Multiple controls on sediment grain properties of Peruvian coastal river basins

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ABSTRACT

Twenty-one coastal rivers located on the western Peruvian margin were analyzed to determine the relationships between fluvial and environmental processes and sediment grain properties such as grain size, roundness and sphericity. Modern gravel beds were sampled along a north-south transect on the western side of the Peruvian Andes, and at each site the long $a$-axis and the intermediate $b$-axis of about 500 pebbles were measured. Morphometric properties such as river gradient, catchment size and discharge of each drainage basin were determined and compared against measured grain properties. Grain size data show a constant value of the $D_{50}$ percentile all along the coast, but an increase in the $D_{84}$ and $D_{96}$ values and an increase in the ratio of the intermediate and the long axis from south to north. Our results then yield better-sorted and less spherical material in the south when compared to the north. No correlations were found between the grain size and the morphometric properties of the river basins when considering the data together. Grouping the results in a northern and southern group shows better-sorted sediments and lower $D_{84}$ and $D_{96}$ values for the southern group of basins. Within
the two groups, correlations were found between the grain size distributions and morphometric basins properties. Our data indicates that fluvial transport is the dominant process controlling the erosion, transport and deposition of sediment in the southern basins while we propose a geomorphic control on the grain size properties in the northern basins. Sediment properties in the northern and southern basins could not be linked to differences in tectonic controls. On the other hand, the north-south trend in the grain size and in the b/a ratio seems controlled by a shift towards a more humid climate and towards a stronger El Nino impact in northern Peru. But, generally speaking, the resulting trends and differences in sediment properties seem controlled by differences in the complex geomorphic setting along the arc and forearc regions.

1. INTRODUCTION

The size and shape of gravel bears crucial information about the transport dynamics of mountain rivers (Hjulström, 1935; Shields, 1936; Blissenbach, 1952; Koiter et al., 2013; Whittaker et al., 2007; Duller et al., 2012; Attal et al., 2015), about sediment provenance (Parker, 1991; Paola et al., 1992a, b; Attal and Lavé, 2006) and about environmental conditions such as uplift and precipitation (Heller and Paola, 1992; Robinson and Slingerland, 1998; Foreman et al., 2012; Allen et al., 2013; Foreman, 2014). The mechanisms by which grain size and shape change from source to sink have often been studied with flume experiments (e.g. McLaren and Bowles, 1985; Lisle et al., 1993) and numerical models (Hoey, 2010). These studies have mainly been directed towards exploring the controls on the downstream reduction in grain size of gravel beds (Schumm and Stevens, 1973; Hoey and Fergusson, 1994; Surian, 2002; Fedele and Paola, 2007). Less attention has, however, been paid to external controls such as climate and tectonic change as well as a complex geomorphic setting on grain size properties.
Here, we present data on sediment grain properties from streams situated on the western margin of the Peruvian Andes (Figure 1A) in order to elucidate the effects of precipitation, hydrological properties, catchment morphometrics, tectonics and the El Niño on those sedimentological characteristics. We will show that differences in tectonic regime do not influence sediment properties, whereas climate anomalies such as the El Niño effect, internal river dynamics, supply patterns and geomorphic setting seem to be the most important factors for determining sediment size and shape.

