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1 Interplay of fluvial incision and rockfalls in shaping periglacial
2 mountain gorges

3 **Thibaut Cardinal¹, Laurence Audin², Yann Rolland³, Stéphane Schwartz², Carole Petit¹,**
4 **Swann Zerathe², Laurent Borgniet⁴, Régis Braucher⁵, Jérôme Nomade², Thierry**
5 **Dumont², Valery Guillou⁵, and ASTER team^{5,*}**

6 **Thibaut Cardinal¹, Laurence Audin², Yann Rolland³, Stéphane Schwartz², Carole Petit¹,**
7 **Swann Zerathe², Laurent Borgniet⁴, Régis Braucher⁵, Jérôme Nomade², Thierry**
8 **Dumont², Valery Guillou⁵, and ASTER team^{5,*}**

9 ¹ *Université Côte d'Azur, CNRS, Observatoire de la Côte d'Azur, IRD, Géoazur, F-06560*
10 *Valbonne, France, cardinal@geoazur-unice.fr, petit@geoazur-unice.fr*

11 ² *Université Grenoble Alpes, Université Savoie Mont Blanc, CNRS, IRD, IFSTTAR, ISTerre,*
12 *38000 Grenoble, France, laurence.audin@ird.fr, thierry.dumont@univ-grenoble-alpes.fr,*
13 *jerome.nomade@univ-grenoble-alpes.fr, stephane.schwartz@univ-grenoble-alpes.fr,*
14 *swann.zerathe@ird.fr*

15 ³ *Université Savoie Mont Blanc, CNRS, Pôle Montagne, Edytem, F-73370 Le Bourget-du-Lac,*
16 *France, yann.rolland@univ-smb.fr*

17 ⁴ *Université Grenoble Alpes, INRAE, LESSEM, F-38000, Grenoble, France*
18 *laurent.borgniet@inrae.fr*

19 ⁵ *CEREGE, Aix-Marseille Univ., CNRS, IRD, Coll. de France, INRAE,*
20 *Technopôle de l'Environnement Arbois-Méditerranée, BP80, 13545 Aix-en-*
21 *Provence, France, braucher@cerege.fr, guillou@cerege.fr, bourles@cerege.fr*

22 **ASTER Team: Georges Aumaître, Didier L. Boulès, Karim Keddadouche*

23 **ABSTRACT**

24 Fluvial incision is the consequence of landscape readjustment to combined tectonic
25 and climatic processes. In the southwestern Alps (Haute Provence Geopark), deep gorges

26 incised by the Bès River attest of efficient erosional processes at the front of the Alpine
27 mountain range. This catchment stands in a peripheral Alpine position, out of the glaciated
28 domain during the last glacial periods, which makes it suitable to quantify fluvial incision and
29 related erosional processes in a glacier-free environment. In this paper, we combine high
30 resolution 3D topographic mapping and in situ produced cosmogenic ^{36}Cl dating of a
31 mountain gorge (the “Clue de Barles” Gorge). First, the very high-resolution 3D topographic
32 modeling from aerial and drone surveys permits to map the erosion markers on the gorge
33 walls and to accurately determine the topographic shielding factor for CRE dating. Secondly,
34 ^{36}Cl Cosmic Ray Exposure (CRE) age distribution highlights two distinct geomorphic
35 domains along the vertical profile: i) the higher section is characterized by clusters of similar
36 CRE ages, interpreted as related to paraglacial rockfall events; ii) the lower section shows
37 increasing ages with height, which are ascribed to fluvial incision occurring at a rate of 0.15
38 mm/yr since 25ka, and of 2 mm/yr since 2ka. Our results for the Clue de Barles, compared to
39 other sites in the South French Alps highlight that: i) the gorge morphology is the result of the
40 combination of both vertical fluvial incision and lateral gravitational processes, ii) the mean
41 Quaternary fluvial incision rate in the Bès River catchment is at least twice lower than further
42 east in the formerly glaciated Alps.

43 **Keywords:** Fluvial incision; Mountain gorge; Rockfalls; CRE ^{36}Cl dating; High-resolution
44 3D mapping; Southwestern Alps

45 1. INTRODUCTION

46 The erosive response of landscapes through times provides a record of the interaction
47 between lithospheric and atmospheric forcing. The lithospheric forcing comprises isostatic
48 readjustment and tectonic motions (England and Molnar, 1990; Lavé and Avouac, 2001;
49 Wobus et al., 2006), while the atmospheric forcing consists of local or global climate
50 variations (Van der Woerd et al., 2002; Pan et al., 2003; Bacon et al., 2009). Fluvial, glacial

51 and gravitational erosion processes play a significant role in the shaping of the landforms in
52 an "erosion-uplift" self-balancing system (Adams, 1985). River dynamics therefore provide
53 quantitative information on landscape evolution because their morphology and erosive power
54 are directly linked to processes that can affect landforms: tectonic, mass movements, climate
55 change (Pratt et al., 2002; Kirby and Whipple, 2012).

56 The study of fluvial landscapes evolution relies on available Quaternary
57 geomorphological markers like terraces and incised river gorges (Pazzaglia et al., 1998;
58 Saillard et al., 2014; Rolland et al., 2017). However, processes that led to the formation of
59 these geomorphological objects are often poorly quantified when it comes to vertical markers.
60 Indeed, these 3D morphologies record a combination of different mechanisms such as fluvial
61 incision, gravitational destabilization, like landslides or rockfalls, or glacier advances related
62 to late glacial episodes (Whipple et al., 1999; Brocklehurst and Whipple, 2002; Montgomery,
63 2002; Brocard, 2003; Valla et al., 2011). Quaternary geomorphological shaping of the Alpine
64 belt and the evolution of landforms are generally explained by the alternation of glacial and
65 inter-glacial phases, which produce significant vertical uplift after each deglaciation
66 (Champagnac et al., 2007, 2008; Valla et al., 2010) and lead to a strong bedrock incision by
67 the river network. The formation of peculiar fluvial markers, like bedrock gorges (named in
68 local French language "clues" when the river runs perpendicular to the bedding), marked by
69 deeply incised rock walls have been variously interpreted as features typical of sub-glacial
70 incisions (Korup and Schlunegger, 2007; Montgomery and Korup, 2010) or of fluvial incision
71 of the Late Quaternary (Saillard et al., 2014; Rolland et al., 2017; Petit et al., 2017; 2019). In
72 all these studies, the contribution of rockfall events has never been put forward as an efficient
73 process for the long-term shaping of mountain gorges. These investigated catchments have
74 headwaters located in high altitude massifs, under the influence of glaciers since the Late
75 Glacial Maximum (LGM), which led to efficient fluvial incision during deglaciation. For all

76 these investigated sites, the CRE data evidenced a strong relation between the onset of
77 incision and the post-LGM deglaciation, which led these authors to propose that climatic
78 variations are the major external factor responsible for the incision through punctual but
79 strong glacial outburst floods during interglacials (e.g. Petit et al., 2017; Rolland et al., 2017).

80 In this paper, we focus on the Clue de Barles (CdB) Gorge in southwestern Alps
81 (Southern French Alps). The site is located at the front of the subalpine fold and thrust belt, in
82 the Bès Valley (Figure 1A), which catchment has likely been disconnected from any
83 significant glacial influence during the LGM (Brisset et al., 2015 and references therein). This
84 valley is currently at the boundary between the stable Alpine foreland and the actively
85 uplifting chain, as detected by vertical GPS measurements (>0.5 mm/yr; Serpelloni et al.,
86 2013; Nocquet et al., 2016; Sternai et al., 2019). It thus appears as a key area to determine the
87 response of a catchment unaffected by glaciers influence and undergoing a slow uplift.

88 In this paper, we aim to highlight the different erosive processes that lead to the gorge
89 formation in a fluvial-dominated catchment, based on the acquisition of a high-resolution
90 Digital Elevation Model (DEM) of the CdB Gorge and its related environment and a high-
91 resolution CRE dating profile of the ~100 meters high, nearly vertical gorge walls. These new
92 data allow us to assess the relative contribution of gravitational and fluvial incision processes
93 in the shaping of gorges along an apparently smooth profile. Finally, we compare these data
94 with previous studies available along different catchments in the Alpine foreland after the
95 LGM.

