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Does pebble abrasion influence detrital age population statistics? A numerical investigation of natural datasets

Citation for published version:

Lavarini ferreira, C, Attal, M, da Costa Filho, CA & Kirstein, L 2018, 'Does pebble abrasion influence detrital age population statistics? A numerical investigation of natural datasets' *Journal of Geophysical Research: Earth Surface*. DOI: 10.1029/2018JF004610

Digital Object Identifier (DOI):

[10.1029/2018JF004610](https://doi.org/10.1029/2018JF004610)

Link:

[Link to publication record in Edinburgh Research Explorer](#)

Document Version:

Peer reviewed version

Published In:

Journal of Geophysical Research: Earth Surface

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22 **Abstract**

23

24 Pebble abrasion is a key factor controlling the release of minerals into sand, but few attempts
25 have been made to model how it could influence the liberation of minerals into the size fraction
26 used in detrital geochronology. We perform a series of experiments with an abrasion model to
27 test this influence using natural and synthetic datasets. Our results demonstrate that pebble
28 abrasion can change the zircon mixing proportions of upstream source units as well as the age
29 distribution of mixed fluvial sands. This change is particularly significant when there is strong
30 contrast in rock resistance within the watershed. Pebble abrasion is one of many factors that
31 can change the mixing proportion of sands, including hillslope gravel supply, erosion rates, and
32 mineral fertility. In our study case (Marsyandi watershed, Himalaya), the abrasion model
33 predicts age distributions that are statistically indistinguishable from those predicted by a no-
34 abrasion model. However, the relative erosion rates estimated by our model largely differ from
35 the results of a no-abrasion model, and are closer to those from other studies that suggest a
36 strong correlation between modern erosion rates, tectonics and precipitation intensity in the
37 Marsyandi watershed. These findings highlight that, even in cases where there is no statistical
38 evidence of change between the modelled age distributions, abrasion can affect the erosion rates
39 estimated from them. Therefore, quantifying the influence of abrasion on sand production is an
40 essential step not only to predict mixing proportions but also to accurately retrieve erosion rates
41 from the measured grain age distributions.

42

43 **Keywords:** sediment, detrital methods, abrasion, provenance, bias, erosion, geochronology,
44 zircon.

45

46 **1 Introduction**

47 Minerals rich in uranium and thorium contain vital clues to unravelling Earth's history.
48 More resistant minerals such as zircon behave as Earth's timekeepers as they can retain
49 information even after crustal or sediment recycling, and so are key tools to reconstruct ancient
50 geological events (e.g., Amelin et al., 1999; Mojzsis et al., 2001; Wilde et al., 2001). For this
51 reason, detrital zircon has been extensively used in investigations about the growth and
52 evolution of continents (e.g., Iizuka et al., 2010; Dhuime et al., 2012; Oliver et al., 2014),
53 documenting sub-glacial erosion (e.g., Cox et al., 2010; Tochilin et al., 2012; Thomson et al.,
54 2013) as well as reconstructing sediment provenance and drainage development (e.g., Singh et
55 al., 2008; Kirstein et al., 2009, 2013; Alizai et al., 2011; Gehrels et al., 2011; Blum and Pecha,
56 2014).

57 But how representative are the sampled grains of the original system? We should not
58 ignore this perennial question if we are to have confidence in our interpretation of preserved
59 sedimentary deposits and what they represent. The importance of investigating source-to-sink
60 processes that may have influenced the preservation of grains is increasingly being recognized
61 (Garzanti et al., 2009; Lukens et al., 2016). Potential biases, if measurable, could have profound
62 effects on the way in which we interpret the sedimentary record. As a result, a number of studies
63 have focused on how different processes such as sediment generation on hillslopes (e.g., Riebe
64 et al., 2015; Lukens et al., 2016), transport in river channels (e.g., Garzanti et al., 2008, 2009;
65 Lawrence et al., 2011a) and sediment mixing in watersheds (Haddadchi et al., 2013, 2014) can
66 affect the way we use detrital information.

67 At the same time, numerical models have increasingly been applied as a tool to unravel
68 the source of zircons in modern rivers (Sundell and Saylor, 2017). Several of these models
69 apply a forward mixing approach, whereby empirical observations such as exposure area and
70 zircon fertility (i.e. the concentration of the mineral of interest in the source area) are used to
71 generate an artificial grain age probability density function which is compared to the best fit of
72 the measured grain age distribution (e.g., Saylor et al., 2013; Kimbrough et al., 2015; Licht et
73 al., 2016; Sharman and Johnstone, 2017). There is often a mismatch between the model-
74 predicted and best-fit age distributions that is typically explained by a variety of natural factors
75 such as differences in erosion rates (e.g., Amidon et al., 2005a), mineral fertility over the study
76 area (e.g., Moecher and Samson, 2006; Dickinson, 2008), and fractionation by transport
77 processes (e.g., hydraulic sorting) (Lawrence et al., 2011b; Malusà et al., 2016).

78 In detrital studies, minerals of interest such as zircon and apatite are more likely to be
79 found in the 63–250 micron sand fraction. Inherent in these studies is the assumption that this
80 fraction is representative of the system under investigation and that the upstream source units
81 are homogeneously mixed. Lukens et al. (2016) showed that detrital methods focusing on a
82 given size fraction (cosmogenic nuclides in sand in their case) could be biased in steep terrain,
83 as some parts of the catchment may generate more sand than others (see also Riebe et al., 2015).
84 Further, implicit in this practice (and by extension in sediment mixing models) is an untested
85 assumption that pebbles with different abrasion rates are not able to statistically change (i.e.,
86 distort) the detrital age distribution of sands. However, fluvial abrasion of clasts has long been
87 considered as one of the main drivers of mineral liberation from coarser to finer size fractions
88 and thus one of the processes which, along with selective transport, promote downstream fining
89 along a river (Krumbein, 1941; Kuenen, 1956; Schumm and Stevens, 1973; Mills, 1979; Parker,
90 1991; Attal and Lavé, 2006, 2009; Le Bouteiller et al., 2011; Domokos and Gibbons, 2012;
91 Miller et al., 2014). The importance of abrasion in generating sand was confirmed by recent
92 studies combining both field and laboratory investigations, (e.g., Sklar and Dietrich, 2001;
93 Lewin and Brewer, 2002; Attal et al., 2006; Attal and Lavé, 2006, 2009).

94 Here, we investigate whether pebble abrasion can statistically change (distort) the
95 detrital age distribution recorded by fluvial sands. The Marsyandi watershed, central Nepal, is
96 an abrasion-dominant setting with exceptional constraints on the parameters that are required
97 to simulate the evolution of sediment grain size and mineralogy: published U-Pb detrital zircon
98 age distributions and zircon fertility datasets (Amidon et al., 2005a) are used together with
99 pebble abrasion rates and hillslope grain size supply data (Attal and Lavé, 2006) to simulate
100 detrital age distortions along the Marsyandi River. In addition, our model predictions are
101 compared to other independent published datasets of sediment mixing (e.g., Garzanti et al.,
102 2007) and erosion rates (e.g., Pratt-Sitaula et al., 2004; Gabet et al., 2008; Burbank et al., 2003)
103 from the study area.

104 We initially test if, by using specific pebble abrasion rates, we are able to simulate
105 statistically significant changes on the U-Pb detrital zircon grain age population from sands by
106 comparing model results with and without abrasion. We also compare our no-abrasion model
107 results with results from Amidon et al. (2005a)'s no-abrasion model as a test of our model's
108 performance. We then assess the magnitude of the distortion other well-known controlling
109 factors (i.e., differences in erosion rates, zircon fertility and hillslope gravel supply) are able to
110 generate in the Marsyandi catchment, and assess if abrasion is able to produce distortions of a

111 comparable magnitude. With these experiments, we test if pebble abrasion is a significant factor
112 influencing the grains ultimately used in detrital studies, and the resultant grain age distributions
113 used to investigate past landscape change.

114

115 **2 Materials and Methods**

116 **2.1 Estimating the source mixing proportion in mixed sand samples**

117 Measuring the U-Pb zircon grain age distribution both in upstream source units and in
118 a downstream mixed river sample should be sufficient to obtain the mixing proportions of these
119 source units by iteratively solving the proportions in which they must be present to produce a
120 best fit (Amidon et al., 2005a,b).

121 The best-fit age distribution $f(x)$ of a downstream sample $g(x)$ derived from n source
122 units is given as:

123

$$124 f(x) = \sum_{i=1}^n \Phi_i f_i(x),$$

125

126

127 where Φ_i is the zircon mixing proportion, equal to $1/n$ if all source rocks are equally represented,
128 and must satisfy:

129

130

$$\sum_{i=1}^n \Phi_i = 1.$$

131

132

133 In Equation (1), $f_i(x)$ is the U-Pb zircon age distribution from the source unit i , and is
134 mathematically represented by the probability density function (PDF):

135

136

$$f_i(x) = \frac{1}{\sigma_i \sqrt{2\pi}} e^{-\frac{1}{2} \left(\frac{x - \mu_i}{\sigma_i} \right)^2},$$

137

138

139 where x is grain age, μ_i is the mean grain age and σ_i is the analytical uncertainty of the dating
140 method (c.f. Saylor and Sundell, 2016).

141 The zircon mixing proportions Φ_i are iteratively estimated by minimizing the area
142 mismatch (M) between the U-Pb zircon grain age distribution of the mixed sample $g(x)$ and the
143 U-Pb zircon grain age best-fit $f(x)$ made of upstream source units $f_i(x)$. This minimization is
144 performed by a mathematical optimization, which is solved in this work through the Sequential
145 Least Squares Programming (SLSQP) method (Nocedal and Wright, 2000). Although PDF
146 cross-plot maximization and Monte Carlo modelling seems to generate more accurate mixing
147 proportions (Saylor et al., 2013; Sundell and Saylor, 2017; Sharman and Johnstone, 2017), we
148 chose the area mismatch method to match the procedures adopted by Amidon et al. (2005a), as
149 we are using their age populations and wish to produce results that are directly comparable with
150 their no-abrasion model.

151 The area mismatch (M) accounts for discrepancies between the total area of two
152 discretized PDFs (Amidon et al., 2005a) and can be calculated as:

153

$$154 \quad M = \sum_{k=1}^n \frac{|f(x_k) - g(x_k)|}{2},$$

155 (4)

156

157 where n represents the number of grain ages considered, x_1 and x_n represent the minimum
158 and maximum ages, respectively, and $f(x_k)$ and $g(x_k)$ are the modelled and mixed sample
159 age distributions, respectively.

160 We also use area mismatch (M) as a metric to analyze the age distributions predicted
161 by the sediment mixing models (see section 2.4).

162

163 **2.2 Mixing models**

164 Both the abrasion and no-abrasion models that we apply in this work are 2D linear
165 mixing models which predict fluvial sediment mixtures by a forward approach based on the
166 characteristics of the zircons (i.e., age) and of the sediment sources units (e.g., fertility, exposure
167 area and abrasion rate). Mixing models can also be used as inverse unmixing models to predict
168 the erosion rates that match the age distributions and the best-fit fluvial sediment mixtures
169 described in Equation 1. The theoretical and quantitative details of both models and how the
170 mixing proportions and U-Pb detrital zircon grain ages are used are described below.

171

172 **2.2.1 No-abrasion model**

173 The no-abrasion model is a reproduction of the linear zircon (un)mixing model proposed
 174 by Amidon et al. (2005a). It predicts the mixing proportion of sands originating from upstream
 175 source units along any point on the river network. It is based on the exposure area and mineral
 176 fertility of the source units. In this model, the predicted zircon proportion Φ_i^P from a specific
 177 source i in a geological setting composed of n sources can be mathematically described as:

$$\Phi_i^P = \frac{A_i C_i}{\sum_{k=1}^n A_k C_k}, \quad (5)$$

181 where:

$$\sum_{k=1}^n A_k = 1, \quad (6)$$

$$\sum_{k=1}^n C_k = 1. \quad (7)$$

182
 183
 184
 185
 186
 187 The predicted zircon mixing proportion (Φ_i^P), equal to $1/n$ if all source rocks are equally
 188 represented, must satisfy:

$$\sum_{i=1}^n \Phi_i^P = 1. \quad (8)$$

189
 190
 191
 192 A_i and C_i refer, respectively, to relative exposure area and relative zircon concentration
 193 (fertility) of the source unit i . Multiplying the PDF of each source unit, $f_i(x)$, by its respective
 194 mixing proportion predicted by the model, Φ_i^P , allows us to create an artificial PDF, $h(x)$,
 195 corresponding to the age distribution expected for a case where pebble abrasion is not
 196 considered. The expression for $h(x)$ is similar to Equation (1) and can be written as:

$$h(x) = \sum_{i=1}^n \Phi_i^P f_i(x). \quad (9)$$

201 The discrepancies between predicted and best-fit mixing proportions estimated in
 202 subsection 2.1 (Φ_i^P and Φ_i , respectively) can then be attributed to different factors, including
 203 different relative erosion rates, Φ_i^R , for the different units (Amidon et al., 2005a) (e.g., a unit
 204 being eroded two times faster than other units will contribute twice the amount of zircon
 205 expected from the procedure above). These relative erosion rates, Φ_i^R , for the no-abrasion
 206 model can be iteratively estimated by:

207

$$208 \quad \Phi_i = \frac{\Phi_i^P \Phi_i^R}{\sum_{k=1}^n \Phi_k^P \Phi_k^R},$$

209 (10)

210

211 where Φ_i^R is equal to $1/n$ if all source rocks are eroded at the same rate and must satisfy:

212

$$213 \quad \sum_{i=1}^n \Phi_i^R = 1.$$

214 (11)

215

216

217 They can also be estimated by minimizing the area mismatch, M , between the age
 218 distributions created by the model, $h(x)$, and the best-fit solution, $f(x)$.

219

220 **2.2.2 Abrasion model**

221 The abrasion model proposed in this work is also a linear (un)mixing model and its key
 222 assumptions are: (1) bedrock incision processes and downstream fining can be treated as steady
 223 state; (2) all particle sizes are moved downstream; (3) selective sorting as well as weathering
 224 are negligible on the considered timescale; (4) size reduction due to both breaking and attrition
 225 to sand is treated with a single abrasion rate; and (5) zircon proportion is homogeneously
 226 distributed in the generated sand fraction. Note that assumptions 1, 2, 3 and 5 are typically
 227 assumed in sediment mixing models. In this work, we also include assumption 4 because the
 228 abrasion experiments performed by Attal and Lavé (2006) do not discriminate abrasion
 229 products according to grain size (e.g., sand, silt, or gravel) and also because the abrasion rates
 230 they calculated encapsulate both breaking and attrition without distinguishing between these
 231 processes. The limitations imposed by our assumptions are discussed in section 4.4.

232 In the model, we assume each point across the catchment is a source of sediment
 233 belonging to a given rock unit i (see model implementation, section 2.3). The sediment supplied
 234 to the river system by each source is made of sand and clasts (“gravel”); we set the initial gravel
 235 mass fraction, F_{g0} , to 75 % in our reference runs, an average value for landslides in the
 236 Marsyandi valley (Attal and Lavé, 2006). We then record the distance d between each source
 237 point and a specific river site, and apply an empirically-defined version of the Sternberg’s law
 238 to calculate the proportion of the sediment initially supplied by the source unit that reaches the
 239 considered river site as gravel (F_g) (Dingle et al., 2017):

$$240 \quad F_g = F_{g0} e^{-\alpha d} \quad (12)$$

244 According to Equation (12), the initial percentage of gravel mass F_{g0} changes to a
 245 percentage F_g at distance d from the origin, at a rate given by the rock unit-dependent abrasion
 246 rate α (in km^{-1}). The percentage of sand mass F_s at d is inversely proportional to the gravel mass
 247 F_g :

$$248 \quad F_s = 1 - F_g \quad (13)$$

252 Note that the Sternberg’s law (Equation 12) as used in our work is a “generalized
 253 Sternberg’s law” that refers to mass loss and not to grain size fining (Miller et al., 2014). It is
 254 important to make this distinction because recent work by Domokos et al. (2014) and Miller et
 255 al. (2014) suggests that grain size fining due to abrasion does not follow the original Sternberg's
 256 law: angular fragments initially experience a rounding phase during which mass is lost but grain
 257 size is not significantly reduced; once the grains have been rounded, both mass and grain size
 258 are reduced in concert. Their work suggests that mass loss described by Equation (12) applies
 259 to both abrasion phases, including the original rounding phase, and is therefore suitable to
 260 describe abrasion of fragments from their source, as in our model.

