

# Chronology of alluvial terrace sediment accumulation and incision in the Pativilca Valley, western Peruvian Andes

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## ABSTRACT

The incision and aggradation of the Pativilca alluvial fan delta system in the western Peruvian Andes through Quaternary time can be traced in detail using well-exposed fill terraces studied by a combination of cosmogenic nuclide dating, terrace mapping and paleo-erosion rate calculations. Two alluvial terraces have been dated through depth-profile exposure dating using in-situ <sup>10</sup>Be. The dating results return an age for the abandonment of the terrace at  $200 \pm 90$  ka in Pativilca and  $1.2 \text{ Ma} \pm 0.3 \text{ Ma}$  in Barranca. These new ages complete the database of previously dated terrace fills in the valley. Together with the results of the terrace mapping and the absolute ages of the terraces, we show that the valley fills are made up of at least four terraces; two terraces near the city of Pativilca and two terraces in the city of Barranca. While previous studies have shown two periods of sediment aggradation, one period around 100 ka (Barranca) and another period around 30 ka (Pativilca), our new results show two additional periods of sediment aggradation and subsequent incision that have not been reported before. Finally, paleo-erosion rates at the time of the deposition of the terrace material were calculated and compared to the available modern estimates. The paleo-erosion rates vary from  $140 \pm 12$  m/Ma to  $390 \pm 40$  m/Ma. The period of sediment accumulation prior to the abandonment of the terrace at 200 ka corresponds to a wet phase and a pulse of erosion. In contrast, the period of sediment accumulation prior to the abandonment of the terrace at 1.2 Ma does not

26 correspond to a pulse of erosion and could rather correspond to a change of the base level possibly  
27 induced by a sea-level rise.

28 **Keywords:**  $^{10}\text{Be}$  depth-profile dating; alluvial terraces; Pativilca Valley; Western Peruvian Andes

## 29 1. Introduction

30 Fluvial sediments originating from mountain belts like the Andes yield important archives of  
31 past environmental or tectonic changes. The sediments can record changes in precipitation rates and  
32 climate (Litty et al., 2016; d'Arcy et al., 2017). They can also record the response to earthquake-  
33 induced landslides (McPhillips et al., 2014). The reconstruction of the timing of alluvial sediment  
34 deposition thus bears important information when the scope lies in the detection of specific climate or  
35 tectonic events as driving forces of landscape evolution. In this context, depth-profile dating based on  
36 in-situ produced  $^{10}\text{Be}$  measured in quartz has been proven a reliable method to establish a chronology  
37 of sediment deposition (e.g., Bookhagen et al., 2006; Hidy et al., 2010). In particular, this  
38 methodology yields an age when sediment aggradation stopped and when a period of sediment  
39 accumulation was superseded by a phase of erosion and incision into the previously deposited  
40 material.  $^{10}\text{Be}$  is the most commonly measured in situ-produced cosmogenic nuclide (Granger et al.,  
41 2013). Its dominance in geological applications stems from several factors, including the abundance  
42 of the target mineral, quartz, a standardized chemistry procedure (Kohl and Nishiizumi, 1992), a  
43 relatively simple production depth profile, and routinely good precision by accelerator mass  
44 spectrometry (AMS) (Granger, 2006). Additionally, isochron burial dating using  $^{10}\text{Be}$  and  $^{26}\text{Al}$  is  
45 becoming increasingly important in studies related to river terraces (e.g., Darling et al., 2012; Erlanger  
46 et al., 2012; Akçar et al., 2017). Isochron-burial dating yields in an age when the investigated material  
47 accumulated. It is thus a variation of traditional burial dating methods. Ages, or alternatively the  
48 burial times of sediment, are determined using the difference between the cosmogenic  $^{26}\text{Al}/^{10}\text{Be}$   
49 surface production ratio at the time of burial and the  $^{26}\text{Al}/^{10}\text{Be}$  ratio measured in buried sediments  
50 (Granger, 2006). Sediments of alluvial terrace deposits with flat tops are ideal for surface exposure  
51 dating and isochron burial dating: they are persistent, easily identifiable as surfaces that were formed  
52 at a specific time and that have been isolated from the fluvial system since deposition. Because they

53 are typically coarse-grained, well drained, and nearly flat, they can be remarkably well preserved and  
54 unaffected by erosion, especially in arid environments like in the western side of the Peruvian Andes  
55 (Litty et al., 2017a; Reber et al., 2017).

56 Alluvial terrace sequences are common features along the coastal margin between Peru and  
57 northern Chile. They are located particularly in lower valley reaches near to the Pacific coast (Steffen  
58 et al., 2009, 2010; Trauerstein et al., 2014; Litty et al., 2017a). Climate change has been considered to  
59 have controlled pulses of erosion on the western Andean margin through the increase in mean surface  
60 runoff resulting either in sediment accumulation along stream segments close to the Pacific coast  
61 (Bekaddour et al., 2014; Norton et al., 2016), or in surface erosion in upstream segments of major  
62 rivers (Veit et al., 2016). These climate-driven changes have been interpreted as being the main  
63 driving force controlling the sediment accumulation and the formation of cut-and-fill terraces on the  
64 western Andean margin (Norton et al., 2016). In the Pativilca Valley, situated on the western margin  
65 of the Peruvian Andes at about 10°S (Fig. 1A), a terrace sequence has been previously dated through  
66 infrared stimulated luminescence (IRSL) techniques (Trauerstein et al., 2014). The results have  
67 disclosed the occurrence of at least two periods of sediment aggradation, one period spanning from 10  
68 ka to 90 ka with an age of the samples cluster around 30 ka and another period spanning the time  
69 interval between 80 ka and 130 ka with an age estimate of the samples cluster around 110 ka  
70 (Trauerstein et al., 2014). While generally wetter climate results in fluvial incision, the results from  
71 Trauerstein et al. (2014) suggested that here wetter climate conditions do correlate with periods of  
72 fluvial aggradation.

73 The aim of this study is to date additional terrace deposits using in-situ terrestrial cosmogenic  
74 nuclides to complete the chronological framework and to infer the history of sediment aggradation  
75 and incision in this alluvial fan delta system. In addition concentrations of in-situ <sup>10</sup>Be recorded by  
76 detrital quartz minerals in the terrace deposits will be used to infer the paleo-erosion rates recorded at  
77 the time when sediment accumulation occurred. These rates will be compared to the modern ones  
78 (Reber et al., 2017) to quantify the erosion in the upstream drainage basin during the phases of  
79 aggradation within the downstream valley. The final aim is to understand the factors controlling  
80 fluvial aggradation and incision in fan delta environments in the western Andes.

81

## 82 **2. Regional settings**

83           The Pativilca Valley is located in central Peru, about 200 km to the northwest of Lima. The  
84 Rio Pativilca, which is trunk stream of the region, debouches into the Pacific at 10.7°S and 77.8°W  
85 (Fig. 1A). The drainage basin has an area of about 4400 km<sup>2</sup>, and the longest flow path measures  
86 approximately 200 km. The upper section of the stream is characterized by a bedrock channel with a  
87 steep gradient (knickzone), whereas in the lower segment the narrow valley floor is covered by  
88 alluvial deposits that are thickening and widening towards the coast, giving way to an alluvial fan  
89 delta. The sedimentological architecture of the deposits is characterized by amalgamated stacks of 20  
90 to 50 m-thick units of poorly sorted, clast-supported conglomerates with a coarse-grained sandy  
91 matrix (Fig. 1B). The clasts are subrounded and sometimes imbricated, but the sedimentary fabrics are  
92 predominantly massive (Fig. 1B). The alluvial conglomerates are part of an alluvial fan delta system  
93 characterized by a suite of individual fill terraces with different altitudes of the tread (Fig. 1B).

94           The precipitation pattern of South America is strongly influenced by the low level Andean jet  
95 and the position of the Inter Tropical Convergence Zone (ITCZ), which experiences seasonal shifts in  
96 response to insolation differences between austral summer and winter. The Andean jet transfers  
97 humidity from the Pacific Ocean and the Amazon basin to the eastern margin of the Andes, and also  
98 to the Altiplano and the western Andean margin (Garreaud, 2009). The Andean mountain range thus  
99 acts as a major topographic barrier to the atmospheric circulation. As a result of this circulation  
100 pattern, the Peruvian western margin shows an E-W contrasting precipitation pattern with high annual  
101 precipitation rates up to 800 mm on the Altiplano and ~0 mm along the coast. From north to south, the  
102 annual rainfall rates on the Altiplano decrease from 1000 mm near the Equator to <200 mm in  
103 northern Chile. Every 2-10 yr, near the Equator, the Pacific coast is subjected to stronger precipitation  
104 than the mean precipitation rates, resulting in high flood magnitude variability related to the El Nino  
105 Southern Oscillation (ENSO) weather phenomenon (DeVries, 1987). Today, this phenomenon is  
106 limited to the coastal area of northern Peru, but during the past, southern Peru might also have been  
107 affected by such events (Lagos et al., 2008).

108           On orbital time scales, the position of the ITCZ has shifted in response to larger insolation  
109 and heat contrasts between the Northern and Southern Hemispheres, which has been related to the  
110 effects of shifts in the Earth's precession (Strecker et al., 2007). The results are stronger upper air  
111 easterlies and more precipitation on the Altiplano (Garreaud et al., 2003). Variations in precipitation  
112 rates and patterns led to remarkable lake level variations on the Altiplano as recorded by lake level  
113 highstands on the plateau (Ouki, Minchin and Tauca pluvial periods, e.g., Fritz et al., 2004). These  
114 climate changes have also controlled pulses of erosion and deposition on the western Andean margin  
115 (Bekaddour et al., 2014; Veit et al., 2016). Related variations in erosional fluxes have been interpreted  
116 as being the main factor controlling the formation of cut-and-fill terrace systems along the western  
117 margin of the Peruvian Andes (Norton et al., 2016).

118

### 119 **3. Methods**

#### 120 *3.1. Cosmogenic nuclides*

121           Over the past 25 yr, cosmogenic nuclides have become an essential tool in Quaternary  
122 geochronology (e.g., Gosse and Phillips, 2001; Granger, 2006). Cosmogenic nuclides are produced  
123 through spallation reactions and muon capture in minerals of rocks and sediment at or near the Earth's  
124 surface (Gosse and Philips, 2001). Cosmogenic  $^{10}\text{Be}$  and  $^{26}\text{Al}$  can be applied to determine a post-  
125 depositional age of a geological layer using their accumulation (depth-profile dating). Alternatively,  
126 they can also be used to determine the timing of sediment accumulation through their radioactive  
127 decay (burial dating) history (e.g., Anderson et al., 1996; Repka et al., 1997; Granger and Smith,  
128 2000; Granger and Muzikar, 2001; Wolkowinsky and Granger, 2004; Balco and Rovey, 2008; Akçar  
129 et al., 2017).

130           Depth-profile dating is based on the exponential decrease of cosmogenic nuclides with depth  
131 (Gosse and Philips, 2001). On the other hand, the burial dating technique uses the difference in half-  
132 lives of  $^{10}\text{Be}$  (1.387 Ma; Korschinek et al., 2010; Chmeleff et al., 2010) and  $^{26}\text{Al}$  (0.705 Ma; Norris et  
133 al., 1983) and thus the  $^{26}\text{Al}$  versus  $^{10}\text{Be}$  ratio to determine the burial time, when the pre-burial and  
134 post-burial concentrations are known or estimated (e.g., Granger and Muzikar, 2001; Akçar et al.,

135 2017). We followed the Erlanger et al. (2012) isochron approach where one of the advantages is the  
136 assumption that post-burial production is identical across a single stratigraphic horizon.

137 The collected samples (see section 3.3 for description of sample sites and sampling strategy)  
138 were processed in the Surface Exposure Laboratory of the Institute of Geological Sciences at the  
139 University of Bern following the lab protocol described in Akçar et al. (2012). The  $^{10}\text{Be}/^9\text{Be}$  and  
140  $^{26}\text{Al}/^{27}\text{Al}$  AMS measurements were then performed at the Swiss Federal Institute of Technology  
141 tandem facility in Zurich (Christl et al., 2013). The long-term weighted average  $^{10}\text{Be}/^9\text{Be}$  ratio of  $(2.41$   
142  $\pm 0.53) \times 10^{-15}$  was used for full process blank correction. Table 1 presents the samples information  
143 and cosmogenic nuclide results.