96 **2. GEOLOGICAL AND GEOMORPHIC SETTING**

97 **2.1. Geological setting: The Barles erosional “half-window”**

98 Our geomorphic target, the “Clue de Barles” (CdB Gorge), is located in the foreland
99 of the southwestern Alps (Figure 1A). This fold-and-thrust belt has undergone tectonic
100 shortening in Cenozoic times due to the Alpine collision (Dumont et al., 2012; Schwartz et

101 al., 2017). The geological structure of the region comprises the Digne nappe, made of a thick
102 Early Jurassic limestone and marl series in the study area, which was thrust over onto the
103 Cenozoic foreland molassic basin presently outcropping in an erosional half-window: the
104 Barles “half-window” in the Digne Geopark (Figure 1B; Hippolyte and Dumont, 2000). At
105 the present time, the region is still undergoing active but very slow deformation, under a
106 compressive tectonic context (Sue et al., 2007), as shown by geodesy (Walpersdorf et al.,
107 2018) and seismicity (Delacou et al., 2004).

108 In the study area, erosion due to the Bès River, a tributary of the Durance River, has
109 participated to the formation of the erosional half-window (Figure 1B) revealing the folded
110 and faulted sedimentary cover in the foreland beneath the Digne Nappe (Figure 1C). The
111 formation of this erosional feature is related to tectonic uplift controlled by Pliocene crustal
112 thickening (Schwartz et al., 2017). Thermochronological inversion modeling by Schwartz et
113 al. (2017) showed that the onset of the half-window exhumation began at 6 Ma (with a
114 denudation rate of ≈ 0.7 mm/yr). Since then, erosion, in response to the tectonic uplift (Figure
115 1C), has removed up to 4 km of the Digne nappe cover.

116 **2.2. Geomorphological setting**

117 The diversity of landscape morphologies in the Bès Valley is partly explained by
118 differential erosion due to the strong lithological variations between marly and carbonate rich
119 formations. Indeed, wide, smooth and open valleys shaped by landslides and gully dynamics
120 are observed in Middle Jurassic shales locally named the “Terres Noires formation” (Figure
121 2A). These low relief areas are delineated by adjacent strata of much more competent Late
122 Jurassic limestones. The Terres Noires formation is exposed in the core of anticlines while the
123 synclines preserve Cretaceous strata, as well as Oligocene to Miocene molassic deposits
124 unconformably lying over the Mesozoic sequence (Figures 1C). The absence of any glacial
125 geomorphological markers, such as moraines or U-shaped valleys, precludes any significant

126 glacial erosion in the Bès catchment during the LGM, as also documented by studies on the
127 maximum glacial extension in the SW Alps (Brisset et al., 2015 and references therein).
128 Recent incision of the Late Jurassic limestones (up to 250m thick) by the Bès River has
129 shaped the CdB Gorge in the southern flank of the overturned “Grande Cloche” anticline
130 (GCa; Figure 1C and 2A).

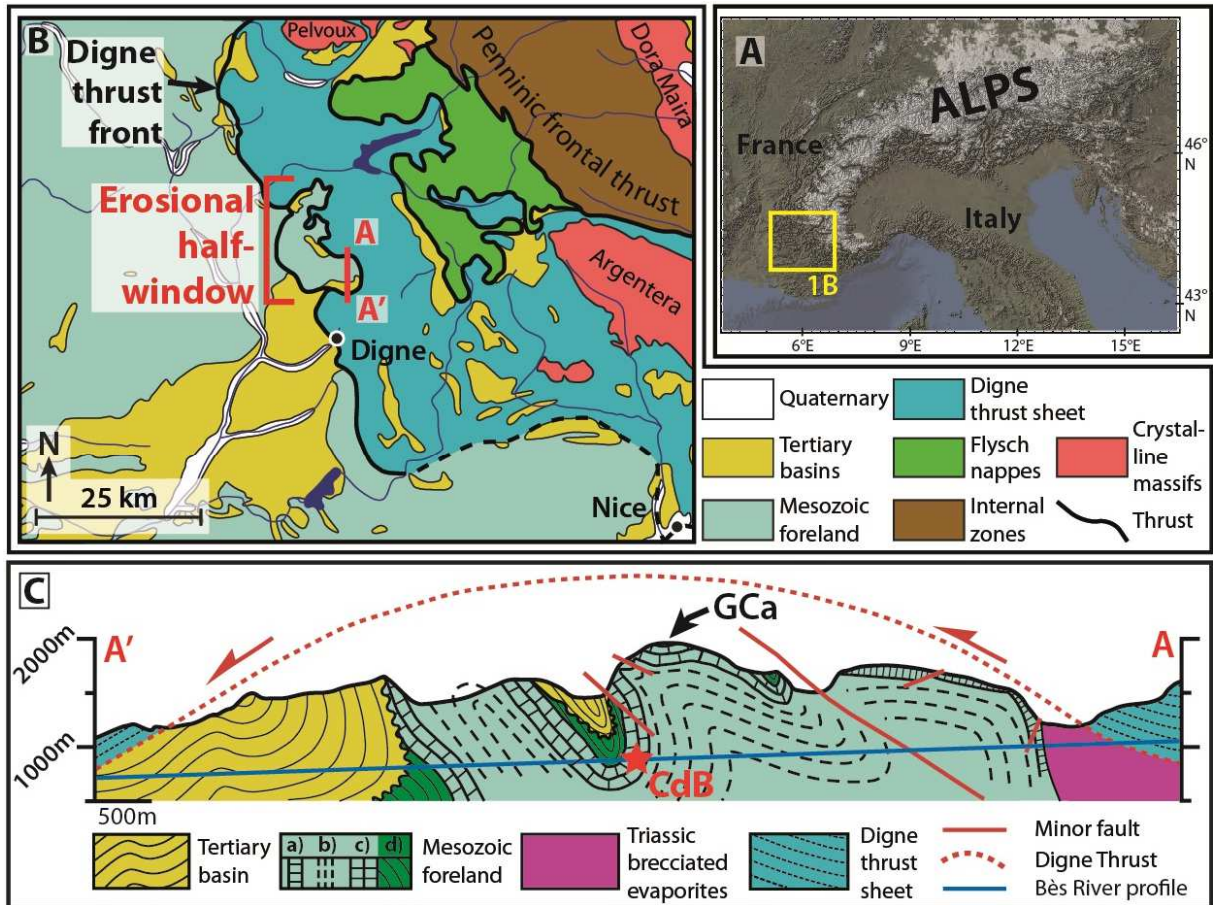
131 Figure 2 presents three different domains along the gorge perpendicular profile:

132 1) sub-horizontal surfaces above the gorge,

133 2) steep slopes of the two gorge walls facing each other that are widening as the
134 altitude increases, reaching ≈ 150 m of width at ≈ 150 m high above the river level,