1.1 Geologic and tectonic setting

The study area is located at the transition from the Peruvian Andes to the coastal lowlands along a transect from the cities of Trujillo in the north (8°S) to Tacna in the south (18°S). In northern and central Peru, a flat, up-to 100 km, broad coastal forearc plain with Paleogene-Neogene and Quaternary sediments (Gilboa, 1977) connects to the western Cordillera. This part of the western Cordillera consists of Cretaceous to late Miocene plutons of various compositions (diorite, but also tonalite, granite and granodiorite) that crop out over an almost continuous 1600-km long arc that is referred to as the Coastal Batholith (e.g. Atherton, 1984; Mukasa, 1986; Haederle and Atherton, 2002; Figure 1B). In southern Peru, the coastal plain gives way to the Coastal Cordillera that extends far into Chile. The western Cordillera comprises the central volcanic arc region of the Peruvian Andes with altitudes of up to 6768 m.asl, where currently active volcanoes south of 14°S of latitude are related to a steep slab subduction. Contrariwise, Cenozoic volcanoes in the central and northern Peruvian arc have been extinct since c. 11 Ma due to a flat slab subduction, which inhibited magma upwelling from the asthenosphere (Ramos, 2010).
The bedrock of the Western Cordillera is dominated by Paleogene, Neogene and Quaternary volcanic rocks (mainly andesitic or dacitic tuffs, and ignimbrites) originating from distinct phases of Cenozoic volcanic activity (Vidal, 1993). These rocks rest on Mesozoic and Early Tertiary sedimentary rocks (Figure 1B). In southern Peru, the segment with steep subduction hosts raised Quaternary marine terraces (Saillard et al., 2011) (Figure 1A). This suggests the occurrence of surface uplift south of 15°S of latitude, while the region dominated by flat slab subduction has most likely subsided at least during the Quaternary (Macharé et al., 1986). Because of these inferences, we expect to see a tectonic control on grain size distribution through larger clasts south of 15°S of latitude compared to the segment north of it.

The local relief along the western Cordillera has been formed by deeply incising rivers that flow perpendicular to the strike of the Andes (Schildgen et al., 2007; 2009). The morphology of the longitudinal stream profiles is characterized by two segments separated by a distinct knickzone (Figure 2; Trauerstein et al., 2013). These geomorphic features have formed through headward retreat in response to a phase of enhanced surface uplift during the late Miocene (e.g., Schildgen et al., 2007). Upstream of these knickzones, the streams are mainly underlain by Tertiary volcanoclastic rocks, while farther downstream incision has disclosed the Coastal Batholith and older meta-sedimentary units (Trauerstein et al. 2013). The upstream edges of these knickzones also delineate the upper boundaries of the major sediment sources (Litty et al., 2017). Contrariwise, little to nearly zero clastic material has been derived from the headwater reaches in the Altiplano, where the flat landscape has experienced nearly zero erosion, as 10Be-based denudation rate estimates (Abbühl et al., 2011) and provenance tracing have shown (Litty et al., 2017).


1.2 Climatic setting

The N-S-oriented, annual rainfall rates decrease from 1000 mm per year near the Equator to 0 mm along the coast in southern Peru and northern Chile (Huffman et al., 2007; Figure 1C). The Peruvian western margin shows an E-W contrasting precipitation pattern with high annual precipitation rates up to 800 mm on the Altiplano and c. 0 mm per year on the coast (Figure 1C). This precipitation gradient in the western Andes is related to the position of the Intertropical Convergence Zone (ITCZ, inset of Figure 1C) associated with an orographic effect on the eastern side of the Andes (Bookhagen and Strecker, 2008). During austral summer (January) the center of the ITCZ is located farther south, transferring the moisture from the Amazon tropical basin to the Altiplano (Garreaud et al., 2009) and leading to a wet climate on the Altiplano with strong precipitation rates. During austral winter, the Altiplano is under the influence of dry air masses from the subsiding branch of the Hadley cell that result in a more equatorial position of the ITCZ and in a dry persistent westerly wind with almost no precipitation on the Altiplano. Additionally, the dry coast is due to the Humboldt Current, which advects cold waters from the Antarctica, cooling down the ocean along the coast. This causes an inverse climate gradient in which hot air cannot sufficiently rise and is trapped against the Andean foothills. The hot air then cools down at high altitudes in the atmosphere thereby inhibiting precipitation. Additionally, the Andes form an orogenic barrier preventing Atlantic winds and rain to reach the coast. Only around Piura, situated in northern Peru at 5°S latitude, the ocean water sufficiently warms up because of the mixing with the tropical current derived from Ecuador, resulting in precipitation in northern Peru. In addition, every 2 to 10 years, near to the Equator, the Pacific coast is subjected to strong precipitation resulting in high flood variability, related to El Nino weather phenomenon (ENSO) (DeVries, 1987).
2. SITE SELECTION AND METHODS

The selected rivers are located along a transect from Trujillo in the north (8°S) to Tacna (18°S) in the south parallel to the Pacific side of the Peruvian Andes (Figure 1A). From north to south, climate becomes generally drier along the coast, with the northern area being susceptible to changes in climate due to the El Niño phenomenon. Also, the tectonic regime changes from little tectonic uplift of the forearc, north of Pisco, to rapid uplift south of Pisco. The grain size data from the selected rivers will therefore be used to identify possible trends (or lacks thereof) along strike of the Peruvian Andes. Additionally, the Majes catchment (marked with red color on Figure 1A), which is part of the 21 studied basins, has been sampled at five sites from upstream to downstream to explore the effects related to the sediment transport processes for a section across the mountain belt, but along stream (Figure 2). The Majes basin has been chosen because of its easy accessibility in the upstream direction. For the other basins, sampling sites were mostly accessible along the Pan-American Highway (see Table 1 for the coordinates of the sampling sites).