261 Given that every source unit i has a specific zircon concentration C_i (fertility), relative
 262 exposure area A_i and relative supply rate by erosion Φ_i^{ZR} , the zircon mixing proportion of the
 263 source unit i in river sands Φ_i^Z is given by:

264

$$\Phi_i^Z = F_s A_i C_i \Phi_i^{ZR} \quad (14)$$

at distance d .

Multiplying each single source unit PDF, $f_i(x)$, by the mixing proportion estimated by the model (Φ_i^Z) allows us to create an artificial PDF, $z(x)$, corresponding to the age distribution of a downstream sand sample as expected when abrasion does occur. The expression of $z(x)$ is similar to Equation (1):

$$z(x) = \sum_{i=1}^n \Phi_i^Z f_i(x). \quad (15)$$

As in the no-abrasion model, the relative erosion rates (Φ_i^{ZR}) can also be inversely estimated by minimizing the area mismatch (M) between the artificially created PDF, $z(x)$, and the best-fit sample age distribution, $f(x)$ (Fig. 1).

2.3 Model implementation

In our simulations, we use topographic data with ~ 90 m spatial resolution of the Marsyandi watershed from the Shuttle Radar Topography Mission (SRTM). From these elevation data, we define the river network (used to route sediment across the catchment) and extract flow length for each pixel across the watershed, using tools from the Geospatial Data Abstraction Library (GDAL). Flow length is used to calculate travel distance (km) from each pixel to a given river site (d in Equation 12). The source units (i in Equation 14) with their spatial extent [km^2] also feed the model as geographic layers. For a given ‘‘sampling’’ location along the river, each contributing pixel is assigned a transport distance d and a source unit i ; the relative exposure area of each unit A_i is calculated based on this information. For each source unit i , the initial percentage of gravel supplied by the hillslopes to the river channel (F_g), zircon concentration (C_i) and supply rate by erosion (Φ_i^{ZR}) are set by the user. After combining all those parameters and retrieving the zircon mixing proportion (Φ_i^Z) of every source unit for the river sands at the considered river site (Equation 14), we use Φ_i^Z as an input to create the artificial PDF ($z(x)$ in Equation 15). All the code used to perform our analysis as well as to

296 generate the figures is open source and can be downloaded from GitHub at
297 <https://github.com/clavarini>.

298

299 **2.4 Statistical analysis of model predictions**

300 The PDFs constructed by the mixing models are statistically assessed by area mismatch
301 (M), similarity coefficient (S), Kolmogorov–Smirnov test ($K-S$), PDF cross-plot analysis and
302 Q-Q plots. The main aim of these analyses is to quantify how different the model predictions
303 are by comparing their resulting age distributions based on specified scenarios.

304 Any statistically significant difference between the age distributions generated by the
305 mixing models is hereafter named distortion.

306

307 **2.4.1 Similarity coefficient (S)**

308 The similarity coefficient S measures if samples have overlapping modes as well as
309 similar proportions of components in each of the modes. Gehrels (2000) defines it as:

310

$$311 \quad S = \sum_{k=1}^N \sqrt{f(x_k)g(x_k)} \quad (16)$$

312

313 where $f(x_k)$ and $g(x_k)$ are the probability density functions (PDFs) of samples one and two,
314 respectively, and x_1 and x_N are the minimum and maximum ages for the population. An S value
315 of 1 indicates that the PDFs are perfectly matched both in the modes and modal proportions,
316 while a value of 0 indicates that the two age populations have no modes in common.

317

318 **2.4.2 Kolmogorov–Smirnov ($K-S$) test**

319 Traditionally, the Kolmogorov–Smirnov ($K-S$) test assesses the null hypothesis that two
320 samples are drawn from parent populations with the same distribution. It calculates the $K-S$
321 statistic D_s , which is the maximum difference between the empirical cumulative distribution
322 functions (CDFs) of the two analyzed samples, and returns a p -value that is inversely
323 proportional to the confidence level at which the two samples fail the hypothesis. The D_s value
324 is calculated as:

325

$$326 \quad D_{S_{1,2}} = \sup_k |F_1(x_k) - F_2(x_k)|,$$

327

328 (17)

329

330 where $\sup(x)$ is the supremum of the set of distances, and F_1 and F_2 are the CDFs of the two
331 samples made from n_1 and n_2 observations, respectively.

332 The probability p that the observed samples are from the same population was calculated
333 by Stephens (1970) as:

334

$$335 \quad p(Ds_{observed} > Ds_{critical}) = Q_{KS}(\lambda) = 2 \sum_{i=1}^{\infty} (-1)^{i-1} e^{-2i^2\lambda^2}$$

336 (18)

337 where

338

$$339 \quad \lambda = \left(\sqrt{n_e} + 0.12 + \frac{0.11}{\sqrt{n_e}} \right) Ds$$

340 (19)

341 and

342

$$343 \quad n_e = \frac{n_1 n_2}{n_1 + n_2}$$

344 (20)

345

346 with limiting values of $Q_{KS}(0) = 1$ and $Q_{KS}(\infty) = 0$.

347 The K - S statistic represents a useful metric to investigate the similarity in the shape of
348 detrital age distributions and to assess our artificially created PDFs. In cases where the distance
349 Ds between the investigated PDFs approaches zero, p (or Q_{KS}) tends to 1, while extreme
350 distances will tend to produce p values approaching 0. In this work, we retrieve both Ds and p
351 values, since some studies have shown that in detrital geochronology Ds is more sensitive than
352 its corresponding probability (p) (Sátkoski et al., 2013; Vermeesch, 2013; Saylor and Sundell,
353 2016).

354

355 **2.4.3 PDF cross-plot and quantile-quantile (Q-Q) plot**

356 In statistics and probability, quantiles refer to specific cut points dividing the range of a
357 probability distribution (PDF) into contiguous intervals with equal probabilities. A quantile-

358 quantile (Q-Q) plot is a plot where quantiles of two datasets are plotted against each other. In
359 detrital studies, Q-Q plots are used to determine if two data sets come from populations with a
360 common distribution. A PDF cross-plot is a Q-Q plot which, rather than using cumulative
361 distribution functions (CDFs), is based on two PDFs (Saylor et al., 2012). The advantage of the
362 cross-plot to examine detrital age distributions is that it is sensitive to the presence or absence
363 of age peaks (e.g., Saylor et al., 2013). Samples with identical age peaks, peak shapes and peak
364 magnitudes have $R^2 = 1$, while for those sharing no age peaks R^2 approaches 0. PDFs that share
365 either some, but not all, peaks, or have peaks of different magnitudes or shapes, will produce
366 cross-plots with R^2 ranging between 0 and 1.

367

368 **2.5 Study area and experimental setting**

369 **2.5.1 The Marsyandi watershed**

370 The Marsyandi watershed, in the central Himalaya, has an area of approximately 4700
371 km², is 57 km wide and 170 km long. The Marsyandi flows into the Trishuli River, which later
372 joins the Ganga River in the Himalayan foreland basin. Elevation varies from 200 m to 8000
373 m. The sediment source units can be grouped into five litho-structural units (Le Fort, 1975;
374 Amidon et al., 2005a; Attal and Lavé, 2006) (Fig. 2).

375 The uppermost source unit (Tethyan Series – “TTS”) comprises Cambrian to Jurassic
376 limestones, sandstones and shales. The Tethyan Series are intruded by a Miocene leucocratic
377 granite (Manaslu granite – “MG”) in its eastern section. The southern margin of the Tethyan
378 Series is marked by a north-dipping, normal-sense shear zone known as the South Tibetan
379 Detachment (STD). Below (south of) the STD lies the Greater Himalayan Series (GHS), a
380 continuous sequence of amphibolite-grade schists and gneisses divided from south to north into
381 three formations, grouped here as pelitic gneisses (Formation I – “FI”) and Paleozoic augen
382 gneiss intrusions in calc-silicate rocks (Formation II-III – “FII-III”) (Le Fort, 1975). The series
383 are in turn bounded to the south by the Main Central Thrust (MCT). The MCT is the structural
384 boundary between the Greater Himalaya and Lesser Himalaya series. Lower-grade schists and
385 meta-sediments of the Lesser Himalayan Series (“LH”) occur in the MCT footwall.

386

387 **2.5.2. The Marsyandi dataset**

388 In our study case, we test the effects of abrasion on detrital information using the
389 Marsyandi catchment as a template. The mixing proportion of sands, pebble abrasion rates and
390 zircon fertility of the source units are derived from Attal and Lavé (2006) and Amidon et al.

391 (2005a). The abrasion rates for rock types (e.g., sandstone, schist, etc.) of Attal and Lavé (2006)
392 (their Table 2) are converted to a representative value for the source units of Amidon et al.
393 (2005a) by applying weighted arithmetic mean corrections (Table 1). The U-Pb detrital zircon
394 grain ages are from Amidon et al. (2005a) (Supporting Information Table S1); age smoothing
395 was applied prior to statistical analysis with the same age window interval (80 Ma) as used by
396 Amidon et al. (2005a). We also performed statistical comparison (i.e., *S*, *M*, PDF cross-plot, Q-
397 Q plot, and *K-S* statistics) between age distributions with and without smoothing to test if
398 statistically significant changes occur and, therefore, biases the sediment (un)mixing results.
399 Our statistical comparison are in the Supporting Information (Tables S3 and S4) and are
400 discussed in a section dedicated to methodological uncertainties (4.4).

401 Shuttle Radar Topography Mission (SRTM) elevation data with ~90 m of spatial
402 resolution are used as topographic data in the mixing models. The modelling calculations are
403 performed for three river locations where samples were collected (Fig. 2). The uppermost
404 sampling point (E) has three contributing source units (TTS, MG and FII-III); the sampling
405 point (G) has four (TTS, MG, FII-III and FI), and the Marsyandi outlet (K) has all five.
406 Numerical tests of the minimizations were performed to solve for the relative erosion rates
407 (presented in section 3).

408

409 **2.5.3 Experimental setting**

410 In all numerical experiments where we test for factors controlling zircon mixing, we
411 use synthetic U-Pb age distributions for the sources in addition to the natural age distributions
412 of Amidon et al. (2005a). The synthetic distributions are normal, with specific age peaks (μ)
413 of 0.5, 0.8, 1 and 1.2 Ga for the Tethyan, Formation II-III, Formation I and Lesser Himalaya
414 sequences, respectively, and a standard deviation (σ) of 5 % (Fig. 2, Equation 3, Supporting
415 information Table S2). This spread of age is comparable to the spread in the real dataset. We
416 adopted ages increasing downstream so that the relative contribution of the different sources
417 is easier to identify in the mixed sample distributions; we also chose to have a distinct peak
418 (Tethyan Series at 0.5 Ga) and three partly overlapping distributions, comparable to the real
419 dataset. We performed additional experiments with four additional synthetic age distributions
420 with various degrees of peak overlap to assess the influence of this factor (discussed hereafter
421 and presented in the Supporting Information).

422

423 **2.5.3.1 Testing the influence of abrasion rates on age distributions**

424 In our first set of simulations, we test the influence of pebble abrasion rates on mixed
425 sample age distributions (scenarios A1–A4). Zircon fertility is the same for all sources, except
426 for the Manaslu granite for which zircon fertility is set to zero to reproduce the behaviour of a
427 non-contributing source region to the age distribution, as Amidon et al. (2005a) found no zircon
428 within the Marsyandi watershed that they could unambiguously relate to the Manaslu granite.
429 The hillslope gravel supply is also set to a uniform value of 75 %. The abrasion rates used in
430 the simulations are based on experimental abrasion rates for rock types of the Marsyandi
431 watershed from Attal and Lavé (2006) (Table 2).

432 In the first scenario (A1), the effect of uniform abrasion is assessed by setting a single
433 abrasion rate of 0.4 %/km, (equivalent to granite) for the whole watershed. In the second
434 scenario (A2), we simulate the behaviour of a watershed with two extreme rock strengths: rocks
435 from the Tethyan Series have a high abrasion rate of 31 %/km, (equivalent to poorly cemented
436 sandstone) and the rest of the rocks are abraded at a low rate of 0.15 %/km (equivalent to
437 quartzite). In the third experiment (A3), we assess how source location impacts fluvial sand
438 composition by inverting the previous scenario: the Lesser Himalaya has the highest abrasion
439 rate (31 %/km) while rocks from the upstream sources are abraded at 0.15 %/km. In the fourth
440 scenario (A4), we apply abrasion rates representative of the different units in the Marsyandi
441 watershed (Attal and Lavé, 2006). The main aim of this experiment is to simulate how the
442 fluvial sand composition behaves in a complex scenario of rocks with multiple abrasion rates
443 but decoupling it from other controlling factors that can bias the sand mixing proportion.

444

445 ***2.5.3.2 Comparing the influence of different controlling factors on age distributions***

446 In a second series of experiments, we test the sensitivity of the age distributions to
447 abrasion rate (B2), erosion rate (B3), fertility (B4), and initial gravel fraction (B5). The
448 experiments are run using both synthetic and natural datasets. The parameter values used to
449 create the scenarios are chosen to emphasise the distortion in sand while keeping within a
450 realistic range. Variations in erosion rate, abrasion rate, hillslope gravel supply and zircon
451 fertility are applied based on values published by Garzanti et al. (2007), Attal and Lavé (2006)
452 and Amidon et al. (2005a), respectively (Table 3). Scenario B1 is the reference scenario with
453 all parameters spatially uniform and no abrasion (see Fig. 3, “no abrasion”). In scenario B2,
454 abrasion rate for Tethyan Series gravel varies between 0.15 and 31 %/km while it is kept at 0.15
455 %/km for the other units; the experiment with the most extreme value (31 %/km) is the same
456 as A2. In B3, the Tethyan Series are eroded between 1 and 5.1 times faster than the rest of the

457 catchment. In B4, the fertility of rocks from the Tethyan Series is 0.8 grains/g while it is set to
458 between 0 and 0.8 grains/g in the rest of the catchment; the experiment where all non-TTS units
459 contributes no zircon (fertility = 0) simulates an extreme scenario with “invisible” units. In B5,
460 sediment initially sourced from the Tethyan Series is made of between 60 and 90 % of gravel
461 (i.e., between 10 and 40 % sand) while this number is 90 % in the rest of the catchment; this
462 range of values encompasses values from landslides in different lithologies measured in the
463 Marsyandi valley (Attal and Lavé, 2006). Scenario B5b is the same as B5, except that the initial
464 gravel fraction varies between 60 and 90 % for the Lesser Himalaya sources (instead of TTS)
465 while this number is 90 % in the rest of the catchment; this scenario tests the influence of peak
466 overlap, as the LH peak in the synthetic dataset overlaps with the Formation I peak (see next
467 section). Finally, we explore a scenario where Tethyan Series have both an extremely high
468 abrasion rate (31 %/km) and the lowest initial gravel fraction (60 %) supplied to the river
469 channel, while the other source units have low abrasion rates (0.15 %/km) and hillslopes with
470 an extremely high gravel content (90 %) (scenario B6). The aim of this experiment is to test the
471 influence of the known covariance between highly abradable source units and higher sand
472 supply from hillslopes due to higher weathering rates in softer rocks (e.g., schist versus
473 quartzite, see Attal and Lavé, 2006).

474

475 ***2.5.3.3 Testing the ability of controlling factors to reproduce the distortion from others***

476 In these experiments, we test how well each controlling factor can mimic the distortion
477 caused by another factor in the most extreme scenarios from experiments B2 to B5, using both
478 synthetic and natural datasets. We use the maximum and minimum values used in the
479 experiments B2 to B5 as bounds to iteratively solve for the best fit between the age distribution
480 created from a factor being tested and a factor whose distortion is intended to be reproduced.

481 To test the ability of the method to cope with relative changes in partly overlapping age
482 peaks, we explore a scenario where the Lesser Himalaya has the smallest gravel fraction (60
483 %) instead of the Tethyan Series (scenario B5b instead of B5, see Table 3) as the LH peak in
484 the synthetic dataset overlaps with the Formation I peak (whereas the TTS peak is isolated).

485

486 ***2.5.3.4 Testing the influence of abrasion on mixing proportions in the Marsyandi*** 487 ***catchment***

488 Finally, we use the Marsyandi dataset to assess the influence of abrasion on both mixing
489 proportions and age distributions in a real scenario, using the parameters described in Table 1.

490 For the three mixed samples E, G and K (Fig. 2), we compare best-fit results using the iterative
491 method described in section 2.1 with the results obtained from the mixing models with and
492 without abrasion. At each site, we discuss the differences and their statistical significance.