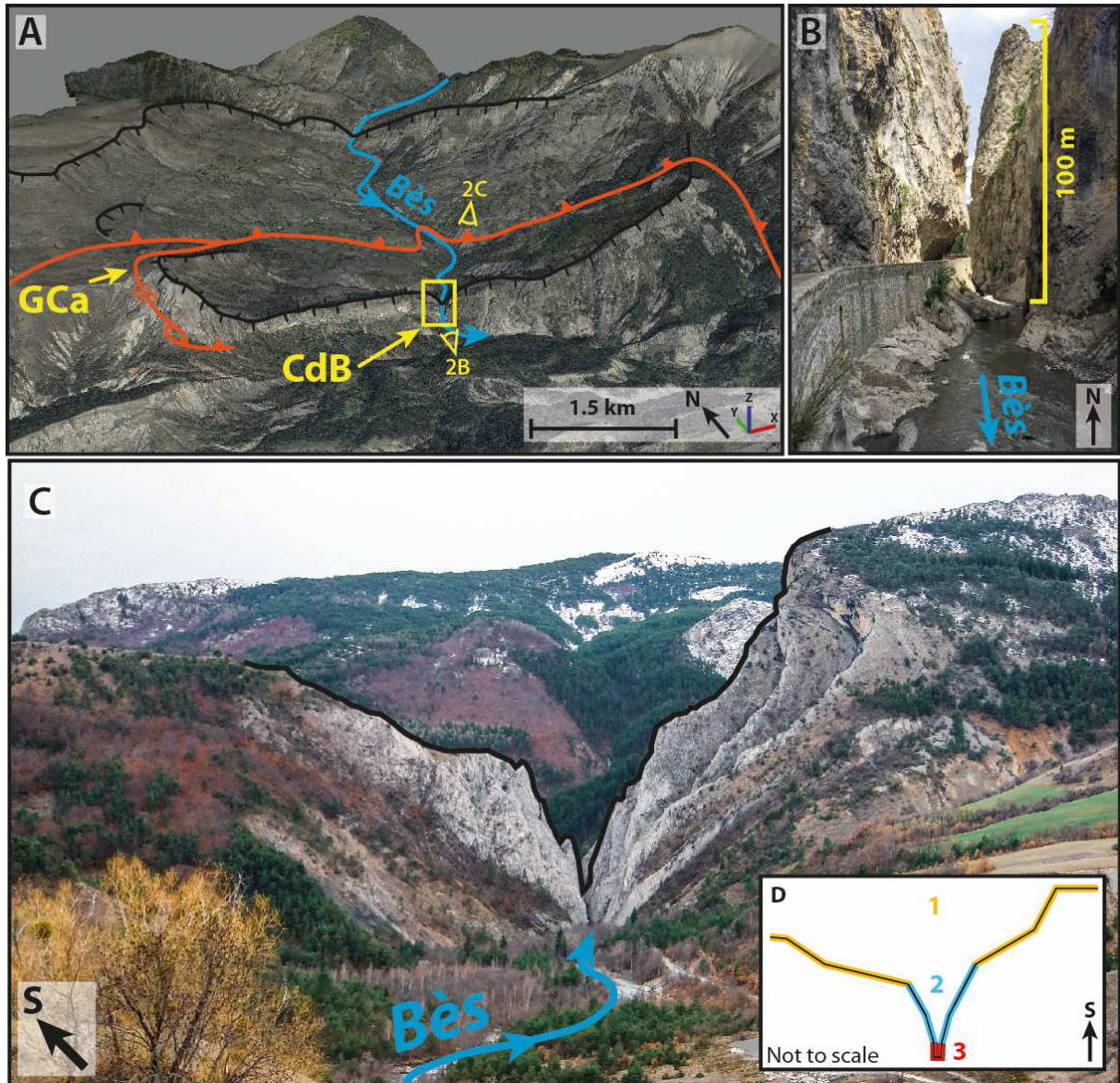
135 3) sub-vertical river polished walls that form a narrow incision canyon in the lowest
136 part (≈ 10 m high) (figure 2B, C and D).

137 The V-shaped profile of the gorge suggests that at larger scale its morphology may not
138 only be controlled by fluvial incision, but also by lateral erosional processes affecting the
139 gorge walls as the Bès River incises vertically.



140

141 Figure 1. A, Location of study area in the European Alps. B, Location of the Barles half-window in the Western
 142 Alps general tectonic framework (modified from Schwartz et al., 2017). C, Geological cross-section of the
 143 Barles erosional half-window along the Bès River profile. Mesozoic foreland a) massive Early Jurassic; b)
 144 Middle to Late Jurassic “Terres Noires”; c) Late Jurassic “Tithonian limestones”; d) Cretaceous. Note the
 145 folding of the Tithonian limestones that form the Grande Cloche anticline (GCa) in which the Clue de Barles
 146 Gorges (red star ; CdB) is dug by the Bès River.



147

148 Figure 2. A, Digital Elevation Model (DEM) based 3D view from the of the study area featuring the incised
 149 limestone bars (thick black lines) north and south of a large open valley. B, Terrestrial photographs of the Clue
 150 de Barles (CdB) Gorge. C, Panoramic view of the CdB Gorge towards the South featuring the vertical Tithonian
 151 limestone strata. Note the V shaped lateral profile of the gorge, highlighted on the photographs (black thick line).
 152 D, schematic interpretation of the V shaped profile of the gorge showing the 3 different domains: 1) sub-
 153 horizontal surfaces above the gorge, 2) steep slopes of the two gorge walls facing each other that are widening as
 154 the altitude increases, reaching ≈ 150 m of width at ≈ 150 m high above the river level, 3) sub-vertical river
 155 polished walls that form a narrow incision in the lowest part (≈ 10 m high)

156 **3. METHODS**

157 **3.1. Strategy and sampling**

158 Gorge walls are theoretically gradually exposed during the incision process (Schaller et
159 al., 2005; Ouimet et al., 2008). Therefore, cosmogenic radionuclide exposure (CRE) dating of
160 the gorge wall should reveal a systematic rejuvenation of the CRE ages towards the current
161 riverbed level through a correlation between the altitude of the samples and their CRE age.
162 However, gravitational processes, like rockfall events, may also cause the rejuvenation of a
163 gorge wall surface. If the wall compartment involved in a rockfall event is thicker than $\approx 2\text{m}$,
164 the resulting exposed surface should not retain any cosmogenic inheritance prior to the
165 gravitational event, as $\approx 95\%$ of the cosmic radiation is absorbed in the first 1.8 m below the
166 surface (Lal, 1991). Hence its concentration in cosmogenic nuclides should be null at the time
167 of the rockfall, and subsequently, the CRE age should correspond to that of the gravitational
168 event. Therefore, cosmogenic radionuclide concentration measurement is a well suited dating
169 method to obtain chronological information of both gravitational and fluvial processes, and
170 thus allows dating rockfall events and quantifying incision rate on the same spot.

171 Sampled surfaces were chosen for incision rate estimation, based on the following
172 morphological indices: i) a surface with evidence of induration varnish or with low apparent
173 superficial dissolution, indicating little erosion since exposure or ii) vicinity to peculiar
174 concave erosional surfaces (“pot holes”) preserved in the gorge walls that points to the last
175 stalling point before the incision phase. The identification of such markers and the necessity
176 to avoid samples with a too large topographic shielding led to the choice of a $\approx 10\text{ m}$ high,
177 well-preserved wall located at the southern (i.e., downstream) extremity of the gorge (Figure
178 3). The dissolution, weathering patina and superficial smoothing of the limestone surface of
179 the gorge prevented us from confidently identifying a priori gravitational markers from the
180 wall morphology through field and DEM based observations, by any rockfall scars
181 characterized by edged surface and distinct coloration due to the lack of patina. We then
182 chose to sample regularly the $\approx 70\text{ m}$ high wall rising above the preserved surface along a

183 sub-vertical profile (Figure 3A and 3C).

184 Along this profile, twenty limestone samples were collected, using a drill, hammer and
185 chisel. The sampled surfaces include the lower and preserved river-polished surface and the
186 upper slightly widening part of the gorge wall. In total, the gorge profile extends from the
187 river up to 80 m high on two parallel vertical limestone strata (Figure 3C). We sampled
188 surfaces with no overhanging relief to minimize the topographic shielding and to simplify the
189 topographic shielding factor determination.

190 In parallel, four samples were collected on the eastern sub-horizontal top of the limestone
191 bar overlooking the gorge to constrain the local denudation rate in this part of the catchment
192 (Figure 2C and 3A)

193 **3.2. Analytical protocol**

194 Samples were prepared at the Laboratoire National des Nucléides Cosmogéniques
195 (LN2C; CEREGE, Aix-en-Provence) following the procedure presented by Schimmelpfennig
196 et al. (2009). ^{36}Cl concentrations were determined by accelerator mass spectrometry (AMS)
197 performed on ASTER, the French national AMS facility (CEREGE, Aix en Provence)
198 (Arnold et al., 2010). All measurements were calibrated against in-House CEREGE SM-CL-
199 12 standard (Merchel et al. 2011). Total uncertainties account for counting statistics, standard
200 evolution during measurements, standard uncertainty and external uncertainties of 2.74%,
201 2.13% and 1.62 % for $^{36}\text{Cl}/^{35}\text{Cl}$, $^{36}\text{Cl}/^{37}\text{Cl}$ and $^{35}\text{Cl}/^{37}\text{Cl}$ ratios, respectively (Braucher et al.,
202 2018). The full chemical compositions of the two sampled Tithonian limestone strata were
203 analyzed at CRPG (Nancy) in order to take into account for the various ^{36}Cl production
204 pathways (Schimmelpfennig et al., 2009). A sea level and high latitude ^{36}Cl production rate
205 for calcium spallation of 42.2 ± 3.4 atoms $^{36}\text{Cl} \text{ g}^{-1} \text{ yr}^{-1}$ (Schimmelpfennig et al., 2009; Braucher
206 et al., 2011) has been used and scaled after Stone (2000) and corrected for topographic
207 shielding (see next paragraph). ^{36}Cl ages have been determined using the approach of

208 Schimmelpfennig et al. (2009) using a limestone density of 2.6 g.cm⁻³. CRE data are
209 displayed in Table 1.

210 Topographic shielding was first determined from field data. Furthermore, we chose to
211 use a high resolution DEM, built from a drone survey of the gorge and its surroundings, in
212 order to be able to precisely recalculate the shielding parameters on each sampled surface.