At each site, around ten digital images were taken for grain size analysis with the software program Image J (Rasband, 1997). It has been shown that using a standard frame with fixed dimensions to assist gravel sampling reduces user-biased selection of gravels (Marcus et al., 1995; Bunte and Abt, 2001a). In order to reduce this bias, we substituted the frame by shooting an equal number of photos at a fixed distance from the ground surface. Photos were taken from an approximately 10m²-large area to take potential spatial variabilities among the gravel bars into account. From those photos, the intermediate \( b \)-axes of around 500 pebbles were
measured, and 500 additional pebbles were used to estimate the ratio between the $b$-axes and long $a$-axes (Bunte and Abt, 2001b). Our sample population exceeds the minimum number of samples needed for statistically reliable estimations of grain size distributions in gravel bars (Howard, 1993; Rice and Church, 1998). The pebbles were characterized on the basis of their median ($D_{50}$), the coarse ($D_{84}$) and the maximum ($D_{96}$) fractions. This means that 50%, 84% and 96% of the sampled fraction is finer than the 50th, 84th and 96th percentile of the samples. On a gravel bar, pebbles tend to lie with their short axis perpendicular to the surface, thus exposing their section that contains the $a$- and $b$-axes (Bunte and Abt, 2001b). However, the principal limitation is the inability to accurately measure the fine particles < 3 mm (see also Whittaker et al., 2010). While we cannot resolve this problem with the techniques available, we do not expect that this adds a substantial bias in the grain size distributions reported here as their relative contributions to the point-count results are minor (i.e. < 5%, based on visual inspection of the digital images).

Grain size distributions of modern bars were then compared to stream runoff, river and basin morphometric properties. River discharge estimates were extracted from the results of annual surveys performed by the National Water Agency of Peru (Autoridad Nacional del Agua, 2016; Table 1). The averaged river gradients and widths at the sampling sites were extracted over a 500-m-long river profile from satellite images and orthophotos. The upstream contributing area of the basins was extracted from the 90-m digital elevation model Shuttle Radar Topography Mission (SRTM) ~90-m resolution (NASA; Table 1).

3. RESULTS

3.1 North-south pattern of grain sizes
The results of the grain size measurement reveal a large variation for the $b$-axis where the values of the $D_{50}$ range from 1.3 cm to 5.5 cm from northern to southern Peru (Figure 3A; Table 1). Likewise, values for the $D_{84}$ vary between 3 cm and 10.5 cm with an increase of the values in the order of c. 0.05 mm/km from south to north (Figure 3A). The sizes for the $D_{96}$ reveal the largest spread, ranging from 6 cm to 31 cm with a generally larger increase (0.15 mm/km towards the north) compared to the $D_{50}$ and $D_{84}$ values. The difference between the $D_{50}$ and the $D_{96}$ is smaller in the south than in the north indicating that sediments are better sorted in the south (Figure 3A). In addition, the ratios between the $b$-axis and $a$-axis (sphericity ratio) increase from south to north indicating that the pebbles are more spherical in the north (Figure 3B).

Another way to analyze the results is to separate the data in two basin groups. The motivation for this grouping lies in the differences in the tectonic conditions with normal slab subduction and an uplifting coast south of 15°S, and flat slab subduction and a flat coastal topography north of 15°S latitude (see above). We thus expect to unravel possible differences in grain size properties in response to these different morphotectonic conditions. Note that in the streams located between 15.6°S and 13.7°S, no gravel bars are encountered along the coast and only sand bars can be found, and therefore no results are exhibited (Figure 3A and B).

