

1 Environmental controls on sediment grain properties of Peruvian
2 coastal river basins

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9

10 **ABSTRACT**

11 Twenty-one coastal rivers located on the western Peruvian margin were analyzed to determine
12 the relationships between fluvial and tectonic processes and sediment grain properties. Modern
13 gravel beds were sampled along a north-south transect on the western side of the Peruvian Andes
14 where the rivers cross the tip of the mountain range, and at each site the long *a*-axis and the
15 intermediate *b*-axis of about 500 pebbles were measured. Morphometric properties of each
16 drainage basin were determined and compared against measured grain properties. Grain size data
17 show a large scatter in the D_{50} , D_{84} , D_{96} values and in the ratio between the intermediate and the
18 long axis. We have not found any correlations between the frequency of earthquakes and the
19 grain size pattern, which suggests that the current seismic, and likewise tectonic, regime has no
20 major controls on the supply of material on the hillslopes and the grain size pattern in the trunk
21 stream. However, positive correlations between water shear stresses, mean basin denudation
22 rates, mean basin slopes and basin sizes on nearly all grain size percentiles suggest a geomorphic
23 control where larger denudation rates operating in larger basins, and steeper basins, paired with

24 larger flow shear stresses, are capable of transporting more and coarser grained material.
25 Furthermore, we use correlations between the clasts' sphericities and transport distances to infer
26 a transport time control on the shape of the clasts. We thus suggest that the grain size distribution
27 of gravel bars and the fabric of individual clasts has dynamically adjusted to water and sediment
28 flux and their specific time scales.

29

30 **1. INTRODUCTION**

31 The size and shape of gravels bear crucial information about (i) the transport dynamics of
32 mountain rivers (Hjulström, 1935; Shields, 1936; Blissenbach, 1952; Koiter et al., 2013;
33 Whittaker et al., 2007; Duller et al., 2012; Attal et al., 2015), (ii) the mechanisms of sediment
34 supply and provenance (Parker, 1991; Paola et al., 1992a, b; Attal and Lavé, 2006), and (iii)
35 environmental conditions such as uplift and precipitation (Heller and Paola, 1992; Robinson and
36 Slingerland, 1998; Foreman et al., 2012; Allen et al., 2013; Foreman, 2014). The mechanisms by
37 which grain size and shape change from source to sink have often been studied with flume
38 experiments (e.g. McLaren and Bowles, 1985; Lisle et al., 1993) and numerical models (Hoey
39 and Ferguson, 1994). These studies have mainly been directed towards exploring the controls on
40 the downstream reduction in grain size of gravel beds (Schumm and Stevens, 1973; Hoey and
41 Fergusson, 1994; Surian, 2002; Fedele and Paola, 2007; Allen et al., 2016). In addition, it has
42 been proposed that the grain size distribution particularly of mountainous rivers reflect the
43 erosional processes at work on the bordering hillslopes. This has recently been illustrated based
44 on a study encompassing all major rivers in the Swiss Alps with sources in various litho-tectonic
45 units of the Central European Alps (Litty and Schlunegger, 2017). Among the various processes,
46 the supply of material through landsliding (van den Berg and Schlunegger, 2012) and torrential

47 floods in tributary rivers (Bekaddour et al., 2013) were proposed to have the greatest influence
48 on the grain size distribution in these rivers (Allen et al., 2013), where tributary pulses of
49 sediment supply alter the caliber of the trunk stream material. Accordingly, the nature of
50 erosional processes on valley flanks are likely to have a measurable impact on the supply of
51 material to the valleys' trunk rivers, and thus on the sediment caliber in these streams.

52 Among the various conditions, hillslope erosion and the supply of material to the trunk stream
53 has been shown to mainly depend on: (i) tectonic uplift resulting in steepening of the entire
54 landscape (Dadson et al., 2003; Wittmann et al., 2007; Ouimet et al., 2009), (ii) earthquakes and
55 seismicity causing the release of large volumes of landslides (Dadson et al., 2003; McPhillips et
56 al., 2014), (iii) precipitation rates and patterns, controlling the streams' runoff and shear stresses
57 (Litty et al., 2017), and (iv) bedrock lithology where low erodibility lithologies are sources of
58 larger volumes of material (Korup and Schlunegger, 2009). Because most of the bedload
59 material of rivers has been derived from hillslopes bordering these rivers, as mapping and grain
60 size analyses of modern rivers in the Swiss Alps have shown (Bekaddour et al., 2014; Litty and
61 Schlunegger, 2017), it is very possible that the grain size distribution of modern rivers either
62 reflect the seismic processes at work, or rather reveal the response to the climate conditions such
63 as rainfall rates and the shear stresses of rivers.

64 The western margin of the Peruvian Andes represents a prime example where these mechanisms
65 and related controls on the grain size distribution of river sediments can be explored. In
66 particular, this mountain belt experiences intense and frequent earthquakes (Nocquet et al., 2014)
67 in response to subduction of the oceanic Nazca plate beneath the continental South American
68 plate at least since late Jurassic times (Isacks, 1988). Therefore, it is not surprising that erosion
69 and the transfer of material from the hillslopes to the rivers has been considered to strongly

70 depend on the occurrence of earthquakes, as measured ^{10}Be concentrations in pebbles suggest
71 (McPhillips et al., 2014). On the other hand, it has also been proposed that denudation in this
72 part of the Andes is controlled by the distinct N-S and E-W precipitation rate gradients. These
73 inferences have been made based on concentrations of in-situ cosmogenic ^{10}Be measured in
74 river-born quartz (Abbühl et al., 2011; Carretier et al., 2015; Reber et al., in press), and on
75 morphometric analyses of the western Andean landscape (Montgomery et al., 2001). Because
76 erosion has been related to either the occurrence of earthquakes and thus to tectonic processes
77 (McPhillips et al., 2014) or rainfall rates (Abbühl et al., 2011; Carretier et al., 2015) and thus to
78 the stream's mean annual runoff (Reber et al., in press), and since hillslope erosion and the
79 supply of material to trunk streams is likely to influence, or at least to perturb, the caliber of the
80 bedload material in mountainous streams (Bekaddour et al., 2013), it is possible that the grain
81 size pattern in Peruvian trunk rivers reflects the ensemble of these mechanisms at work.

82 Here we present data on sediment grain properties from rivers situated on the western margin of
83 the Peruvian Andes (Figure 1A) in order to elucidate the possible effects of intrinsic factors such
84 as morphometric properties of the drainage basins, and extrinsic properties (runoff and seismic
85 activity) on sediment grain properties. To this extent, we collected grain size data from gravel
86 bars of each stream along the entire western Andean margin of Peru that are derived from 21,
87 over 700-km²-large basins. Sampling sites were situated at the outlets of valleys close to the
88 Pacific Coast.

89

90 *1.1 Geologic and tectonic setting*

91 The study area is located at the transition from the Peruvian Andes to the coastal lowlands along
92 a transect from the cities of Trujillo in the north (8°S) to Tacna in the south (18°S). In northern

93 and central Peru, a flat, up-to 100 km, broad coastal forearc plain with Paleogene-Neogene and
94 Quaternary sediments connects to the western Cordillera. This part of the western Cordillera
95 consists of Cretaceous to late Miocene plutons of various compositions (diorite, but also tonalite,
96 granite and granodiorite) that crop out over an almost continuous 1600-km long arc that is
97 referred to as the Coastal Batholith (e.g. Atherton, 1984; Mukasa, 1986; Haederle and Atherton,
98 2002; Figure 1B). In southern Peru, the coastal plain gives way to the Coastal Cordillera that
99 extends far into Chile. The western Cordillera comprises the central volcanic arc region of the
100 Peruvian Andes with altitudes of up to 6768 m.asl, where currently active volcanoes south of
101 14°S of latitude are related to a steep slab subduction. On the other hand, Cenozoic volcanoes in
102 the central and northern Peruvian arc have been extinct since c. 11 Ma due to a flat slab
103 subduction, which inhibited magma upwelling from the asthenosphere (Ramos, 2010).

104 The bedrock of the Western Cordillera is dominated by Paleogene, Neogene and Quaternary
105 volcanic rocks (mainly andesitic or dacitic tuffs, and ignimbrites) originating from distinct
106 phases of Cenozoic volcanic activity (Vidal, 1993). These rocks rest on Mesozoic and Early
107 Tertiary sedimentary rocks (Figure 1B).

108 The local relief along the western Cordillera has been formed by deeply incising rivers that flow
109 perpendicular to the strike of the Andes (Schildgen et al., 2007). The morphology of the
110 longitudinal stream profiles is characterized by two segments separated by a distinct knickzone
111 (Trauerstein et al., 2013). These geomorphic features have formed through headward retreat in
112 response to a phase of enhanced surface uplift during the late Miocene (e.g., Schildgen et al.,
113 2007). Upstream of these knickzones, the streams are mainly underlain by Tertiary
114 volcanoclastic rocks, while farther downstream incision has disclosed the Coastal Batholith and
115 older meta-sedimentary units (Trauerstein et al. 2013). The upstream edges of these knickzones

116 also delineate the upper boundaries of the major sediment sources (Litty et al., 2017). In contrast,
117 little to nearly zero clastic material has been derived from the headwater reaches in the Altiplano,
118 where the flat landscape has experienced nearly zero erosion, as ^{10}Be -based denudation rate
119 estimates (Abbühl et al., 2011) and provenance tracing have shown (Litty et al., 2017).

120 The tectonic conditions of the western Andean are characterized by strong N-S gradients in
121 Quaternary uplift, seismicity and long-term subduction processes. In particular, the coastal
122 segment south of 13°S and particularly south of 16°S hosts raised Quaternary marine terraces
123 (Regard et al., 2010), suggesting the occurrence of surface uplift at least during Quaternary
124 times. This is also the segment of the Andes where the Nazca plate subducts at a steep angle and
125 where the current seismicity implies a relatively high degree of interseismic coupling, resulting
126 in a high frequency of earthquakes with magnitudes $M > 4$ (Nocquet et al., 2014). In contrast, the
127 northern segment of the coastal Peruvian margin hosts a coastal plain that has been subsiding
128 (Hampel, 2002). Also in this region, the interseismic coupling along the plate interface is low, as
129 revealed by the relatively low frequency of earthquake occurrence (Nocquet et al., 2014).