493

494 **3 Results**

495 **3.1 Simulations for sensitivity analysis**

496 ***3.1.1 Influence of abrasion rates on age distributions***

497 Simulations A1 to A4 demonstrate how pebble abrasion affects the zircon mixing
498 proportions of upstream sediment source units in the sand fraction and ultimately distorts the
499 grain age distributions (PDPs) of the mixed samples derived from them (Fig. 3). Modifications
500 in the zircon mixing proportions (Fig. 3a) and in the shape of the PDPs are recorded in all
501 experiments but not all of them are significant (Fig. 3c, e). The experiments that simulate
502 extreme contrast in abrasion rates (A2 and A3) have changes in the zircon mixing proportion
503 that distort all U-Pb grain age distributions investigated (see the R^2 values of the PDF cross-
504 plots). Extremely high abrasion rates (31 %/km versus 0.15 %/km) lead to rapid release of
505 zircon from gravel to sand for the unit in question. The unit therefore ends up overly represented
506 in the mixed sand sample: more than 50 % of the zircons in the mixed sample are sourced from
507 TTS and LH in scenarios A2 and A3, respectively (Fig. 3a). In the synthetic datasets (Fig. 3b),
508 this is shown by the clear growth of the TTS and LH source peaks, respectively.

509 The trends with the natural datasets are less clear, as peaks are not as well defined,
510 overlap, and do not have a normal distribution; units are not characterised by a single peak
511 neither (Fig. 2). All scenarios (A1-A4) show significant statistical changes in the age
512 distributions, overall greater than with the synthetic datasets (Fig. 3d, e). The only exception is
513 scenario A2, in which more distortion is observed with the synthetic dataset (Fig. 3c, e). This
514 can be explained by the fact that TTS shares its major peaks (in range 0.5-1 Ga) with Formations
515 I, II and III (Fig. 2): a relative increase in zircons from TTS in the range 0.5-1 Ga due to rapid
516 abrasion is counterbalanced by a relative decrease in zircons from Formations I, II and III in
517 the same age range. On the other hand, the dominant age peak from LH at ~1.8 Ga is unique,
518 leading to the greatest amount of distortion ($R^2 = 0.69$, Fig. 3e) and a clear growth of this peak
519 in experiment A3 (Fig. 3d).

520 Interestingly, numerical changes in the zircon mixing proportions and age distributions
521 in the uniform abrasion scenario (A1) are comparable to when abrasion reflects the real
522 variations of the rocks from the Marsyandi watershed (A4), both with synthetic and natural

523 datasets. Statistically, however, in both cases (A1 and A4), the *K-S* tests and PDF cross-plots
524 are not able to demonstrate that these populations are different from a no-abrasion scenario
525 (with 95 % confidence) and therefore no statistically significant change (distortion) is
526 identified. The similarity coefficient (*S*) and Q-Q plot statistics are less sensitive in detecting
527 changes in the grain age distributions but also mirror the trends identified by the PDF cross-
528 plots and area mismatch (*M*) (Supporting Information Table S5-S6 and Fig. S2). Finally,
529 additional experiments with synthetic datasets characterised by peaks with various shapes and
530 degrees of overlap provide very similar results overall (Supporting Information Fig. S1, S2 and
531 Table S11): R^2 values for experiments A1 and A4 are barely affected by the changes (changes
532 are within 5 %) and experiments A2 and A3 generate the greatest amount of distortion.
533 However, the isolation and broadness of the peak targeted by the change in abrasion rate seem
534 to affect the relative amount of distortion in scenarios A2 and A3: A3 generates greater
535 distortion than A2 when peaks are well isolated (age distributions 1 and 2), and the opposite
536 when there is significant overlap (age distributions 3-5). This demonstrates a sensitivity of the
537 results to the shape of the age distributions, though the R^2 values for experiments A2 and A3
538 tend to be very close, no more than 16 % from each other.

539

540 **3.1.2 Influence of the different controlling factors on age distributions**

541 We produced age populations in a range of scenarios, whereby the Tethyan Series are
542 assigned distinct values from all other units for abrasion rate, erosion rate, zircon fertility and
543 gravel fraction in sediment supply (scenarios B2, B3, B4 and B5, respectively; Table 3). The
544 results are populations where the peak at 0.5 Ga is enhanced with respect to the other peaks
545 (Fig. 4a-d). The experiments highlight that all of these controlling factors affect the zircon
546 mixing proportions and statistically distort the age distribution of modern river sands. The
547 response is linear for erosion rate, fertility and initial gravel fraction (e.g., a doubling of erosion
548 rate in the TTS units leads to twice more zircon from this unit); the response is strongly non-
549 linear with respect to abrasion rates, with high sensitivity at low abrasion rates and no sensitivity
550 at rates above 2 %/km (Fig. 4a). When combining both high abrasion rate and high initial sand
551 content at the source (scenario B6), we observe increased distortion compared to scenarios with
552 either high abrasion rate or high initial sand content at the source (Fig. 4f): the TTS unit is
553 overrepresented in the sand sample due to a relatively greater proportion of zircons from other
554 units being “retained” in gravel, as a comparatively greater amount of gravel from these units
555 is supplied at the source and this gravel persists for longer (lower abrasion rate).

556 We find that, within the realistic range of values for the Marsyandi catchment, the
557 factors that can produce the highest distortion are, from highest to lowest: fertility, erosion,
558 hillslope gravel supply and, lastly, pebble abrasion (Fig. 5). This order is valid for both synthetic
559 and natural datasets, though the amount of distortion in the natural dataset tends to be lower,
560 possibly due again to the fact that TTS shares peaks with other units (Fig. 5). We note that
561 increasing peak overlap in the synthetic datasets leads to a systematic increase in distortion
562 (lower R^2 values in PDF cross-plots) for all scenarios (Supporting Information Fig. S3 and
563 Table S11).

564 As in the previous section (3.1.1), metrics such as the similarity coefficient (S) and Q-
565 Q plot statistics are the least sensitive to detecting changes in the grain age distributions but
566 mirror the trends identified using the PDF cross-plots and area mismatch (M) (Supporting
567 Information Table S7, S8 and Figure S3, S4).

568

569 ***3.1.3 Ability of controlling factors to reproduce the distortion from others***

570 We assess the capability of different distorting factors to reproduce the distortion created
571 in experiments B2–B6. We use the optimization method to assess whether, for example, the age
572 distribution produced by scenario B2 (Tethyan Series rocks abraded at 31 %/km) can be
573 mimicked by allowing other parameters (relative erosion rates, fertility and gravel supply) to
574 vary, in turn, within the range of realistic values (Fig. 6, see also experiments with different
575 synthetic datasets in Supporting Information Fig. S5).

576 We find that all the factors are able to perfectly reproduce the impact of abrasion on the
577 zircon grain age distribution (B2) (Fig. 6; statistics in Supporting Information Table S9, S10).
578 The effect of having Tethyan Series rocks abraded at 31 %/km while the others are abraded at
579 0.15 %/km can be replicated by having the Tethyan Series' erosion rate, fertility or initial sand
580 supply ($= 1 - \text{initial gravel supply}$) around three times greater than that of the other units
581 (Supporting Information Table S13). On the contrary, abrasion is not able to fully reproduce
582 the distortions caused by any other controlling factor (Fig. 6). Changes in fertility are able to
583 fully reproduce the distortion caused by differences in relative erosion rates (B3 – erosion of
584 Tethyan Series five time faster than other units), but changes in abrasion rates or gravel fraction
585 can produce distributions similar enough (not statistically distinct; Fig. 6). No factor can fully
586 reproduce the distortion caused by extreme differences in fertility (B4); this occurs as a result
587 of having three “invisible lithologies” with fertility = 0. Any lithology containing zircons will
588 appear in the mixed sand sample, irrespective of their abrasion rate, initial gravel fraction or

589 relative erosion rate (except in an unimaginable scenario where erosion rate = 0 or gravel supply
590 = 100 % and abrasion rate = 0). All factors except abrasion are able to reproduce the age
591 distribution resulting from variation in hillslope gravel supply, even in a situation where the
592 peak that is affected (i.e. Lesser Himalaya) partly overlaps with other peaks (scenario B5b,
593 Table 3, Fig. 6). These results apply to both synthetic and natural datasets (Fig. 6).

594 It is interesting to note that in all cases, abrasion produces peaks that are not high enough
595 to replicate the extreme distortion caused by the other factors. In other words, not enough sand
596 is produced by abrasion from the Tethyan Series in experiments B3 and B4 and from the Lesser
597 Himalaya in experiment B5b. This results from abrasion rates being allowed to vary only
598 between 0.15 and 31 %/km. When looking at the statistics of the results, however, we find that
599 the “best fit” is given for abrasion rates of 3.5 and 3.3 %/km for the Tethyan Series for
600 experiments B3 and B4, respectively, while the other lithologies are being abraded at 0.15
601 %/km (Table S6). This is unexpected as, in theory, more sand from the Tethyan Series could
602 be generated with greater abrasion rates (up to 31 %/km). This occurs as a result of the
603 termination threshold in the minimization procedure in the model, as iterations stop when the
604 minimization does not reduce the misfit by more than 0.1 % in the cost function. In case B3,
605 for example, we find that the proportions of zircon sourced from the Tethyan Series are 52.48
606 % and 52.54 % with abrasion rates of 3.5 and 31 %/km, respectively: mixing proportions are
607 insensitive to abrasion rates beyond a given value, as shown in the sensitivity analysis (Fig. 4a).
608 On the other hand, the best-fit abrasion rates in scenario B5b are 30.3 %/km for the Lesser
609 Himalaya and 0.15 %/km for the other lithologies: in this case, the proximity of the Lesser
610 Himalaya units to the outlet makes the mixing proportions more sensitive to changes in abrasion
611 rates for these units. These results highlight the non-linear dependency of mixing proportions
612 on abrasion rates, as opposed to the other factors (a doubling of fertility in one unit can be
613 mimicked by a doubling of relative erosion rate for this unit). They also demonstrate the
614 effectiveness, and limitations, of the optimization method.

615

616 **3.2 Study case (Marsyandi watershed)**

617 In this last section of the analysis, we consider the real datasets to assess the importance
618 of abrasion in controlling the age distribution of mixed samples and the relative erosion rates
619 retrieved from them. In the following, we mix the real source age distributions to match the
620 mixed sample age distributions measured in locations E, G and K (Fig. 2). We first produce a
621 best-fit mixed sample distribution using the mismatch minimization method described in

622 section 2.1 and used in section 3.1.2. We then use our full mixing models (abrasion and no-
623 abrasion, see section 2.2) that include field-derived parameters (Table 1) to attempt to replicate
624 the best-fit distributions and retrieve relative erosion rates for the different units that make up
625 the Marsyandi watershed. As mentioned earlier, the minimization method is an iterative
626 procedure that stops when the iteration does not reduce the misfit by more than 0.1 % in the
627 cost function. The cost function we use to produce the best-fit mixed sample distribution is the
628 ratio of predicted to measured sums of squares of zircon ages (see section 2.1). The cost function
629 we use for the full mixing models is area mismatch, to follow the procedure by Amidon et al.
630 (2005a). Results for this section for the three sampling sites (E, G and K) are presented in
631 figures 7, 8 and 9, respectively (see also Supporting Information S14, S15, and S16). We find
632 that the grain age distributions created with the abrasion and no-abrasion models are statistically
633 indistinguishable in all river reaches analyzed. However, the zircon mixing proportions and the
634 relative erosion rates estimated from the same ages are different.

635 In the uppermost sampling site (E), only two sources are contributing (Tethyan Series
636 and Formation II-III). When trying to best fit the no-abrasion and abrasion models (Fig. 7), we
637 find a difference of 6 % between the zircon mixing proportions estimated by the two models
638 (Fig. 7a). In spite of this, the modelled ages have an indistinguishable distribution ($R^2 = 0.988$).
639 However, the relative erosion rates derived from these two models are significantly different:
640 the relative contribution of the FII-III rises from 58.3 to 71.3 % when abrasion is accounted for,
641 to counterbalance the increased zircon contribution from the Tethyan Series due to its relatively
642 high abrasion rates (4.3 %/km, compared to 0.4 %/km for FII-III) (Fig. 7). The strong contrast
643 in rock resistance to abrasion in this case (an order of magnitude) leads to a strong difference
644 in predicted relative erosion rates.

645 At the intermediate site (G), the influence of abrasion is mostly visible in the proportions
646 of Tethyan Series and FI: the abrasion model predicts that the Tethyan Series contributes 12 %
647 more zircon at the sampling site than the no-abrasion model (65 instead of 53 %), while the
648 contribution of FI is reduced from 28 to 16 % (Fig. 8a). This may be the result of the two units
649 sharing part of their peaks in their age distributions (Fig. 2). Interestingly, this change is
650 accommodated by relative erosion rates with an opposite trend, as Tethyan Series rocks are the
651 most erodible and thus release more sand (and zircons) as they are transported further
652 downstream: relative erosion rate of FI increases from 25.6 to 39.3 % while it drops from 40 to
653 29.3 % for the Tethyan Series. All modelled distributions are statistically indistinguishable from
654 each other (Fig. 8b, c).

655 At the outlet sampling site (K), the results are not consistent with results from previous
656 sampling sites (Fig. 9). Firstly, the best-fit distribution predicts zircon mixing proportions that
657 are significantly different from those derived from the no-abrasion and abrasion models: the
658 mixing models (both abrasion and no-abrasion) predict a much lower contribution from Tethyan
659 Series and Lesser Himalaya (by up to 10 % each) and a much greater contribution from FI (by
660 15–20 %). This highlights the non-uniqueness of the solutions and the sensitivity to the
661 approach used, in particular when sources have distributions that partly overlap (Fig. 2).
662 Secondly, the relative erosion rates predicted for the abrasion and no-abrasion scenarios are
663 very similar, despite the significant differences at the sites upstream: differences in relative
664 erosion rates for each unit do not exceed 2.2 % (Fig. 9a) and the distributions produced are
665 nearly identical (Fig. 9b, c). In some circumstances, overlap of the distributions and spatial
666 differences in abrasion rates may conspire to compensate for abrasion and erosion effects,
667 leading to a limited influence on the inversion outcomes.

668

669 **4 Discussion**

670 **4.1 Abrasion as a distorting factor**

671 Our numerical simulations using empirically-derived abrasion rates agree with recent
672 research that highlights grain size biasing as one of the factors controlling the mineralogy and,
673 therefore, the grain information of sands transported by rivers (e.g., Aguilar et al., 2014;
674 Codilean et al., 2014; Carretier et al., 2015). The importance of abrasion in distorting grain age
675 distributions is, however, more debatable. Although changes in the zircon mixing proportion
676 can occur in watersheds of homogeneous lithology (e.g, experiment A1) and of diverse abrasion
677 rates (e.g., A4), the resulting age distributions may not appear significantly distorted. Recently,
678 Saylor and Sundell (2016) highlighted the limitations in the current statistical methods to assess
679 changes in PDFs and, earlier, Vermeesch (2012) discussed the low sensitivity of PDPs to
680 changes in zircon proportions. In both cases, there is supporting evidence explaining why
681 numerical changes in the zircon mixing proportions are not necessarily followed by distortions
682 of the age distribution statistics.

683 However, in watersheds of very different rock strengths (e.g., experiments A2 and A3,
684 and sampling site E in the Marsyandi watershed), the distortions caused by abrasion are
685 unambiguous. These findings highlight that sources of different rock strengths such as quartzite
686 and sandstone found in complex tectonic environments (e.g., pro- and retro-foreland basins)
687 can have their detrital age signatures significantly changed in modern river sands. Moreover,
688 distorted grain age distributions within sediment reaching continental platforms can be

689 preserved in siliciclastic rocks and in the product of their recycling (e.g., metamorphic rocks)
690 (Campbell et al., 2005; Perez and Horton, 2014; Sharman and Johnstone, 2017). Therefore,
691 recognizing these distortions is important to more accurately (un)mix grain age distributions
692 through modelling and inform provenance analysis from sedimentary archives.