213 **3.3. Topographic shielding estimation in a narrow gorge**

214 The estimation of topographic shielding (TS) allows the calibration of the sampled
215 surfaces exposure ages by evaluating how much cosmic rays were obstructed by the
216 surrounding topography, which decreases the cosmogenic nuclides production rate (Dunne et
217 al., 1999). The TS factor is defined as the ratio of the received cosmic flux at a given point
218 over the maximum flux at this point assuming an unshielded exposure (Dunne et al. 1999;
219 Gosse and Phillips 2001). It is commonly calculated using the following equation from Dunne
220 et al. (1999):

$$221 \quad C_T = 1 - \frac{1}{2\pi} \sum_{i=1}^n \Delta\phi_i \sin^{m+1}(\theta_i)$$

222 Where C_T is the TS factor, n is the number of topographic obstructions that are measured
223 around a sampled surface, each obstruction being represented by a pair of azimuth ϕ_i and
224 elevation angles θ_i , m is a constant which commonly cited value is 2.3 (Gosse and Phillips
225 2001). This factor is commonly estimated in the field during surface sampling by measuring,
226 using a compass, the horizon elevation at 360° around the sampled surface (Gosse and
227 Phillips, 2001). However, such protocol is difficult to implement in gorges while sampling the
228 vertical wall, and is complexified by the 3D geometry of the gorge.

229 Numerical methods exist to estimate TS from Digital Elevation Models (DEM), which
230 have been demonstrated on basin-averaged denudation rate studies (e.g. Codilean, 2006;
231 Balco et al., 2008). In this paper, we used the tools developed by Li (2013), for the GIS
232 software ArcGis, using high-resolution DEMs of the CdB Gorge and its surrounding. The

233 DEM used are built from the Structure-from-Motion method, using aerial photographs
234 acquired by plane, for the surrounding gorge topography, and UAV, for the mapping of the
235 vertical parts (gorges walls), following an adaptation of the methodology presented in
236 Vasquez-Tarrio et al. (2017).

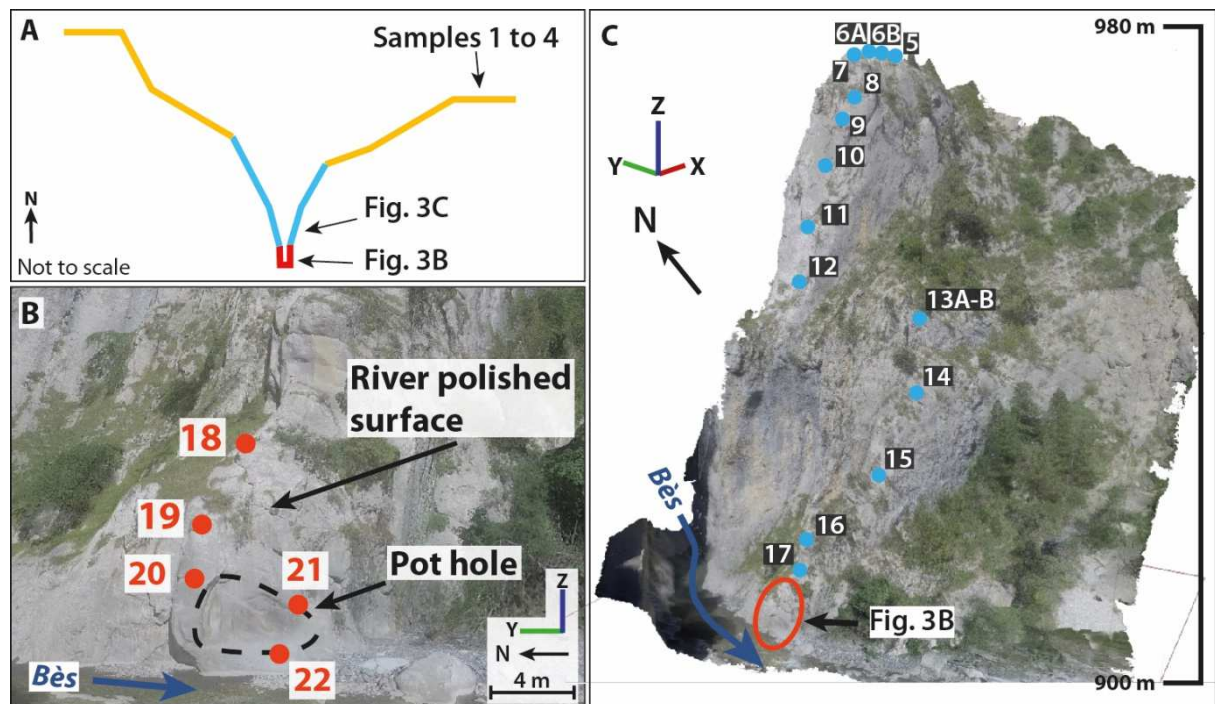
237 The resulting data set has a resolution of 50 cm (precision RMSE of 2.6m), for the model
238 surroundings used for the TS factor determination, and 7cm with a precision of 16.8 cm
239 (RMSE) for the DEM used for the mapping of the incision markers in the gorge. Such
240 precision has been achieved in a vertical environment, such as the CdB Gorge without GPS
241 signal, with the use of a total station (Leica TS02) for the acquisition of Ground Control Point
242 (GCP). The code by Li (2018) allows us to calculate the maximum elevation for each azimuth
243 value (horizontal angle from 0° to 360° by 5° increment) around the sampled surface.

244 In a previous study, Norton and Vanacker (2009) mentioned that the use of a DEM with
245 resolution lower than 5 m (5 m being the optimal resolution) can cause an overestimation of
246 the TS factor, because of the ability of cosmic rays to pass through small obstructions without
247 any significant interaction (Norton and Vanacker, 2009). However, in gorges, the use of a
248 higher resolution DEM is required for the numerical determination of the TS factor, as the
249 samples were all gathered in a narrow horizontal (XY) space, even if they lie at a larger
250 distance from each other in the vertical Z dimension. Furthermore, the only obstructions in
251 the gorge are the \approx 200 m thick limestone walls. A precise estimate of TS is very important in
252 the CdB Gorge, as it has a large impact on the calculated CRE ages.

253 **3.4. Denudation rates**

254 Denudation, which includes mechanical and chemical erosion, is an important process
255 in the shaping of carbonate landscapes (Ryb et al., 2014a; 2014b). The efficiency of the
256 denudation process is controlled in part by the slope and convexity of the surfaces that are
257 involved (Godard et al., 2016; Thomas et al., 2017). Gravitational processes must be

258 considered, but also the spatial variability of the carbonate dissolution efficiency, which
 259 results from numerous slope morphological irregularities (overhangs, recesses, fractures).
 260 Because the radionuclide concentration at the surface results from a constant competition
 261 between surface denudation and production by exposure to cosmic rays, the denudation rate is
 262 an important factor that needs to be determined in order to calculate the CRE ages. In the SW
 263 Alps, a regional denudation rate of ≈ 30 mm/kyr has been estimated in the literature (e.g.
 264 Godard et al., 2016; 2020; Thomas et al., 2017), and this parameter has also been constrained
 265 locally for our site by using steady-state radionuclide concentrations. For this purpose, four
 266 sub-horizontal surfaces have been sampled on the top of the limestone bar in which the gorge
 267 was incised (≈ 250 m above riverbed) (Figure 2C and 3A). The denudation rates are
 268 calculated assuming a steady-state between radionuclide production and denudation, after the
 269 procedure described Schimmelpfennig et al. (2009).