144 Depth-profile ages were modelled with MATLAB® using Monte Carlo simulations  
145 developed by Hidy et al. (2010). Depth-profile patterns were simulated based on exposure age,  
146 erosion rate and inheritance. Table 2 shows the input parameters for the Barranca and Pativilca depth-  
147 profile simulations. We applied no correction factor for topographic shielding. We justify this  
148 approach because there is no significant topography around the sampling sites that could block a  
149 portion of incoming cosmic radiations (Dunne et al., 1999; Gosse and Phillips, 2001), as the sampling  
150 sites are located on the widest and flattest part of the valley close to the coast. We did not consider  
151 snow cover to have a major impact on the results as the mean basin elevation of the sampled  
152 catchment is largely situated below the snow line. The  $^{10}\text{Be}$  half-life with a value of  $1.387 \pm 0.012$  Ma  
153 was utilized (Chmeleff et al., 2010; Korschinek et al., 2010). The local production rate was scaled to  
154 the Lal (1991) and Stone (2000) scheme using a production rate caused by spallation (SLHL: at sea-  
155 level, high latitude) of  $4.01 \pm 0.12$  atoms  $\text{g}_{\text{SiO}_2}^{-1}$  (CRONUS calculator update from v. 2.2 to v. 2.3  
156 published by Balco in August 2016 after Balco et al., 2008; Borchers et al., 2016). Thus a site-specific  
157 spallogenic production rate of  $2.5 \pm 0.5$  atoms  $\text{g}^{-1} \text{a}^{-1}$  was obtained for Barranca and for Pativilca. We  
158 applied a bulk density ranging between 1.6 and 2.1  $\text{g cm}^{-3}$  for the sediment samples in Barranca and  
159 Pativilca. Finally, to model a depth-profile age we simulated 100,000 profiles and used a  $\chi^2$  cut-off  
160 value of  $\leq 20$  for Barranca and  $\leq 3$  for Pativilca (Table 2).

161

162 *3.2. Paleo erosion rates*

163 Paleo basin-averaged erosion rates can be calculated using the cosmogenic nuclide  
164 concentrations of past sediment samples following Granger et al. (1996) and von Blanckenburg  
165 (2005). To calculate the basin averaged paleo-erosion rate, we used the  $^{10}\text{Be}$  cosmogenic nuclide  
166 concentrations of the sand embedded in the terrace deposits after corrections have been made for  
167 shielding, post-depositional nuclide production at sample depth  $z$ , and atom loss due to radioactive  
168 decay during time  $t$  (both considered in Eq. (1); Balco et al., 2008). These equations can be used  
169 assuming: (i) The material was well mixed in the upstream basin and finally embedded in the terrace  
170 fill. This appears to be the case in the western Peruvian valleys where the fluvial processes have  
171 dominated the transport of sediment (Litty et al., 2017b), thus providing well-mixed material. (ii) The  
172 paleo-erosion is representative for the entire catchment. Indeed, the sediments of the Pleistocene  
173 terrace fills in western Peru record an origin from both the upper flat part of the catchments and the  
174 lower steep reaches (Litty et al., 2017a). (iii) The residence of the material on the hillslopes and the  
175 channels is much shorter than the erosional timescale. This is the case in the western Peruvian valleys  
176 where regolith was considered to have been rapidly stripped from hillslopes, which most likely  
177 resulted in the supply of large volumes of sediment to the trunk streams during the periods of  
178 sediment aggradation (Norton et al., 2016). (iv) The individual terraces have not experienced multiple  
179 phases of erosion and re-deposition, so that major internal unconformities are not present (von  
180 Blanckenburg, 2005). This appears to be the case in the Pativilca Valley as no unconformities in the  
181 individual terrace fills have been observed in the field.

182

### 183 3.3. *Sampling sites*

184 Two previously undated alluvial terrace fills were sampled for depth-profile exposure dating.  
185 These terraces are located along the lowermost reach of the Pativilca River and in the city of Barranca  
186 (Fig. 1; Table 1). At each sampling site, six samples were collected along a vertical profile from 0.9 to  
187 4.7 m beneath the tread of the terrace in Pativilca, and from 0.4 to 3.2 m beneath the tread of the  
188 terrace in Barranca (Fig. 1A). Two to three kilograms of medium grained sand embedded between the  
189 pebbles were taken for each sample. Additionally, the lowermost samples of the two depth profiles  
190 (PAT-DP6 and BAR-DP6) were used to infer a paleo-erosion rate at the time when the sediments of

191 the two newly dated terraces were deposited. Two other samples (PAT-PE and BAR-PE2) were  
192 collected in two other terrace fills previously dated (Trauerstein et al., 2014) for the calculation of  
193 paleo-erosion rates (one in Pativilca and one in Barranca; Table 4). Additionally, quartz bearing clasts  
194 were sampled for isochron burial dating (Fig. 1B; Table 1). For each isochron burial site, the samples  
195 were collected from the same sedimentologic unit and from a single stratigraphic horizon following  
196 Erlanger et al. (2012). Three horizons were sampled in Barranca and two horizons have been sampled  
197 in Pativilca (Fig. 1B; Table 1). Depth-profile dating and isochron burial dating techniques have be  
198 chosen as sand lenses that are required for IRSL sampling are not present in every terrace fill.

199

## 200 **4. Results**

### 201 *4.1. Cosmogenic nuclides: isochron burial dating*

202 The measured  $^{26}\text{Al}$  concentrations are plotted versus  $^{10}\text{Be}$  concentrations including  $2\sigma$   
203 uncertainties (Fig. 2). The cosmogenic nuclide results are shown in Table 1. As the Al/Be ratios are  
204 higher than the surface ratio, it is not possible to calculate an isochron burial age from these samples  
205 (for details, see Erlanger et al., 2012). The surface ratio of  $^{26}\text{Al}/^{10}\text{Be}$  is not constant since it depends  
206 on the time of exposure and erosion. On a banana-plot, the ratios decrease from 8.4 to  $\sim 3$ , and a  
207 regression through these yields a surface ratio around 6.8. Therefore, in most of the isochron burial  
208 applications this ratio has been used as the surface ratio. Recently, Akçar et al. (2017) showed that  
209 this ratio varied between 7 and 12 in deeply eroding landscapes, particularly in glacial environments.  
210 However, these mechanisms fail to explain the  $^{26}\text{Al}/^{10}\text{Be}$  ratios  $> 12$  obtained in this study as glacial  
211 processes were most likely not the most important erosional mechanisms. Therefore, we tentatively  
212 attribute these ratios to the analytical problems related to the measurements of the total Al or to the  
213 quartz purification process. Given that no age can be determined from these samples; isochron burial  
214 dating is therefore not further discussed in this paper.

215

### 216 *4.2. Cosmogenic nuclides: depth-profile dating*

217 4.2.1. *Barranca*

218 AMS-measured  $^{10}\text{Be}/^9\text{Be}$  (with uncertainties) as well as calculated  $^{10}\text{Be}$  concentrations for  
219 each sample are shown in Table 1. The concentrations of the six sediment samples vary from  $\sim 12 \times$   
220  $10^5$  atoms  $\text{g}^{-1}$  for the uppermost sample to  $\sim 1 \times 10^5$  atoms  $\text{g}^{-1}$  for the lowermost sample (Table 1). In  
221 Fig. 3, the  $^{10}\text{Be}$  concentrations together with  $1\sigma$  uncertainties are plotted against depth. They display  
222 an exponential decrease with depth. The simulated best fit curve through the six data points is  
223 illustrated in Fig. 4, whereas the possible solution space with a  $\chi^2$  cut-off value of  $\leq 20$  is shown in  
224 Fig. 5.

225 The simulation yields a best-fit solution to the measured nuclide concentrations for a modal  
226 depth-profile age of  $1.2 \pm 0.3$  Ma, and a modal top erosion rate of  $0.07 \pm 0.02$   $\text{cm ka}^{-1}$  (Table 3A). The  
227 modal values of the age and erosion rate are similar to the mean and median values of the simulation,  
228 thus the errors of the modal values are based on the minimum and maximum values generated by the  
229 simulation. Note that the Monte Carlo simulation code requires a constraint on the net erosion on the  
230 top of the section as a modal input parameter to calculate an age (Hidy et al., 2010). This parameter is  
231 iteratively adjusted within a range of values.

232

233 4.2.2. *Pativilca*

234 The concentrations of the six sediment samples vary from  $\sim 86 \times 10^4$  atoms  $\text{g}^{-1}$  for the  
235 uppermost sample to  $\sim 44 \times 10^4$  atoms  $\text{g}^{-1}$  for the lowermost sample (Table 1). In Fig. 6, the  $^{10}\text{Be}$   
236 concentrations together with  $1\sigma$  uncertainties are plotted against depth. The best fit through the six  
237 data points is illustrated in Fig. 7, whereas the possible solution space with a  $\chi^2$  cut-off value of  $\leq 3$  is  
238 shown in Fig. 8.

239 The simulation yields a best-fit solution to the measured nuclide concentrations for a modal  
240 depth-profile age of  $200 \pm 90$  ka, a modal top erosion of  $0.48+ 0.41- 0.13$   $\text{cm ka}^{-1}$  and an inheritance  
241 of  $35,100+ 8700-8000$  atoms  $\text{g}^{-1}$  (Table 3B). The modal values are similar to the mean and median  
242 values of the simulation, thus the errors of the modal values are based on the minimum and maximum  
243 values generated by the simulation.

244 The results of the depth-profile dating return a surface exposure age of ~1.2 Ma in Barranca  
245 and of ~200 ka in Pativilca. These results show minimum ages when the accumulation of material has  
246 terminated and when dissection of the previously deposited material started, yielding in the formation  
247 of a terrace level. These two periods when sediment aggradation was superseded by dissection, have  
248 not been dated before. These new results together with the ones from Trauestein et al. (2014) suggest  
249 the occurrence of at least four terraces referred to as T1 to T4 from older to younger (Figs. 9 and  
250 10A), corresponding to at least four different periods of sediment accumulation. Terrace deposits were  
251 correlated on the basis of landscape position, tread altitude and absolute dating (Figs. 9 and 10A).

252

#### 253 4.3. *Paleo-erosion rates*

254 The in-situ  $^{10}\text{Be}$  analytical data together with the inferred paleo-erosion rates recorded by the  
255 alluvial terrace sediments are presented in Table 4. The paleo-erosion rate values are  $143 \pm 12 \text{ m Ma}^{-1}$   
256 at the time of the accumulation of the terrace deposits T1 (~1.2 Ma ago),  $302 \pm 28 \text{ m Ma}^{-1}$  at the time  
257 when terrace material T2 was deposited,  $392 \pm 40 \text{ m Ma}^{-1}$  at the time of the deposition of the terrace  
258 sediments T3, and finally  $297 \pm 29 \text{ m Ma}^{-1}$  at the time terrace T4 was constructed (Fig. 10B). In  
259 addition, Reber et al. (2017) reported a modern catchment-averaged denudation rate of  $260 \pm 23 \text{ m}$   
260  $\text{Ma}^{-1}$ .

## 261 5. Discussion

### 262 5.1. *Chronology of sediment accumulation and incision*

263 The fluvial aggradation and subsequent incision in the Pativilca Valley has occurred in  
264 multiple episodes through the Quaternary (Figs. 9 and 10). Figure 11 shows the position of the active  
265 river and the position of the sediment accumulation during the periods of aggradation. Our dating  
266 results imply that the sediments of terrace T1 in Barranca have been deposited prior to 1.2 Ma. The  
267 aggradation then ceased and the tread formation began ~1.2 Ma ago (terrace T1; Fig. 11A). During  
268 the period of the terrace fill, the erosion rate was two times lower than the modern rate (Fig. 12).  
269 Following this, for approximately 1 Ma, either a period of no sedimentation occurred in the valley or  
270 no sediments have been preserved. The river then moved its course towards Pativilca. The sediments

271 of terrace T2 in Pativilca have been deposited prior to 200 ka. The accumulation of sediment then  
272 stopped and exposed the terrace tread at around 200 ka (terrace T2; Fig. 11B). During the period of  
273 sediment accumulation, the erosion rate was up to  $\sim 300 \text{ m.Ma}^{-1}$  (Fig. 12). The river bed again  
274 changed its course towards Barranca, and a phase of accumulation occurred around 100 ka (deposition  
275 of the sediment of T3; Fig. 11C; Trauerstein et al., 2014). In this period, the erosion rate was at its  
276 highest ( $\sim 400 \text{ m Ma}^{-1}$ ; Fig. 12). Finally, the lobe of the Pativilca fan delta moved back towards the  
277 city of Pativilca close to its current course, and a phase of aggradation occurred from 10 to 45 ka ago  
278 (deposition of the sediment of T4; Fig. 11D; Trauerstein et al., 2014). During this period, the  
279 catchment-wide denudation rate dropped back to  $\sim 300 \text{ m Ma}^{-1}$  (Fig. 12). This phase was followed by  
280 a period of incision exposing the tread and riser of terrace level T4. Today the erosion rate is slightly  
281 lower than during the past at  $\sim 200 \text{ ka}$  (Fig. 12) and the river appears to be incising.