693 The circumstances under which bias from abrasion is expected to be significant are
694 summarised in Fig. 10. Even in the absence of contrasts in rock resistance to abrasion, bias will
695 be expected if transport distance is short relative to abrasion rate (Fig. 10a, b). As sediment is
696 transported downstream, the relative proportion of remaining gravel (and therefore “trapped”
697 zircon) decreases downstream: in catchments where sediment has been transported over long
698 distances, most of the gravel is turned into sand and most zircons have therefore been released
699 in the sand fraction, limiting bias (Attal and Lavé, 2006, 2009; Dingle et al., 2017). What
700 defines “long” or “short” distances is the abrasion rate (Fig. 10b): in a simple model where
701 sediment is constantly supplied along a linear river system and gravel is abraded at a given rate
702 (Attal and Lavé, 2006, 2009), we can calculate the amount of gravel that has been turned into
703 sand at a given distance downstream. For very erodible gravel abrading at 20 %/km, more than
704 60 % of all gravel that has been supplied to the river has been turned into sand 10 km
705 downstream from the river origin: we can therefore expect limited bias after distances in the
706 order of 10-20 km. For gravel abrading at 2 %/km, this figure is 10 %: a significant amount of
707 zircon remains “trapped” within gravel. The result is shown in Fig. 1b: at a point 20 km
708 downstream of a river system made of half a lithology 1 and half a lithology 2, we find that 72
709 % of the sand sampled comes from the lithology exposed in the top half of the catchment due
710 to greater transport distance, despite the fact that the river has been supplied the same amount
711 of sediment from both units and that gravel from both units is abraded at the same rate of 2
712 %/km. For lithologies abrading at such rate, we expect limited bias after transport distance of
713 the order of 100-200 km (Fig. 10a, b; Attal and Lavé, 2006, 2009; Dingle et al., 2017). Finally,
714 gravel from resistant rocks (abrasion rate ≤ 0.2 %/km, e.g. quartzite, volcanics, mica-poor
715 gneiss or granite, see Attal and Lavé, 2009) will persist for distances in excess of 1000 km (Fig.
716 10b): a significant amount of zircon from these units is therefore likely to remain trapped in
717 gravel even in very large, continental-scale catchments, leading to their underrepresentation in
718 sand samples. This is why strong contrasts in rock resistance to erosion and the presence of
719 hard rocks will lead to bias from abrasion, irrespective of catchment size (Fig. 10a).

720

721 **4.2 Influence of abrasion versus other factors**

722 According to our simulations, abrasion is one of the factors with the lowest capability
723 of distorting the detrital age distribution of sands among all currently considered controlling
724 factors. Based on the Marsyandi's natural datasets, all considered factors are able to reproduce
725 the distortion caused by abrasion in the age distribution, which may explain why abrasion has
726 long been stated as a factor of minor influence in detrital geochronology (e.g., Malusà et al.,
727 2013). Unlike abrasion, the other parameters tested have a linear relationship with the mixing
728 proportions: for example, a doubling of erosion rate or fertility from one unit will lead to a
729 doubling of the zircon contribution from this unit in a mixed sand sample further downstream.
730 This is in stark contrast with our result showing that the effect of having Tethyan Series rocks
731 abraded at 31 %/km while the other lithologies are abraded at 0.15 %/km can be replicated by
732 having the Tethyan Series' erosion rate, fertility or initial sand supply (the converse of gravel
733 supply in our study) around three times greater than that of the other units (Table S5 and S6).
734 It is important to note, however, that this number is strongly controlled by the initial gravel (or
735 sand) supply: in our reference scenarios, the initial sand supply is set to 25 % for all units. As a
736 result, total abrasion of Tethyan Series gravel into sand (due to an extremely high abrasion rate)
737 will lead to an extra 75 % of sand at the outlet, that is, a quadrupling of the amount of sand
738 sourced from the Tethyan Series (compared to a scenario with no abrasion). This would lead to
739 zircons from the Tethyan Series being four times more abundant in our mixed sample, if gravel
740 from other lithologies were not abraded. We found Tethyan Series zircons around thrice more
741 abundant in our scenario (experiment B2, Table S13), due to gravel from other lithologies being
742 abraded. The initial gravel fraction therefore puts an upper limit on the amount of distortion
743 that can be generated through abrasion when strong differences in abrasion rates exist. Initial
744 gravel supply of 90% could potentially generate abrasion-driven differences in mixing
745 proportions of up to an order of magnitude, as discussed below.

746 Zircon fertility is a highly variable parameter, with some units potentially being devoid
747 of zircon and therefore being invisible in subsequent mineral selective dating. In our
748 simulations, zircon fertility of the source units has the largest control on grain age distortion.
749 Recent research on terrains of varied zircon fertility suggests that fertility is the main driver of
750 natural bias in detrital geochronology, and that constraining this bias is an essential step in
751 improving the reliability of dating techniques (Moecher and Samson, 2006; Glotzbach et al.,
752 2017).

753 In our study, we vary hillslope gravel supply between 60 and 90 %, so sand supply
754 varies within a factor of ~4, between 10 and 40 %. Whereas sources of sediment may have

755 gravel supplies beyond these bounds (e.g., glacial sediment can have up to 70 % of its volume
756 made of particles finer than 1 mm), we believe that this range is representative of most sediment
757 sources in active mountain ranges (e.g., Attal and Lavé, 2006). Confirming this point, Casagli
758 et al. (2003) measured grain size for 42 landslide dams in the Northern Apennines, Italy, and
759 found that ~90 % of the studied deposits had a “gravel” fraction (> 2 mm) making up between
760 60 and 90 % of their volume. The lower potential variability in gravel supply compared to
761 fertility limits the potential bias created by variations in this parameter. In addition, these
762 variations will be irrelevant if the source units are abraded rapidly and/or if transport distance
763 to the sampling point is long, as in these cases most of the gravel will have been turned into
764 sand by the time it reaches the sampling point (Dingle et al., 2017). It is important however to
765 recognize gravel supply as a potential source of bias for catchments with strong contrasts in
766 gravel abrasion rates and/or short catchments, as illustrated in the following experiments (Fig.
767 10c).

768 Here, we use again the simple linear model of sediment supply and abrasion (Attal and
769 Lavé, 2006, 2009) to calculate the amount of sand coming from the abrasion of gravel as a
770 function of distance downstream, initial gravel supply and abrasion rate (Fig. 10c). Initial gravel
771 supply controls the maximum amount of sand that can be released by abrasion (and therefore
772 create bias), whereas abrasion rate dictates how quickly this sand is produced. If the initial sand
773 supply (the converse of gravel supply) is low, then most sand will come from abrasion, leading
774 to greater potential for bias. If the initial sand supply is high, then most of the sand in the river
775 will originate from the source rather than from abrasion, at least in the upper part of the
776 catchment (short transport distance = low amount of zircon released by abrasion); differences
777 in relative zircon proportions from different lithologies will therefore more likely reflect
778 differences in initial sand supply between the lithologies. We consider a point 50 km
779 downstream from the river origin (Fig. 10c): if the lithologies exposed in the catchment are
780 abrading at 20 %/km, then most of the gravel (> 90 %, see Fig. 10b) will have been turned into
781 sand so there will be no bias from abrasion, whatever the initial gravel fraction is. If the
782 lithologies exposed in the catchment are abrading at 0.2 %/km, then most of the sand will have
783 originated from the initial supply (e.g., > 90 % of the sand if the initial gravel supply is 60 %,
784 Fig. 10c); in this case, difference in relative zircon proportions will reflect differences in initial
785 gravel supply (e.g., if one lithology has an initial 40 % sand fraction and the other 10 %, then
786 there will be four times more sand from the former in the mixed sample, all else equal). The
787 trade-offs between initial gravel supply and abrasion rate are not entirely intuitive and certainly

788 require further work; however, the model highlights again the strong potential for bias by
789 abrasion in the presence of highly resistant rocks.

790

791 **4.3 Abrasion and erosion in the Marsyandi region**

792 Inverse modelling of sediment grain age distributions in the Marsyandi River using our
793 mixing models reveals that the estimated relative erosion rates are highly sensitive to abrasion,
794 despite the amount of grain age distortion not necessarily being statistically significant. For the
795 sampling site E (upstream), calculated erosion rates are in rough agreement with those estimated
796 by other studies (e.g., Burbank et al., 2003; Pratt-Sitaula et al., 2004; Garzanti et al., 2007;
797 Gabet et al., 2008). For instance, Garzanti et al. (2007) found relative erosion rates of 22.5 %
798 for Tethyan Series and 77.5 % for Formation II-III, against 29 % for Tethyan Series and 71 %
799 for Formation II-III from our abrasion model (Fig. 7). The no-abrasion model yields distinct
800 relative erosion rates, with 42 % and 58 % for the Tethyan Series and Formation II-III,
801 respectively.

802 At sampling site G (intermediate), our relative erosion rates are again in good agreement
803 with published research which tends to show a downstream increase in erosion rates (Fig. 8).
804 For instance, when converted to relative erosion, Garzanti et al. (2007) found relative erosion
805 rates of 10 %, 34 % and 56 %, while our abrasion model suggests 29 %, 32 % and 39 % for the
806 Tethyan Series, Formation II-III and Formation I, respectively. The relative erosion rates
807 estimated by the no-abrasion model suggest an upstream increase in relative erosion rates, with
808 rates varying from 26 % (Formation I) to 40 % (Tethyan Series). Modern erosion rates in the
809 Himalaya suggest a spatial correlation between precipitation gradients and erosion that is
810 enhanced by the tectonic uplift of the MCT hanging-wall (Hodges et al., 2004; Deal et al., 2017;
811 Olen et al., 2015). Our modelling suggests that abrasion is also important as the no-abrasion
812 model predicts different trends.

813 At the Marsyandi outlet (K), differences in relative erosion rates for each unit do not
814 exceed 2.2 % and the distributions produced by the abrasion and no-abrasion models are nearly
815 identical (Fig. 9). The abrasion model predicts relative erosion rates ~ 2 % greater for Formation
816 I, but the difference is too small to be attributed it to any specific factor. Such a result would be
817 expected if all gravel had been turned into sand, as in this case the mixing proportions would
818 mimic a no-abrasion scenario. The transport distance over which around 90 % of the initial
819 gravel is turned into sand by abrasion can be calculated as $250/\alpha$, where α is the abrasion rate
820 in % mass loss / km (Equation (12)) (Attal and Lavé, 2006; Dingle et al., 2017). Based on the

821 abrasion rates used in this study (Table 1), this distance is 58, 625, 179 and 27 km for the
822 Tethyan Series, Formation II-III, Formation I and Lesser Himalaya, respectively. Tethyan
823 Series gravels will have travelled at least 130 km (Fig. 2) so very few of them would have
824 survived to the outlet (site K). Formation I sediment will have travelled between 70 and 120
825 km so we expect no more than a quarter of it to have reached site K as gravel. Lesser Himalaya
826 units are exposed closest to the outlet but their high abrasion rate (9.4 %/km) means that a large
827 part of the sediment derived from it will also reach site K as sand (the distance between MCT
828 and site K is 80 km, see Fig. 2). However, transport distances for the resistant Formation II-III
829 range between 100 and 140 km, meaning that between 40 and 50 % of the sediment sourced
830 from this unit should reach site K as gravel. This should lead to a strong underrepresentation of
831 the Formation II-III in the mixed sand sample and therefore greater calculated erosion rates to
832 counterbalance this effect, which we do not observe. We hypothesize that this is a coincidence
833 potentially resulting from overlapping source age distributions (e.g., shared peak at ~0.5 Ga in
834 Tethyan Series and Formation II-III, see Fig. 2): in some circumstances, this overlap combined
835 with spatial differences in abrasion rates may compensate for abrasion and erosion effects,
836 leading to a limited influence on the inversion outcomes. In general however, we expect the
837 effect of abrasion on mixing proportions to decrease with increasing transport distance in the
838 absence of very strong lithologies.

839 Overall, with the exception of sampling site K, our predictions of relative erosion rates
840 using an abrasion model are better correlated with documented rates and spatial variability
841 found by other studies. Pebble abrasion, based on lithology, can therefore be an important factor
842 to consider when inversely solving for modern erosion rates.

843

844 **4.4 Methodological uncertainties and limitations**

845 Inverse modelling to predict erosion rates is known to be difficult and subject to model
846 specifications as well as uncertainties in grain age distributions. There is no consensus on how
847 to choose statistical analyses to (un)mixing age distributions (Saylor and Sundell, 2016). In our
848 case, we worked with area mismatch (M) to be able to compare our results directly with those
849 from Amidon et al. (2005a). However, this metric is known to have limitations when used to
850 unravel grain age distributions (Sundell and Saylor, 2017) and may not be the most sensitive
851 method to identify the influence of abrasion rates in detrital grain age signatures. Furthermore,
852 working with unique solutions of mixing proportions can be problematic (Saylor and Sundell,
853 2016; Sundell and Saylor, 2017; Sharman and Johnstone, 2017), since small variations in

854 mixing proportions may produce statistically similar (and fitting) distributions but significantly
855 impact the results of inverse erosion modelling (e.g., relative erosion rates). These issues can
856 be dramatically enhanced when smoothing the age distributions (see Supporting Information
857 Tables S3 and S4). In the natural age distributions (samples E, G and K), the smoothing
858 procedure produces statistically significant changes in two samples (TTS and mixed sample,
859 K). Additionally, by reducing age variability, it favours convergence when finding mixing
860 proportions from source units (Amidon et al., 2005a). These differences in the sensitivity of the
861 (un)mixing techniques can obscure detectable variations in the age distributions caused by
862 pebble abrasion.

863 Another important consideration is the effect of intrinsic characteristics of age
864 distributions (i.e., the ages and their relative probability) in statistical analyses. Our experiments
865 with different age peaks show that the ability of statistical metrics to identify changes is affected
866 by the spread, overlap and shape of the peaks. Thus, there is an intrinsic bias in any age
867 distribution under investigation. Future research on this issue could bring significant
868 contribution to minimize this bias in a quantitative way. It also reinforces the non-uniqueness
869 of solutions to (un)mixing age distributions as highlighted by several authors (e.g., Sundell and
870 Saylor, 2017).

871 It is important to consider the implications of some of our assumptions, in particular
872 regarding the transfer of zircon from gravel to sand. In our model, we assume that all products
873 of abrasion are in the sand fraction, and that the zircons are homogeneously distributed in this
874 sand. In reality, the fraction finer than 2 mm is far more heterogeneous than assumed here, both
875 in the initial sediment supply from the hillslope to the river and in the fluvial sediment
876 transported (Attal and Lavé, 2006, Attal et al., 2015; Riebe et al., 2015, Lukens et al., 2016,
877 Sklar et al., 2017). In addition, abrasion will also produce fragments and particles in a wide
878 range of sizes, leading to potentially different mineral compositions depending on the fraction
879 sampled. For example, the abrasion of granite tends to produce sand, whereas abrasion of
880 limestone will produce more silt and clay (Bradley, 1970; Attal and Lavé, 2009). However,
881 given that no constraints about the grain size of abrasion products in the Marsyandi watershed
882 exist, we cannot estimate quantitatively how distorted our own analyses can be due to this
883 process. We must also mention that an important covariation exists between grain size of
884 abrasion products, abrasion rates and hillslope grain size supply (Attal and Lavé, 2006). Less
885 resistant bedrock types are more likely to have higher weathering rates and to produce regolith
886 with higher content of fine material (i.e., sand, silt and clay) than hard rock types, leading to

887 lower initial gravel supply to the river channels and consequently smaller amount of gravel
888 available for abrasion. The covariation of hillslope grain size, grain size of abrasion products
889 and abrasion rate associated with a given rock type can produce unusual effects, as shown in
890 Section 4.2, and requires further attention. Because most detrital studies focus on a given
891 sediment fraction (usually sand), it is becoming increasingly important to understand the
892 production and evolution of the fine fraction of the sediment spectrum, from the hillslopes to
893 the sedimentary basin, as a result of chemical and physical processes (Sklar et al., 2017);
894 including abrasion during fluvial transport.

895 Hydrodynamic fractionation of grain sizes, whereby larger sediment grains travel slower
896 than smaller ones, operates on a range of scales (bedload versus suspended load, as well as
897 differences within bedload and within suspended load) in the majority of natural environments
898 (e.g., Miller et al., 2014). Recent findings suggest potential bias from downstream hydraulic
899 sorting in cases where a relationship between zircon grain age and size exists, e.g., larger grains
900 are younger and smaller ones are older (Yang et al., 2012). The influence of grain density is
901 also important, given that relative enrichment in gravel bars, river pools and other common
902 sampling sites for detrital studies can bias denser minerals such as zircon. However, because
903 our work focuses only on one type of mineral (zircon) and uses the relative proportions of
904 zircons from different units, it seems reasonable to assume that zircons from all units will be
905 affected in a similar way and that the outcomes of our work would not be significantly affected
906 by the processes mentioned above, except in a case where zircons from different units have
907 different sizes, which we cannot assess.

