase from the youngest terrace
838 T4 to terrace T2 and then decrease for terrace T1, whose tread is slightly steeper than the
839 others and is affected by a higher denudation rate.

840

841 **Figure 6:** A) Plot of the ^{10}Be concentrations as a function of the altitude and of the relative
842 distance along the main Bitut valley. B) Histograms of the single clast concentrations for
843 strath terraces (T) and active alluvia (A) and colluvia (C). Samples shown in a pale color and
844 marked by an asterisk were not taken into account for the calculation of the weighted means.

845

846 **Figure 7:** A) Distribution of the ^{10}Be concentrations on the summit plateau and on the
847 surrounding slopes (pictures by R. Vassallo and M. Jolivet). Note the concentration 2 orders
848 of magnitude higher in the central part than on the edge and the progressive increase in
849 concentrations downslope in the colluvia. B) Detail of the plateau morphology and of the
850 bedrock sampled (IB001).

851

852 **Figure 8:** Picture of the canyon down-cutting strath terrace T4 (picture by A. Chauvet). Even
853 though the vertical bedrock wall is supposed to be exposed to cosmic rays for the same period
854 as the alluvial cover, after river incision and terrace abandonment, the former has a
855 concentration 10 times lower than the latter.

856

857 **Figure 9:** Evolution of the tread of an alluvial deposit. Starting from a bar-and-swale
858 morphology, the denudation of the surface flattens the deposit and exhumes clasts of different
859 sizes. The initial depth and size of the clasts determine the relative time of their exhumation
860 among the others and the chances of preservation in the original position during the

861 denudation of the deposit. Distribution pattern of the desert varnish on the outcropping part of
862 the clasts is an important indication of their limited remobilization after the deposit.

863

864 **Figure 10:** Panorama of the lower reaches of the Bitut river with the position of the four main
865 strath terraces (picture by J-F. Ritz). In the close-up, picture of sample MO05-08, whose
866 desert varnish distribution shows the thickness of the recent denudation (picture by R.
867 Braucher). Mean ^{10}Be concentration of terrace T3 at the outlet is up to 3 times higher than
868 upstream. Values are systematically lower than expected when slopes are steeper (the same
869 consideration can be applied to T1 and P0, see text).

870

871 **Figure 11:** Diagram of the evolution of the ^{10}Be concentration through time for three different
872 inheritances, for given production and denudation rates. The measured ^{10}Be concentration of a
873 sample, depending on the inheritance, may either correspond to a steady-state value for a 425
874 ka minimum age (green curve, no inheritance), or to non steady-state values with much lower
875 minimum ages (red and blue curves, inheritances are respectively 8 and 15% of the total
876 concentration).

877

878 **Table 1:** Results of the ^{10}Be analysis. Calibration against NIST Standard Reference Material
879 4325. Production rates have been calculated following Stone (2000) using the modified
880 scaling functions of Lal (1991) and a modern ^{10}Be production rate in quartz of 4.5 ± 0.3
881 at/g/yr at sea level and high latitude. Data from this study are marked by symbol §. Outlying
882 data marked by symbol * have not been taken into account for the calculation of the surfaces
883 weighted means (see text).

884

885