282

## 283 5.2. *Implications for climate variability as controls on cyclic deposition and erosion*

284 A stratigraphic record of river terrace sediments is formed and preserved as a stream changes  
285 its activity between incision, lateral planation, and aggradation (Pederson et al., 2006). These fill  
286 terraces in the Pativilca Valley represent a relatively complete archive of both incision and deposition.  
287 They can be used to understand the response to climate or to other driving forces that have an impact  
288 on the balance between sediment transport and deposition (Pederson et al., 2006). These terrace fills  
289 have been formed in the alluvial fan delta of the Pativilca River and they might also record the change  
290 in the position of the different lobes of the delta through shifts in transport and sediment capacity.  
291 Alternatively, a phase of accumulation requires the availability of sediments on the hillslopes to be  
292 eroded, transported and deposited (Hancock and Anderson, 2002). This implies that the river  
293 experiences an increase in the ratio between sediment supply and the stream's capacity to control the  
294 deposition the supplied material (Tucker and Slingerland, 1997). The youngest period of sediment  
295 accumulation ranging from 10 to 45 ka (terrace T4) could correspond to the wet intervals recorded by  
296 the Minchin (47.8–36 ka ago) and Tauca (26–14.9 ka ago) paleolakes (Fritz et al., 2004). The period  
297 of sediment accumulation ranging from 80 to 130 ka (terrace T3) could correspond to the wet period  
298 characterized by the Ouki paleolakes (120–98 ka ago; Fritz et al., 2004). These two periods of

299 sediment accumulation previously dated by Trauerstein et al. (2014) are thus correlated with phases of  
300 enhanced precipitation with higher water discharge in the river. These wet conditions could have been  
301 induced by summer insolation forcing of the South American summer monsoon at precessional time-  
302 scales (Baker et al., 2001a,b). Indeed, the precession together with the obliquity has been considered  
303 to control the seasonal cycles of insolation (Milankovitch, 1941). The wettest phases, and hence the  
304 highest lake levels (Bills et al., 1994; Sylvestre et al., 1999; Placzek et al., 2006), were additionally  
305 forced by warm North Atlantic sea surface temperatures (Baker et al., 2001a). These climate changes  
306 were also used to explain the pulses of upland erosion and deposition in the stream valleys on the  
307 western Andean margin (Bekaddour et al., 2014), which agree with our data of relative fast paleo-  
308 erosion rates recorded by these two terraces. Indeed, the 10-45 ka denudation rate was >10% higher  
309 than the modern one and the 80-130 ka denudation rate was even >30% higher than the modern rates  
310 (Fig. 12). Fluvial aggradation is here correlated with wetter climates and an increased sediment supply  
311 from the uplands. However, we also note that wetter climates can result in fluvial incision and terrace  
312 formation because of greater stream discharge (Veit et al., 2016), provided that the hillslopes have  
313 been depleted of material (Norton et al., 2016). In our case, the start of the incision phases could then  
314 correspond to the end of the pluvial period and the time of decrease of the supply of sediment to the  
315 river. Alternatively, it is also possible that erosional recycling of the terrace material started within the  
316 pluvial periods, when the preceding phase of rapid hillslope erosion resulted in the depletion of the  
317 sediment reservoirs, yielding high ratios between water and sediment fluxes in the trunk stream. The  
318 Altiplano lake sediment cores do not record climatic variations older than 130 ka (Placzek et al.,  
319 2006). In this context, we cannot correlate the two older periods of sediment accumulation (prior to  
320 ~200 ka and prior to ~1.2 Ma) to any lake level variations. However, the high paleo-erosion rate  
321 calculated for the newly dated fills of the terrace T2 (~15% higher than the modern one) appears also  
322 to correspond to a pulse of upland erosion, which could point towards a period of wet conditions.  
323 Support for this interpretation is provided by the periodicity of about 100 ka for this orbital-induced  
324 summer insolation forcing (Milankovitch, 1941; Lisiecki, 2010; Abe-Ouchi et al., 2013). If this  
325 interpretation is valid, then the ages of 100 ka (T3) and 200 ka (T2) would then correspond to this 100  
326 ka periodicity, suggesting that the period prior to ~200 ka might also have corresponded to a wet

327 phase on the Altiplano. The oldest dated period of sediment accumulation (terrace T1) does not record  
328 a distinct pulse of erosion as the calculated paleo erosion rate was twice as low as the modern one.  
329 The production of sediments on the hillslopes through weathering and erosion can occur through an  
330 increase in precipitation rates (e.g., Bookhagen et al., 2005; Norton et al., 2016), for which there is no  
331 evidence from the records reported here indicating that sediment accumulation of the terrace T1 has  
332 not been induced by a phase of enhanced precipitation. Alternatively, this T1 phase of accumulation  
333 could have occurred in response to a rise in sea level. Indeed, a rise in sea level would cause a back  
334 filling and a super-elevation of the channel, which then would cause the delta lobe to switch positions.  
335 Supporting evidence for this interpretation has been provided by Pillans et al. (1998), who proposed  
336 that the ~1.2 Ma-old period was relatively warm and corresponded to a rising sea level. Nevertheless,  
337 we note that further research in the region is required to sustain this interpretation.

338

## 339 **6. Conclusions**

340 The results of the depth-profile dating together with the previously published IRSL ages  
341 (Trauerstein et al., 2014) disclose at least four terraces located in the fan delta of the Pativilca River.  
342 The sediments of terrace T1 accumulated until ~1.2 Ma ago and terraces T2, T3 and T4 were  
343 deposited prior to ~200 ka, ~100 ka ago and ~30 ka ago respectively. Additionally, paleo-erosion  
344 rates at the time of the deposition of the terrace fills were calculated and compared to the modern  
345 rates. The modern erosion rate is ~260 mm/ka, while the paleo-erosion rates vary from ~143 mm/ka to  
346 ~391 m Ma<sup>-1</sup>.

347 The oldest period of accumulation does not correspond to a distinct pulse of erosion and could  
348 rather correspond to a period when the sea level was rising. The three younger phases of sediment  
349 accumulation most likely correspond to wet phases and pulses of erosion in the uplands. These wet  
350 conditions were likely to have been induced by summer insolation forcing of the South American  
351 summer monsoon at precessional time scales (Baker et al., 2001a, 2001b). Generally, wetter climate  
352 results in fluvial incision caused by greater stream discharge. However, wetter climate is here  
353 correlated with fluvial aggradation due to the inferred increased sediment supply from the uplands.  
354 The abandonment of the terrace treads would then correspond to the end of the pluvial period and thus

355 a decrease of the sediment supplied to the river. Additionally, this long period of preservation of the  
356 alluvial sediments on a coastal area implies a constant base level after the deposition of the terrace T1  
357 despite the occurrence of an active subduction zone.

358

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364

### 365 **References**

366

367 Abe-Ouchi, A., Saito, F., Kawamura, K., Raymo, M. E., Okuno, J. I., Takahashi, K., Blatter, H., 2013.  
368 Insolation-driven 100,000-year glacial cycles and hysteresis of ice-sheet volume. *Nature* 500(7461),  
369 190-193.

370

371 Akçar, N., Deline, P., Ivy-Ochs, S., Alfimov, V., Hajdas, I., Kubik, P.W., et al., 2012. The 1717 AD  
372 rock avalanche deposits in the upper Ferret Valley (Italy): a dating approach with cosmogenic <sup>10</sup>Be.  
373 *Journal of Quaternary Science* 27(4), 337–440.

374

375 Akçar, N., Ivy-Ochs, S., Alfimov, V., Schlunegger, F., Claude, A., Reber, R., Christl, M.,  
376 Vockenhuber, C., Dehnert, A., Rahn M., Schlüchter, C. 2017. Isochron-burial dating of glaciofluvial  
377 deposits: First results from the Swiss Alps. *Earth Surface Processes Landforms*. In Press.

378

379 Anderson, R.S., Repka, J.L., Dick, G.S., 1996. Explicit treatment of inheritance in dating depositional  
380 surfaces using in situ <sup>10</sup>Be and <sup>26</sup>Al. *Geology* 24(1), 47-51.

381

382 Baker P.A., Seltzer G.O., Fritz, S.C., Dunbar, R.B., Grove, M.J., Tapia, P.M., Cross, S.L., Rowe,  
383 H.D., Broda, J.P. 2001a. The history of South American tropical precipitation for the past 25,000  
384 years. *Science* 291,640–643.

385

386 Baker, P.A., Rigsby, C.A., Seltzer, G.O., Fritz, S.C., Lowenstein, T., Bacher, N., Veliz, C. 2001b.  
387 Tropical climate changes at millennial and orbital timescales on the Bolivian Altiplano. *Nature* 409,  
388 698–701.

389

390 Balco, G., Rovey, C.W., 2008. An isochron method for cosmogenicnuclide dating of buried soils and  
391 sediments. *American Journal of Sciences* 308, 1083–1114.

392

393 Balco, G., Stone, J.O., Lifton, N.A., Dunai, T.J., 2008. A complete and easily accessible means of  
394 calculating surface exposure ages or erosion rates from Be-10 and Al-26 measurements. *Quaternary*  
395 *Geochronology* 3, 174–195.

396

397 Bekaddour, T., Schlunegger, F., Vogel, H., Delunel, R., Norton, K. P., Akçar, N., Kubik, P., 2014.  
398 Paleo erosion rates and climate shifts recorded by Quaternary cut-and-fill sequences in the Pisco  
399 Valley, central Peru. *Earth and planetary science letters* 390, 103-115.

400  
401 Bills, B.G., De Silva, S.L., Currey, D.R., Emenger, R.S., Lillquist, K.D., Donnellan, A., Worden, B.,  
402 1994. Hydro-isostatic deflection and tectonic tilting in the central Andes: Initial results of a GPS  
403 survey of Lake Minchin shorelines. *Geophysical Research Letters* 21(4), 293-296.  
404  
405 Bookhagen, B., Thiede, R. C., Strecker, M. R., 2005. Abnormal monsoon years and their control on  
406 erosion and sediment flux in the high, arid northwest Himalaya. *Earth and Planetary Science Letters*,  
407 231(1), 131-146.  
408  
409 Bookhagen, B., Fleitmann, D., Nishiizumi, K., Strecker, M. R., Thiede, R. C., 2006. Holocene  
410 monsoonal dynamics and fluvial terrace formation in the northwest Himalaya, India. *Geology* 34(7),  
411 601-604.  
412  
413 Borchers, B., Marrero, S., Balco, G., Caffee, M., Goehring, B., Lifton, N., Nishiizumi, K., Phillips, F.,  
414 Schaefer, J., Stone, J., 2016. Geological calibration of spallation production rates in the CRONUS-  
415 Earth project. *Quaternary Geochronology* 31, 188–198.  
416  
417 Braucher, R., Merchel, S., Borgomano, J., Bourles, D.L., 2011. Production of cosmogenic  
418 radionuclides at great depth: A multi element approach. *Earth and Planetary Science Letters* 309(1),  
419 1–9.  
420  
421 Chmeleff, J., von Blanckenburg, F., Kossert, K., Jakob, D., 2010. Determination of the Be-10 half-life  
422 by multicollector ICP-MS and liquid scintillation counting. *Nuclear Instruments and Methods in*  
423 *Physics, Research Section B: Beam Interactions with Materials and Atoms* 268.  
424  
425 Christl, M., Vockenhuber, C., Kubik, P.W., Wacker, L., Lachner, J., Alfimov, V., Synal, H.A., 2013.  
426 The ETH Zurich AMS facilities: Performance parameters and reference materials. *Nuclear*  
427 *Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and*  
428 *Atoms* 294, 29-38.  
429  
430 D'arcy, M., Whittaker, A.C., Roda-Boluda, D.C., 2017. Measuring alluvial fan sensitivity to past  
431 climate changes using a self-similarity approach to grain-size fining, Death Valley, California.  
432 *Sedimentology* 64(2), 388-424.  
433  
434 Darling, A.L., Karlstrom, K.E., Granger, D.E., Aslan, A., Kirby, E., Ouimet, W. B., Cole, R. D., 2012.  
435 New incision rates along the Colorado River system based on cosmogenic burial dating of terraces:  
436 Implications for regional controls on Quaternary incision. *Geosphere* 8(5), 1020-1041.  
437  
438 DeVries, T.J., 1987, A review of geological evidence for ancient El Nino activity in Peru. *J. Geophys.*  
439 *Res* 92(14), 471–14  
440  
441 Dunne, J., Elmore, D., Muzikar, P., 1999. Scaling factors for the rates of production of cosmogenic  
442 nuclides for geometric shielding and attenuation at depth on sloped surfaces. *Geomorphology* 27, 3–  
443 11.  
444  
445 Erlanger, E.D., Granger, D.E., Gibbon, R. J., 2012. Rock uplift rates in South Africa from isochron  
446 burial dating of fluvial and marine terraces. *Geology* 40(11), 1019-1022.  
447