908 Finally, although we applied the same procedure adopted by Amidon et al. (2005a) to
909 directly compare our results with theirs and assess the influence of abrasion, our no-abrasion
910 model produces mixing proportions and relative erosion rates that are slightly different from
911 their no-abrasion model results. Our predictions are different by 2 % and 4 % in the mixing
912 proportions and erosion rates estimated for site E. At the sampling site G, our predictions differ
913 by up to 2 % and 5 % in the mixing proportion and erosion rates, respectively. At the outlet (K),
914 these differences become higher, reaching up to 6 % in the mixing proportion and 5 % in the
915 relative erosion rates. A possible explanation for these differences is small changes in the
916 quality of the Digital Elevation Model and/or in the minimization procedures adopted. In all
917 cases, however, our no-abrasion model mirrors the same pattern of zircon mixing proportion
918 and erosion estimated by the no-abrasion model of Amidon et al. (2005a).

919

920 **5 Conclusion**

921 Our numerical simulations provide evidence of the role of pebble abrasion in distorting
922 detrital grain age information from modern sands. This distortion is significant in settings with
923 large contrasts in rock strength or short catchments. In long catchments with no resistant
924 lithologies, most of the gravel initially supplied from the hillslopes will have been turned into
925 sand by the time it reaches the outlet, leading to the release of most detrital grains and limited
926 bias potential from abrasion. Conversely, gravel from resistant lithologies (e.g., quartzite,
927 volcanics, mica-poor granite or gneiss) can persist for transport distances of hundreds of km,
928 locking detrital minerals within them and increasing the bias potential from abrasion: abrasion
929 will likely lead to the underrepresentation of units characterised by such resistant rock in a sand
930 sample. We find however that pebble abrasion is the factor with the lowest distortion capability
931 when compared with other well-known factors that might bias the preserved sedimentary record
932 (i.e., relative erosion rates, zircon fertility and hillslope gravel supply). Abrasion has a non-
933 linear impact on the mixing proportion of river sand, and this impact is modulated by the initial
934 gravel supply: whereas a doubling a zircon fertility or erosion rate in a unit will lead to a
935 doubling of the zircon contribution from this unit in a mixed sample, the impact of doubling the
936 abrasion rate may be much lower. We find, in one of our scenarios, that the equivalent effect of
937 having rocks from one unit abraded 200 times faster than rocks from other units can be
938 replicated by tripling the fertility or erosion rate of this unit.

939 The relative erosion rates of source units estimated by inverse modelling are impacted
940 by abrasion, despite minimal (statistically insignificant) variations in the grain age distributions.
941 In the Marsyandi catchment, our abrasion model predicts erosion rates that are closer to those
942 found by the majority of previous studies, compared to a no-abrasion model. These results
943 suggest that even when statistics are not able to identify significant changes in the age
944 distribution of samples, the erosion rates deconvolved from them can still be significantly
945 affected. Therefore, assessing the influence of abrasion on the evolution of the composition of
946 river sediment is essential if we are to accurately estimate erosion rates from inverse modelling,
947 using detrital methods based on a given sediment fraction (e.g., sand), in particular when the
948 source units feature large variations in rock strength.

949 We identify research into the trade-offs between initial gravel supply and abrasion rates
950 and into the size distribution of the products of abrasion for rocks of different lithologies as
951 priorities to develop models that would better constrain the influence of abrasion and other
952 factors on biases in detrital studies.

953

954 **Acknowledgments**

955 The topographic data used in this paper is freely available from
956 <http://www.opentopography.org>. All the code used to perform our analysis as well as to
957 generate the figures is open source and can be downloaded from GitHub at
958 <https://github.com/clavarini>. This research is supported by the CAPES Brazilian foundation
959 through Ph.D. scholarships provided to two of the authors (grants BEX 13193-13-9 to C.L. and
960 0061-13-1 to C.A.d.C.F.). The authors would like to thank David Whipp and two anonymous
961 reviewers for their useful comments. We thank the Associate Editor Jon Warrick and the Editor
962 Giovanni Coco for their additional comments. We are extremely grateful to William Amidon
963 for providing the U-Pb Marsyandi's river dataset.

964

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1187 **TABLES**

1188

1189 **Table 1:** Published parameters used in this work to predict the mixing proportion and relative
 1190 distribution of erosion rates at sampling points in the Marsyandi watershed.

Source ^a	Zircon fertility (grains/g) ^b	Abrasion rate (% mass loss/km) ^c	Gravel supply (%) ^d
TTS	0.6	4.3	75
MG	0	0.4	75
F II-III	0.3	0.4	75
F I	0.8	1.4	75
LH	0.3	9.4	75

1191

1192 ^a TTS = Tethyan series, MG = Manaslu granite, F II-III = Formation II-III, F I = Formation I,
 1193 LH = Lesser Himalaya.

1194 ^b Estimated by Amidon et al. [2005a].

1195 ^c Estimated from experimental abrasion rates by Attal and Lavé [2006].

1196 ^d Average percentage of hillslope supply coarser than sand (i.e., > 2 mm), estimated by Attal
 1197 and Lavé [2006].

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1200

1201 **Table 2:** Parameters used in the numerical experiments testing the influence of pebble
 1202 abrasion rates in the age distribution of sands. TTS = Tethyan Series, F II-III = Formation II-
 1203 III, F I = Formation I, LH = Lesser Himalaya.

1204

Experiment	Zircon fertility (grains/g) ^a	Abrasion rate (% mass loss/km) ^b			
		TTS	F II-III	F I	LH
A1	1	0.4	0.4	0.4	0.4
A2	1	31	0.15	0.15	0.15
A3	1	0.15	0.15	0.15	31
A4	1	4.3	0.4	1.4	9.4

1205

1206 ^a Estimated by Amidon et al. [2005a].

1207 ^b Estimated by Attal and Lavé [2006].

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1209

1210 **Table 3:** Parameters used in the numerical experiments comparing the distortion caused by
 1211 well-known controlling factors (erosion rate, zircon fertility, hillslope gravel supply and
 1212 abrasion). TTS = Tethyan Series, F II-III = Formation II-III, F I = Formation I, LH = Lesser
 1213 Himalaya. A sensitivity analysis was also carried out for experiments B2 to B5b, with results
 1214 shown in Figure 4: TTS' abrasion rate was varied between 0.15 and 31 %/km in B2; TTS'
 1215 erosion rate was varied between 1 and 5.1 mm/yr in B3; fertility of non-TTS units was varied
 1216 between 0 and 0.8 grains/g in B4; gravel supply from TTS and LH was varied between 60 and
 1217 90 % in B5 and B5b, respectively.
 1218

Experiment	Factor	Coefficients			
		TTS	F II-III	F I	LH
B1	All uniform - no abrasion				
B2	Abrasion rate (% mass loss/km)	31	0.15	0.15	0.15
B3	Erosion rate (mm/a)	5.1	1	1	1
B4	Zircon fertility (grains/g)	0.8	0	0	0
B5	Gravel supply (%)	60	90	90	90
B5b*	Gravel supply (%)	90	90	90	60
B6	Gravel supply (%) + Abrasion rate (% mass loss/km)	60 31	90 0.15	90 0.15	90 0.15

1219
 1220 * B5b is similar to B5 except that LH has the smallest gravel supply instead of TTS; see text
 1221 for details.
 1222

1223 **FIGURE CAPTION**

1224 **Figure 1.** Conceptual representation of the variables used in the abrasion mixing model and the
1225 resulting impact on the modelled U-Pb detrital age distribution $z(x)$ used to estimate erosion
1226 rates. In this representation, different travelled distances d impact the proportion of sand
1227 sourced from the two units. This leads to a change in the zircon mixing proportion Φ_i^Z that
1228 modifies the detrital age distribution $z(x)$ in the 63-125 μm fraction used in geochronology. (a)
1229 Controlling factors of mass and zircon concentration of sands in the abrasion model: top –
1230 bedrock control: exposure area (km^2) and mineral fertility (grains/g); bottom – sediment
1231 control: hillslope gravel fraction (coarser than sand) and abrasion rate (% mass loss/km), with
1232 abrasion progressively transferring zircons from the gravel to the sand fraction as sediment is
1233 transported downstream. (b) On a spatial scale, two contributing single source units (S1 and
1234 S2) are mixed downstream (S3). Sample S3 reflects the mixture of upstream controlling factors,
1235 including abrasion; in this case, source one is over-represented as the longer transport distance
1236 leads to a greater sand production from abrasion and therefore contribution in the mixed sand
1237 sample (S3). This is exemplified by the inset (bottom left) showing the mass of sand along a
1238 linear river system coming from sources 1 and 2 in a simple model based on *Attal and Lavé's*
1239 (2006, 2009): 1000 tons of sediment are supplied to the system every km (all gravel in this
1240 scenario), from source 1 over the first 10 km and from source 2 over the next 10 km. Gravel is
1241 abraded according to the Sternberg's law (see text) at a rate of 2 % mass loss/km. Total amount
1242 of sand (black) is sum of sand from sources 1 (pink) and 2 (purple). The contribution from
1243 source 1 in a sand sample is shown by green dashed line; it is 72% after a distance of 20 km
1244 (sample S3). As gravel from source 1 experienced greater transport distance, more sand has
1245 been released from source 1 compared to source 2.

1246

1247 **Figure 2.** Source units of the Marsyandi watershed and their U-Pb detrital age distribution. (a)
1248 Geological map for the Marsyandi watershed superimposed on hillshade derived from 30-m
1249 resolution Shuttle Radar Topography Mission (SRTM) data. Geological units are derived from
1250 *Le Fort (1975)* (see also *Amidon et al., 2005a*, and *Attal and Lavé, 2006*). Sample locations and
1251 U-Pb detrital ages distributions (samples A to K) measured by *Amidon et al. (2005a)* are also
1252 indicated; they are used in this work as a study case and in the numerical simulations. Grey
1253 PDFs indicate mixed samples, whereas coloured PDFs represent source samples, with the
1254 colour relating to the unit in question. MCT is Main Central Thrust; STD 1 and 2 are South

1255 Tibetan Detachment as mapped by *Searle and Godin* (2003), and *Colchen et al.* (1987),
1256 respectively. (b) Synthetic U-Pb age distributions (samples 1-5) created in this work to facilitate
1257 the statistical assessment of our numerical experiments: samples 1 to 4 are sources (indicated
1258 by colours) and sample 5 is mixed sand sample predicted at outlet without abrasion (location K
1259 in (a)). The vertical axis in the PDFs is relative probability ($\times 10^{-3}$) and the horizontal axis is U-
1260 Pb grain age (Ga).

1261

1262 **Figure 3.** Results of the numerical simulations that tested the statistics of synthetic U-Pb zircon
1263 age populations (PDPs) derived from zircon mixing modelling using abrasion scenarios (Table
1264 2): uniform abrasion rate (A1), very high abrasion rate for TTS (A2) or for LH (A3), and
1265 realistic values for the different units based on *Attal and Lavé* (2006) (A4). (a) Percentage zircon
1266 from the different rock units in sand at the catchment outlet. Mixing proportions in the no-
1267 abrasion case reflect the relative exposure area of the different units; dashed lines indicate
1268 change with respect to the no-abrasion scenario. (b) and (d) Probability density plots (PDPs)
1269 generated using the mixing proportions predicted by the abrasion model on synthetic and
1270 natural age distribution, respectively. Arrows identify peaks associated with the four sources.
1271 (c) and (e) Statistical assessment of the PDPs through PDF cross-plots. Additional statistical
1272 assessment (e.g., Q-Q plots) can be found in the supporting information (Table S5, S6, Fig. S2).
1273 Note that scenarios A2 and A3 lead to the greatest amount of distortion with the synthetic
1274 dataset (see R^2 values in (c)), with greater distortion in case A2 due to the TTS peak being
1275 isolated compared to the LH peak. With the natural dataset, only scenario A3 leads to a
1276 significant amount of distortion compared to the other scenarios (see R^2 values in (e)), which
1277 we explain by LH having a unique peak at ~ 1.8 Ga; most TTS peaks are shared with other units.
1278

1279 **Figure 4.** Synthetic zircon age populations (PDPs) derived from zircon mixing in numerical
1280 experiments B2-B6 (Table 3), showing sensitivity of PDPs to (a) abrasion (B2), (b) erosion rate
1281 (B3), (c) fertility (B4) and (d-e) hillslope gravel supply (B5-B5b). An additional experiment B6
1282 has a low initial gravel supply and high abrasion rate for TTS (Table 3). B1 is the reference
1283 case (all factors uniform, no abrasion); B2 is the same as simulation A2. Note the quasi linear
1284 response to erosion rate, fertility and hillslope gravel supply (b-e), in stark contrast with the
1285 influence of abrasion rate (a). Combining low gravel supply with high abrasion rate leads to
1286 increased distortion (f): TTS is overrepresented in a sand sample at the outlet with respect to
1287 other units, due to both greater sand contribution at the source (hillslope) and greater release of

1288 sand through abrasion of gravel (high abrasion rate). Full statistical assessment can be found in
1289 the supporting information (Table S7-S8).

1290

1291 **Figure 5.** (a, c) Probability density plots (PDPs) and (b, d) PDF cross-plots of the end-member
1292 scenarios from experiments B2-B6 (Table 3). (a, b) are based on synthetic age distributions. (c,
1293 d) are based on natural age distributions. Additional statistical assessment can be found in the
1294 supporting information (Table S7-S8, Fig. S4). Note the clear distortion generated by the
1295 different parameters with the synthetic dataset (b); the distortion is not as significant with the
1296 natural dataset (d), which we explain as due to overlapping peaks, though the relative influence
1297 of the different parameters is the same in both datasets (with fertility having the greatest effect).

1298

1299 **Figure 6.** Results of the numerical simulations comparing the capability of each controlling
1300 factor to reproduce the distortions of abrasion (B2), erosion (B3), fertility (B4) and hillslope
1301 gravel supply (B5b) in the zircon age populations (PDPs). (a, c) Probability density plots (PDPs)
1302 of the experiments, comparing the distribution created by varying a given factor (grey) with the
1303 best fit distributions obtained by varying one of the other parameters (curves). Factors that can
1304 perfectly reproduce the distribution are grouped in “Others”. (b, d) PDF cross-plots and their
1305 R^2 comparing how the (tested) factors can reproduce a distortion caused by a specific (targeted)
1306 factor; thickness of circles refers to scenario, whereas colour refers to tested factor. (a, b) are
1307 based on synthetic age distributions. (c, d) are based on natural age distributions. Note the
1308 similar performance (R^2) with both synthetic and natural datasets. Additional statistical
1309 assessment can be found in the supporting information (Table S9, S10).

1310

1311 **Figure 7.** Results of the numerical mixing models for the Marsyandi uppermost sampling site
1312 (E): resulting U-Pb age distributions (PDPs), relative erosion rates and statistical assessment.
1313 (a) Percentage zircon from the different rock units in sand at site E (pink) and predicted relative
1314 erosion rates (blue) for the no-abrasion and abrasion models; dashed lines indicate change with
1315 respect to the best-fit approach (see text). (b) PDPs of the measured grains, modelled best-fit,
1316 no-abrasion and abrasion models. (c) PDF cross-plots comparing the modelled PDFs (no
1317 abrasion and abrasion) to the best-fit PDF (in blue and green) as well as comparing the modelled
1318 PDFs among themselves (in yellow); key shows “X-axis PDF” x “Y-axis PDF”.

1319

1320 **Figure 8.** Results of the numerical mixing models for the intermediate Marsyandi sampling
1321 site (G): their resulting age distributions (PDPs), relative erosion and statistical assessment.
1322 (a) Percentage zircon from the different rock units in sand at site G (pink) and predicted
1323 relative erosion rates (blue) for the no-abrasion and abrasion models; dashed lines indicate
1324 change with respect to the best-fit approach (see text). (b) PDPs of the measured grains,
1325 modelled best-fit, no-abrasion and abrasion models. (c) PDF cross-plots comparing the
1326 modelled PDFs (no-abrasion and abrasion) to the best-fit PDF (in blue and green) as well as
1327 comparing the modelled PDFs among themselves (in yellow); key shows “X-axis PDF” x “Y-
1328 axis PDF”.