270
 271 Figure 3. A, schematic interpretation of the gorge V shaped profile and location of the sample gathered for CRE
 272 dating. B, Digital Elevation Model (DEM) based 3D view of the lower part of the sampling profile and location
 273 of the corresponding samples (18 to 20). Note the presence of a “pot hole” that indicates the preserved nature of
 274 the river polished sampled surface. Above sample 18, the preservation of the fluvial polished surface on the

275 gorge wall is not sure and might have suffer post-incision erosion processes (dissolution and/or gravitational
276 processes). C, All samples located on the high-resolution 3D DEM of the 80 m high CdB Gorge wall.

277 **4. RESULTS**

278 **4.1. Flat upper surface: steady-state denudation rates**

279 Measured radionuclide concentrations (samples 1 to 4, Figure 2C and 3A, \approx 250m above
280 river) for the horizontal high hanging paleo surfaces of the limestone bar range from 1.56 to
281 2.84×10^6 ^{36}Cl at/g (Table 1). Assuming these samples at steady state (i.e. their exposure time
282 is long enough to ensure that concentrations have reach a plateau), yields to steady-state
283 denudation rates ranging between 18.74 ± 1.05 and 32.54 ± 1.76 mm/ka for these top samples.
284 These values are in agreement with previous estimates (e.g. Godard et al., 2016; 2020;
285 Thomas et al., 2017, Siame et al., 2004; Zerathe et al., 2013), for the SW Alps.

286 **4.2. Gorge steep slope / middle part: rockfall markers**

287 **4.2.1. Fracturation**

288 The CdB Gorge walls are heavily fractured and prone to rock mass movements, as
289 observed by our field structural analysis: two major fracture families have been measured on
290 the gorge walls, both trending N30°E (i.e., parallel to the gorge strike), the first one dipping
291 \sim 70°W and the second one dipping 40-50°E, while the bedding is \sim EW and vertical (Figure
292 4).

293 **4.2.2. CRE age**

294 Denudation rates obtained on horizontal surfaces do not reflect the true denudation that
295 has affected the vertical walls of the gorge. Indeed, it is generally considered that vertical and
296 sub-vertical surfaces undergo less dissolution than gently dipping or horizontal surfaces, as
297 they receive much less water runoff, and water does not stagnate or percolate (Sadier et al.,
298 2012). Compiling denudations rates determined from our data and those from literature, we
299 have decided to consider a denudation rate of 10 mm/ka for vertical or sub-vertical surfaces,
300 following Sadier et al. (2012). CRE ages determined from the ^{36}Cl concentrations are reported

301 in the age-elevation plots (Figure 5A). The profile displays ages between 22 and 8 ka We can
302 observe two ages clusters, one at ≈ 17 ka (samples 5 to 9) and the other one at ≈ 10 ka (samples
303 10 to 13A), respectively.

304 As shown on Figure 5A, the CRE ages distribution does not correlate with the altitude of
305 the samples and especially, we do not see any systematic rejuvenation of the CRE ages
306 towards the base of the gorge at the current riverbed level, as it would be expected for a gorge
307 slope affected by post-incision erosion processes (such as rockfall or dissolution). The
308 interpretation of these ages therefore requires a more detailed analysis taking into account the
309 3D morphology of the gorge walls, and the processes that may have affected the history of
310 their exposure to cosmic rays.

311 **4.3. River polished vertical surface / lower part: fluvial incision**

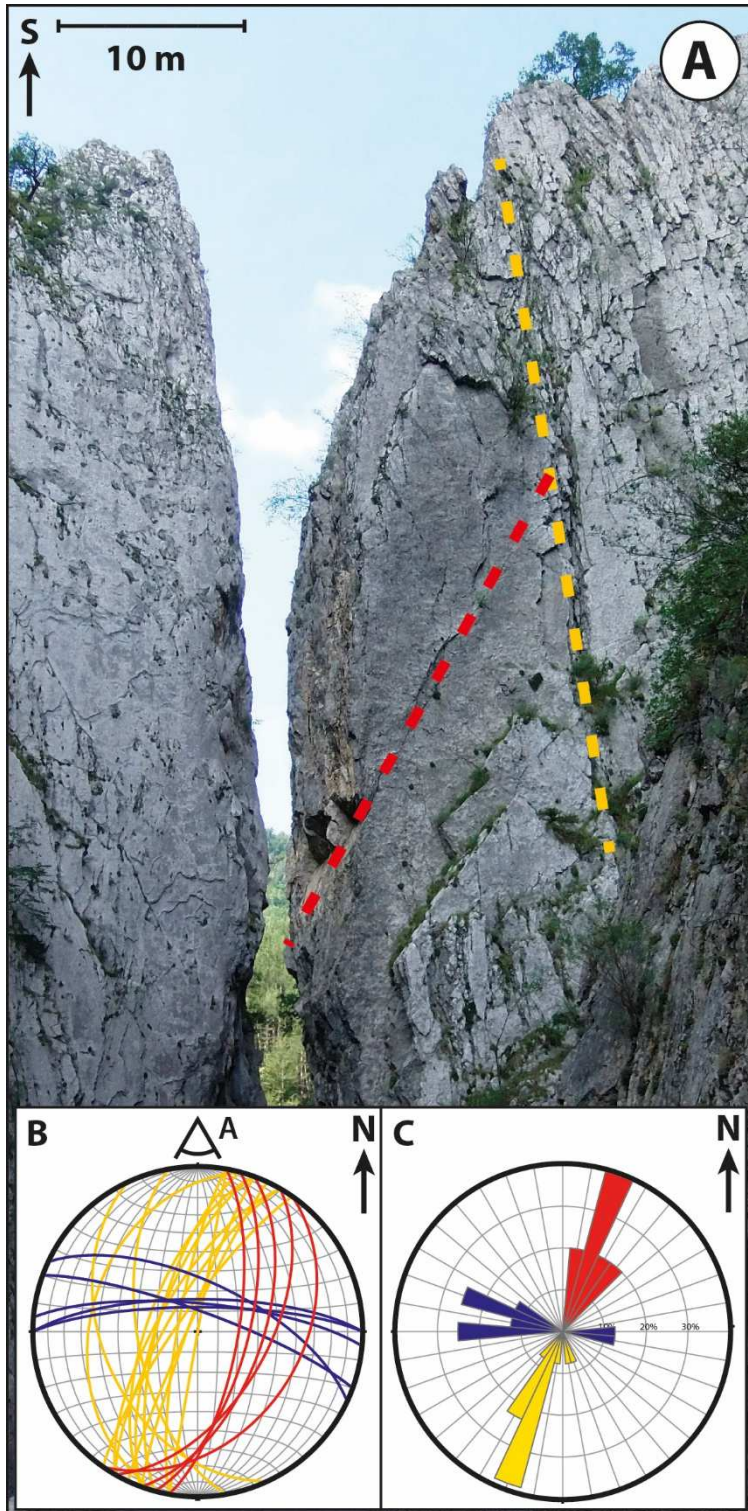
312 CRE ages determined from the ^{36}Cl concentrations in the gorge lower part are reported in
313 the age-elevation plots (Figure 5B). The five samples (18 to 22) display ages between 25 ka
314 and 800 a (Table 1). From these ages, we can compute two distinct incision rates: 0.15 mm/yr
315 from 25 ka to 2 ka and 1.97 mm/yr from 2 ka to present day, assuming a y-intercept equal to
316 zero.