448 Fritz, S.C., Baker, P.A., Lowenstein, T.K., Seltzer, G.O., Rigsby, C.A., Dwyer, G.S., and Luo, S.,  
449 2004, Hydrologic variation during the last 170,000 years in the southern hemisphere tropics of South  
450 America: *Quaternary Research* 61, 95–104, doi: 10.1016/j.yqres.2003.08.007.  
451  
452 Garreaud, R. D., 2009. The Andes climate and weather. *Advances in Geosciences* 22, 3.  
453  
454 Garreaud, R., Vuille, M., Clement, A. C., 2003. The climate of the Altiplano: Observed current  
455 conditions and mechanisms of past changes. *Paleogeography, Paleoclimatology, Paleoecology* 194,  
456 5–22.  
457  
458 Gosse, J.C., Phillips, F.M., 2001. Terrestrial in situ cosmogenic nuclides: theory and application.  
459 *Quaternary Science Reviews* 20(14), 1475-1560.  
460  
461 Granger DE. 2006. A review of burial dating methods using <sup>26</sup>Al and <sup>10</sup>Be. *Geological*  
462 *Society of America Special Publication* 415, 1-16.  
463  
464 Granger, D.E., Smith, A.L., 2000. Dating buried sediments using radioactive decay and muogenic  
465 production of <sup>26</sup>Al and <sup>10</sup>Be. *Nuclear Instruments and Methods in Physics Research*, B172, 822-826.  
466  
467 Granger, D.E., Kirchner, J.W., Finkel, R.C., 1996. Spatially averaged long-term erosion rates  
468 measured from in situ-produced cosmogenic nuclides in alluvial sediment. *Journal of Geology* 104,  
469 249-257.  
470  
471 Granger, D.E., Muzikar, P.F., 2001. Dating sediment burial with in situ-produced cosmogenic  
472 nuclides: theory, techniques, and limitations. *Earth and Planetary Science Letters* 188, 269–281.  
473  
474 Granger, D.E., Lifton, N.A., Willenbring, J.K., 2013. A cosmic trip: 25 years of cosmogenic nuclides  
475 in geology. *Geological Society of America Bulletin* 125(9-10), 1379-1402.  
476  
477 Hancock, G.S., Anderson, R.S., 2002. Numerical modeling of fluvial strath-terrace formation in  
478 response to oscillating climate. *Geological Society of America Bulletin* 114(9), 1131-1142.  
479  
480 Hidy, A.J., Gosse, J.C., Pederson, J.L., Mattern, J.P., Finkel, R.C., 2010. A geologically constrained  
481 Monte Carlo approach to modeling exposure ages from profiles of cosmogenic nuclides: An example  
482 from Lees Ferry, Arizona. *Geochemistry Geophysics, Geosystems* 11.  
483  
484 Kohl, C.P., Nishiizumi, K., 1992. Chemical isolation of quartz for measurement of in-situ-produced  
485 cosmogenic nuclides. *Geochimica et Cosmochimica Acta* 56(9), 3583-3587.  
486  
487 Korschinek, G., Bergmaier, A., Faestermann, T., Gerstmann, U.C., Knie, K., Rugel, G., 2010. A new  
488 value for the half-life of Be-10 by heavy-ion elastic recoil detection and liquid scintillation counting.  
489 *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials*  
490 *and Atoms* 268, 187-191.  
491  
492 Lagos, P., Silva, Y., Nickl, E., Mosquera, K., 2008. El Niño? related precipitation variability in Perú.  
493 *Advances in Geosciences* 14, 231-237.  
494

495 Lal, D., 1991. Cosmic-ray labeling of erosion surfaces—In situ nuclide production-rates and erosion  
496 models. *Earth and Planetary Science Letters* 104, 424–439.

497

498 Lisiecki, L.E., 2010. Links between eccentricity forcing and the 100,000-year glacial cycle. *Nature*  
499 *Geosci.* 3, 349–352.

500

501 Litty C., Duller R., Schlunegger F., 2016. Paleohydraulic reconstruction of a 40 kyr-old terrace  
502 sequence implies that water discharge was larger than today. *Earth Surface Processes and Landforms*  
503 41, 884-898. DOI: 10.1002/esp.3872.

504

505 Litty, C., Lanari, P., Burn, M., Schlunegger, F., 2017a. Climate-controlled shifts in sediment  
506 provenance inferred from detrital zircon ages, western Peruvian Andes. *Geology* 45(1), 59-62.

507

508 Litty, C., Schlunegger, F., Viveen, W., 2017b. Possible threshold controls on sediment grain  
509 properties of Peruvian coastal river basins. *Earth Surface Dynamics* 5, 1-13.  
510 <https://doi.org/10.5194/esurf-5-1-2017>

511

512 McPhillips, D., Bierman, P.R., Rood, D. H., 2014. Millennial-scale record of landslides in the  
513 Andes consistent with earthquake trigger. *Nature Geoscience* 7(12), 925-930.

514

515 NASA Land Processes Distributed Active Archive Center (LP DAAC). ASTER GDEM. USGS/Earth  
516 Resources Observation and Science (EROS) Center, Sioux Falls, South Dakota, 2001.

517

518 Norris, T.L., Gancarz, A.J., Rokop, D.J., Thomas, K.W., 1983. Half-life of <sup>26</sup>Al. *Journal of*  
519 *Geophysical Research, Solid Earth* 88(S01).

520

521 Norton, K.P., Schlunegger, F., Litty. C., 2016. On the potential for regolith control of fluvial terrace  
522 formation in semi-arid escarpments. *Earth Surf. Dynam* 4, 147-157, [https://doi.org/10.5194/esurf-4-](https://doi.org/10.5194/esurf-4-147-2016)  
523 [147-2016](https://doi.org/10.5194/esurf-4-147-2016).

524

525 Milankovitch, M. *Kanon der Erdbestrahlung und seine Anwendung auf das Eiszeitproblem* (R.  
526 *Serbian Acad.*, 1941).

527

528 Pederson, J.L., Anders, M.D., Rittenhour, T.M., Sharp, W.D., Gosse, J. C., Karlstrom, K.E., 2006.  
529 Using fill terraces to understand incision rates and evolution of the Colorado River in eastern Grand  
530 Canyon, Arizona. *Journal of Geophysical Research: Earth Surface* 111(F2).

531

532 Pillans, B., Chappell, J., Naish, T.R., 1998. A review of the Milankovitch climatic beat: template for  
533 Plio–Pleistocene sea-level changes and sequence stratigraphy. *Sedimentary Geology* 122(1), 5-21.

534

535 Placzek, C., Quade, J., Patchett, P.J., 2006. Geochronology and stratigraphy of late Pleistocene lake  
536 cycles on the southern Bolivian Altiplano: implications for causes of tropical climate change.  
537 *Geological Society of America Bulletin* 118, 515–532.

538

539 Reber, R., Delunel, R., Schlunegger, F., Litty, C., Madella, A., Akçar, N., Christl, M., 2017.  
540 Environmental controls on <sup>10</sup>Be-based catchment-averaged denudation rates along the western  
541 margin of the Peruvian Andes. *Terra Nova*.

542

543 Repka, J.L., Anderson, R.S., Finkel, R.C., 1997. Cosmogenic dating of fluvial terraces, Fremont  
544 River, Utah. *Earth and Planetary Science Letters* 152(1), 59-73.  
545  
546 Steffen, D., Schlunegger, F., Preusser, F., 2009. Drainage basin response to climate change in the  
547 Pisco Valley, Peru. *Geology* 37, 491–494.  
548  
549 Steffen, D., Schlunegger, F., Preusser, F., 2010, Late Pleistocene fans and terraces in the Majes  
550 Valley, southern Peru, and their relation to climatic variations. *International Journal of Earth Sciences*  
551 99(8), 1975-1989.  
552  
553 Stone, J.O., 2000. Air pressure and cosmogenic isotope production. *Journal of Geophysical Research:*  
554 *Solid Earth* 105(B10), 23753-23759.  
555  
556 Strecker, M.R., Alonso, R.N., Bookhagen, B., Carrapa, B., Hilley, G.E., Sobel, E.R., Trauth, M.H.,  
557 2007, Tectonics and climate of the southern central Andes: *Annual Review of Earth and Planetary*  
558 *Sciences* 35, 747–787, doi: 10.1146/annurev.earth.35.031306.140158.  
559  
560 Sylvestre, F., Servant, M., Servant-Vildary, S., Causse, C., Fournier, M., Ybert, J. P., 1999. Lake-  
561 level chronology on the Southern Bolivian Altiplano (18–23 S) during late-glacial time and the early  
562 Holocene. *Quaternary Research* 51(1), 54-66.  
563  
564 Trauerstein M, Lowick SE, Preusser F, Schlunegger F. 2014. Small aliquot and single grain IRSL and  
565 post-IR IRSL dating of fluvial and alluvial sediments from the Pativilca Valley, Peru. *Quaternary*  
566 *Geochronology* 112, 163–174.  
567  
568 Tucker GE, Slingerland R. 1997. Drainage basin response to climate change. *Water Resources*  
569 *Researc.* 33, 2031–2047.  
570  
571 Veit, H., May, J.H., Madella, A., Delunel, R., Schlunegger, F., Szidat, S., Capriles, J. M., 2016.  
572 Palaeo-geocological significance of Pleistocene trees in the Lluta Valley, Atacama Desert. *Journal*  
573 *of Quaternary Science* 31(3), 203-213.  
574  
575 Von Blanckenburg F. 2005. The control mechanisms of erosion and weathering at basin scale from  
576 cosmogenic nuclides in river sediment. *Earth and Planetary Science Letters* 237(3), 462–479.  
577  
578 Wolkowinsky, A.J., Granger, D.E., 2004. Early Pleistocene incision of the San Juan River, Utah,  
579 dated with <sup>26</sup>Al and <sup>10</sup>Be. *Geology* 32(9), 749-752.  
580  
581

## 582 **Tables and Figures captions**

583  
584 **Table 1:** Sample and cosmogenic nuclide data.  
585

586 **Table 2:** Input parameters for the Monte Carlo simulator in Matlab® (Hidy et al., 2010).  
587

588 **Table 3:** Results of the Monte Carlo simulations with Matlab® for (A) Barranca and (B) Pativilca.  
589 Total number of simulated profiles is 100,000. The bold numbers represent the modelled values and  
590 are therefore the ones that are used in this paper.

591

592 **Table 4:** Information relevant for interpreting  $^{10}\text{Be}$  concentrations. Modern and paleo catchment-  
593 averaged denudation were calculated using the SRTM DEM with a 90 m resolution. A  $^{10}\text{Be}$  half-life  
594 of  $1.39 \pm 0.01$  Ma was used (Chmeleff et al., 2010; Korschinek et al., 2010) and a SLHL  $^{10}\text{Be}$   
595 production rate of  $4.01 \text{ g}^{-1} \text{ a}^{-1}$ . A density of  $2.65 \text{ g cm}^{-3}$  was employed.

596

597 **Fig. 1:** (A) Maps of the study area showing the location of Pativilca and Barranca on the western side  
598 of the Peruvian Andes. (B) Field photographs showing the alluvial terraces in Barranca and Pativilca.  
599 Samples PAT-DP-1 to 6 (Pativilca), BAR-DP 1 to 6 (Barranca) were collected for depth-profile  
600 dating. The white lines represent the bracket level where quartz bearing clasts were sampled for  
601 isochron burial dating purposes. The concentrations obtained for the samples BAR-DP6 and PAT-  
602 DP6 were used for the calculation of the paleo-basin wide denudation rates

603

604 **Fig. 2:** Measured  $^{26}\text{Al}$  concentrations plotted vs.  $^{10}\text{Be}$  concentrations of the isochron-burial dating  
605 samples in Barranca (BAR-IS1, BAR-IS2 and BAR-IS3) and in Pativilca (PAT-IS1 and PAT-IS2).  
606 The sampling sites are shown on Fig. 1B. The errors represent  $2\sigma$  uncertainties. The dash lines  
607 illustrate the surface production rate ratio of 6.75 (Balco et al., 2008).

608

609 **Fig. 3:** Measured  $^{10}\text{Be}$  concentrations including the  $1\sigma$  uncertainties of the Barranca depth-profile  
610 samples plotted against depth.

611

612 **Fig. 4:** Modal output of the Monte Carlo simulations showing frequency distributions and  $\chi^2$  values  
613 for exposure age, erosion rate and inheritance.