130

131 *1.2 Climatic setting*

132 The N-S-oriented, annual rainfall rates decrease from 1000 mm per year near the Equator to 0
133 mm along the coast in southern Peru and northern Chile (Huffman et al., 2007; Figure 1C). The
134 Peruvian western margin shows an E-W contrasting precipitation pattern with high annual
135 precipitation rates up to 800 mm on the Altiplano and c. 0 mm per year on the coast (Figure 1C).
136 This precipitation gradient in the western Andes is related to the position of the Intertropical
137 Convergence Zone (ITCZ, inset of Figure 1C) associated with an orographic effect on the eastern
138 side of the Andes (Bookhagen and Strecker, 2008). During austral summer (January) the center

139 of the ITCZ is located farther south, transferring the moisture from the Amazon tropical basin to
140 the Altiplano (Garreaud et al., 2009) and leading to a wet climate on the Altiplano with strong
141 precipitation rates. During austral winter, the Altiplano is under the influence of dry air masses
142 from the subsiding branch of the Hadley cell that result in a more equatorial position of the ITCZ
143 and in a dry persistent westerly wind with almost no precipitation on the Altiplano. Additionally,
144 the Andes form an orogenic barrier preventing Atlantic winds and moisture to reach the coast.
145 Only in northern Peru around 5°S latitude, the ocean water sufficiently warms up because of the
146 mixing with the tropical current derived from Ecuador, resulting in precipitation in northern
147 Peru. In addition, every 2 to 10 years, near to the Equator, the Pacific coast is subjected to strong
148 precipitation resulting in high flood variability, related to the El Niño weather phenomenon
149 (ENSO) (DeVries, 1987).

150

151 **2. SITE SELECTION AND METHODS**

152 We selected river basins between 8°S and 18°S latitude situated on the western margin of the
153 Peruvian Andes, because of the presence of marked N-S contrasts in precipitation rates and the
154 presence of strong seismic activity due to the subduction of the Nazca plate (Table 1). Only the
155 main river basins were selected, which were generally larger than 700 km². These basins have
156 recently been analyzed for ¹⁰Be-based catchment averaged denudation rates and mean annual
157 water fluxes (Reber et al., in press). This allows us to explore whether sediment flux, which
158 equals the product between ¹⁰Be-based denudation rates and basin size, has a measurable impact
159 on the grain size pattern. In addition, also for these streams, Reber et al. (in press) presented data
160 on mean annual water discharge using the records of gauging stations and the TRMM-

161 V6.3B43.2 precipitation dataset as basis (Huffman et al., 2007). We will use this information to
162 explore the controls of water shear stresses on the caliber of the bedload material (see below).

163 Sampling sites were situated in the main river valleys in the western Cordillera just before it
164 gives way to the coastal margin. We selected the downstream end of these rivers because the
165 grain size pattern at these sites is likely to record the ensemble of the main conditions and forces
166 controlling the supply of material to the trunk stream farther upstream. We randomly selected c.
167 five longitudinal bars where we collected our grain size dataset. Sampling sites are all accessible
168 along the Pan-American Highway (see Table 1 for the coordinates of the sampling sites).

169 Additionally, the Majes basin (marked with red color on Figure 1A), which is part of the 21
170 studied basins, has been sampled at five sites from upstream to downstream to explore the effects
171 related to the sediment transport processes for a section across the mountain belt, but along
172 stream (Figure 2; Table 2). The Majes basin has been chosen because of its easy accessibility in
173 the upstream direction and because the morphology of this basin has been analyzed in a previous
174 study (Steffen et al., 2010).

175 It has been shown that using a standard frame with fixed dimensions to assist gravel sampling
176 reduces user-biased selections of gravels (Marcus et al., 1995; Bunte and Abt, 2001a). In order to
177 reduce this bias, we substituted the frame by shooting an equal number of photos at a fixed
178 distance (c. 1 m) from the ground surface at each longitudinal bar. Ten photos were taken from
179 an approximately 10 m²-large area to take potential spatial variabilities among the gravel bars
180 into account. From those photos, the intermediate *b*-axes and the ratio of the *b*-axes and the long
181 *a*-axis of around 500 randomly chosen pebbles were manually measured (Bunte and Abt, 2001b)
182 and processed using the software program ImageJ (Rasband, 1997). Our sample population

183 exceeds the minimum number of samples needed for statistically reliable estimations of grain
 184 size distributions in gravel bars (Howard, 1993; Rice and Church, 1998).

185 The pebbles were characterized on the basis of their median (D_{50}), the D_{84} and the coarse (D_{96})
 186 fractions. This means that 50%, 84% and 96% of the sampled fraction is finer grained than the
 187 50th, 84th and 96th percentile of the samples. On a gravel bar, pebbles tend to lie with their short
 188 axis perpendicular to the surface, thus exposing their section that contains the a - and b -axes
 189 (Bunte and Abt, 2001b). However, the principal limitation is the inability to accurately measure
 190 the fine particles < 3 mm (see also Whittaker et al., 2010). While we cannot resolve this problem
 191 with the techniques available, we do not expect that this adds a substantial bias in the grain size
 192 distributions reported here as their relative contributions to the point-count results are minor (i.e.
 193 $< 5\%$, based on visual inspection of the digital images).

194 Catchment-scale morphometric parameters and characteristics, including drainage area slope
 195 angle and slope at sampling site (Table 1), were extracted from the 90-m-resolution digital
 196 elevation model Shuttle Radar Topography Mission (SRTM; Reuter et al., 2007). The distances
 197 from the sample sites to the upper edge of the Western Escarpment (Trauerstein et al., 2013)
 198 have been measured.

199 Because grain size patterns largely depend on water shear stresses, we explored where such
 200 correlations exist for the Peruvian rivers. We thus computed water shear stresses τ following by
 201 Hancock and Anderson (2002) and Litty et al. (2016), where:

$$202 \quad \tau = 0.54\rho g \left(\frac{Q}{W}\right)^{0.55} S^{0.93} \quad (1).$$

203 Here, $\rho=1000 \text{ kg/m}^3$ is the water density, g the gravitational acceleration, Q (m^3/s) is mean
 204 annual water discharge that we have taken from Reber et al. (in press), W (m) the channel width,

205 and S (m/m) is the channel gradient. Channel gradients at the sampling sites were calculated
206 using the 90-m-resolution DEM as a basis. In addition, stream channel widths at each sampling
207 site and at the time of the sampling campaign (May 2015) were measured on satellite images
208 when available, and on field images with uncertainties of about 2 m. In addition, we have
209 considered the basin mean denudation rates (Reber et al., in press; Table 1) as variable because
210 larger denudation rates points towards a larger relative sediment flux, which in turn could
211 influence downstream fining rates of grain sizes (Dingle et al., 2017).

212 Possible covariations and correlations between grain size and/or morphometric parameters and
213 basin characteristics were evaluated using Pearson correlation coefficients; thus providing
214 corresponding r -values (Table 3) and p -values with a significance level $\alpha < 0.1$ (Table 4).
215 The r -values measure the linear correlations between variables. The values range between +1 and
216 -1, where +1 reflects a 100% positive linear correlation, 0 reflects no linear correlation, and -1
217 indicates a 100% negative linear correlation (Pearson, 1895). Threshold values of $> + 0.30$ and $<$
218 $- 0.30$ were selected to assign positive and negative correlations, respectively.

219

220 **3. RESULTS**

221 **3.1 Grain size**

222 The results of the grain size measurements reveal a large variation for the b -axis where the
223 values of the D_{50} range from 1.3 cm to 5.5 cm for rivers along the entire western Peruvian
224 margin (Figure 3h; Table 1). Likewise, D_{84} values vary between 3 cm and 10.5 cm. The sizes for
225 the D_{96} reveal the largest spread, ranging from 6 cm to 31 cm. In addition, the ratio between the
226 lengths of the b -axis and a -axis (sphericity ratio) varies between 0.67 and 0.74 (Figure 3i). Note
227 that between 15.6°S and 13.7°S , no gravel bars are encountered in the rivers where they leave the

228 mountain range, and only sand bars can be found. Therefore no results are exhibited for these
229 latitudes (Figure 3h and 3i).

230

231 ***3.2 The Majes basin***

232 The D_{50} percentile of the b -axis decreases from 6.2 cm at 106 km river upstream to a value of 5.2
233 cm at 20 km upstream for the Pacific coast (Figures 2 and 4 and Table 2). Likewise, the D_{84}
234 decreases from 19 cm to 8.7 cm, and the D_{96} decreases from 31 cm to 11.6 cm (Figure 4).
235 Geomorphologists widely accept the notion that the downstream hydraulic geometry of alluvial
236 channels reflects the decrease of particle size within an equilibrated system involving stream
237 flow, channel gradient, sediment supply and transport (e.g. Hoey and Ferguson, 1994; Fedele and
238 Paola, 2007; Attal and Lavé, 2009). Sternberg (1875) formalized these relations and predicted an
239 exponential decline in particle size in gravel bed rivers as a consequence of abrasion and
240 selective transport where the gravel is transported downstream. The relation follows the form: D_x
241 $= D_0 e^{-\alpha x}$ (Sternberg, 1875). Here, the exponent α decreases from 0.3 for the largest percentile
242 (i.e., the D_{96}) to c. 0.1 for the D_{50} (Figure 4).

243

244 ***3.3 Correlations between grain sizes and morphometric properties***

245 Table 3 shows the Pearson correlation coefficients (r-value) between the grain sizes, the
246 morphometric parameters and the characteristics of the basins. As was expected, the D_{50} , D_{84} and
247 D_{96} all strongly correlate with each other ($0.73 < r\text{-value} < 0.93$), but the b/a ratios do not
248 correlate with any of the 3 percentiles ($-0.1 < r\text{-value} < 0.1$). The D_{50} values positively (but
249 weakly) correlate with the sizes of the catchment area ($r\text{-value} = 0.31$), the distances from the
250 Western Escarpment ($r\text{-value} = 0.35$), the mean annual shear stress at the sampling site ($r\text{-value} =$

251 0.23), the denudation rates (r-value = 0.34) and the sediment fluxes (r-value = 0.42; Figure
252 5A). The sediment fluxes show the highest significance level; p-value = 0.05 (Table 4). The D_{84}
253 and the D_{96} values correlate positively with the shear stress exerted by the water on an mean
254 annual basis with r-value = 0.33 and 0.39 and p-value = 0.14 and 0.08 respectively (Figure 5B
255 and C).

256 The ratio of the intermediate axis over the long axis negatively correlates with the distance from
257 the Western Escarpment (r-value = -0.33), but a strong and positive correlation is found with the
258 mean slope angles of the basins (r-value = 0.63; p-value = 0.01; Figure 5D).