3.2 The Majes basin

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

### 3.3 Correlations between grain sizes and morphometric properties

If all river basins are considered, without grouping them into northern and southern domains, no distinct positive nor negative correlations were found between the \( D_{50} \), \( D_{84} \) and \( D_{96} \) percentiles of the gravel size and the long-stream distance to the knickzone reaches where the main sediment sources are located (Figure 5A and B). Likewise, no correlations have been identified between the grain size and the local river gradient (Figure 5C and 5D). Also no correlations have been found between the different grain size percentiles and the annual mean (Figure 5E) and maximum water discharge estimates (Figure 5F).

Contrariwise, positive correlations do exist between the grain size distributions and the river properties when the results are separated into northern and southern domains (see Figure 1). In the southern group of basins, a positive, yet weak, correlation has been found between the \( D_{50} \) and the mean runoff if normalized over the catchment area (Figure 6A; Table 1). The normalization has been made to identify the controls of effective precipitation on the grain size distribution. In particular, this normalization allows to identify the amount of rainfall per year, which explicitly contributes to runoff (after absorption of water through groundwater and evapotranspiration). Contrariwise, in the northern basins, a positive correlation has been found between the river gradient at sampling site and the \( D_{96} \) (Figure 6B).
4. DISCUSSION

4.1 Downstream fining trends at Majes indicates fluvial controls

In fluvial environments the sorting of the sediment depends on the downstream distance from its source (Hoey and Ferguson, 1994; Kodoma, 1994; Paola and Seal, 1995). This is particularly the case for the Majes river, where the sorting gets better in the downstream direction. In particular, we do see an exponential downstream fining trend of the three percentiles in the Majes river (Figure 4). This is somewhat surprising because sufficiently voluminous sediment input from other sources may perturb any downstream fining trends in the grain size distribution (Rice and Church, 1998). Likewise, in the Majes basin, the sediment supply from the hillslopes to the trunk stream has occurred mainly through debris flow processes and landsliding (Steffen et al., 2010; Margirier et al., 2015). Therefore, the exponential downstream fining indicates that in the Majes basin fluvial transport is the dominating process controlling the transport and evacuation of sediment from their sources down to the Pacific Ocean.

4.2 Lack of tectonic controls suggests a geomorphic influence on grain size patterns

No correlations were found between the presence or absence of the uplifted coast and the grain size distributions. Indeed, we would expect larger grain sizes where the area is uplifting through an increase of the river gradient, unless the rivers are able to compensate any uplift by incision in the underlying bedrock or alluvium. In that case the rivers remain in a state of semi-equilibrium without a change in river gradient, particularly along their lower flat segments (Bull, 1991; Maddy, 1997; Viveen et al., 2013). The fact that this is not the case here is demonstrated by the steep river profiles and pronounced knickzones (Schildgen et al., 2009). Interestingly, we
see the contrary in our data: smaller and better sorted grains in the uplifted coastal area where the drainage basins are larger, and larger grains with a lower degree of sorting in the north where recent uplift seems to be lacking and where the sizes of the catchments are relatively small. We thus infer primarily a geomorphic control based on these relationships where smaller rivers in smaller basins are less capable of sorting the material upon transport.

4.3. Climatic control

In addition to the geomorphic control on grain size inferred here through correlations between basin morphometric properties and grain size distributions, a general south-north increasing trend in grain size is visible that overlies the patterns discussed earlier (Figure 3). Large-magnitude, low-frequency rainfall events are an important driver for catchment-scale soil erosion over variable temporal scales (Baartman et al., 2013). Floods in temperate environments are generally characterized by larger magnitudes when compared to arid regions if similar upstream basin sizes are considered (Molnar et al., 2006). This could provide an explanation for the generally larger grain sizes in the north compared to the south, certainly if they are associated with periodic glacial melt. In particular, a more humid climate, as is the case in northern Peru, could induce larger floods (compared to the south) with the effect that the material will be transported more efficiently compared to the southern domains. We acknowledge, however, that a lack of vegetation in arid climates such as in the south can lead to more intensely erosion (Morgan and Rickson, 2003). We also note that the coastal area of northern Peru is subjected to El Niño precipitation events yielding larger flood variability (Wells, 1990; Garreaud and Aceituno, 2001), which could also explain why the river sediments tend to be larger and worse sorted.
4.4 Possible controls of a complex pattern of sediment supply