614

615 **Fig. 5:** Output of the Monte Carlo depth-profile age simulation. (A) Illustration of the best fit through  
616 the samples for the lowest  $\chi^2$  value. (B) Possible solution space with a  $\chi^2$  cut-off values of  $< 20$ .

617

618 **Fig. 6:** Measured  $^{10}\text{Be}$  concentrations including the  $1\sigma$  uncertainties of the Pativilca depth-profile  
619 samples plotted against depth.

620

621 **Fig. 7:** Modal output of the Monte Carlo simulations showing frequency distributions and  $\chi^2$  values  
622 for exposure age, erosion rate and inheritance.

623

624 **Fig. 8:** Output of the Monte Carlo depth-profile age simulation. (A) Illustration of the best fit through  
625 the samples for the lowest  $\chi^2$  value. (B) Possible solution space with a  $\chi^2$  cut-off values of  $< 3$ .

626

627 **Fig. 9:** Map of the alluvial terraces in Pativilca and Barranca showing the age of the different terraces.

628

629 **Fig. 10:** (A) Summary of the IRSL and depth-profile ages in Pativilca and Barranca. The black dots  
630 represent the IRSL samples from Trauerstein et al. (2014) and the white dot represents the depth  
631 profile (this study). (B) Summary of the paleo-catchment wide denudation rates. The transect A-B can  
632 be seen in Fig. 9.

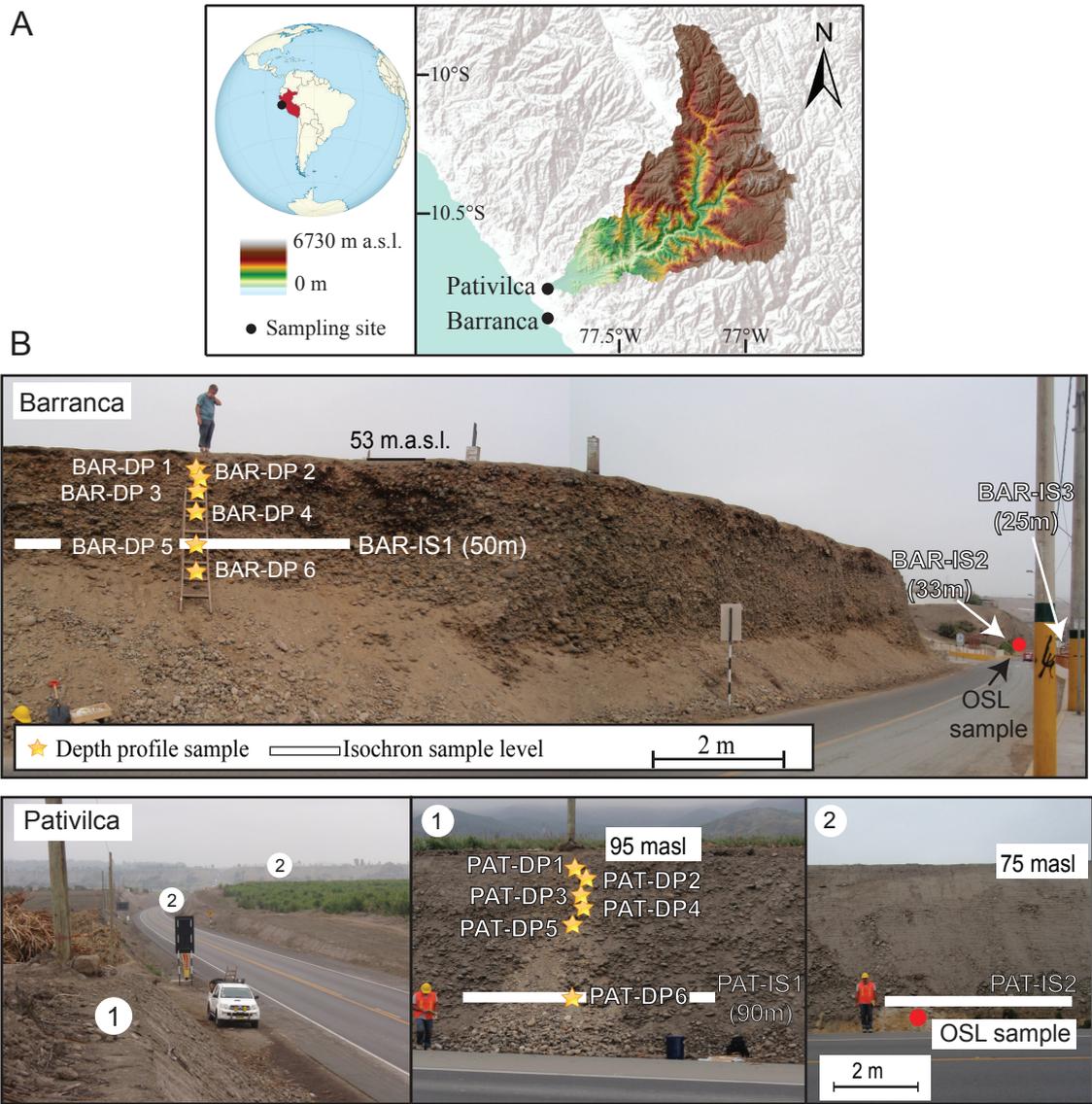
633

634 **Fig. 11:** Maps showing the inferred channel belt position during the sediment accumulation phases in  
635 the Pativilca Valley. (A) prior to  $\sim 1.2$  Ma ago. (B) prior to  $\sim 200$  ka ago. (C)  $\sim 100$  ka ago. (D)  $\sim 30$  ka  
636 ago.

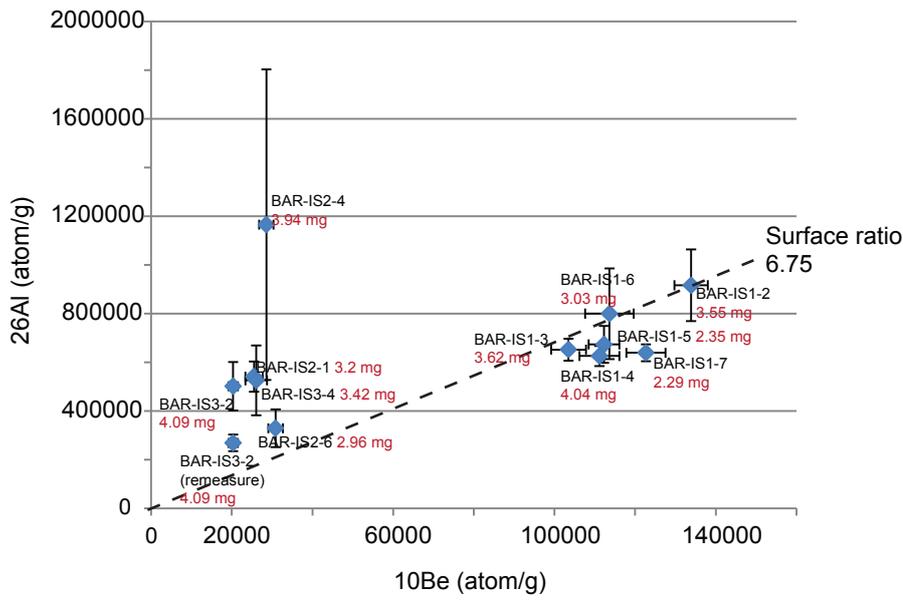
637

638 **Fig. 12:** Erosion rates versus time.

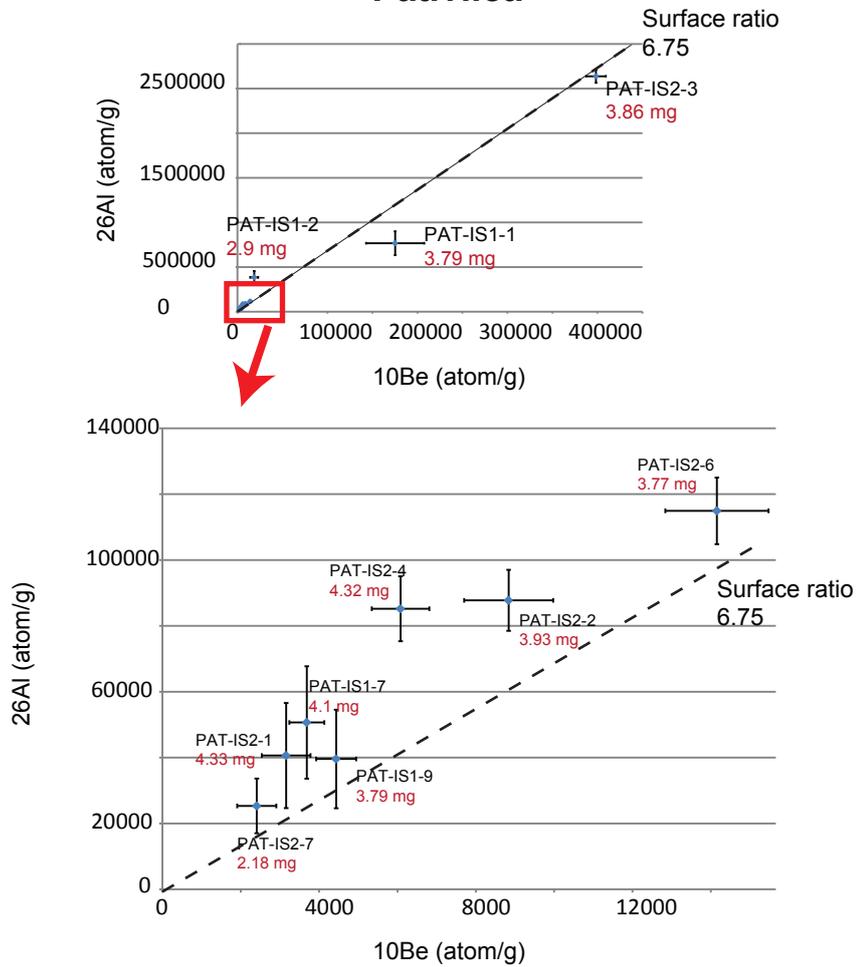
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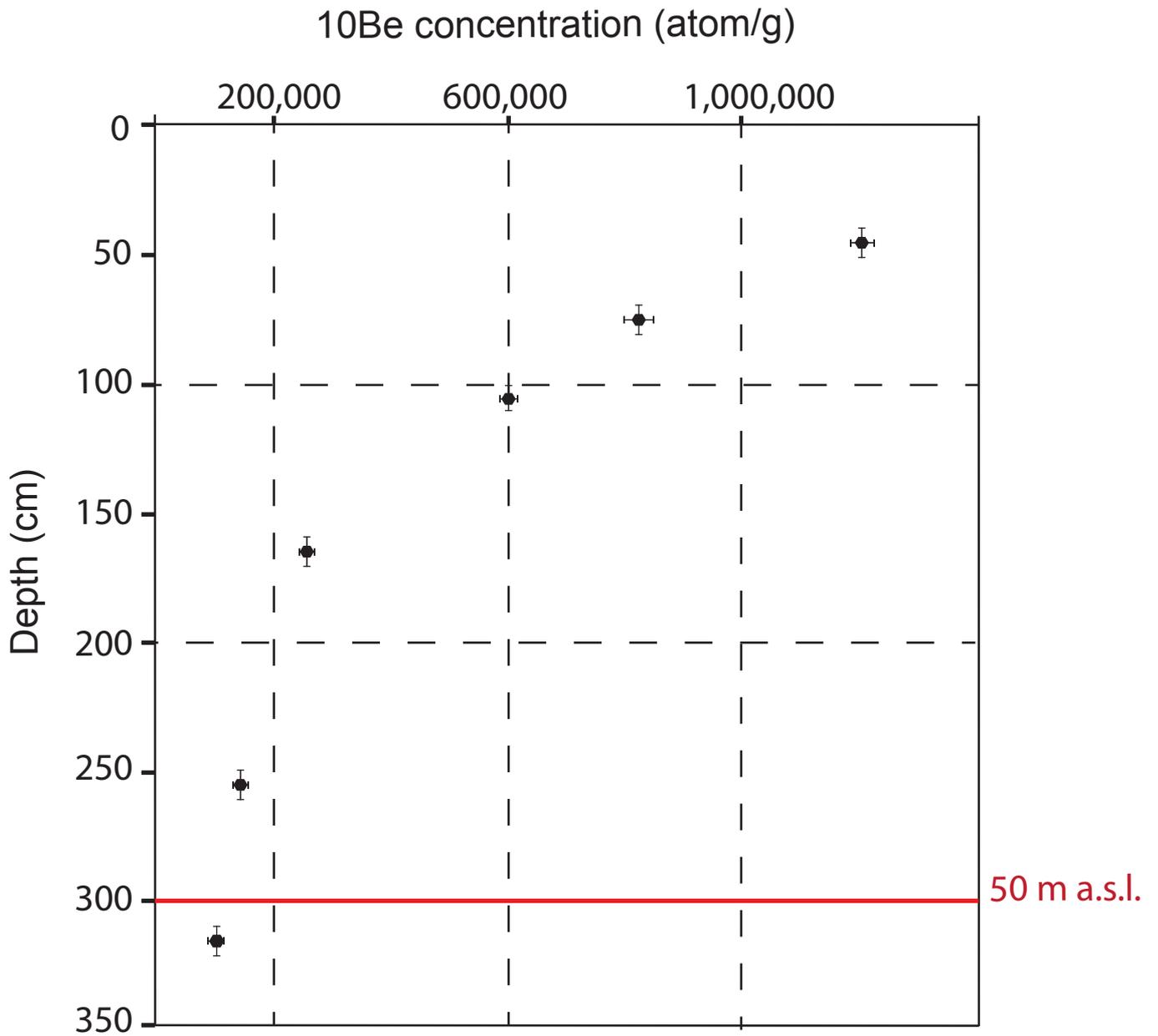
### Barranca