259

260 **4. DISCUSSION**

261 4.1 CONTROLS ON GRAIN SIZE

262 *Downstream fining trends in the Majes basin indicate fluvial controls*

263 In fluvial environments, the sorting of the sediment depends on the downstream distance from its
264 source (Hoey and Ferguson, 1994; Kodoma, 1994; Paola and Seal, 1995). This is particularly the
265 case for the Majes river, where the sorting gets better in the downstream direction. In particular,
266 we do see an exponential downstream fining trend of the three percentiles in the Majes river
267 (Figure 4). This is somewhat surprising because sufficiently voluminous sediment input from
268 other sources may perturb any downstream fining trends in the grain size distribution (Rice and
269 Church, 1998). Likewise, in the Majes basin, the sediment supply from the hillslopes to the trunk
270 stream has occurred mainly through debris flow processes and landsliding (Steffen et al., 2010;
271 Margirier et al., 2015). Accordingly, while the supply of hillslope-derived material is likely to
272 have been accomplished by mass wasting processes, the evacuation and transport of this

273 sediment down to the Pacific Ocean has predominantly occurred through fluvial transport, as the
274 exponential downstream fining of the grains implies.

275

276 *Absence of gravels in rivers between 15.6°S and 13.7°S*

277 In the rivers located between 15.6°S and 13.7°S, no gravel bars are encountered where these
278 rivers leave the mountain range, and only sand bars can be found. This suggests that the transition
279 from a gravel- to a sand-covered bed, i.e. the gravel front, is located along a more upstream reach
280 of these rivers. This transition is generally rapid (Dingle et al., 2017) and often associated with a
281 break in slope (Knighton, 1999). The gravel-sand transition has been interpreted to be controlled
282 by either the elevation of the local base level, an excess of sand supply, and breakdown of fine
283 gravels by abrasion (Dingle et al., 2017), or a combination of these parameters (Knighton, 1999).
284 In our case, these rivers do not show any particular differences compared to the other rivers
285 where coastal gravel bars have been found. In particular, there is no particular evidence why
286 preferential breakdown of gravels along these rivers should be more efficient than in rivers
287 farther north and south because the upstream morphometry and bedrock geology is similar. The
288 other explanation would be an excess of sand supplied to these rivers. However, available
289 information and geological maps do not display any major differences in bedrock lithologies
290 along strike (Figure 1B), but we note that the resolution of the geological map does not provide
291 enough detail about the weathering of the bedrock or the amount of regolith, which could be a
292 source of sand. However, these rivers are situated in the segment where the buoyant Nazca Ridge
293 is being subducted beneath the South American continental plate (Figure 3), which resulted in an
294 uplift pulse of the forearc during Pliocene-Quaternary times, accompanied by enhanced erosion
295 on the surface and at interface between the subducting and the hangingwall plate through

296 tectonic shear (Hampel, 2002; Hampel et al., 2004). These effects are generally recorded in the
297 morphology and sedimentary facies of the forearc (Hampel, 2002). Additionally, based on a
298 detailed morphometric analysis of the region, Wipf et al. (2008) showed that this coastal uplift
299 has rerouted and deflected the rivers in this area and has lengthened the downstream end of these
300 rivers. It is thus possible that these tectonically-driven mechanisms caused the gravel front to
301 step back farther into the mountain range, with the effect that the downstream terminations of
302 these rivers only display sand bars. But we note that this interpretation warrants further detailed
303 investigations, which includes a down-stream survey of the sediments in these rivers from the
304 headwaters to the site where they discharge into the Pacific Ocean (similar to the analyses made
305 along the Majes river, please see above).

306

307 *Grain size and earthquake frequency*

308 Landslides and debris flows represent the main processes of hillslope erosion and the main
309 source of sediment in tectonically active orogens (Hovius et al., 1997; Korup et al., 2011). They
310 are generally associated with triggers such as earthquakes and generally supply coarse and
311 voluminous sediments to the trunk rivers (Dadson et al., 2003; McPhillips et al., 2014). In that
312 sense we would infer a positive correlation between the frequency of large earthquakes and the
313 grain size where an increase of earthquake frequency would induce an increase of landslide
314 occurrence, thereby supplying coarser grained sediment from the hillslopes to the rivers.
315 However, no correlation has been found between the seismicity and the grain size data when
316 looking at the number of recorded historical earthquakes (Figure 3). We then infer that seismic
317 activity and particularly the subduction mechanisms do not exert a measurable control on the
318 grain size in the rivers of the western Peruvian Andes. Nevertheless, we do consider that the lack

319 of gravels in rivers where the subduction of the buoyant Nazca ridge has caused uplift of the
320 hangingwall plate was explained by a tectonic driving force (see section above). In particular,
321 since this uplift caused a re-routing of these rivers (Wipf et al., 2006) and thus a lengthening of
322 the river courses, the gravel front might have stepped back relative to the river mouth into the
323 Pacific Ocean, as we have noted above.

324

325 *Supply control on the grain size pattern*

326 Because we have found positive correlations between the D_{50} and the basins scale properties
327 (basin area, mean basin slope, mean basin denudation rates, water shear stresses, sediment
328 fluxes), we infer that the mean grain size reflects the ensemble of a complex pattern of erosional
329 and sediment transport processes operating in the Peruvian basins. In particular, the positive
330 correlation between the size of the D_{50} , the basin averaged denudation rate and the morphometry
331 of these basins leads us to propose that environmental factors exert a major control on the pattern
332 of the D_{50} encountered for the rivers in western Peru. In this context, it is very likely that the bulk
333 supply of hillslope-derived sediment to the trunk stream increases with larger basin size, mean
334 basin slope and basin-averaged denudation rate, as the recent study by Reber et al. (in press) has
335 revealed. Furthermore, while tectonic processes such as earthquake frequencies have no
336 measurable impact on the grain size pattern, as we have outlined above, we consider it more
337 likely that hillslope processes occurred in response to strong precipitation events, as suggested
338 Bekaddour et al. (2014) and as recently shown by the devastating mudflows and floods in coastal
339 Peru (March 2017) due to an El Niño event. The consequence is that higher denudation rates, and
340 larger basins, result in a larger sediment flux in the trunk stream, which in turn yields an increase
341 in the scale at which transport and deposition of material occurs (Armitage et al., 2011). Related

342 mechanisms are likely to shift gravel fronts in rivers towards more distal sites, which could
343 positively influence the mean grain size percentile of the trunk rivers in the sense that the
344 material will coarsen.

345 We note that following the results from the Majes basin, we would expect a decrease in the size
346 of the D_{50} for larger basins and larger distances from the uppermost edge of the Western
347 Escarpment, because of larger transport distances and thus a higher impact related to any
348 downstream fining trends. While these mechanisms, i.e, fining trends of all percentiles, are likely
349 to be observed at the scale of individual basins, we do not consider that transport distance alone
350 is capable of explaining the D_{50} pattern in rivers at the scale of the entire western Andean margin
351 of Peru. In particular, the fining rate not only depends on the abrasion (Dingle et al., 2017) and
352 the selective entrainment processes upon transport (Ashword and Ferguson, 1989), but also on
353 the rate at which sediment is supplied to the rivers (e.g. McLaren, 1981; McLaren and Bowles,
354 1985). Particularly, in basins where the rate of hillslope-derived supply of sediment from the
355 hillslopes to the trunk stream is large, the overall downstream fining rate of the material is
356 expected to be less, because lateral sediment pulses are likely to cause the grain size fraction to
357 increase. This has been exemplified for modern examples in the Swiss Alps (Bekaddour et al.,
358 2013) and for the Pisco river in Peru (Litty et al., 2016), where fining rates of modern stream
359 sediment, which record low denudation rates (Bekaddour et al., 2014), are greater than those of
360 Pleistocene fluvial terraces, which record fast paleo-denudation rates (Bekaddour et al., 2014).
361 Support for this interpretation is also provided by the positive correlation between the D_{50} and
362 the mean basin denudation rate, where larger hillslope-derived material is likely to increase the
363 overall sediment flux within the rivers. The consequence is a downstream shift of the gravel front
364 and thus of the larger size fraction of the material, as we have interpreted above.

365

366 *Hydrological control on the grain size distribution*

367 Hydrodynamic conditions of rivers influence the grain size upon entrainment, transport, and
368 deposition (Hjulström, 1935; Komar and Miller 1973; Surian, 2002). In this sense, rivers with
369 larger shear stresses are capable of transporting larger clasts. Accordingly, at equilibrium
370 conditions, we expect a correlation between the grain-size distributions and the shear stresses
371 exerted by the water at our surveying sites, because greater flow strengths are required to entrain
372 the coarser fractions of the material that make up the river beds (e.g., Ferguson et al. 1989;
373 Komar and Shih 1992). This is the case in our study where the grain sizes correlate with the
374 shear stress values. Interestingly, the correlation coefficients between the shear stress and the
375 grain size percentiles increase from 0.23 for the D_{50} to 0.33 for the D_{84} and to 0.39 for the D_{96} .
376 This suggests that the shear stress exerted by mean annual water flows has a greater impact on
377 the coarse fractions than on the fine fractions of the stream sediments. While we cannot fully
378 explain why the larger percentiles reveal a better correlation with shear stresses of mean annual
379 flow conditions with the available dataset, we do infer a hydraulic control on grain size
380 distribution of the Peruvian rivers.

381

382 4.2 TRANSPORT DISTANCE AND SLOPE ANGLE CONTROLS ON SPHERICITY

383 We consider a control of the transport distance on the sphericity of the pebbles. We indeed see a
384 negative correlation between the sphericity and the distance from the Western Escarpment where
385 the major sediment sources are situated, as provenance tracing investigations have shown (Litty
386 et al., 2017). This suggests a decrease of the sphericity with a larger transport distance. As
387 particles are transported over longer distances, we actually would expect abrasion (Dingle et al.,

388 2017) to equalize the length of the three axes, thus making a particle more spherical. While this
389 concept is likely to be valid for pebbles with a homogenous fabric, it likely fails to describe the
390 abrasion and break-down of material with an inherited planar geologic fabric (such as gneisses
391 and sediments). Indeed, pebbles flatten as effects of abrasion and 3D heterogeneities of bedrock
392 that becomes more obvious with time and transport distance (Sneed and Folk, 1958). We note
393 that this is only valid if we assume a linear correlation between river length and transport time.
394 The reincorporation of previously abraded gravels from earlier erosion and multiple transport
395 cycles of clasts that were temporarily stored in cut-and-fill terrace sequences, as e.g., put forward
396 by Bekaddour et al. (2014) in their study about cut-and-fill terraces in the Pisco valley at c.
397 13.7°S latitude, would positively contribute to this effect upon increasing the time scale of
398 sediment evacuation.