Sample	Altitude above sea level (m)	Height above river (m)	Lat	Long	Spall. scaling	³⁵ Cl (ppm)	Ca (%)	Atoms ³⁶ Cl (at/g)	Atoms ³⁶ Cl uncertainty (at/g)	CRE age (yr)	Denudation rate (mm/ka)	TS factor	Surface strike and dip
1	1165.0	263.0	44.23	6.26	2.64	60.5	36.0	18885474	111338	-	32.83 ± 1.94	0.99	Sub-horizontal
2	1155.6	253.6	44.23	6.26	2.62	48.5	39.0	2767824	155686	-	18.74 ± 1.05	0.99	Sub-horizontal
3	1151.7	249.7	44.23	6.26	2.61	81.3	38.2	2844314	195423	-	22.91 ± 1.57	0.99	Sub-horizontal
4	1154.9	252.9	44.23	6.26	2.62	38.0	31.9	1563115	84417	-	32.54 ± 1.76	0.99	Sub-horizontal
5	975.2	73.2	44.23	6.26	2.27	29.1	32.1	414312	21132	13598 ± 694	-	0.85	N118E23
6A	975.7	73.7	44.23	6.26	2.27	17.2	24.7	463710	20942	19805 ± 894	-	0.87	N22E4
6B	975.5	73.5	44.23	6.26	2.27	102.8	27.6	840309	279136	19240 ± 6391	-	0.87	N21W12
7	975.1	73.1	44.23	6.26	2.27	20.6	38.9	518890	23489	15334 ± 694	-	0.87	N171W33
8	969.3	67.3	44.23	6.26	2.26	32.6	32.2	397913	24537	15229 ± 639	-	0.72	N151W37
9	966.8	64.8	44.23	6.26	2.25	17.5	38.2	451597	21698	15810 ± 760	-	0.76	N170W68
10	959.8	57.8	44.23	6.26	2.24	23.6	37.2	321967	15754	9877 ± 483	-	0.84	N145W72
11	950.7	48.7	44.23	6.26	2.22	23.5	38.6	310801	16034	9791 ± 505	-	0.80	N77W72
12	944.0	42.0	44.23	6.26	2.21	22.3	37.4	298013	15522	11668 ± 608	-	0.67	N14W72
13A	940.4	38.4	44.23	6.26	2.21	28.0	38.0	290021	15713	10276 ± 556	-	0.71	N106W87
13B	940.4	38.4	44.23	6.26	2.21	43.3	38.4	257546	22005	8397 ± 717	-	0.71	N106W87
14	930.9	28.9	44.23	6.26	2.19	29.8	37.3	467713	23683	19233 ± 974	-	0.65	N140E89
15	922.4	20.4	44.23	6.26	2.17	25.3	37.3	330443	16938	16245 ± 833	-	0.55	N4E84
16	915.4	13.4	44.23	6.26	2.16	27.3	31.8	341914	17288	22348 ± 1130	-	0.47	N162W26
17	911.6	9.6	44.23	6.26	2.16	22.9	37.7	229307	13073	13660 ± 779	-	0.45	N13W71
18	908.2	6.2	44.23	6.26	2.15	29.0	38.0	396966	22406	25803 ± 1456	-	0.43	N140W80
19	907.2	5.2	44.23	6.26	2.15	30.4	35.7	268197	14974	18429 ± 1029	-	0.40	N179W61
20	905.4	3.4	44.23	6.26	2.14	28.8	33.2	98729	8562	6581 ± 572	-	0.41	N0E84
21	904.5	2.5	44.23	6.26	1.49	21.2	37.5	26219	3368	1267 ± 163	-	0.52	N155E83
22	903.6	1.6	44.23	6.26	1.49	22.6	37.4	17964	3489	830 ± 161	-	0.53	N150E56

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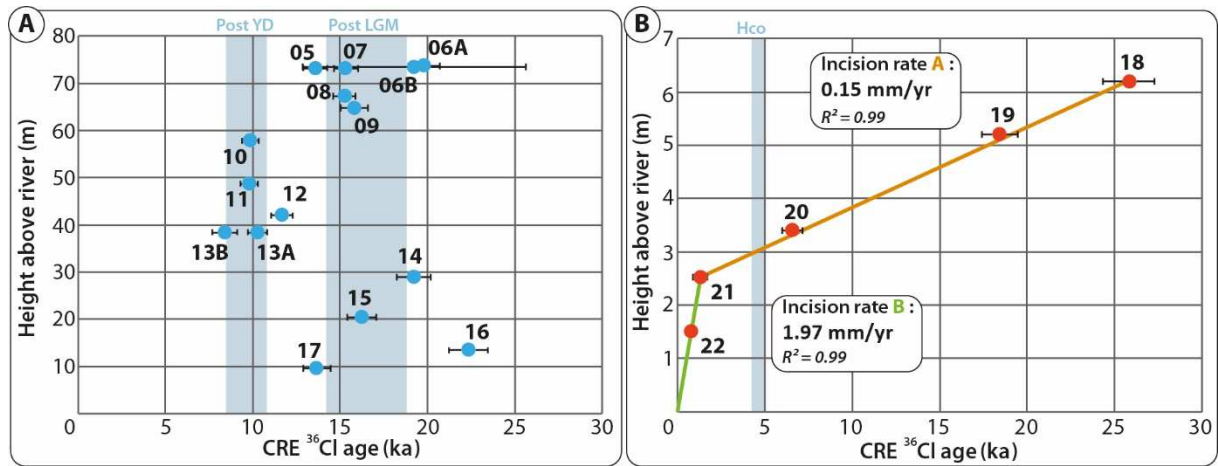
318 Table 1. ³⁶Cl CRE sample characteristics and geochronological data. Sample field information, natural chlorine, calcium, and cosmogenic ³⁶Cl contents in the limestone

319 samples and resulting ³⁶Cl CRE ages and denudation rates, TS factor and strike and dip of the sampled surfaces are indicated.



320

321 Figure 4. A, West flank of CdB Gorge viewed towards the south with the two major representative fracture
 322 planes highlighted by red and yellow dashed lines. B, Projection of bedding plane (in blue), major fracture
 323 planes visible in A (red and yellow), Wulff projection, lower hemisphere. C, Rose diagram of bedding and
 324 fracture planes (same colors).



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Figure 5. Height above river bed versus exposure age, determined by ³⁶Cl concentration, for the 18 dated samples collected in the middle (A) and lower part (B) of the CdB Gorge. The dot colors are in reference to the Figure 3: the red dots refer to the river polished lower part, and the blue dots refer to the middle part of profile. With the five CRE ages ascribed to the fluvial incision process (B), we are able to compute incision rates ranging from 0.15 mm/yr to 1.97 mm/yr, which might suggest an acceleration of incision after 2 ka. Known deglaciation periods are chronologically represented by light blue columns: post LGM (Last Glacial Maximum): ≈ 19-14 ka Clark et al. (2009); Post YD (Post Younger Dryas): ≈ 11-8 ka. Darnault et al. (2012); Hco (Holocene climatic optimum): ≈ 5-4 ka; Zerathe et al. (2014).

5. DISCUSSION

5.1. Geomorphological interpretation of the CRE ages

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Field and DEM observations evidence that the CdB Gorge walls have been rejuvenated several times in the middle part of the sampling profile (samples 5 to 17).

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Actually, detailed field structural investigations of the gorge (Figure 4) and DEM-based morphological analysis of the sampled wall (Figure 6A, B, C) attest of such gravitational processes in the CdB Gorge. All the planes (fractures and bedding) described in previous section 4.2. (Figure 4) can play a role in the occurrence of rockfall events by isolating polygonal blocks susceptible to fall from the rock scarp. Furthermore, differential erosion between the various vertical limestone strata of different thickness, ranging from ≈ 20m to > 1m, destabilizes the vertical walls and thus leads more competent strata to be in an unstable overhanging position. These observations highlight the predisposing factors and vulnerability

346 of the gorge to rockfall hazard. The combination of vertical incision and lateral gravitational
347 processes can therefore explain the peculiar V-profile of the CdB Gorge.

348 The main fracture orientations (yellow; Figure 4 and 6A, B, C), are parallel to the surface
349 of the profile in its middle part (from samples 07 to 12; Figure 6C) suggesting that this
350 surface may result from rockfall events. The fracture pattern and the morphology of the wall
351 suggest the toppling of a large vertical column (≈ 20 m high; Figure 6D), prepared by joints
352 opened within the vertical limestone beds. Following this observation and the CRE ages, it
353 appears that the column was toppled by two distinct events, involving first the upper part of
354 the column (samples 7 to 9) and then its lower part (samples 10 to 12) at ≈ 17 ka and ≈ 10 ka
355 respectively (Figure 5). Other sampled surfaces, from samples 5 to 6B and 13A to 17, show
356 an age distribution with three clusters ranging from 14.5 to 22 ka, from 10 to 30m above
357 riverbed. The age versus height distribution does not show any clear trend, which suggests
358 that these surfaces were later rejuvenated by gravitational processes.

359 Finally, in the lower part of the profile, the linear decrease of CRE ages towards the
360 riverbed is suggestive of fluvial incision, which can be separated into two phases: i) from
361 sample 18 to 21 (0.15 mm/yr), and ii) from sample 21 to riverbed (2.15 mm/yr). However, the
362 latter incision rate only concerns the foot of the gorge wall (>2.5 m high) which can be
363 rejuvenated by punctual and recent flood events, and is constrained by only two points (three
364 of we take into account the (0,0) point corresponding to the river bed). Hence, the estimated
365 incision rate of 2.15 mm/yr is not representative of the long-term fluvial incision process
366 that is responsible for the formation of the CdB Gorge.