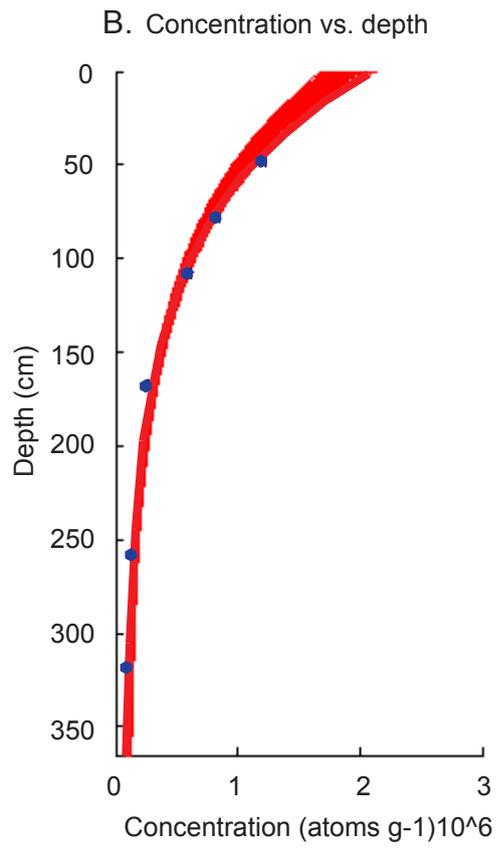
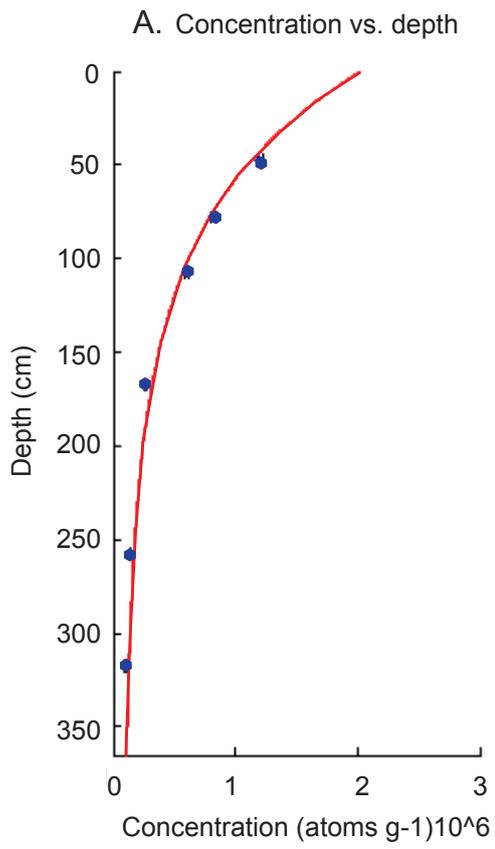
### Pativilca

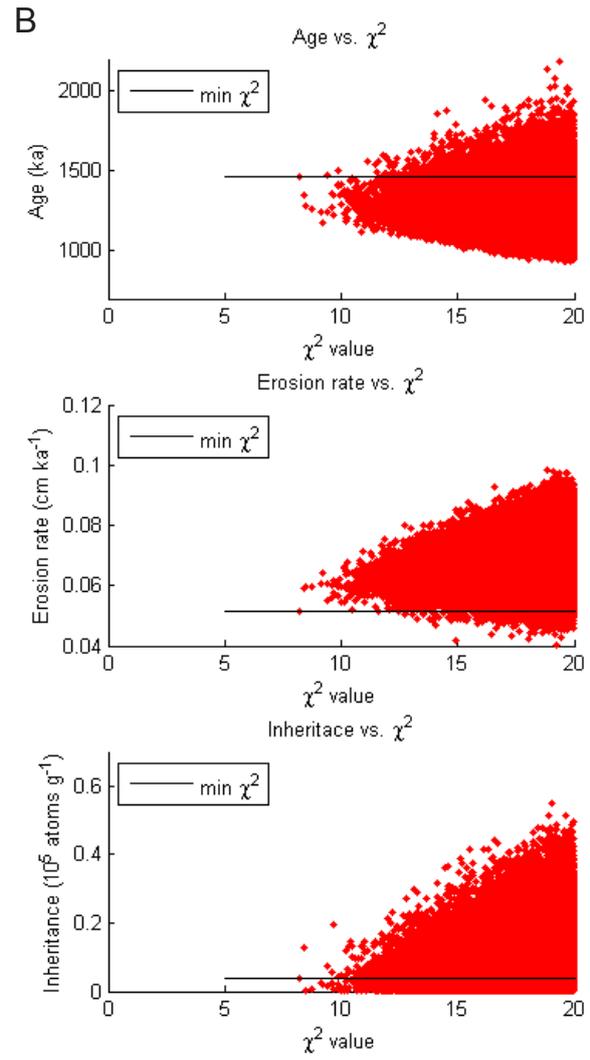
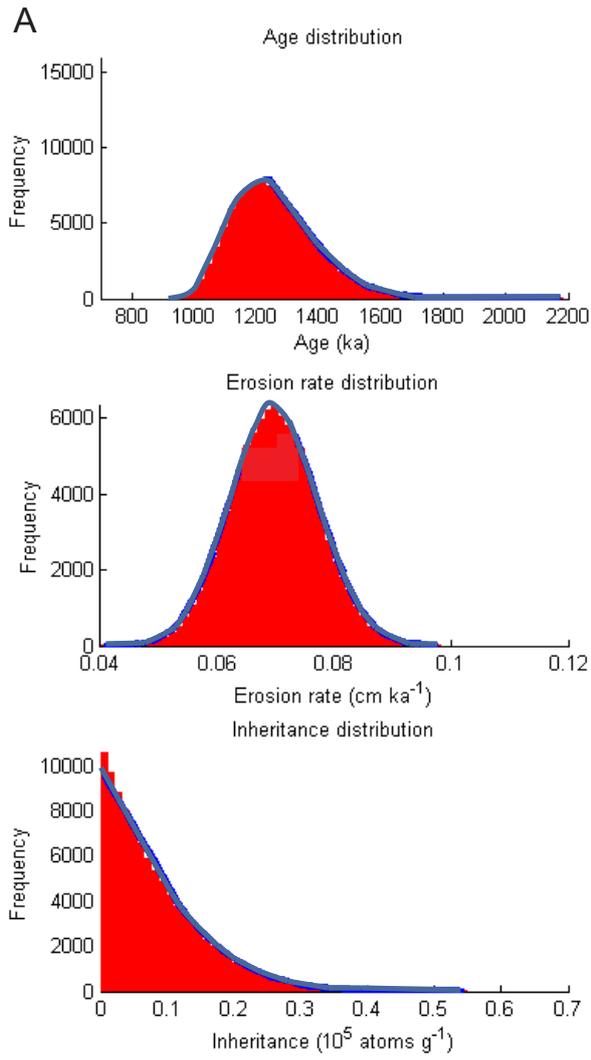


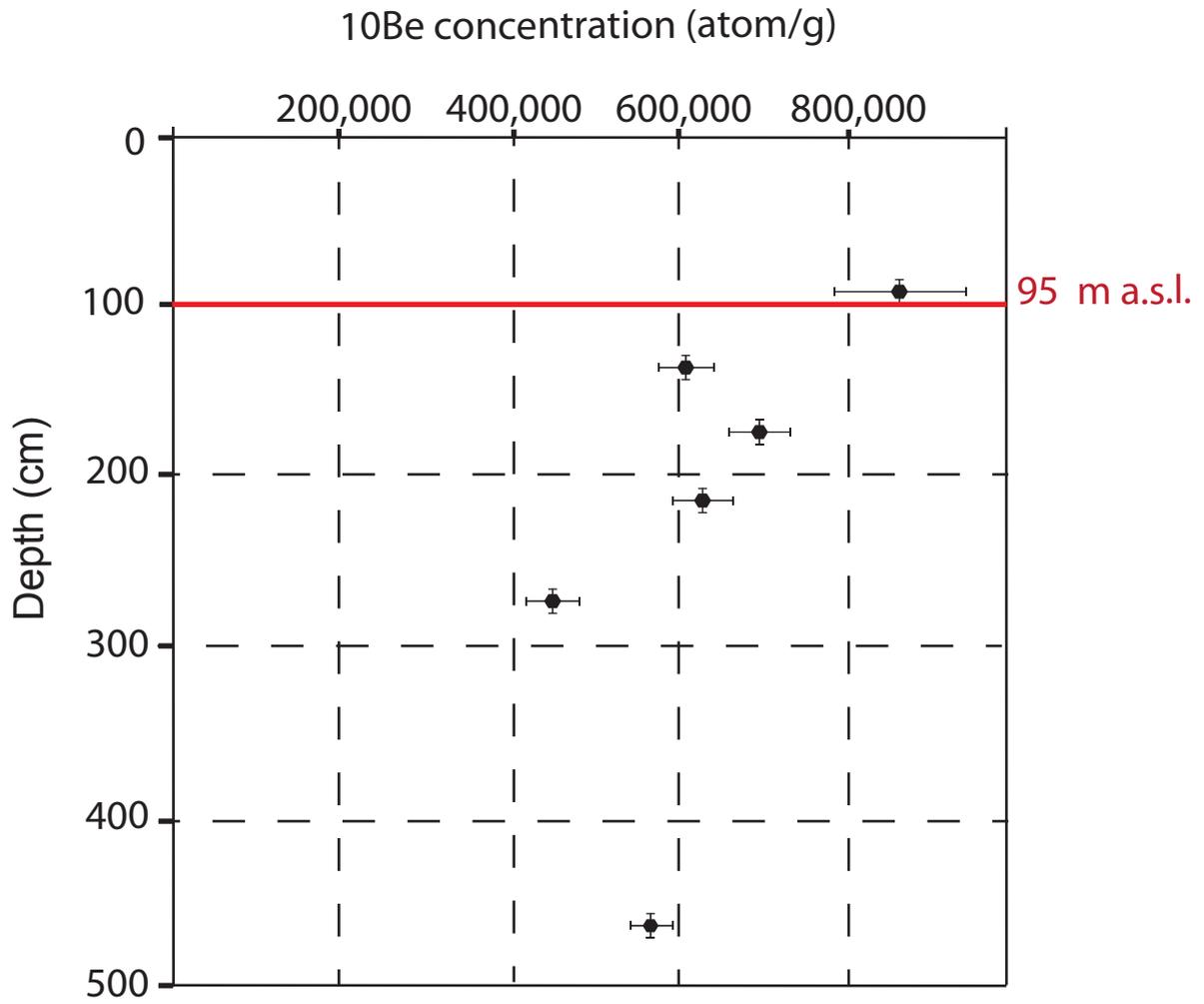
# Barranca Depth Profile (Peru)