399 Additionally, we consider a control of the mean catchment slope on the sphericity of the pebbles,
400 where correlations are positive, i.e. the steeper a basin the rounder the pebbles (Figure 5). We do
401 not consider that this pattern is due to differences in exposed bedrock in the hinterland because
402 the litho-tectonic architecture is fairly constant along the entire Peruvian margin (Figure 1).
403 Instead, the observations point toward the same control mechanisms on the pebble sphericity as
404 noted above. Steeper slope angles are most likely associated with faster denudation rates as the
405 Peruvian study by Reber et al. (in press) has shown. Accordingly, we infer a shorter transport
406 distance of the material and thus a shorter time scale of transport compared to the evacuation
407 time in long and less steep rivers. Similar to what we have noted above, we see the positive
408 correlation between mean hillslope angle and the sphericity of pebbles as a very likely
409 consequence of shorter transport times in steeper basins, but we note that this hypothesis needs to

410 be confirmed by detailed real-time surveys of material transport from sources down to the end of
411 these rivers.

412

413 **Conclusion**

414 We have conducted a grain size analysis of gravel bars in all major rivers that are situated on the
415 western Andean margin of Peru where they leave the mountain belt. We have not found any
416 correlations to the current seismic regimes, where a larger seismicity is expected to increase the
417 supply of coarse-grained material. Instead, we found positive correlations between water shears
418 stresses, mean basin denudation rates, mean basin slopes and basin sizes on nearly all grain size
419 percentiles. We interpret these results as the combined effect of various geomorphic conditions
420 where larger denudation rates operating in larger basins, and steeper slopes, paired with larger
421 flow shear stresses, are capable of transporting more and coarser-grained material. Furthermore,
422 we unravel a transport time control on the shape of the clasts where steeper slopes and smaller
423 basins (i.e., shorter distances to the edge of the Western Escarpment) are anticipated to shorten
424 the residence time of the clasts in the system, thereby yielding more spherical clasts. In
425 particular, longer residence times would allow abrasion to be more selective because of a planar
426 lithologic fabric of most of the clasts, which in turn, would cause clasts to flatten upon longer
427 exposure towards abrasion. This suggest that the ensemble of erosional and sediment transport
428 processes have reached an equilibrium at the scale of individual clasts, but also at the reach scale
429 of rivers where the sedimentary architecture and the clast fabric of the channel fill has
430 dynamically adjusted to water and sediment flux and their specific time scales. Accordingly, we
431 see the western Peruvian margin as ideal laboratory to analyze the relationships between
432 sediment supply and water runoff on the grain size pattern of the bedload, and we propose that

433 the bedload caliber of these streams has reached an equilibrium to environmental conditions
434 including water discharge, sediment flux and channel geometries.

435

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438

439 **REFERENCES CITED**

440 Abbühl, L.M., Norton, K.P., Jansen, J.D., Schlunegger, F., Aldahan, A., and Possnert, G., 2011,
441 Erosion rates and mechanisms of knickzone retreat inferred from ¹⁰Be measured across
442 strong climate gradients on the northern and central Andes Western Escarpment: *Earth*
443 *Surface Processes and Landforms*, v. 36, p. 1464–1473.

444 Allen, G. H., Barnes, J. B., Pavelsky, T. M. and Kirby, E., 2013, Lithologic and tectonic controls
445 on bedrock channel form at the northwest Himalayan front: *Journal of Geophysical*
446 *Research: Earth Surface*, v. 118, no. 3, p. 1806-1825.

447 Allen, P. A., Michael, N. A., D'Arcy, M., Roda-Boluda, D. C., Whittaker, A. C., Duller, R. A.,
448 and Armitage, J. J., 2016. Fractionation of grain size in terrestrial sediment routing
449 systems. *Basin Research*.

450 Armitage, J. J., Duller, R. A., Whittaker, A. C., and Allen, P. A., 2011. Transformation of
451 tectonic and climatic signals from source to sedimentary archive. *Nature Geoscience*,
452 4(4), 231-235.

453 Ashworth, P. J. and Ferguson, R. I., 1989. Size-selective entrainment of bed load in gravel bed
454 streams. *Water Resources Research*, v. 25(4), p. 627-634.

455 Atherton, M. P., 1984. The coastal batholith of Peru. In *Andean Magmatism* (pp. 168-179).
456 Birkhäuser Boston.

457 Attal, M. and Lavé, J., 2006, Changes of bedload characteristics along the Marsyandi River
458 (central Nepal): Implications for understanding hillslope sediment supply, sediment load
459 evolution along fluvial networks, and denudation in active orogenic belts: *Geological*
460 *Society of America Special Papers*, v. 398, p.143-171.

- 461 Attal, M. and Lavé, J., 2009. Pebble abrasion during fluvial transport: experimental results and
462 implications for the evolution of the sediment load along rivers. *J. Geophys. Res.*
463 114:F04023. doi:10.1029/2009JF001328.
- 464 Attal, M., Mudd, S. M., Hurst, M. D., Weinman, B., Yoo, K. and Naylor, M., 2015, Impact of
465 change in erosion rate and landscape steepness on hillslope and fluvial sediments grain
466 size in the Feather River basin (Sierra Nevada, California): *Earth Surface Dynamics*, v. 3,
467 p. 201-222.
- 468 Bekaddour, T., Schlunegger, F., Attal, M., and Norton, K. P., 2013. Lateral sediment sources and
469 knickzones as controls on spatio-temporal variations of sediment transport in an Alpine
470 river. *Sedimentology*, v. 60(1), p. 342-357.
- 471 Bekaddour, T., Schlunegger, F., Vogel, H., Delunel, R., Norton, K. P., Akçar, N., and Kubik, P.,
472 2014. Paleo erosion rates and climate shifts recorded by Quaternary cut-and-fill
473 sequences in the Pisco valley, central Peru. *Earth and planetary science letters*, v. 390, p.
474 103-115.
- 475 Blissenbach, E., 1952. Relation of surface angle distribution to particle size distribution on
476 alluvial fans: *J. Sediment. Petrol.*, v. 22, p. 25–28.
- 477 Bookhagen, B. and Strecker, M. R., 2008, Orographic barriers, high-resolution TRMM rainfall,
478 and relief variations along the eastern Andes, *Geophysical Research Letters*, v. 35, p.
479 L06403.
- 480 Bunte, K., Abt, S.R., 2001a. Sampling frame for improving pebble count accuracy in coarse
481 gravel-bed rivers. *Journal of the American Water Resources Association*, v. 37 (4), p.
482 1001- 1014.
- 483 Bunte, K., Abt, S.R., 2001b. Sampling surface and subsurface particle-size distributions in
484 wadable gravel- and cobble-bed rivers for analyses in sediment transport, hydraulics,
485 and streambed monitoring. General Technical Report RMRS-GTR-74. United States
486 Department of Agriculture; Forest Service; Rocky Mountain Research Station. Fort
487 Collings, USA, p. 428.
- 488 Carretier, S., Tolorza, V., Rodríguez, M. P., Pepin, E., Aguilar, G., Regard, V. and Hérail, G.,
489 2015. Erosion in the Chilean Andes between 27° S and 39° S: tectonic, climatic and
490 geomorphic control. *Geological Society, London, Special Publications*, v. 399(1), p. 401-
491 418.

- 492 Dadson, S. J., Hovius, N., Chen, H., Dade, W. B., Hsieh, M. L., Willett, S. D. and Lague, D.,
493 2003. Links between erosion, runoff variability and seismicity in the Taiwan orogen.
494 *Nature*, v. 426(6967), p. 648-651.
- 495 DeVries, T. J., 1987, A review of geological evidence for ancient El Nino activity in Peru. *J.*
496 *Geophys. Res.*, v. 92, no. 14, p. 471–14.
- 497 Dingle, E. H., Attal, M., and Sinclair, H. D., 2017. Abrasion-set limits on Himalayan gravel flux.
498 *Nature*, v. 544(7651), p. 471-474.
- 499 Duller, R. A., Whittaker, A. C., Swinehart, J. B., Armitage, J. J., Sinclair, H. D., Bair, A. and
500 Allen, P. A., 2012, Abrupt landscape change post-6 Ma on the central Great Plains,
501 USA: *Geology*, v. 40, p. 871-874.
- 502 Fedele, J. J. and Paola C., 2007, Similarity solutions for fluvial sediment fining by selective
503 deposition: *Journal of Geophysical Research: Earth Surface* (2003–2012), v. 112.
- 504 Ferguson, R. I., Prestegard, K. L. and Ashworth, P. J., 1989. Influence of sand on hydraulics
505 and gravel transport in a braided gravel bed river. *Water Resources Research*, v. 25(4), p.
506 635-643.
- 507 Foreman, B. Z., Heller, P. L. and Clementz, M. T., 2012, Fluvial response to abrupt global
508 warming at the Palaeocene/Eocene boundary: *Nature*, v. 491, no. 7422, p. 92-95
- 509 Foreman, B. Z., 2014, Climate-driven generation of a fluvial sheet sand body at the Paleocene–
510 Eocene boundary in north-west Wyoming (USA): *Basin Research*, v. 26, no. 2, p. 225-
511 241.
- 512 Garreaud, R. D., Vuille, M., Compagnucci, R., and Marengo, J., 2009, Present-day South
513 American climate. *Palaeogeography, Palaeoclimatology, Palaeoecology*, v. 281, no. 3, p.
514 180-195.
- 515 Haederle, M. and Atherton, M. P., 2002. Shape and intrusion style of the Coastal Batholith, Peru.
516 *Tectonophysics*, v. 345(1), p. 17-28.
- 517 Hampel, A., 2002. The migration history of the Nazca Ridge along the Peruvian active margin: a
518 re-evaluation. *Earth and Planetary Science Letters*, v. 203(2), p.665-679.
- 519 Hampel, A., Adam, J., and Kukowski, N., 2004. Response of the tectonically erosive south
520 Peruvian forearc to subduction of the Nazca Ridge: Analysis of three-dimensional
521 analogue experiments. *Tectonics*, 23(5).