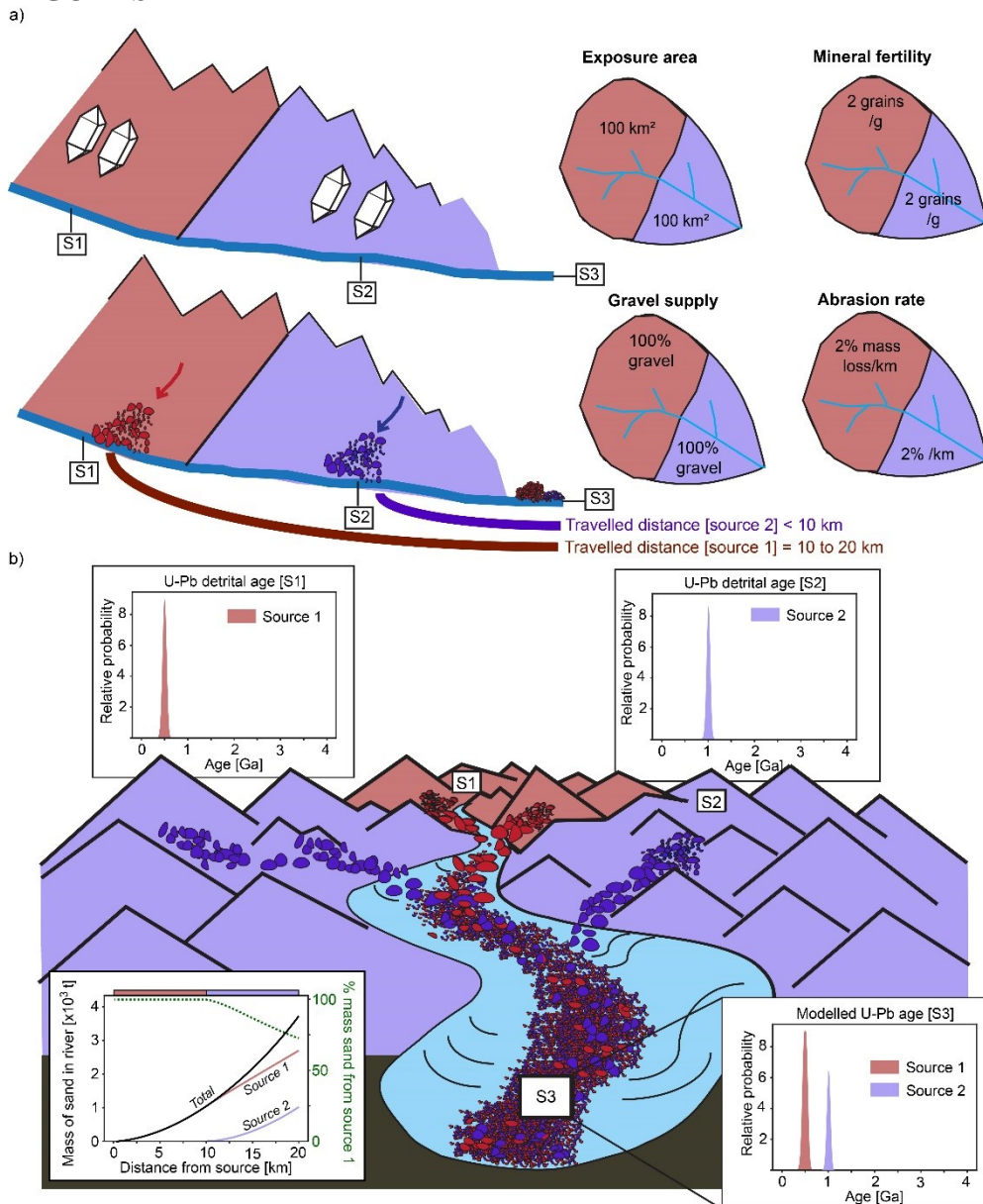
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1330 **Figure 9.** Results of the numerical mixing models for the Marsyandi outlet (K): their resulting
1331 age distributions (PDPs), relative erosion and statistical assessment. A) Percentage zircon from
1332 the different rock units in sand at site K (pink) and predicted relative erosion rates (blue) for the
1333 no-abrasion and abrasion models; dashed lines indicate change with respect to the best-fit
1334 approach (see text). B) PDPs of the measured grains, modelled best-fit, no-abrasion and
1335 abrasion models. C) PDF cross-plots comparing the modelled PDFs (no-abrasion and abrasion)
1336 to the best-fit PDF (in blue and green) as well as comparing the modelled PDFs among
1337 themselves (in yellow) ; key shows “X-axis PDF” x “Y-axis PDF”.

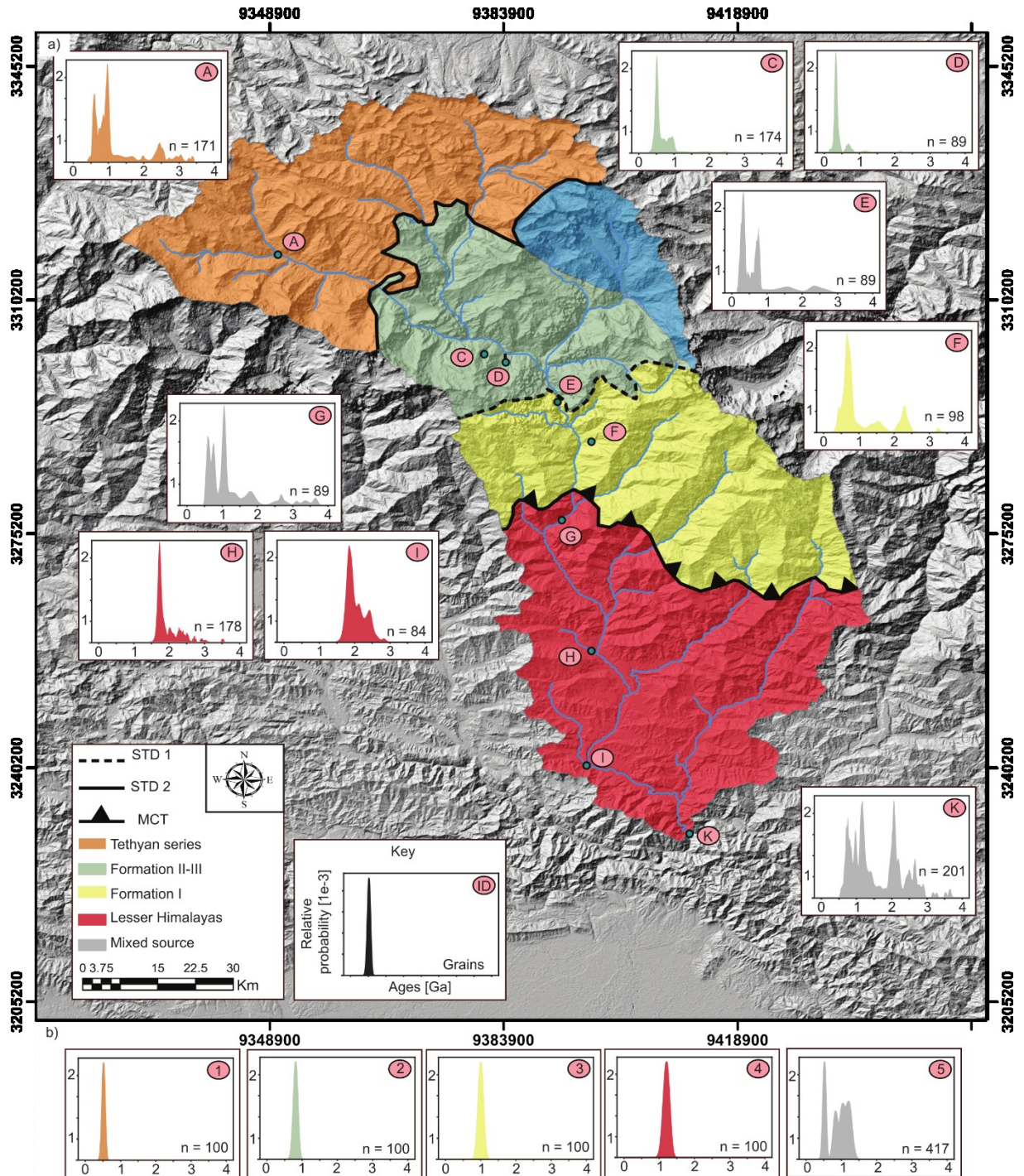
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1339 **Figure 10. (a)** Schematic diagram summarising the circumstances under which bias from
1340 abrasion can be expected in a sand sample. Bias is expected to decrease with increasing length
1341 of the river system, as the relative amount of sand (and therefore zircons or any other tracer
1342 minerals) retained in gravel decreases downstream. How quickly sand is released from gravel
1343 through abrasion is a function of the abrasion rate, so “short” and “long” have relative meanings
1344 for a catchment (*, see (b)). Strong contrast in rock resistance to abrasion will enhance bias, as
1345 gravel from hard lithologies will persist for long distances, therefore limiting the release of
1346 zircon or any other tracer minerals from this lithology (in the figure, rock type 2 is harder,
1347 leading to underrepresentation in sand sample). (b) Downstream conversion from gravel to sand
1348 as a function of abrasion rate (note log scale on x-axis). These results are based on a simple
1349 linear river model from *Attal and Lavé’s* (2006, 2009) (see also Fig. 1b): a given amount of
1350 sediment is supplied to the system every km and gravel is abraded according to Sternberg’s
1351 law. At a distance of 10 km downstream, 61 % of all gravel supplied to the system has been
1352 turned into sand for a mass loss of 20 %/km (39 % of gravel remaining). This figure is 10 %

1353 and 1 % for a mass loss of 2 and 0.2 %/km, respectively. At a distance of 100 km, nearly all
1354 gravel supplied to the system has been turned into sand for a mass loss of 20 %/km (4 % of
1355 gravel remaining). This figure is 58 % and 9 % for a mass loss of 2 and 0.2 %/km, respectively.
1356 Gravel from resistant lithologies can persist over hundreds of km. (c) Influence of abrasion rate
1357 and initial gravel fraction on relative contribution of abrasion to sand. Key is as in (b): abrasion
1358 rate of 0.2, 2 and 20 %/km are shown by solid (light blue), short dash (dark brown) and long
1359 dash (black) lines, respectively. % value on curves indicates initial gravel fraction from
1360 hillslopes. Curves show the relative contribution of sand from abrasion in a sand sample taken
1361 at a given distance downstream.
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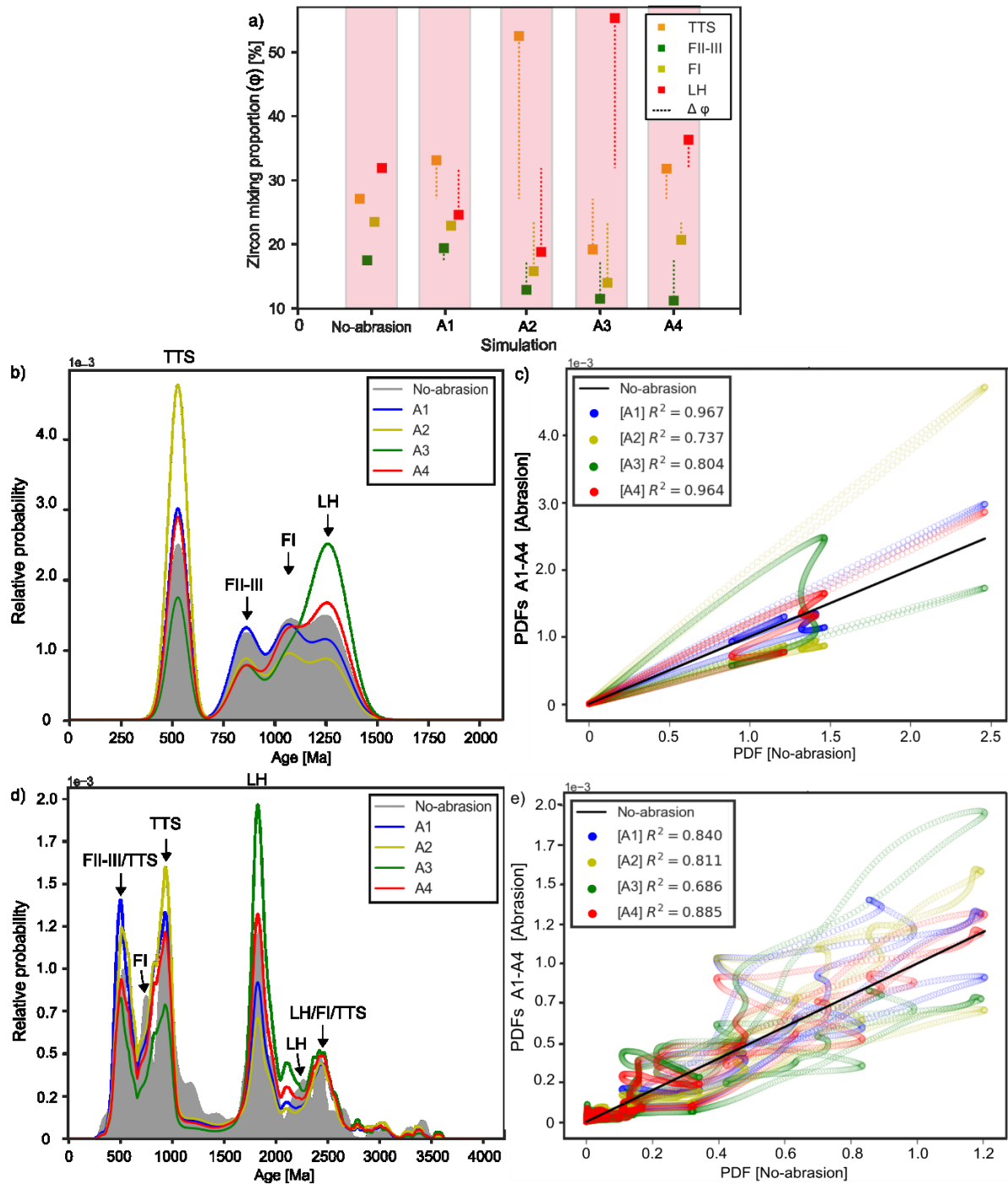