In addition to the aforementioned controls, it is possible that the generally S-N increasing trend in grain size reflects, at a smaller scale, the complexity of processes and hillslope-channel coupling relationships, paired with contrasts in fractures of bedrock and effects related to glacial pre-conditioning. This complexity of morphology and bedrock lithologies complicates the interpretation of grain size patterns. As an example, the uplifted, flat Moquegua graben system (c. 17°S; Decou et al., 2011) forms the headwaters of the southern rivers, and those rivers are also famous for their agricultural terraces (pre)dating Inca times (e.g. Londoño, 2008). Alluvial fans are also very common in those basins (Steffen et al., 2010). Such flat, stepped elements generally decrease the amount of landscape erosion (Baartman et al., 2013) and halt the incorporation of larger, primarily gravity-driven rocks and boulders into the fluvial system. Contrariwise, the headwaters of the northern basin group encompass the largest area of tropical glaciers in the world (Rabatel et al., 2013). U-shaped walls from glacier valleys provide a significant contribution to catchment erosion because their steepness favors rock fall and other gravity-driven sediment movements (Baartman et al., 2013). Glacier melt and associated processes such as landsliding (Emmer et al., 2016; Klimes et al., 2016) and glacial lake outburst floods (Vilimek, 2016) provide significant transport of large blocks into the fluvial domain. In the north, the Peruvian forearc has been intruded by various generations of magmatic intrusions (Haederle and Atherton, 2002) and their cooling has led to a dense network of fractures. Pre-fractured rock is easier to erode and may provide an additional source of larger boulders of granitic composition into the fluvial system. Granite is generally an abrasion-resistant type of rock and those clasts will retain their initial larger sizes longer while in transport. The southern
(fore)arc region on the other hand, experiences active volcanism. Volcanic rock is generally softer and easier to break down and reduces the possibility of maintaining larger clasts in fluvial transport. This could provide an additional explanation for the generally larger grains in the north compared to the south.

4.5. Lithological and transport distance controls on sphericity

Studies have shown that lithologies and variation in the grain-size distribution of the supplied sediment play a role in controlling the fining rate within a stream through abrasion and fracturing (Attal and Lavé 2009; Litty and Schlunegger, 2017). Pebbles from different geological parent material expose variable predispositions for evolution during the fluvial processes. This appears to be corroborated by our observations. Rivers from the southern basins show more spherical gravels in correlation with the presence of volcanic rocks from the forearc region whereas the rivers from the northern basins show less spherical pebbles in correlation with the presence of intrusive rocks. The cooling of intrusive rocks in the northern Peruvian forearc has led to the formation of prefractured rocks. These rocks when eroded from the bedrock are more prolate and the supplied pebbles to the streams are then less spherical too. We then infer that the lithology of the parent material affects the shape of the pebbles.

We also consider a control of the transport distance on the N-S trends in the sphericity of the pebbles. As particles are transported over longer distances, abrasion tends to equalize the length of the three axes, thus making a particle more spherical. But this concept does not appear to be generally true. Indeed, pebbles flatten as effects of abrasion and 3D heterogeneities of bedrock that becomes more obvious with time and transport distance (Sneed and Folk, 1958). As the transport distances are larger for the southern basins than for the northern ones (Table 3), the
pebbles should be less spherical in the southern basins than in the northern ones, which is what we can see in our data (Figure 3). We note that this is only valid if we assume a linear correlation between river length and transport time. The reincorporation of previously abraded gravels from earlier erosion and transport cycles that were temporarily stored in the catchment cannot be considered here.

5. CONCLUSIONS

Twenty-one rivers on the western Peruvian margin were analyzed to determine the relationships between fluvial processes, tectonics, climate and grain size and shape. The measurements of the grain sizes reveal a large spread from north to south for the \( b \)-axis with constant values of the \( D_{50} \) percentile and an increase of the \( D_{84} \) and \( D_{96} \) towards the north. The difference between the \( D_{50} \) and \( D_{96} \) percentiles is smaller in the south indicating that river sediments are better sorted in the south than in the north. In addition, the sphericity of the pebbles increases from south to north. A division in a northern and southern group of river basins was made. The southern group comprises the basins are located between 18.1°S and 15.6°S while the northern group comprises the catchments between 13.7°S and 7.3°S. These two groups show differences in their grain size distributions. Rivers in the southern group show better-sorted sediments and lower \( D_{84} \) and \( D_{96} \) values compared to basins of the northern group. Similarly, for gravel bars situated in the southern basins, correlations have been found between the \( D_{50} \) and the mean annual runoff. In the northern basins, the only correlation that has been found is a positive correlation between the gradient at sampling site and the \( D_{96} \).