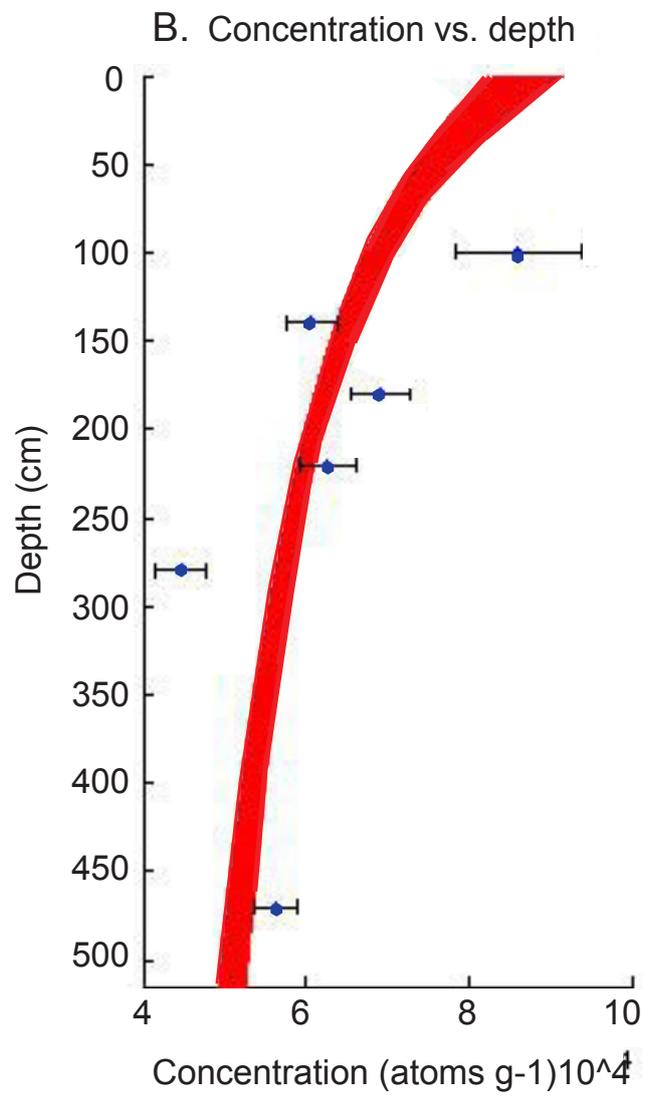
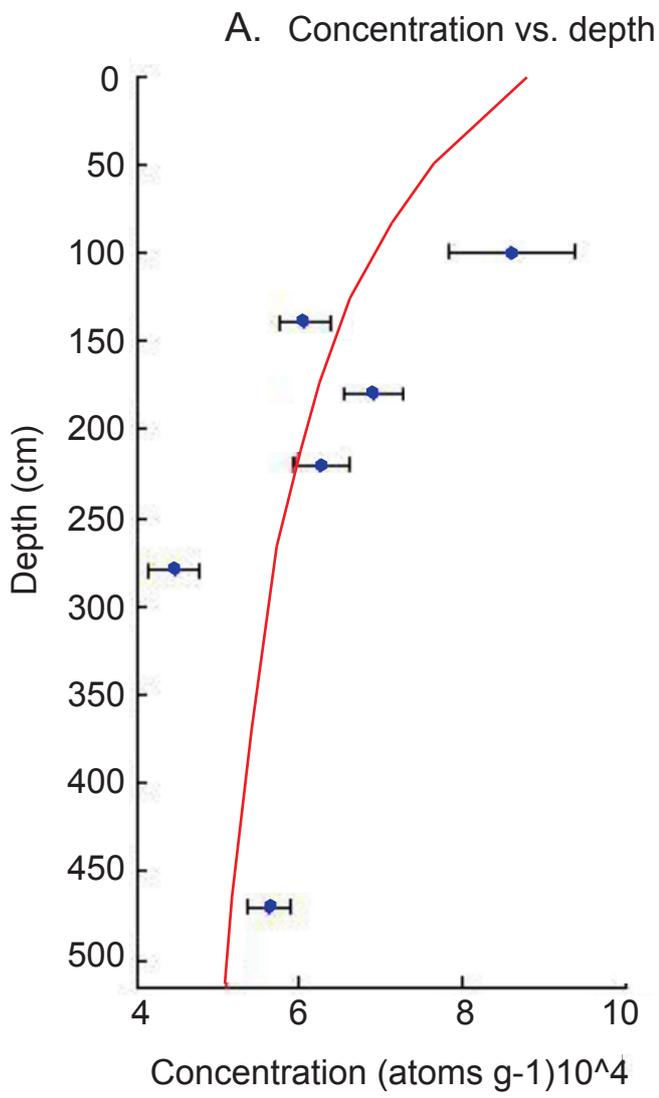


Figur  
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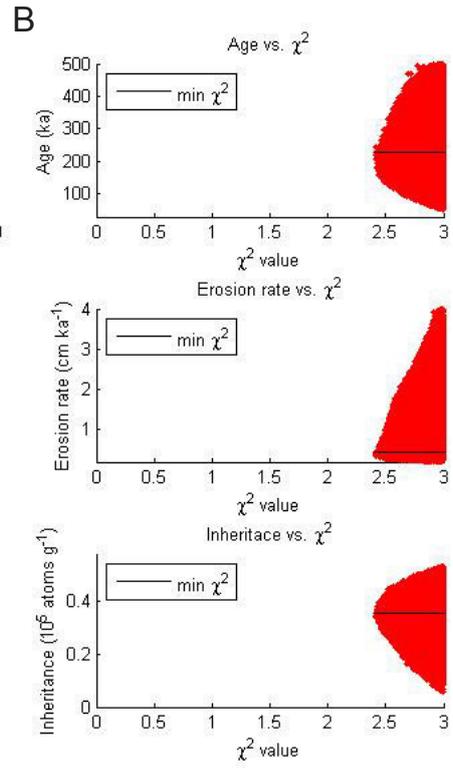
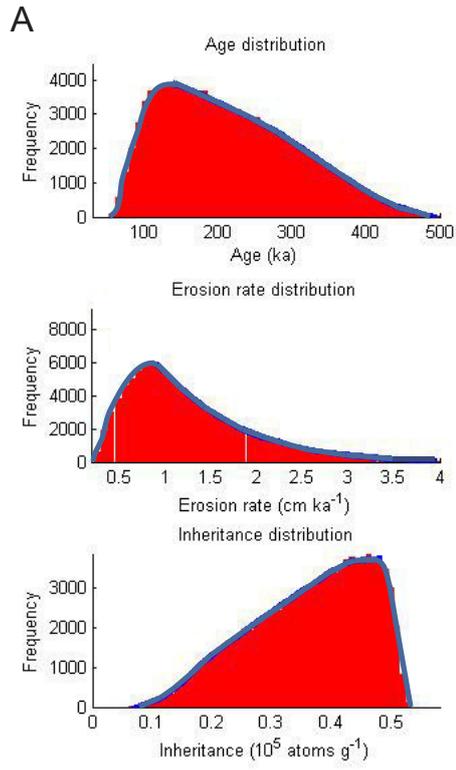
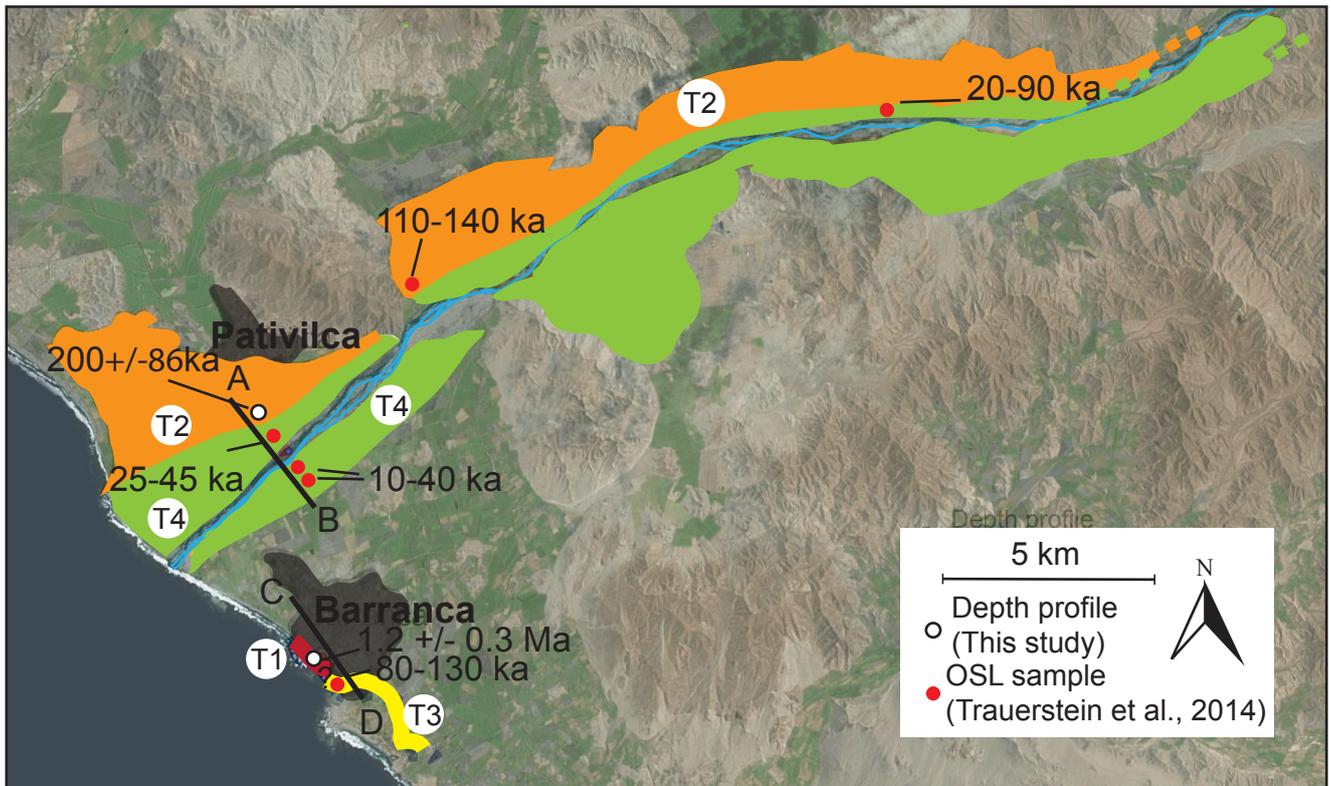
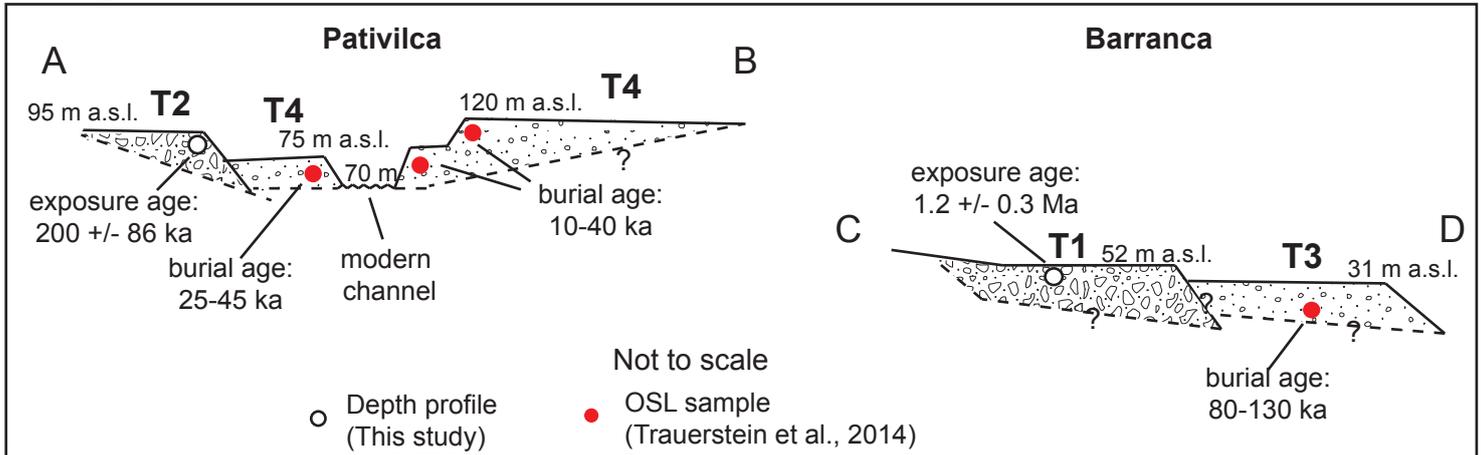