367 **5.2. Climatic control on gravitational events**

368 Major rockfall events can be interpreted as the result of changing climate conditions,
369 as these processes are well known to be sensitive to permafrost degradation during warming
370 phases (e.g. Ravanel et al., 2010; Hilger et al., 2021). Based on our case example, these

371 gravitational processes appear to be an important factor of the gorge erosion process. We
372 obtained two age clusters which we interpret as two instantaneous rockfall events having
373 occurred at ≈ 17 and ≈ 10 ka respectively. These ages correspond to the two last major
374 deglaciation phases: post LGM (≈ 19 -14 ka; Clark et al., 2009) and post Younger Dryas (\approx
375 11-8 ka; Darnault et al., 2012) (Figure 5). Although reconstructions of permafrost are still
376 lacking for this period of time, we suggest that this relatively high-altitude area could have
377 been under permafrost influence, due to its elevation above the equilibrium line altitude for
378 glaciers during the LGM and Younger Dryas, and its proximity to the glacier front (Brisset et
379 al., 2015 and references therein). Therefore, these gravitational events could have been caused
380 by permafrost degradation, adding to a potential increased of freezing and thawing cycles
381 during glacial phases (Sanchez et al., 2010; Lebrouc et al., 2013; Hilger et al., 2021). These
382 observations therefore suggest that the CdB Gorge results from a vertical fluvial incision
383 process, and is later widened by glacial and postglacial processes related to climate phases.

384 **5.3. Regional comparison of river incision rates in SW Alps and possible controlling** 385 **factors: climate, fluvial regime and surface uplift**

386 Several studies based on CRE dating have been carried out on gorges and valleys of
387 the SW Alps (Saillard et al., 2014; Rolland et al., 2017; Petit et al., 2019; Figure 7). The
388 comparison of fluvial incision at the scale of SW Alps from gorges formed in valleys with or
389 without glacial influence shows the dominance of high and variable incision rates in formerly
390 glaciated catchments, while catchments devoid of glacial influence have lower incision rates
391 since the LGM. Indeed, glaciated areas accumulate topographic disequilibrium during
392 glaciation (Brocard and van der Beek, 2006). Readjustments after glacial perturbations imply
393 enhanced erosion by fluvial and hillslopes processes, especially during deglaciation (Norton
394 et al., 2010; Fox et al., 2015). In catchments dominated by glaciers during the LGM and
395 Younger Dryas in their higher part, the above authors determined incision rates ranging from

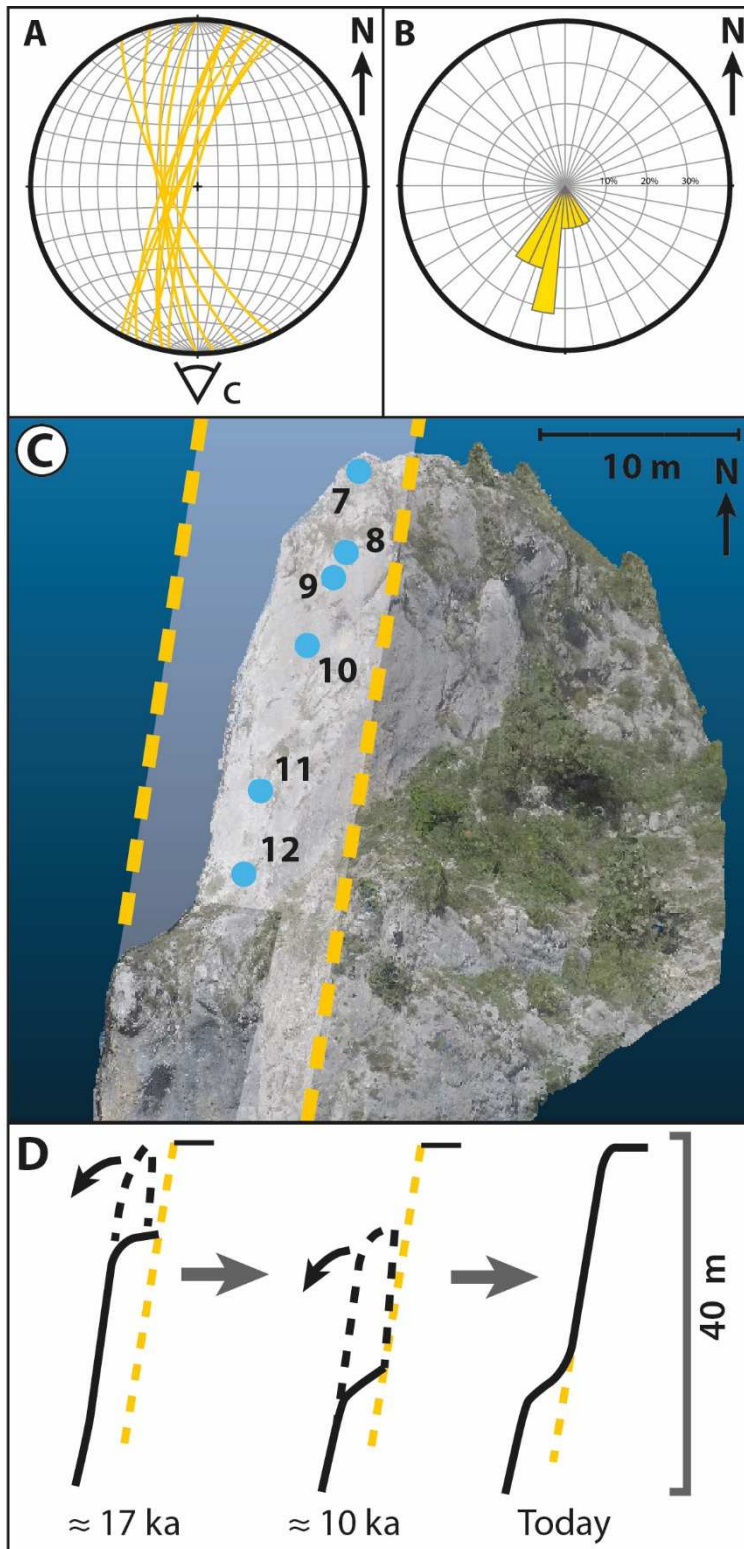
396 1 mm/yr to ≈ 8 mm/yr (Figure 7B), which they attributed to efficient fluvial incision. The most
397 extreme values are restricted to the catchments higher altitude ($>900\text{m}$) and can be attributed
398 to transient incision of late glacial morphologies after the Younger Dryas (Rolland et al.,
399 2017). In formerly glaciated areas, the post-LGM incision might be controlled by climatic
400 variations, through punctual post-glacial outbursts, and topographic readjustment through
401 transient headward erosion. Therefore, these locally very high incision rates cannot be used to
402 infer any long-term tendency.

403 Out of the influence of glaciers, the incision rates estimated for the Estéron River
404 (Petit et al., 2019) and the Bès River (this study) are of ≈ 1.0 and 0.15 mm/yr respectively
405 (Figure 7; Petit et al., 2019; this study). However, if we compare incision rates between the
406 Vésubie, Estéron and Bès rivers after the last cold climatic event (i.e., the Younger Dryas),
407 despite the fact that all three profiles are measured in a similar lithology and under
408 comparable climatic settings, the mean incision rate of the Bès river (0.15 mm/yr) appears
409 significantly lower than in the Vésubie (2.0 ± 0.1 mm/yr), like for all catchments with glacial
410 influence. In comparison to a catchment positioned in a similar glacier-free setting, the
411 Esteron River (1.0 ± 0.1 mm/yr), the river incision rate value estimated for the Bès is still
412 significantly lower.