1365
 1366 **Figure 1.** Conceptual representation of the variables used in the abrasion mixing model and the resulting impact
 1367 on the modelled U-Pb detrital age distribution $z(x)$ used to estimate erosion rates. In this representation, different
 1368 travelled distances d impact the proportion of sand sourced from the two units. This leads to a change in the zircon
 1369 mixing proportion Φ_i^Z that modifies the detrital age distribution $z(x)$ in the 63-125 μm fraction used in
 1370 geochronology. (a) Controlling factors of mass and zircon concentration of sands in the abrasion model: top –
 1371 bedrock control: exposure area (km^2) and mineral fertility (grains/g); bottom – sediment control: hillslope gravel
 1372 fraction (coarser than sand) and abrasion rate (% mass loss/km), with abrasion progressively transferring zircons
 1373 from the gravel to the sand fraction as sediment is transported downstream. (b) On a spatial scale, two contributing
 1374 single source units (S1 and S2) are mixed downstream (S3). Sample S3 reflects the mixture of upstream controlling
 1375 factors, including abrasion; in this case, source one is over-represented as the longer transport distance leads to a
 1376 greater sand production from abrasion and therefore contribution in the mixed sand sample (S3). This is
 1377 exemplified by the inset (bottom left) showing the mass of sand along a linear river system coming from sources
 1378 1 and 2 in a simple model based on *Attal and Lavé's* (2006, 2009): 1000 tons of sediment are supplied to the
 1379 system every km (all gravel in this scenario), from source 1 over the first 10 km and from source 2 over the next
 1380 10 km. Gravel is abraded according to the Sternberg's law (see text) at a rate of 2 % mass loss/km. Total amount
 1381 of sand (black) is sum of sand from sources 1 (pink) and 2 (purple). The contribution from source 1 in a sand
 1382 sample is shown by green dashed line; it is 72% after a distance of 20 km (sample S3). As gravel from source 1
 1383 experienced greater transport distance, more sand has been released from source 1 compared to source 2.
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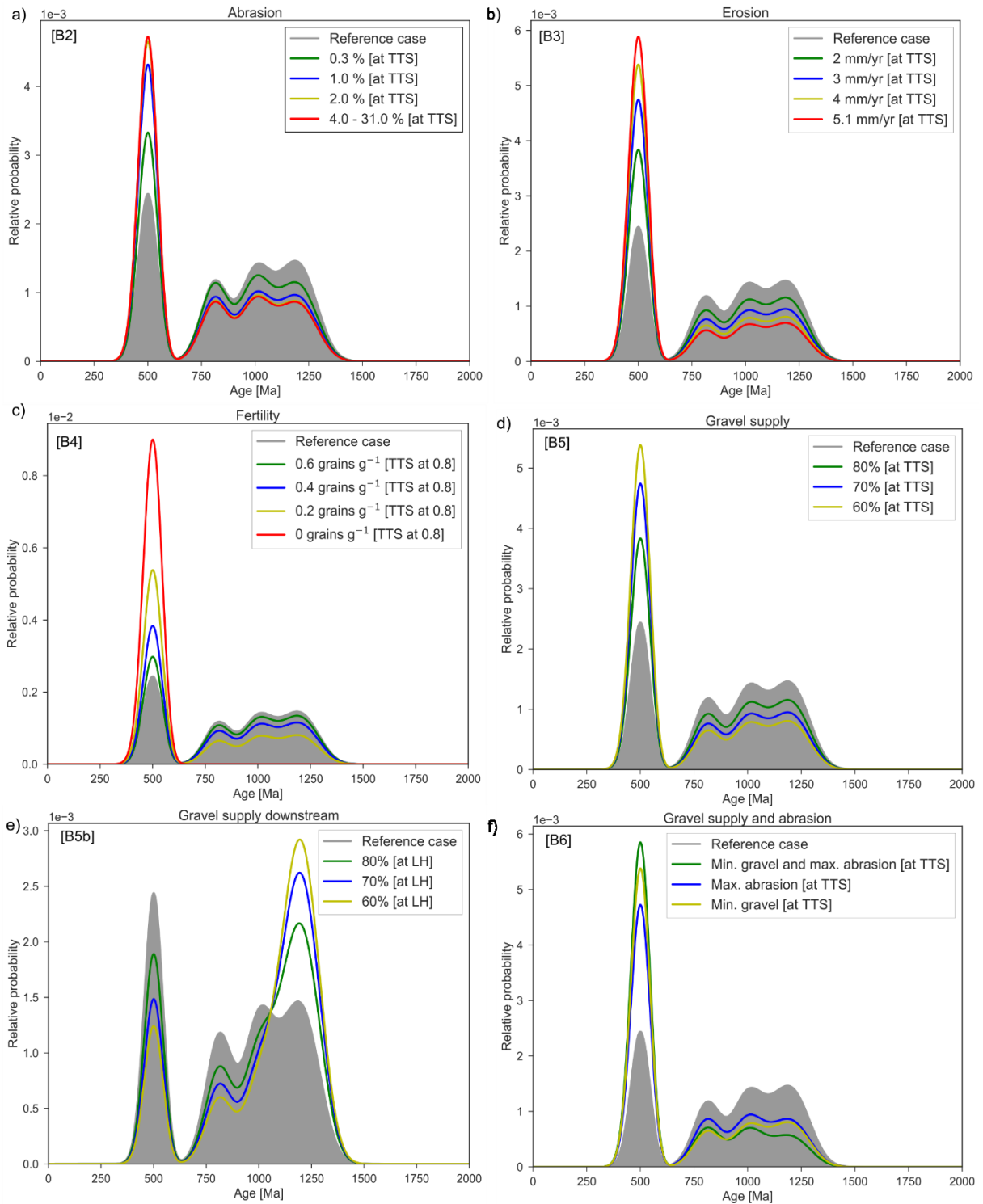
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Figure 2. Source units of the Marsyandi watershed and their U-Pb detrital age distribution. (a) Geological map for the Marsyandi watershed superimposed on hillshade derived from 30-m resolution Shuttle Radar Topography Mission (SRTM) data. Geological units are derived from *Le Fort* (1975) (see also *Amidon et al.*, 2005a, and *Attal and Lavé*, 2006). Sample locations and U-Pb detrital ages distributions (samples A to K) measured by *Amidon et al.* (2005a) are also indicated; they are used in this work as a study case and in the numerical simulations. Grey PDFs indicate mixed samples, whereas coloured PDFs represent source samples, with the colour relating to the unit in question. MCT is Main Central Thrust; STD 1 and 2 are South Tibetan Detachment as mapped by *Searle and Godin* (2003), and *Colchen et al.* (1987), respectively. (b) Synthetic U-Pb age distributions (samples 1-5) created in this work to facilitate the statistical assessment of our numerical experiments: samples 1 to 4 are sources (indicated by colours) and sample 5 is mixed sand sample predicted at outlet without abrasion (location K in (a)). The vertical axis in the PDFs is relative probability ($\times 10^{-3}$) and the horizontal axis is U-Pb grain age (Ga).



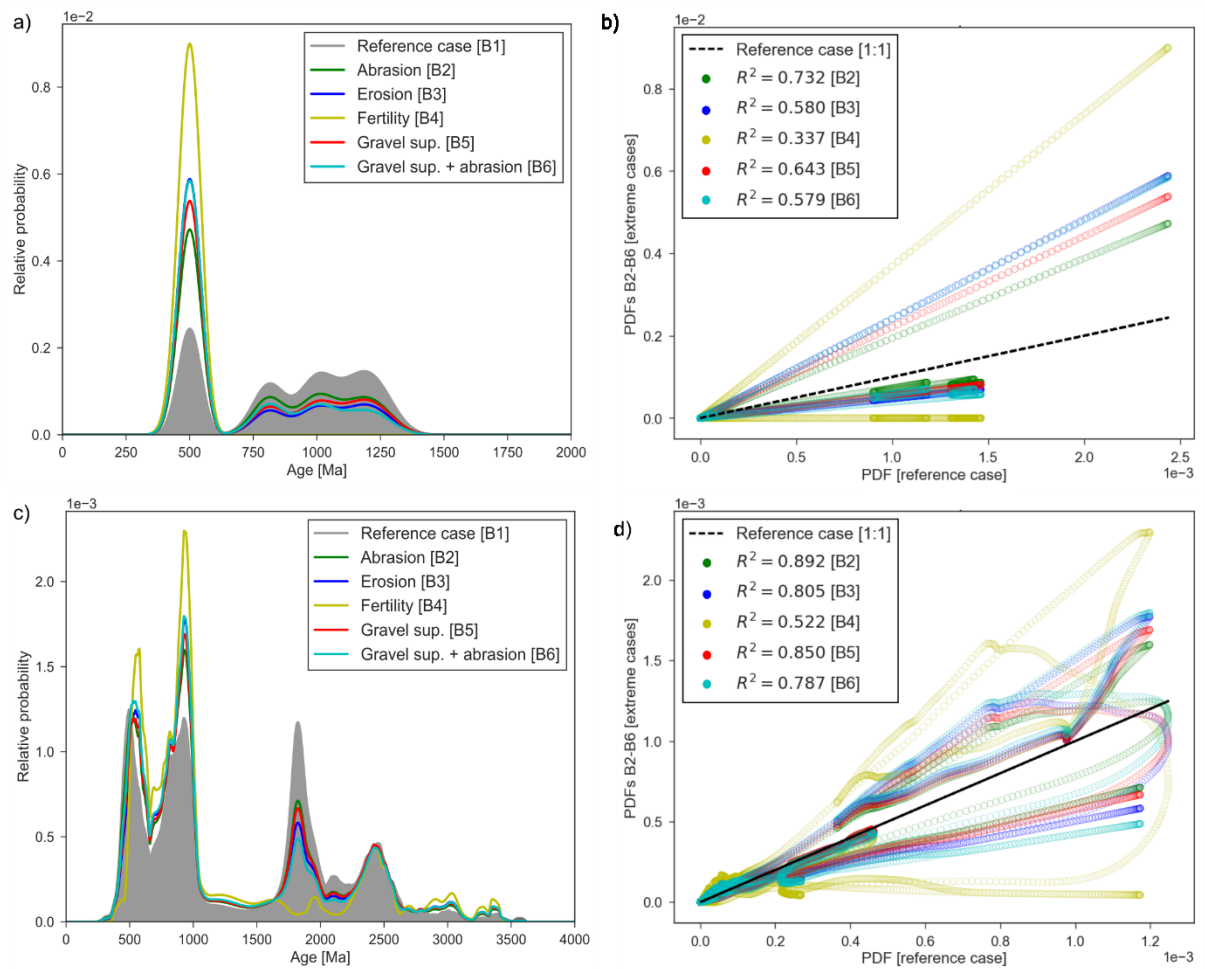
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Figure 3. Results of the numerical simulations that tested the statistics of synthetic U-Pb zircon age populations (PDPs) derived from zircon mixing modelling using abrasion scenarios (Table 2): uniform abrasion rate (A1), very high abrasion rate for TTS (A2) or for LH (A3), and realistic values for the different units based on *Attal and Lavé* (2006) (A4). (a) Percentage zircon from the different rock units in sand at the catchment outlet. Mixing proportions in the no-abrasion case reflect the relative exposure area of the different units; dashed lines indicate change with respect to the no-abrasion scenario. (b) and (d) Probability density plots (PDPs) generated using the mixing proportions predicted by the abrasion model on synthetic and natural age distribution, respectively. Arrows identify peaks associated with the four sources. (c) and (e) Statistical assessment of the PDPs through PDF cross-plots. Additional statistical assessment (e.g., Q-Q plots) can be found in the supporting information (Table S5, S6, Fig. S2). Note that scenarios A2 and A3 lead to the greatest amount of distortion with the synthetic dataset (see R^2 values in (c)), with greater distortion in case A2 due to the TTS peak being isolated compared to the LH peak. With the natural dataset, only scenario A3 leads to a significant amount of distortion compared to the other scenarios (see R^2 values in (e)), which we explain by LH having a unique peak at ~ 1.8 Ga; most TTS peaks are shared with other units.



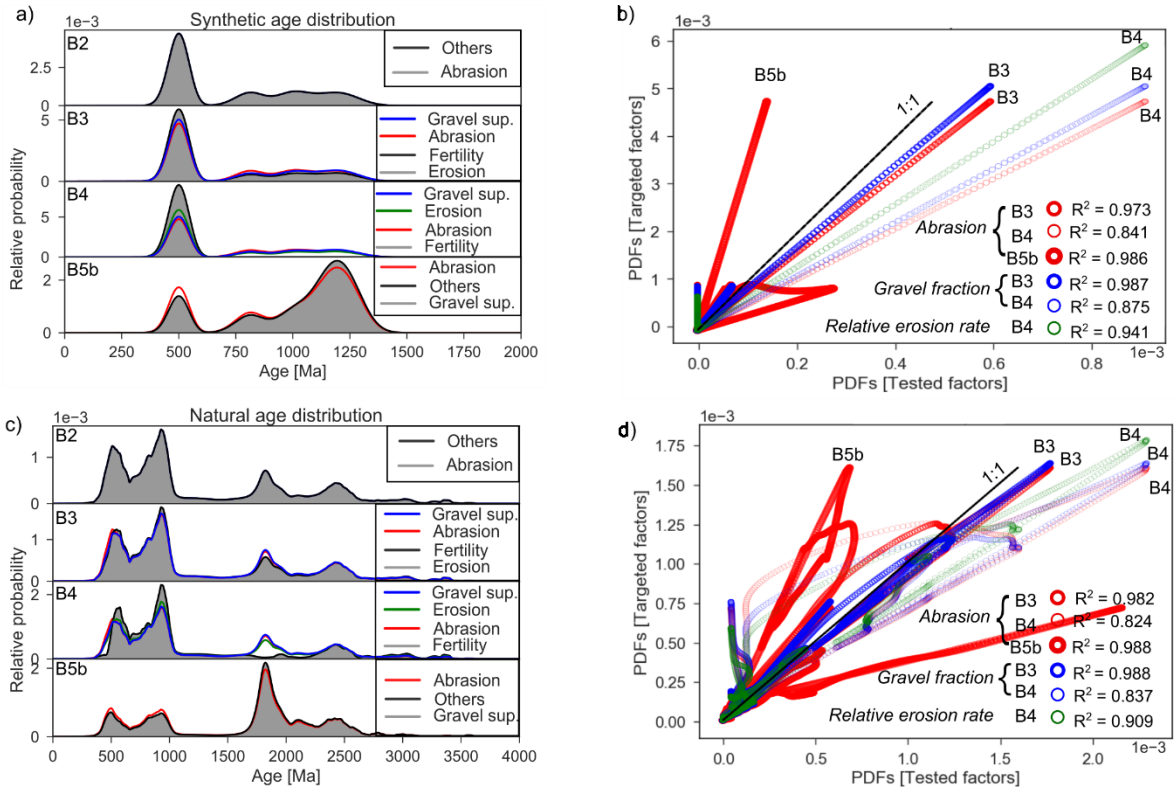
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Figure 4. Synthetic zircon age populations (PDPs) derived from zircon mixing in numerical experiments B2-B6 (Table 3), showing sensitivity of PDPs to (a) abrasion (B2), (b) erosion rate (B3), (c) fertility (B4) and (d-e) hillslope gravel supply (B5-B5b). An additional experiment B6 has a low initial gravel supply and high abrasion rate for TTS (Table 3). B1 is the reference case (all factors uniform, no abrasion); B2 is the same as simulation A2. Note the quasi linear response to erosion rate, fertility and hillslope gravel supply (b-e), in stark contrast with the influence of abrasion rate (a). Combining low gravel supply with high abrasion rate leads to increased distortion (f): TTS is overrepresented in a sand sample at the outlet with respect to other units, due to both greater sand contribution at the source (hillslope) and greater release of sand through abrasion of gravel (high abrasion rate). Full statistical assessment can be found in the supporting information (Table S7-S8).



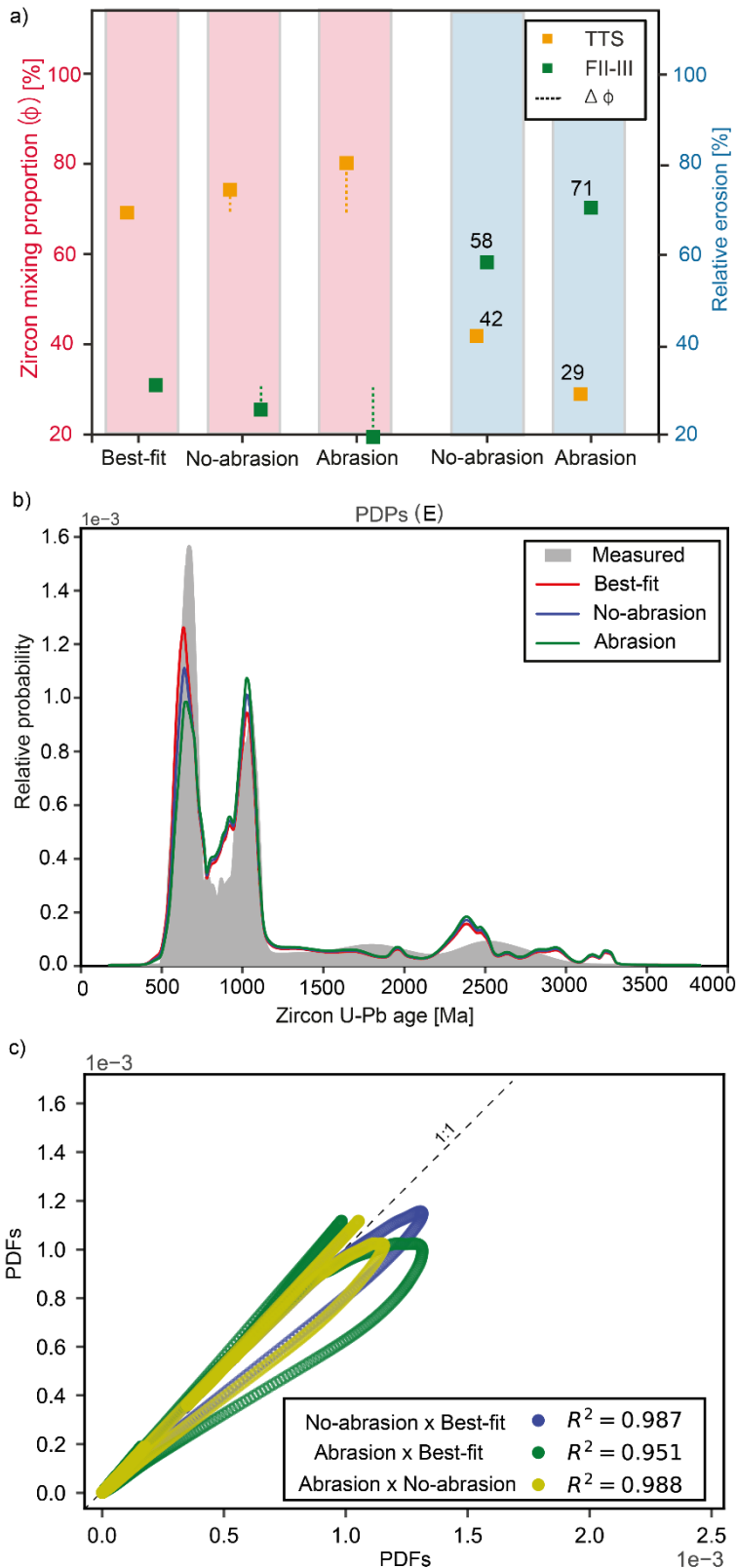
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Figure 5. (a, c) Probability density plots (PDPs) and (b, d) PDF cross-plots of the end-member scenarios from experiments B2-B6 (Table 3). (a, b) are based on synthetic age distributions. (c, d) are based on natural age distributions. Additional statistical assessment can be found in the supporting information (Table S7-S8, Fig. S4). Note the clear distortion generated by the different parameters with the synthetic dataset (b); the distortion is not as significant with the natural dataset (d), which we explain as due to overlapping peaks, though the relative influence of the different parameters is the same in both datasets (with fertility having the greatest effect).