- 522 Hancock, G. S. and Anderson, R. S., 2002. Numerical modeling of fluvial strath-terrace
523 formation in response to oscillating climate. *Geological Society of America Bulletin*, v.
524 114(9), p. 1131-1142.
- 525 Heller, P. L. and Paola, C., 1992, The large-scale dynamics of grain-size variation in alluvial
526 basins, 2: Application to syntectonic conglomerate: *Basin Research*, v. 4, no. 2, p. 91-
527 102.
- 528 Hjulström, F., 1935, Studies in the morphological activity of rivers as illustrated by the river
529 Fyris: *Bulletin of the Geological Institution of the University of Uppsala*, v 25, p. 221-
530 528.
- 531 Hoey, T. B. and Ferguson, R., 1994, Numerical simulation of downstream fining by selective
532 transport in gravel bed rivers: Model development and illustration: *Water resources*
533 *research*, v.30, p. 2251-2260.
- 534 Hovius, N., Stark, C. P. and Allen, P. A., 1997. Sediment flux from a mountain belt derived by
535 landslide mapping. *Geology*, v. 25(3), p. 231-234.
- 536 Howard, J.L., 1993. The statistics of counting clasts in rudites: a review with examples from the
537 upper Paleogene of southern California, USA. *Sedimentology* 40, 157-174.
- 538 Huffman, G. J., Bolvin, D. T., Nelkin, E. J., Wolff, D. B., Adler, R. F., Gu, G. and Stocker, E. F.,
539 2007, The TRMM multisatellite precipitation analysis (TMPA): Quasi-global, multiyear,
540 combined-sensor precipitation estimates at fine scales. *Journal of Hydrometeorology*, v.
541 8, no. 1, p. 38-55.
- 542 Isacks, B. L., 1988. Uplift of the central Andean plateau and bending of the Bolivian orocline.
543 *Journal of Geophysical Research: Solid Earth*, v. 93(B4), p. 3211-3231.
- 544 Knighton, A. D., 1999. The gravel–sand transition in a disturbed catchment. *Geomorphology*, v.
545 27(3), p. 325-341.
- 546 Kodoma, Y., 1994, Downstream changes in the lithology and grain size of fluvial gravels, the
547 Watarase River, Japan: Evidence of the role of abrasion in downstream fining: *Journal of*
548 *Sedimentary Research, Section A: Sedimentary Petrology and Processes*, v. 64A, p. 68-
549 75.
- 550 Koiter, A. J., Owens, P. N., Petticrew, E. L. and Lobb, D. A., 2013, The behaviour characteristics
551 of sediment properties and their implications for sediment fingerprinting as an approach
552 for identifying sediment source sin river basins: *Earth Science Reviews*, v. 125, p. 24-42.

- 553 Komar, P. D. and Miller, M. C., 1973. The threshold of sediment movement under oscillatory
554 water waves. *Journal of Sedimentary Research*, v. 43(4).
- 555 Komar, P. D. and Shih, S. M., 1992. Equal mobility versus changing bedload grain sizes in
556 gravel-bed streams. *Dynamics of gravel-bed rivers*, p. 73-106.
- 557 Korup, O. and Schlunegger, F., 2009. Rock-type control on erosion-induced uplift, eastern Swiss
558 Alps. *Earth and Planetary Science Letters*, v. 278(3), p. 278-285.
- 559 Korup, O. and Weidinger, J. T., 2011. Rock type, precipitation, and the steepness of
560 Himalayan threshold hillslopes. *Geological Society, London, Special Publications*, v.
561 353(1), p. 235-249.
- 562 Lisle, T.E., Iseya, F. and Ikeda, H., 1993, Response of a channel with alternate bars to a
563 decrease in supply of mixed-size bed load: A flume experiment: *Water resources*
564 *research*, v. 29, p. 3623–3629.
- 565 Litty, C., Duller, R., and Schlunegger, F., 2016. Paleohydraulic reconstruction of a 40 ka-old
566 terrace sequence implies that water discharge was larger than today. *Earth surface*
567 *processes and landforms*.
- 568 Litty and Schlunegger, 2017. Controls on Pebbles' Size and Shape in Rivers of the Swiss Alps.
569 *The Journal of Geology*., v. 125, p. 101–112.
- 570 Litty, C., Lanari, P., Burn, M., and Schlunegger, F., 2017, Climate-controlled shifts in sediment
571 provenance inferred from detrital zircon ages, Western Peruvian Andes. *Geology*. v. 45;
572 no. 1; p. 59–62.
- 573 Marcus, W.A., Ladd, S.C., Stoughton, J.A., Stock, J.W., 1995. Pebble counts and the role of
574 user-dependent bias in documenting sediment size distributions. *Water Resources*
575 *Research*, v. 31 (10), p. 2625-2631.
- 576 Margirier, A., Audin, L., Carcaillet, J., Schwartz, S., and Benavente, C., 2015, Tectonic and
577 climatic controls on the Chuquibamba landslide (western Andes, southern Peru). *Earth*
578 *Surface Dynamics*, 3(2), 281-289.
- 579 McLaren, P., 1981. An interpretation of trends in grain size measures. *Journal of Sedimentary*
580 *Research*, 51(2).
- 581 McLaren, P. and Bowles, D., 1985, The Effects of Sediment Transport on Grain-Size
582 Distributions: *Journal of Sedimentary Petrology*, v. 55, p. 457-470.

- 583 McPhillips, D., Bierman, P. R., & Rood, D. H., 2014. Millennial-scale record of landslides in the
584 Andes consistent with earthquake trigger. *Nature Geoscience*, v. 7(12), p. 925-930.
- 585 Montgomery, D. R., Balco, G. and Willett, S. D., 2001. Climate, tectonics, and the morphology
586 of the Andes. *Geology*, v. 29(7), p. 579-582.
- 587 Mukasa, S. B., 1986. Zircon U-Pb ages of super-units in the Coastal batholith, Peru: Implications
588 for magmatic and tectonic processes. *Geological Society of America Bulletin*, v. 97(2), p.
589 241-254.
- 590 Nocquet, J. M., Villegas-Lanza, J. C., Chlieh, M., Mothes, P. A., Rolandone, F., Jarrin, P. and
591 Martin, X., 2014. Motion of continental slivers and creeping subduction in the northern
592 Andes. *Nature Geoscience*, v. 7(4), p. 287-291.
- 593 Ouimet, W. B., Whipple, K. X., & Granger, D. E., 2009. Beyond threshold hillslopes: Channel
594 adjustment to base-level fall in tectonically active mountain ranges. *Geology*, v. 37(7), p.
595 579-582.
- 596 Paola, C., Heller, P. L. and Angevinet, C. L., 1992a, The large-scale dynamics of grain-size
597 variation in alluvial basins, 1: Theory: *Basin Research*, v. 4, p. 73-90.
- 598 Paola, C. and Seal, R., 1995, Grain size patchiness as a cause of selective deposition and
599 downstream fining: *Water Resources Research*, v. 31, p. 1395-1407.
- 600 Parker, G., 1991, Selective sorting and abrasion of river gravel. 1: Theory: *Journal of*
601 *Hydraulic Engineering*, v. 117, no. 2, p. 131-147.
- 602 Pearson, K., 1895, Notes on regression and inheritance in the case of two parents, *Proceedings of*
603 *the Royal Society of London*, v. 58, p. 240–242.
- 604 Ramos, V. A., 2010. The tectonic regime along the Andes: Present-day and Mesozoic regimes.
605 *Geological Journal*, v. 45(1), p. 2-25.
- 606 Rasband, W.S., ImageJ, U. S. National Institutes of Health, Bethesda, Maryland, USA,
607 <http://imagej.nih.gov/ij/>, 1997-2016.
- 608 Reber, R., Delunel, R., Schlunegger, F., Litty, C., Madella, A., Akçar, N., Christl, M. In press in
609 *Terra Nova*. Environmental controls on ¹⁰Be-based catchment averaged denudation rates
610 along the western margin of the Peruvian Andes.
- 611 Regard, V., Saillard, M., Martinod, J., Audin, L., Carretier, S., Pedoja, K. and Hérail, G., 2010.
612 Renewed uplift of the Central Andes Forearc revealed by coastal evolution during the
613 Quaternary. *Earth and Planetary Science Letters*, v. 297(1), p. 199-210.

- 614 Reuter, H. I., Nelson, A. and Jarvis, A., 2007. An evaluation of void-filling interpolation
615 methods for SRTM data. *International Journal of Geographical Information Science*, v.
616 21(9), p. 983-1008.
- 617 Rice, S. and Church, M., 1998, Grain size along two gravel-bed rivers: Statistical variation,
618 spatial pattern and sedimentary links: *Earth Surface Processes and Landforms*, v. 23, p.
619 345-363.
- 620 Robinson, R. A. and Slingerland, R. L., 1998, Origin of fluvial grain-size trends in a foreland
621 basin: the Pocono Formation on the central Appalachian basin: *Journal of Sedimentary*
622 *Research*, v. 68, no. 3.
- 623 Schildgen, T. F., Hodges, K. V., Whipple, K. X., Reiners, P. W. and Pringle, M. S., 2007, Uplift
624 of the western margin of the Andean plateau revealed from canyon incision history,
625 southern Peru. *Geology* 35, 523–526.
- 626 Schumm, S. A. and Stevens, M. A., 1973, Abrasion in place: a mechanism for rounding and size
627 reduction of coarse sediments in rivers: *Geology*, v. 1, p. 37-40.
- 628 Shields, A., 1936, Anwendung der Ähnlichkeitsmekanik und der Turbulenzforschung auf die
629 Geschiebebewegung, *Mittlung der preussischen Versuchsanstalt für Wasserbau und*
630 *Schiffbau*, 26. (Berlin).
- 631 Sneed, E.D., and Folk, R.L., 1958. Pebbles in the lower Colorado River, Texas a study in particle
632 morphogenesis. *The Journal of Geology*, 114-150.
- 633 Steffen, D., Schlunegger, F., and Preusser, F., 2010, Late Pleistocene fans and terraces in the
634 Majes valley, southern Peru, and their relation to climatic variations. *International*
635 *Journal of Earth Sciences*, v. 99(8), p. 1975-1989.
- 636 Sternberg, H., 1875, Untersuchungen über längen-und Querprofil geschiebeführender Flüsse, *Z.*
637 *Bauwes.*, 25, 486–506.
- 638 Surian, N., 2002, Downstream variation in grain size along an Alpine river: analysis of
639 controls and processes: *Geomorphology*, v. 43, p. 137-149.
- 640 Trauerstein, M., Norton, K. P., Preusser, F., and Schlunegger, F., 2013, Climatic imprint on
641 landscape morphology in the western escarpment of the Andes. *Geomorphology*, v. 194,
642 p. 76-83.

- 643 Van den Berg, F., and Schlunegger, F., 2012. Alluvial cover dynamics in response to floods of
644 various magnitudes: The effect of the release of glaciogenic material in a Swiss Alpine
645 catchment. *Geomorphology*, v. 141, p. 121-133.
- 646 Vidal, J. C., 1993, *Geologia de los cuadrangulos de Huambo y Orcopampa*, v 46. Instituto
647 Geologico Minero y Metalurgico, Lima.
- 648 Whittaker, A. C., Cowie, P. A., Attal, M., Tucker, G. E. and Roberts, G. P., 2007, Bedrock
649 channel adjustment to tectonic forcing: Implications for predicting river incision rates:
650 *Geology*, v. 35, no. 2, p.103-106.
- 651 Whittaker, A. C., Attal, M. and Allen, P.A., 2010, Characterising the origin, nature and fate of
652 sediment exported from catchment perturbed by active tectonics. *Basin Research*. v. 22. p.
653 809-828.
- 654 Wittmann, H., von Blanckenburg, F., Kruesmann, T., Norton, K. P., and Kubik, P. W., 2007.
655 Relation between rock uplift and denudation from cosmogenic nuclides in river sediment
656 in the Central Alps of Switzerland. *Journal of Geophysical Research: Earth Surface*,
657 112(F4).
- 658 Wipf, M., Zeilinger, G., Seward, D., and Schlunegger, F., 2008. Focused subaerial erosion
659 during ridge subduction: impact on the geomorphology in south-central Peru. *Terra Nova*,
660 v. 20(1), p. 1-10.