413 Surface uplift, which is a combination of isostatic rebound, tectonic uplift and erosion,
414 may also cause incision rate variability (e.g. Kirby and Whipple, 2012). Isostatic rebound,
415 either induced by Quaternary erosion and LGM glacier retreat, has been shown to be
416 insignificant in the SW Alps (Norton and Hampel, 2010; Champagnac et al., 2017; Sternai et
417 al., 2019). Regarding the tectonic uplift component, cooling rates from Apatite Fission Track
418 measurements in the external crystalline massif of the Argentera-Mercantour (Bogdanoff et
419 al., 2000; Bigot-Cormier et al., 2006) lead to long-term exhumation rates of 1.1 - 1.4 mm/yr
420 (rock uplift) over the last 10 Myr. Closer to our study area, Schwartz et al. (2017)

421 demonstrated by low-temperature thermochronometry that the Barles erosional half-window
422 area has been exhuming at a long-term rate of ≈ 0.7 mm/yr since 5 Ma. Recent studies using
423 GPS monitoring in the Alps (Walpersdorf et al., 2018; Sternai et al., 2019) evidence a
424 present-day surface uplift rate of 0.5 to 1 mm/yr in the highest parts of the Alpine massifs,
425 while GPS stations closer to our study area (La Javie and Moustiers-Sainte-Marie) have short-
426 term uplift rates of 0.025 ± 0.9 and -0.41 ± 0.58 mm/yr, respectively (Sternai et al., 2019).

427 Hence, the relatively high incision rates recorded in the Var catchment and tributaries
428 compared to the slow rates determined at the CdB gorge may reflect the east to west (i.e.
429 massifs highest parts to Alpine foreland) regional variability of both long-term and short-term
430 uplift rates. Nevertheless, in order to better discriminate the respective role of local catchment
431 dynamics (glacial or not) and uplift rates variability on fluvial incision process, further
432 constraints on incision rates are needed at the scale of SW Alps.



433

434 Figure 6. Geometrical characteristics of the rockfall domain in the middle part of the CdB Gorge profile. A-B,

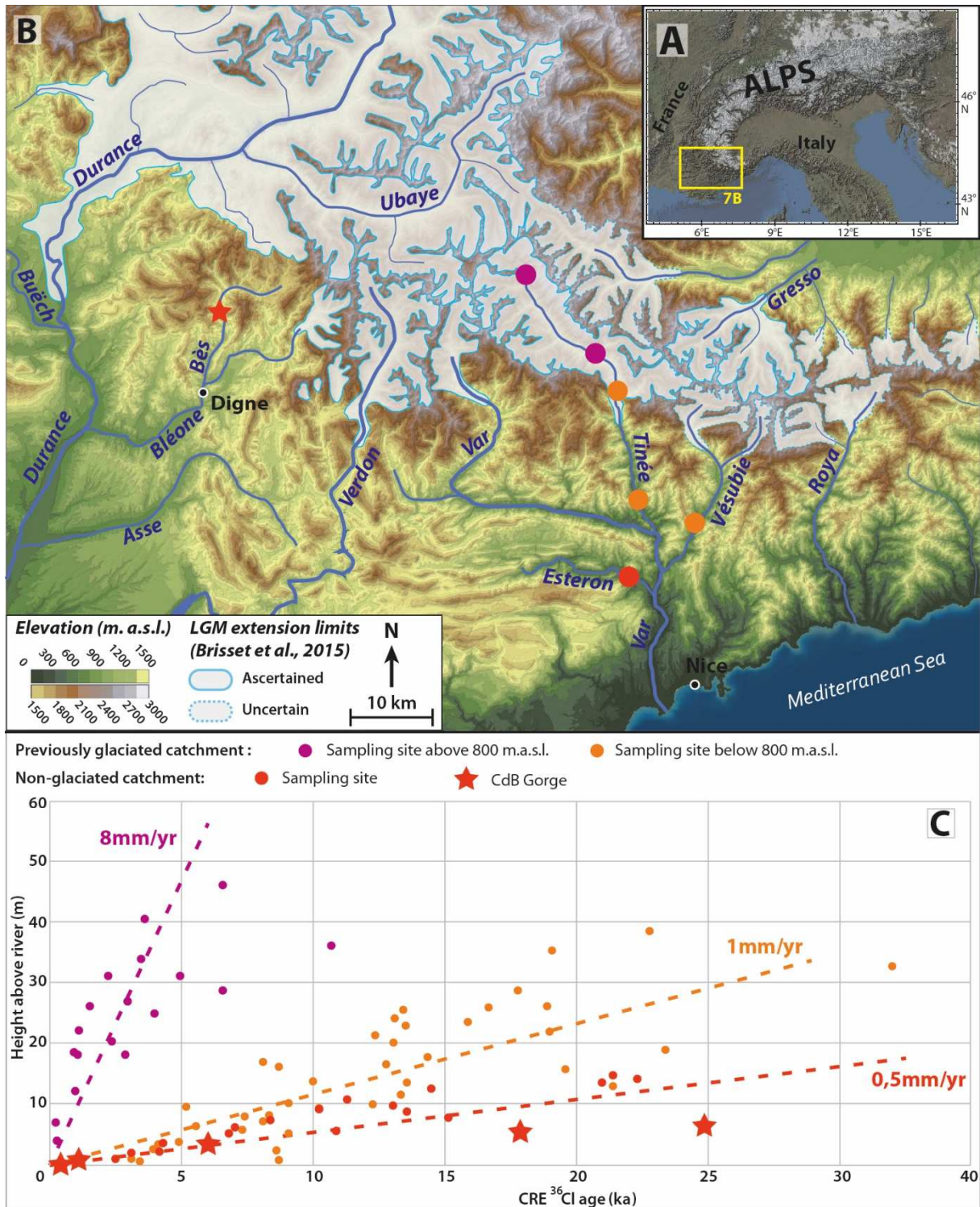
435 Dip and strike measurements of the sample profile upper part (calculated from the DEM) in a Wulff

436 stereographic projection, lower hemisphere (A) and in a Rose diagram (B). C, Mean plane deduced from the

437 DEM calculated strike and dip of the upper sampled surface (yellow dashed framed rectangle) and location of

438 the rejuvenated samples (samples 7 to 12; blue dots). D. Interpretation of the rockfall process by toppling that

439 may have caused the rejuvenation of the sampled surface.



440

441 Figure 7. A, Location of study area in the European Alps. B, Location of the CdB Gorge from this study and
442 previous ones (Saillard et al., 2014; Petit et al., 2019; Rolland et al., 2017) in the SW Alps set against the Last
443 Glacial Maximum (LGM) extension limits (modified from Brisset et al., 2015). Note that the glaciated/non-
444 glaciated specification refers to the glaciation of the catchment during the LGM, and not the sampling site itself.
445 C, Comparison of incision rate determined by CRE dating from this study (red stars) and previous ones (Saillard

446 et al., 2014; Petit et al., 2019; Rolland et al., 2017). Note the increase of site specific incision rate according to
447 their altitude and location in regard of the LGM extension limits.

448 **5. CONCLUSION**

449 We sampled and measured in situ-produced ^{36}Cl concentrations in twenty Jurassic
450 limestone samples along an 80 m high sub-vertical and continuous profile of the V-shaped
451 CdB Gorge (SW Alps) and in four samples collected at the top of the Jurassic limestone bar in
452 which the CdB Gorge is incised. High-resolution DEM analysis and CRE ages show that the
453 CdB Gorge was first dug by fluvial incision and subsequently widened by secondary
454 gravitational processes. The top four samples are suggestive of a steady-state ^{36}Cl
455 concentration that allows quantifying a denudation rate between 18 and 33 mm/kyr in the
456 flatter upper, perfectly exposed surfaces on the shoulders of the gorge. CRE ages of the 10 m
457 above riverbed profile allow quantifying a mean fluvial incision rate of 0.15 mm/yr over the
458 last 25 ka, with an acceleration up to 2 mm/yr for the last 2 ka that can be linked to extreme
459 flood events. The comparison of CRE dating results at the scale of SW Alps shows that the
460 fluvial incision of Bès River is significantly lower than in other basins, which is ascribed to its
461 frontal position in the Alps and glacier-free watershed during glacial phases. Moreover, CRE
462 ages obtained in the middle part of the gorge are suggestive of two main rockfall events,
463 which occurred ≈ 17 ka and ≈ 10 ka ago. These two events correspond to deglacial stages of
464 the LGM and Younger Dryas, respectively, while their geometry suggests debuttressing along
465 two recognized fracture families identified in the field. These data suggest the triggering of
466 rockfalls in a warming climate during periglacial episodes. More sporadic rockfalls may
467 explain age variability in the profile middle part. Based on this example, fluvial gorges in
468 periglacial settings could be efficiently shaped by rockfalls during deglaciation periods, once
469 fluvial incision has exposed the walls.

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