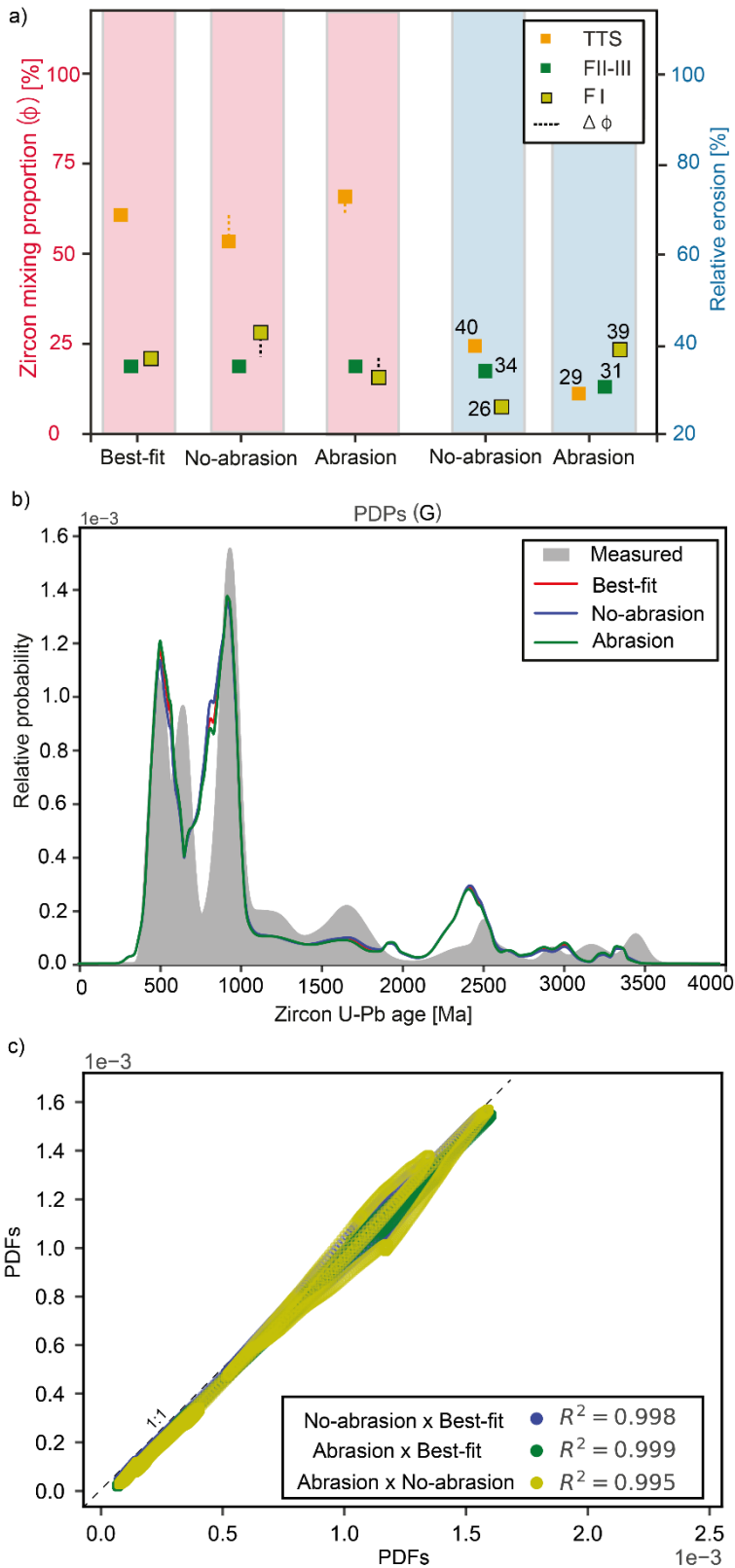
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Figure 6. Results of the numerical simulations comparing the capability of each controlling factor to reproduce the distortions of abrasion (B2), erosion (B3), fertility (B4) and hillslope gravel supply (B5b) in the zircon age populations (PDPs). (a, c) Probability density plots (PDPs) of the experiments, comparing the distribution created by varying a given factor (grey) with the best fit distributions obtained by varying one of the other parameters (curves). Factors that can perfectly reproduce the distribution are grouped in “Others”. (b, d) PDF cross-plots and their R^2 comparing how the (tested) factors can reproduce a distortion caused by a specific (targeted) factor; thickness of circles refers to scenario, whereas colour refers to tested factor. (a, b) are based on synthetic age distributions. (c, d) are based on natural age distributions. Note the similar performance (R^2) with both synthetic and natural datasets. Additional statistical assessment can be found in the supporting information (Table S9, S10).



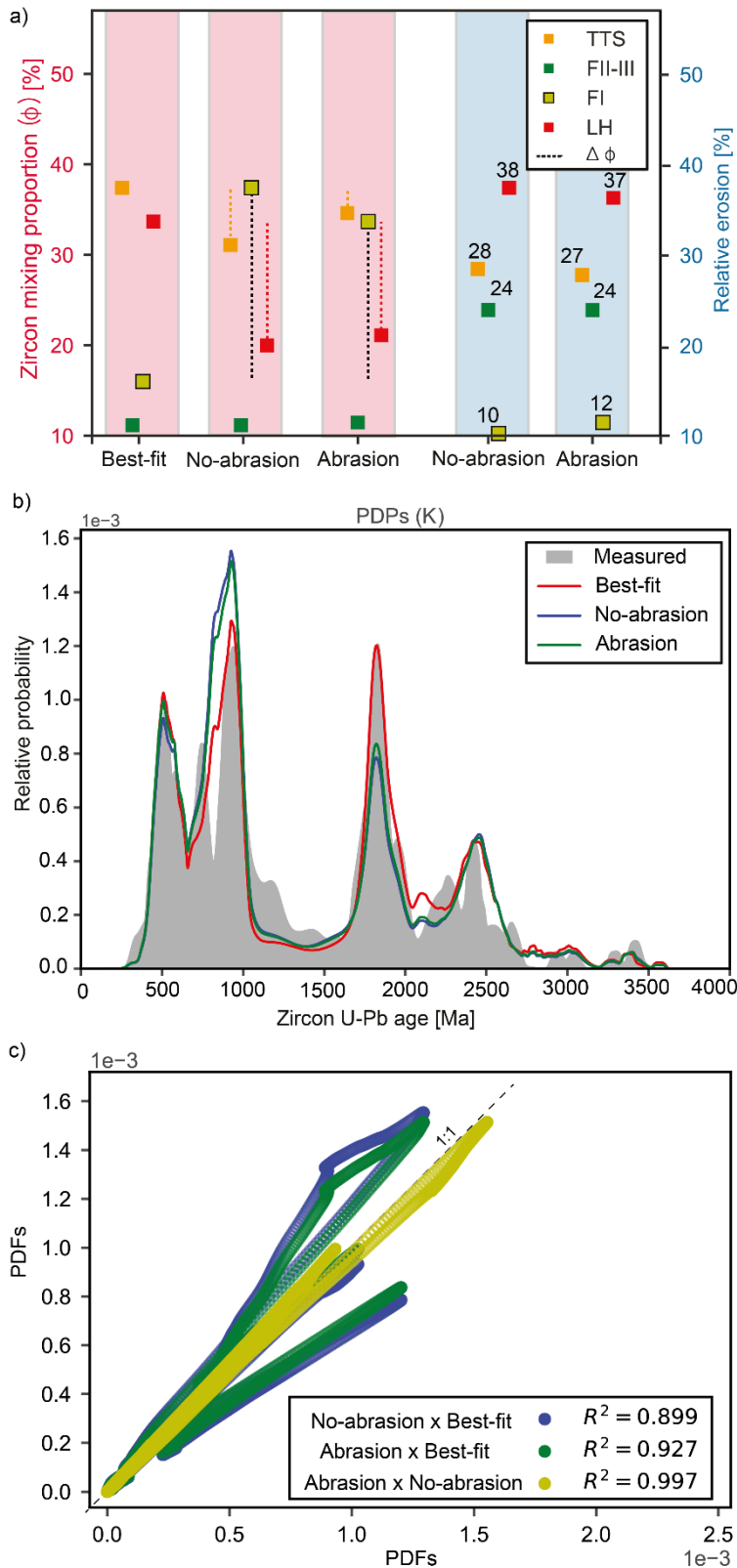
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Figure 7. Results of the numerical mixing models for the Marsyandi uppermost sampling site (E): resulting U-Pb age distributions (PDPs), relative erosion rates and statistical assessment. (a) Percentage zircon from the different rock units in sand at site E (pink) and predicted relative erosion rates (blue) for the no-abrasion and abrasion models; dashed lines indicate change with respect to the best-fit approach (see text). (b) PDPs of the measured grains, modelled best-fit, no-abrasion and abrasion models. (c) PDF cross-plots comparing the modelled PDFs (no abrasion and abrasion) to the best-fit PDF (in blue and green) as well as comparing the modelled PDFs among themselves (in yellow); key shows “X-axis PDF” x “Y-axis PDF”.



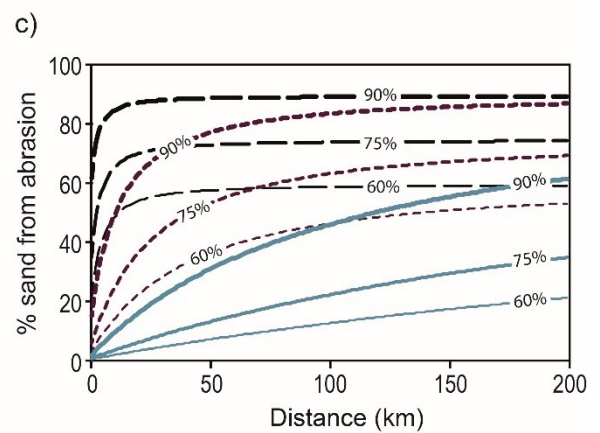
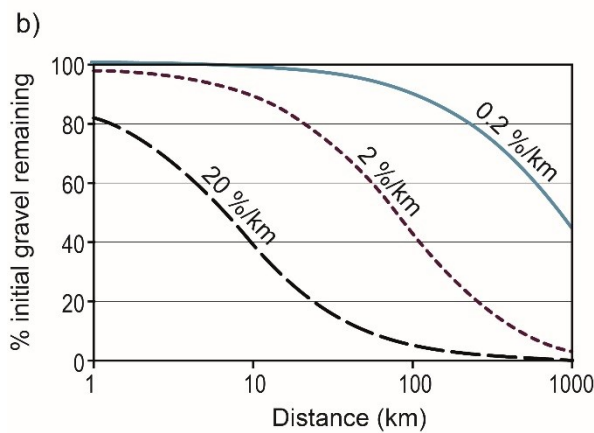
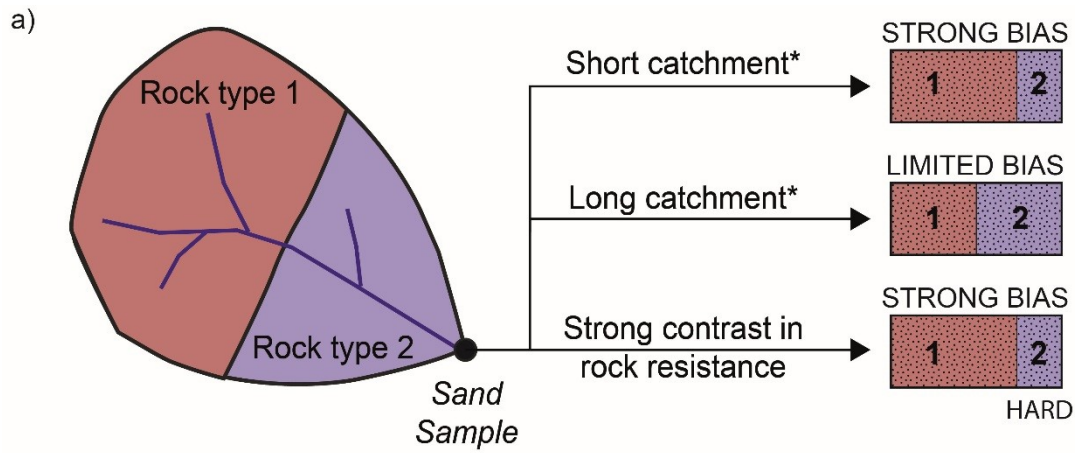
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Figure 8. Results of the numerical mixing models for the intermediate Marsyandi sampling site (G): their resulting age distributions (PDPs), relative erosion and statistical assessment. (a) Percentage zircon from the different rock units in sand at site G (pink) and predicted relative erosion rates (blue) for the no-abrasion and abrasion models; dashed lines indicate change with respect to the best-fit approach (see text). (b) PDPs of the measured grains, modelled best-fit, no-abrasion and abrasion models. (c) PDF cross-plots comparing the modelled PDFs (no-abrasion and abrasion) to the best-fit PDF (in blue and green) as well as comparing the modelled PDFs among themselves (in yellow); key shows “X-axis PDF” x “Y-axis PDF”.



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Figure 9. Results of the numerical mixing models for the Marsyandi outlet (K): their resulting age distributions (PDPs), relative erosion and statistical assessment. A) Percentage zircon from the different rock units in sand at site K (pink) and predicted relative erosion rates (blue) for the no-abrasion and abrasion models; dashed lines indicate change with respect to the best-fit approach (see text). B) PDPs of the measured grains, modelled best-fit, no-abrasion and abrasion models. C) PDF cross-plots comparing the modelled PDFs (no-abrasion and abrasion) to the best-fit PDF (in blue and green) as well as comparing the modelled PDFs among themselves (in yellow); key shows “X-axis PDF” x “Y-axis PDF”.



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Figure 10. (a) Schematic diagram summarising the circumstances under which bias from abrasion can be expected in a sand sample. Bias is expected to decrease with increasing length of the river system, as the relative amount of sand (and therefore zircons or any other tracer minerals) retained in gravel decreases downstream. How quickly sand is released from gravel through abrasion is a function of the abrasion rate, so “short” and “long” have relative meanings for a catchment (*, see (b)). Strong contrast in rock resistance to abrasion will enhance bias, as gravel from hard lithologies will persist for long distances, therefore limiting the release of zircon or any other tracer minerals from this lithology (in the figure, rock type 2 is harder, leading to underrepresentation in sand sample). (b) Downstream conversion from gravel to sand as a function of abrasion rate (note log scale on x-axis). These results are based on a simple linear river model from *Attal and Lavé’s* (2006, 2009) (see also Fig. 1b): a given amount of sediment is supplied to the system every km and gravel is abraded according to Sternberg’s law. At a distance of 10 km downstream, 61 % of all gravel supplied to the system has been turned into sand for a mass loss of 20 %/km (39 % of gravel remaining). This figure is 10 % and 1 % for a mass loss of 2 and 0.2 %/km, respectively. At a distance of 100 km, nearly all gravel supplied to the system has been turned into sand for a mass loss of 20 %/km (4 % of gravel remaining). This figure is 58 % and 9 % for a mass loss of 2 and 0.2 %/km, respectively. Gravel from resistant lithologies can persist over hundreds of km. (c) Influence of abrasion rate and initial gravel fraction on relative contribution of abrasion to sand. Key is as in (b): abrasion rate of 0.2, 2 and 20 %/km are shown by solid (light blue), short dash (dark brown) and long dash (black) lines, respectively. % value on curves indicates initial gravel fraction from hillslopes. Curves show the relative contribution of sand from abrasion in a sand sample taken at a given distance downstream.