661

662 **FIGURES AND TABLES CAPTIONS**

663

664 **Table 1:** Location of the sampling sites with the altitude in meters above sea level. The table also
665 displays grain size results together with the rivers' and basins' properties and hydrological
666 properties.

667

668 **Table 2:** Location of the sampling sites in the Majes basin and grain size results in the Majes
669 basin.

670

671 **Table 3:** Results of the statistical investigations, illustrated here as correlation matrix of the r-
672 values. The values in bold show significant correlation between the grain size data and the
673 different catchment scale properties.

674

675 **Table 4:** Results of the statistical investigations, illustrated here as correlation matrix of the p-
676 values. The values in bold have a significance level $\alpha < 0.1$

677

678 **Figure 1: A:** Map of the studied basins showing the sampling sites and the western escarpment
679 (western escarpment modified after Trauerstein et al., 2013). The southern and northern group of
680 basins represent catchments displaying differences in terms of their sizes and relationships with
681 grain sizes (see Results) **B:** Geological map of the western Peruvian Andes. **C:** Map of the
682 precipitation rates showing the spatial extend of the ITCZ, modified after Huffman et al., 2007.

683

684 **Figure 2:** Geological map of the Majes basin overlain by the precipitation pattern (Precipitation
685 data from Steffen et al., 2010., where the black dashed lines show precipitation rates (mm/yr).
686 GS1 to GS5 represent sites where grain size data has been collected. The right corner shows the
687 Majes river long profile.

688

689 **Figure 3:** Topography of subducting Nazca plate, where slab depth data has been extracted from
690 earthquake.usgs.gov/data/slab/. This N-S projection also illustrates: a) tectonic lineaments such
691 as submarine ridges and MFZ: Mendaña Fracture Zone; NFZ: Nazca Fracture Zone; b) Holocene
692 Volcanoes; c) Earthquake data, taken from earthquake.usgs.gov/earthquakes/search/; number of
693 earthquakes $M > 4$ within 30 km radius window. d) Coastal elevation. The data has been extracted

694 from a 20 km-wide swath profile along the coast. The three lines represent maximum, mean and
695 minimum elevations within the selected swath; e) Catchment averaged denudation rates have
696 been corrected for quartz contents (Reber et al. in press); f) Mean annual precipitation rates
697 (Reber et al., in press); g) Mean annual water discharge (Reber et al., in press); h) Grain size
698 results for the intermediate (b)-axis of the pebbles in the rivers from north to south at the
699 sampling sites presented in Figure 1; i) Ratio between the intermediate axis and the long (a)-axis
700 (modified after Reber et al., in press).

701

702 **Figure 4:** Grain size results along the Majes River.

703

704 **Figure 5:** Correlations between the grain size data and the river parameters. **A:** D_{50} versus
705 sediment fluxes. **B:** D_{84} versus shear stress exerted by the water. **C:** D_{96} versus shear stress
706 exerted by the water. **D:** Ratio b/a versus mean catchment slope.

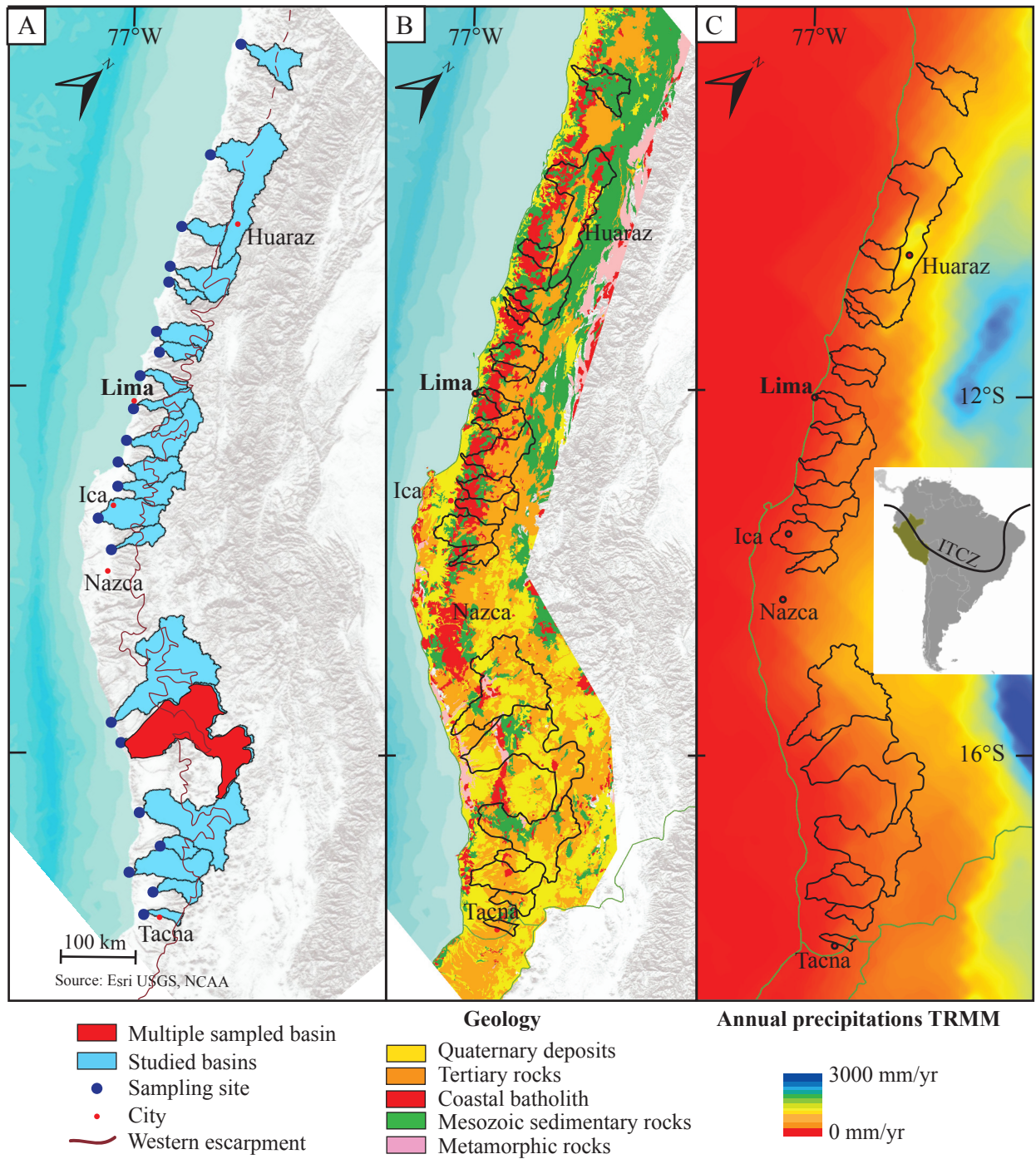


Figure 1: **A:** Map of the studied basins showing the sampling sites and the western escarpment (western escarpment modified after Trauerstein et al., 2013). **B:** Geological map of the western Peruvian Andes. **C:** Map of the precipitation rates showing the spatial extend of the ITCZ, modified after Huffman et al., 2007.)

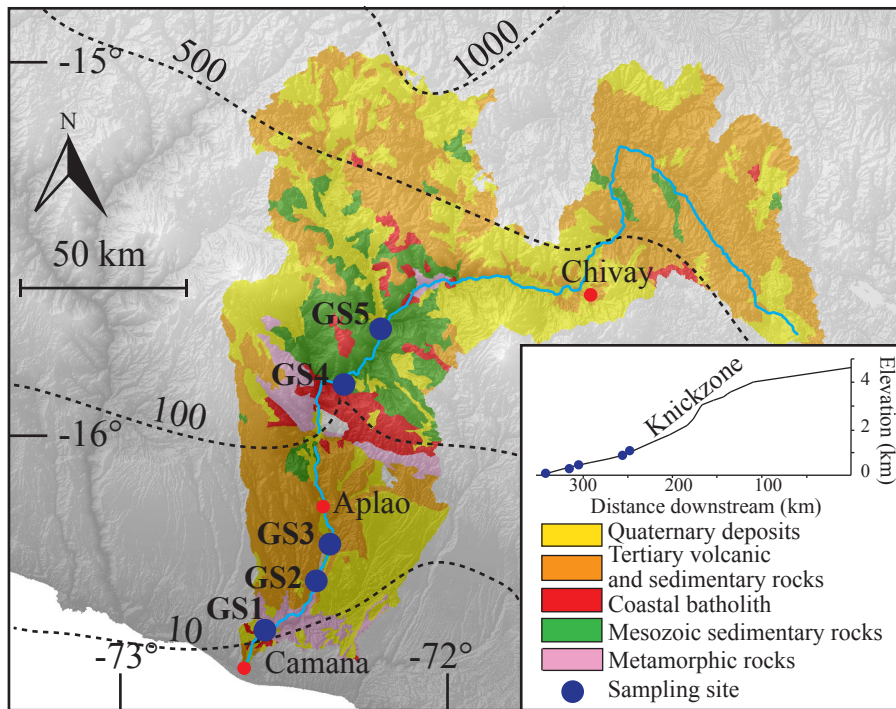
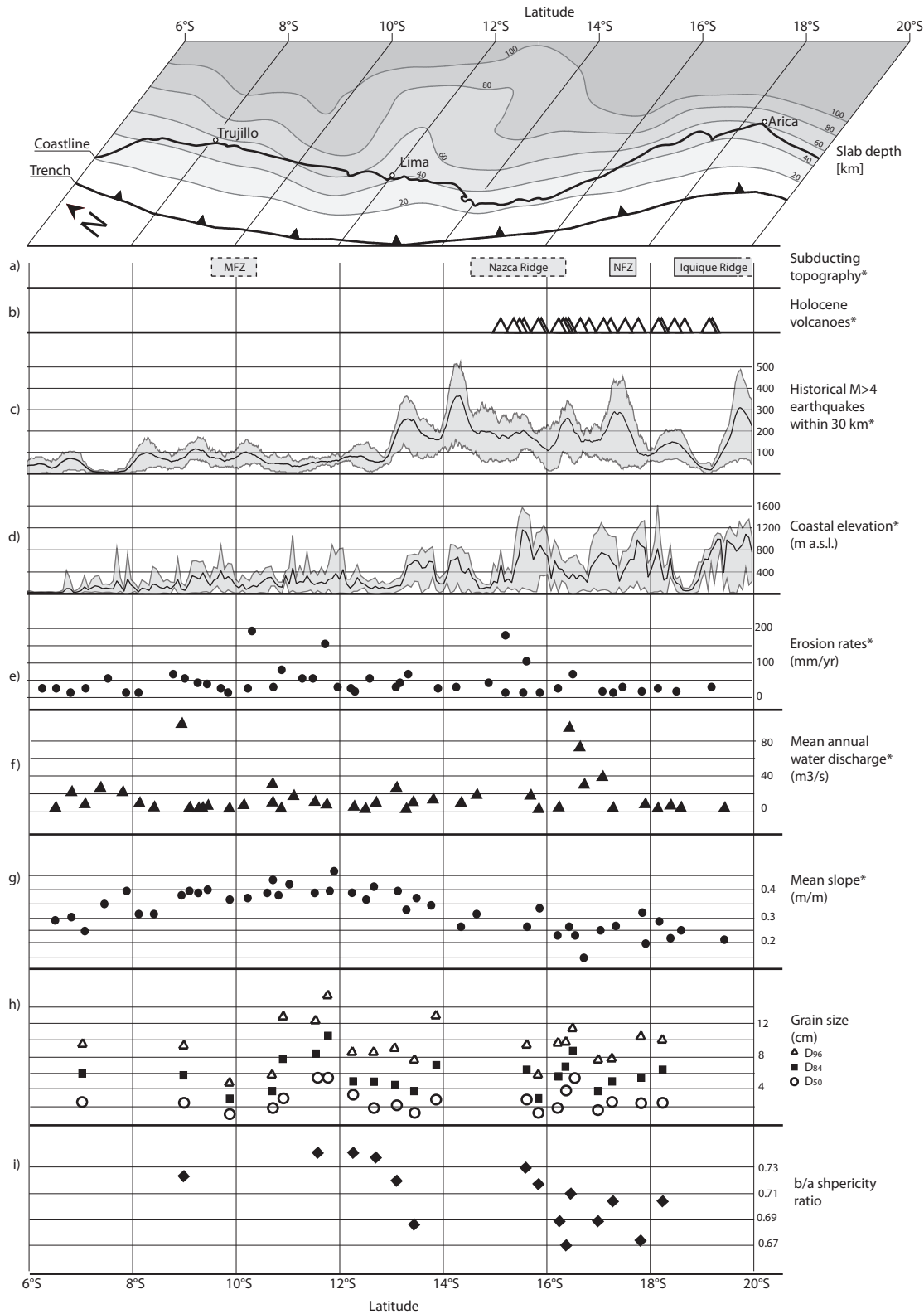