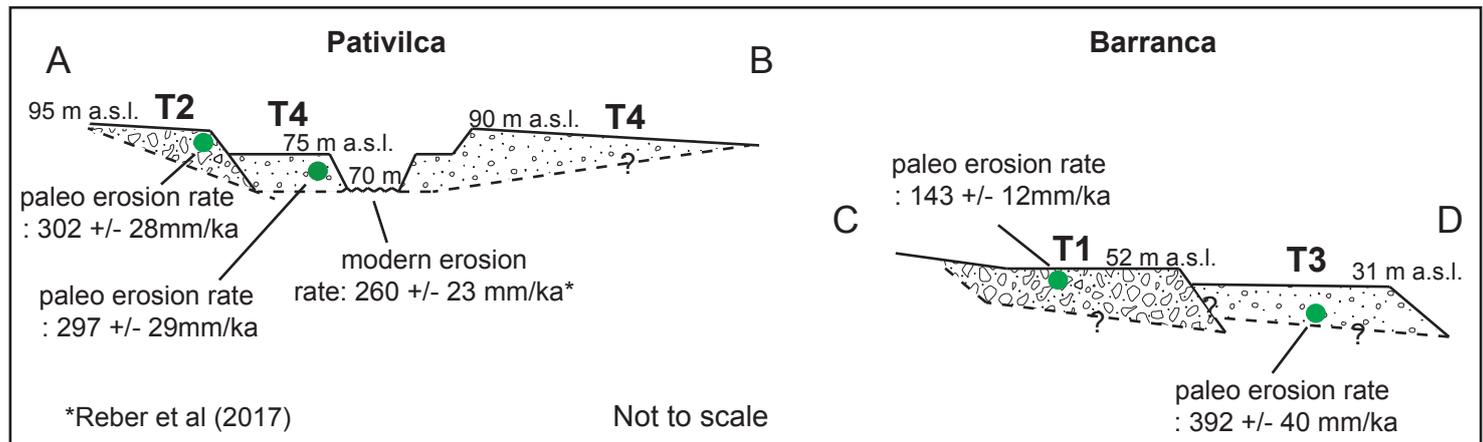
Figure 9



A. Ages



B. Erosion rates



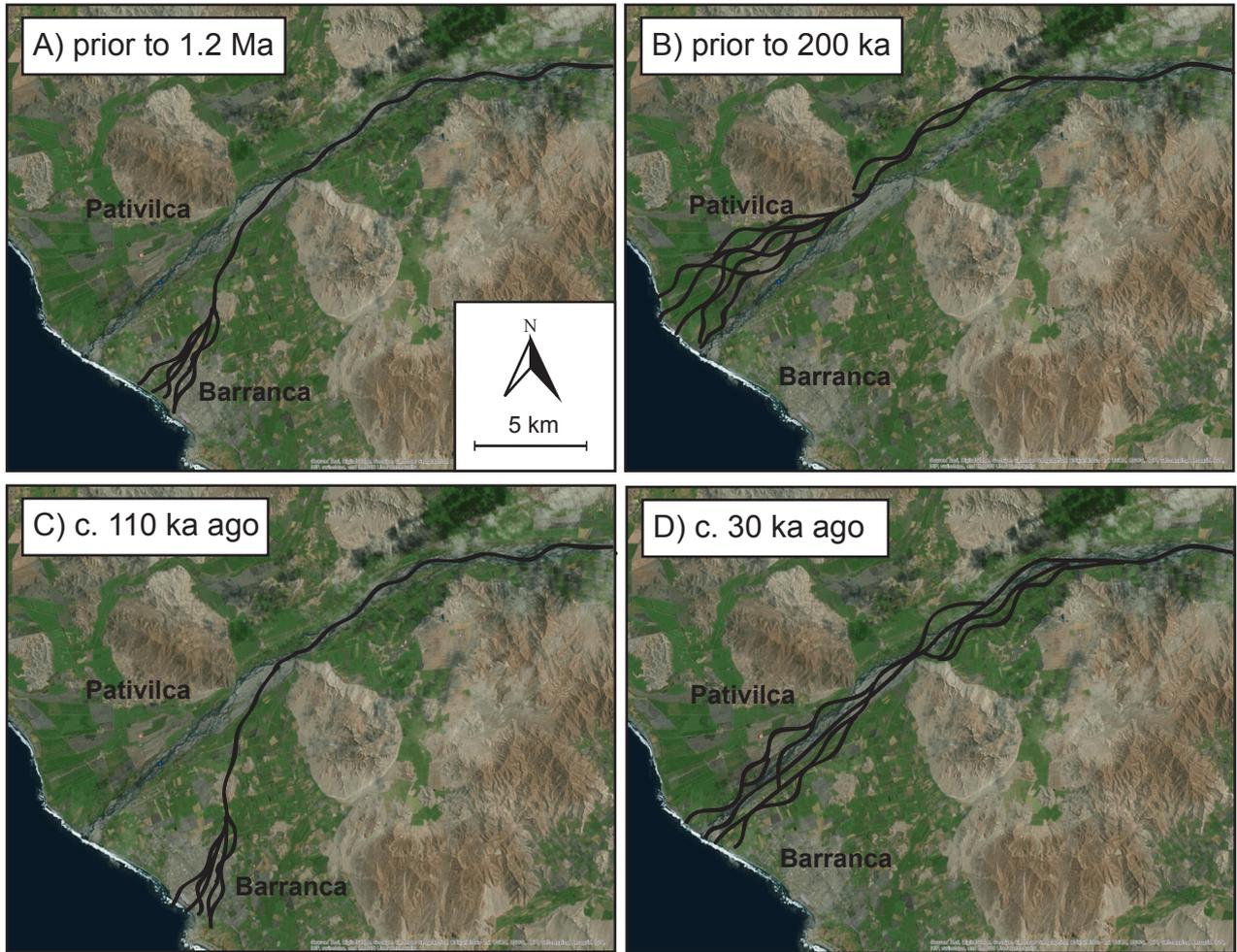


Figure  
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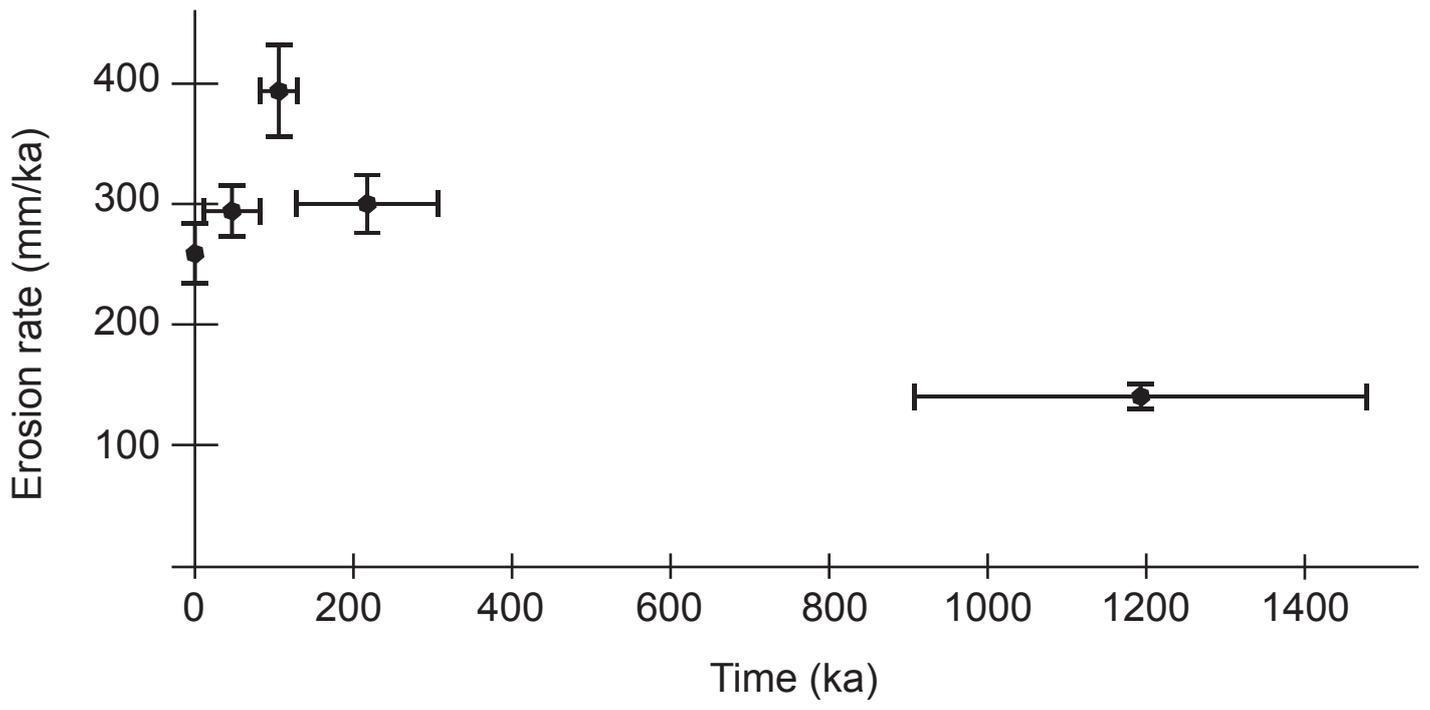




Table 2  
Input parameters for the Monte Carlo simulator in Matlab (Hidy et al., 2010).

<b>Barranca</b>		<b>Pativilca</b>	
Parameter	Value	Parameter	Value
Latitude (degree)	-10,758	Latitude (degree)	-10,704
Longitude (degree)	-77,765	Longitude (degree)	-77,776
Altitude (m)	53	Altitude (m)	96
Strike (degree)	0	Strike (degree)	0
Dip (degree)	0	Dip (degree)	0
Shielding correction factor	1	Shielding correction factor	1
Cover correction factor	1	Cover correction factor	1
Uncertainty of 10Be Half-life (%)	1	Uncertainty of 10Be Half-life (%)	1
Local spallogenic production rate (at g-1 a-1)	2,50	Local spallogenic production rate (at g-1 a-1)	2,50
Error in local spallogenic production rate (at g-1 a-1)	± 0.5	Error in local spallogenic production rate (at g-1 a-1)	± 0.5
Depth of muon fit (m)	6	Depth of muon fit (m)	6
Error in total production rate (%)	5	Error in total production rate (%)	5
Density (g cm-3)	1.6-2.1	Density (g cm-3)	1.6-2.1
X2 value	20	X2 value	3
Numbers of profiles	100,000	Numbers of profiles	100,000
Age (a)	700,000-2,200,000	Age (a)	30,000-500,000
Erosion rate (cm ka-1)	0.04-0.12	Erosion rate (cm ka-1)	0.2-4
Total erosion threshold (cm)	75-400	Total erosion threshold (cm)	75-400
Inheritance (at g-1)	0-70,000	Inheritance (at g-1)	0-58,000
Attenuation length (g cm-2)	160 ± 5	Attenuation length (g cm-2)	160 ± 5

		Table Barranca		
A		Results of the Monte Carlo simulations with Matlab		
		Age (ka)	Inheritance (atom/g)	Erosion rate (cm/ka)
	Mean	1254.3	8300	0.07
	Median	1239.4	6400	0.07
	Mode	<b>1197.1</b>	<b>300</b>	<b>0.07</b>
	Minimum X2	1261.5	1200	0.06
	Maximum	1503.0	5,8000	0.09
	Minimum	1043.2	0	0.05

		Table Pativilca		
B		Results of the Monte Carlo simulations with Matlab		
		Age (ka)	Inheritance (atom/g)	Erosion rata (cm/ka)
	Mean	200.6	3,5500	0.52
	Median	200.3	3,5500	0.51
	Mode	<b>204.1</b>	<b>3,5100</b>	<b>0.48</b>
	Minimum X2	217.6	3,7800	0.35
	Maximum	314.3	4,3800	0.89
	Minimum	125	2,7100	0.25

Sample name	Paleo/modern erosion rates	Age of the deposits	Latitude (DD.DD) WGS84	Longitude (DD.DD) WGS84	Altitude of the top of the terrace (m.a.s.l)	Sample depth (cm)	Quartz dissolved (g)	9Be spike (mg)	Measured 10Be/9Be ratio (10 <sup>-12</sup> )	AMS error (%)	10Be concentration (at/g)	Concentration at the time of deposition (at/g)	Denudation rates (mm/ka)
PAT-ME	Modern erosion rates	Modern Pativilca river	10.717°S	77.767°W	71	Surface	50.11	0.1991	0.24	4.0	6,4052 +/- 2695	6,4052 +/- 2695	260 +/- 23
PAT-DP6	Paleo erosion rates	Terrace T1 (Pativilca) : 200 ka	10.704°S	77.775°W	95	465 cm	49.88	0.1743	0.24	4.6	5,6219 +/- 2634	5,5203 +/- 2539	302 +/- 28
PAT-PE	Paleo erosion rates	Terrace T3 (Pativilca) : 40 ka	10.708°S	77.772°W	75	400 cm	49.97	0.1953	0.22	5.5	5,6468 +/- 3144	5,6004 +/- 3080	297 +/- 29
BAR-DP6	Paleo erosion rates	Terrace (Barranca) : 1.2 Ma	10.758°S	77.765°W	52	315 cm	33.25	0.1744	0.30	4.4	10,2942 +/- 4574	11,6020 +/- 2464	143 +/- 12
BAR-PE2	Paleo erosion rates	Terrace (Barranca) : 100 ka	10.759°S	77-764°W	33	400 cm	41.24	0.1984	0.14	6.3	4,4416 +/- 2823	4,2570 +/- 2682	392 +/- 40