Figure 2: Geological map of the Majes basin overlain by the precipitation pattern (Precipitation data from Steffen et al., 2010., where the black dashed lines show precipitation rates (mm/yr). GS1 to GS5 represent sites where grain size data has been collected. The right corner shows the Majes river long profile.



* Data from Reber et al., in Press

Figure 3: Topography of subducting Nazca plate, where slab depth data has been extracted from earthquake.usgs.gov/data/slab/. This N-S projection also illustrates: a) tectonic lineaments such as submarine ridges and MFZ: Mendaña Fracture Zone; NFZ: Nazca Fracture Zone; b) Holocene Volcanoes; c) Earthquake data, taken from earthquake.usgs.gov/earthquakes/search/; number of earthquakes M>4 within 30 km radius window; d) Coastal elevation. The data has been extracted from a 20 km-wide swath profile along the coast. The three lines represent maximum, mean and minimum elevations within the selected swath; e) Catchment averaged denudation rates have been corrected for quartz contents; f) Mean annual water discharge; g) Mean basin slope. h) Grain size results for the intermediate (b)-axis of the pebbles in the streams from north to south at the sampling sites presented in Figure 1; i) Ratio between the intermediate axis and the long (a)-axis (modified after Reber et al., in press).

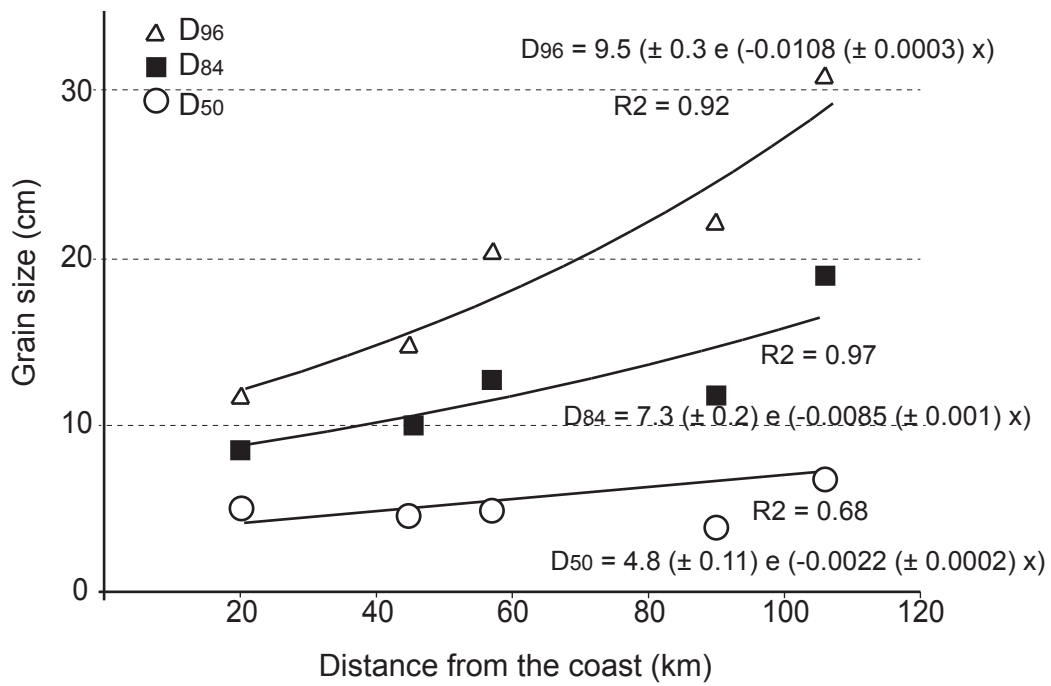


Figure 4: Grain size results along the Majes River.

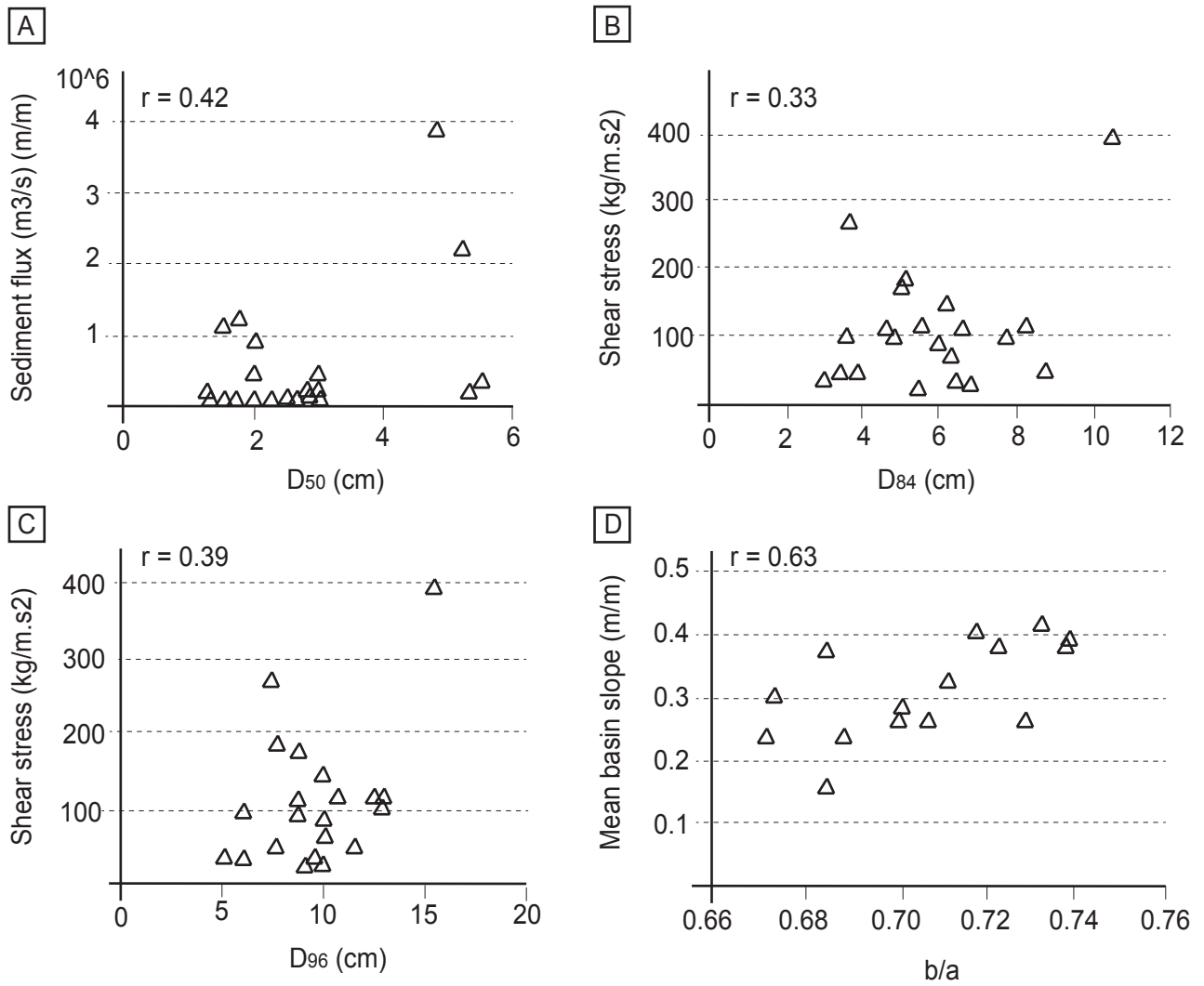


Figure 5: Correlations between the grain size data and the river parameters. A: D₅₀ versus sediment fluxes. B: D₈₄ versus shear stress exerted by the water. C: D₉₆ versus shear stress exerted by the water. D: Ratio b/a versus mean catchment slope.

River name	Sample name	Altitude (m)	Latitude (DD WGS84)	Longitude (DD WGS84)	D50 (cm)	D84 (cm)	D96 (cm)	b/a	Catchment area (km ²)	Mean slope (m/m) (Reber et al., in review)	Slope at the sampling site (m/m)	Distance from the western escarpment (km)	Channel width at the sampling site (m)	Mean annual water discharge (m ³ /s) (Reber et al., in review)	Shear stress (kg/m.s ²)	Sediment flux (m ³ /s)	Denudation rates (mm/ka) (Reber et al., in review)	Denudation rates uncertainties (mm/ka) (Reber et al., in review)	Denudation rates corrected for Qz content in bedrock (mm/ka) (Reber et al., in review)
Tacna	PRC-ME1	231	-18.12	-70.33	2.3	6.2	10.0	0.70	899	0.28	0.015	48	6	3.4	142.68	11952	13.3	3.6	12.2
Rio Sama Grande	PRC-ME3	455	-17.82	-70.51	2.5	5.5	10.6	0.67	2150	0.3	0.013	73	6	4	114.14	61495	28.6	5.3	27.7
Ilo / Rio Osmore	PRC-ME5	1072	-17.29	-70.99	2.6	5.1	7.8	0.70	1783	0.26	0.018	53	7	3.4	184.18	38146	21.4	4.8	18.6
Rio Tambo	PRC-ME6	145	-17.03	-71.69	1.5	3.6	7.5	0.69	12885	0.24	0.051	141	26	38.1	265.69	1155744	89.7	16.7	72.1
Tambillo / Rio Sihuas	PRC-ME802	117	-16.34	-72.13	2.0	6.0	10.0	0.69	1708	0.15	0.019	70	15	30.1	88.78	58087	34	6.4	27.7
Camana / Rio Majes	PRC-ME7	69	-16.51	-72.64	5.2	8.7	11.6	0.67	17401	0.23	0.005	188	100	68.4	46.06	2218568	127.5	23.4	106.8
Ocona / Rio Ocona	PRC-ME9	14	-16.42	-73.12	4.8	6.8	10.0	0.71	16084	0.26	0.004	192	70	91.1	26.25	3893878	242.1	45	184.1
Nasca / Rio Grande	PRC-ME1402	15	-15.85	-74.26	1.3	3.0	6.0	0.71	1412	0.32	0.014	48	3	20.4	34.10	65093	46.1	8.6	29.4
Chacaltana / Rio Ica	PRC-ME15	3	-15.63	-74.64	2.9	6.4	9.6	0.73	4677	0.26	0.003	88	23	12.1	33.01	126266	27	5.7	25.1
Humay District / Rio Pischo	PRC-ME16	400	-13.73	-75.89	3	6.6	13		3649	0.34	0.013	62	20	13.6	112.91	379865	104.1	20.4	69.1
Chinca Alta / Rio San Juan	PRC-ME17	75	-13.47	-76.14	1.3	3.8	7.6	0.69	3090	0.37	0.01	78	5	10.1	48.54	189112	61.2	11.7	44.1
Rio Canete	PRC-ME19	23	-13.12	-76.39	2	4.6	8.8	0.72	6029	0.4	0.01	100	60	26.4	112.24	402743	66.8	12.3	51.2
Rio Omas	PRC-ME20	33	-12.67	-76.65	1.6	4.8	8.8	0.73	2322	0.41	0.0076	78	22	8.2	95.14	62913	27.1	5.4	17.9
Rio Lurin	PRC-ME22	40	-12.25	-76.89	3	5	8.8	0.74	1572	0.38	0.022	70	5	3.7	176.26	60515	38.5	7.1	23.6
Lima / Rio Chillon	PRC-ME39	402	-11.79	-76.99	5.3	10.5	15.5		1755	0.39	0.018	51	40	4.9	392.89	144272	82.2	15.5	53.4
Rio Chancay	PRC-ME23	72	-11.61	-77.24	5.5	8.3	12.5	0.74	3059	0.39	0.01	66	20	8.9	111.55	298866	97.7	18.4	52.8
Rio Supe	PRC-ME25	74	-11.07	-77.59	2.8	7.7	13		4306	0.38	0.012	82	5	3.8	98.55	179550	41.7	7.7	25.6
Rio Pativilca	PAT-ME	10	-10.72	-77.77	1.8	3.6	6		4607	0.44	0.014	74	30	30.9	96.30	1198281	260.1	48.8	190.9
Huarmey	PRC-ME38	24	-10.07	-78.16	1.7	3.4	5.2		2072	0.37	0.004	78	15	9.8	38.34	40816	19.7	4.5	10.1
Rio Santa	PRC-ME27	80	-8.97	-78.62	2	5.4	9	0.72	12313	0.38	0.005	65	40	96.1	23.08	876699	71.2	13.4	70.4
San Martin de Porres	PRC-ME30	67	-7.32	-79.48	2.9	6.3	10		3882	0.34	0.007	126	40	25.4	65.72	118401	30.5	5.9	25.8

Table 1 : Location of the sampling sites with the altitude in meters above sea level. The table also displays grain size results together with the rivers' and basins' properties and hydrological properties. Morphometric dataset for the sampled drainage basins. All calculations are based on the 90 m resolution DEM (NASA). The precipitation, water discharge data and the denudation rates are from Reber et al., in review

	Distance from the coast (km)	Altitude (m)	Latitude (°)	Longitude (°)	D50	D84	D96	b/a
GS1	20	69	-16.51	-72.64	5.2	8.7	11.6	0.67
GS2	45	283	-16.37	-72.49	4.8	10	15	0.69
GS3	57	378	-16.28	-72.45	5.4	12.7	21	0.65
GS4	90	700	-16.00	-72.48	3.3	12	22.5	0.67
GS5	106	882	-15.86	-72.45	6.2	19	31	0.71

Table 2: Location of the sampling sites in the Majes basin and grain size results in the Majes basin.

	Altitude (m)	Latitude (DD WGS84)	Longitude (DD WGS84)	D50 (cm)	D84 (cm)	D96 (cm)	b/a	Catchment area (km ²)	Mean slope (m/m)	Distance form the western escarpment (km)	Mean annual water discharge (m ³ /s)	Shear stress (kg/m.s ²)	Sediment flux (m ³ /s)	Denudation rates (mm/ka)	Denudation rates corrected for Qz content in bedrock (mm/ka)
Altitude (m)	1.00														
Latitude (DD WGS84)	-0.36	1.00													
Longitude (DD WGS84)	0.46	-0.97	1.00												
D50 (cm)	0.09	0.00	-0.01	1.00											
D84 (cm)	0.14	0.04	-0.03	0.87	1.00										
D96 (cm)	0.18	0.02	-0.02	0.73	0.93	1.00									
b/a	-0.30	0.66	-0.71	0.09	0.00	-0.02	1.00								
Catchment area (km ²)	-0.25	-0.12	0.12	0.31	0.16	0.04	-0.25	1.00							
Mean slope (m/m)	-0.23	0.72	-0.78	-0.07	-0.10	-0.03	0.63	-0.28	1.00						
Distance form the western escarpment (km)	-0.32	-0.14	0.14	0.35	0.16	0.03	-0.33	0.84	-0.35	1.00					
Mean annual water discharge (m ³ /s) (Reber et al., in review)	-0.30	0.03	-0.01	0.18	0.05	-0.07	-0.13	0.87	-0.23	0.64	1.00				
Shear stress (kg/m.s ²)	0.45	-0.11	0.14	0.23	0.33	0.39	-0.06	-0.21	0.06	-0.23	-0.37	1.00			
Sediment flux (m ³ /s)	-0.23	-0.19	0.17	0.42	0.17	0.03	-0.21	0.86	-0.24	0.82	0.80	-0.22	1.00		
Denudation rates (mm/ka) (Reber et al., in review)	-0.23	0.04	-0.09	0.34	0.09	0.00	-0.09	0.56	0.12	0.48	0.56	-0.07	0.79	1.00	
Denudation rates corrected for Qz content in bedrock (mm/ka) (Reber et al., in review)	-0.22	0.01	-0.04	0.30	0.06	-0.03	-0.17	0.64	0.05	0.54	0.65	-0.11	0.84	0.99	1.00

Table 3: Results of the statistical investigations, illustrated here as correlation matrix values. The values in bold show significant correlation between the grain size data and the morphometric parameters and basins characteristics

	Altitude (m)	Latitude (DD WGS84)	Longitude (DD WGS84)	D50 (cm)	D84 (cm)	D96 (cm)	b/a	Catchment area (km ²)	Mean slope (m/m)	Distance form the western escarpment (km)	Mean annual water discharge (m ³ /s)	Shear stress	Sediment flux	Denudation rates (mm/ka)	Denudation rates corrected for Qz content in bedrock (mm/ka)
Altitude (m)	< 0.00001														
Latitude (DD WGS84)	0.11	< 0.00001													
Longitude (DD WGS84)	0.03	< 0.00001	< 0.00001												
D50 (cm)	0.69	1.00	0.96	< 0.00001											
D84 (cm)	0.54	0.86	0.89	< 0.00001	< 0.00001										
D96 (cm)	0.43	0.93	0.93	0.000172	< 0.00001	< 0.00001									
b/a	0.27	0.007	0.003	0.75	1	0.94	< 0.00001								
Catchment area (km ²)	0.27	0.60	0.60	0.17	0.48	0.86	0.37	< 0.00001							
Mean slope (m/m)	0.31	0.0002	< 0.00001	0.76	0.66	0.89	0.01	0.22	< 0.00001						
Distance form the western escarpment (km)	0.15	0.54	0.54	0.11	0.48	0.89	0.22	< 0.00001	0.11	< 0.00001					
Mean annual water discharge (m ³ /s) (Reber et al., in press)	0.18	0.89	0.96	0.43	0.82	0.77	0.64	< 0.00001	0.31	< 0.00001	< 0.00001				
Shear stress	0.04	0.63	0.54	0.31	0.14	0.08	0.83	0.36	0.79	0.31	0.098	< 0.00001			
Sediment flux	0.31	0.40	0.46	0.05	0.46	0.89	0.45	< 0.00001	0.29	< 0.00001	< 0.00001	0.33	< 0.00001		
Denudation rates (mm/ka) (Reber et al., in press)	0.31	0.86	0.69	0.13	0.69	1.00	0.75	0.01	0.60	0.027	0.008	0.76	< 0.00001	< 0.00001	
Denudation rates corrected for Qz content in bedrock (mm/ka) (Reber et al., in press)	0.33	0.96	0.86	0.18	0.79	0.89	0.55	0.001	0.82	0.011	0.0014	0.63	< 0.00001	< 0.00001	< 0.00001

Table 4: Results of the statistical investigations, illustrated here as correlation matrix of the p-values. The values in bold have a significance level alpha < 0.1