We primarily suggest an geomorphic control on the grain size pattern at the scale of the entire western Andean margin where larger basins host finer grained and better sorted material through
a combination of selective entrainment and winnowing, the effects of which become more obvious with transport distance and thus larger basins. In addition, the overlaying north-south trend in the grain size could reflect a climatic control on the grain size distribution where a shift towards a more humid climate towards the north of Peru correlates with larger grains and worse sorted sediments. Superimposed to these controls, however, differences in hillslope-channel coupling relationships and complex patterns of sediment supply may perturb this large-scale pattern. Additionally, differences in the main lithologies along with different transport distance in-between the north and the south appear to have a control on the pebbles sphericity.

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FIGURE CAPTIONS

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

Table 3: Differences of the basins characteristics between the southern group of basins and the northern group as showed in Figure 1 and 4A.

Figure 1: A: Map of the studied basins showing the sampling sites and the western escarpment (western escarpment modified after Trauerstein et al., 2013). The southern and northern group of basins represent catchments displaying differences in terms of their sizes and relationships with grain sizes (see Results) 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.

Figure 3: A: 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. B: Ratio between the intermediate axis and the long \( (a) \)-axis from north to south at the sampling sites presented in Figure 1.

Figure 4: Grain size results along the Majes River.
Figure 5: Grain size data. A: $D_{50}$ versus distance from the uppermost edge of the western Escarpment (taken from Trauerstein et al., 2013). B: $D_{96}$ versus distance from the uppermost edge of the western Escarpment. C: $D_{50}$ versus gradient averaged over a 500 m-long reach. D: $D_{96}$ versus gradient averaged over a 500 m-long reach. E: $D_{50}$ versus mean annual runoff. F: $D_{96}$ versus maximum annual runoff. We only present the plot of the river properties versus the $D_{50}$ and $D_{96}$. We found the same absence of correlation for the 84th percentile.

Figure 6: A: $D_{50}$ versus the mean annual runoff normalized over the catchment area for the southern basins. B: $D_{96}$ versus local gradient at the sampling site for the northern basins.
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<th>Latitude (°)</th>
<th>Longitude (°)</th>
<th>D50 (cm)</th>
<th>D84 (cm)</th>
<th>D96 (cm)</th>
<th>b/a</th>
<th>Catchment area (km²)</th>
<th>Gradient at the sampling site</th>
<th>Distance from the western escarpment (km)</th>
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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.
<table>
<thead>
<tr>
<th>Sample name/name of the river</th>
<th>Hydrology Gauging station name</th>
<th>Latitude (°)</th>
<th>Longitude (°)</th>
<th>Altitude (m)</th>
<th>Mean annual runoff (m³/s)</th>
<th>Maximum annual runoff (m³/s)</th>
<th>Years of record</th>
<th>Number of measured months</th>
<th>Catchment area (m²)</th>
<th>Mean runoff (m³/s) / catchment area (m²)</th>
<th>Maximum runoff (m³/s) / catchment area (m²)</th>
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<td>-17.616</td>
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<tr>
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<td>26.54</td>
<td>38.03</td>
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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.
<table>
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<th>Distance from the coast (km)</th>
<th>Altitude (m)</th>
<th>Latitude (°)</th>
<th>Longitude (°)</th>
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<th>D84</th>
<th>D96</th>
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Table 2: Location of the sampling sites in the Majes basin and grain size results in the Majes basin.
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<tr>
<td>Mean distance from escarpment (km)</td>
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Table 3: Differences of the basins characteristics between the southern group of basins and the northern group as showed in Figure 1 and 4A.
Figure 1: A: Map of the studied basins showing the sampling sites and the western escarpment (western escarpment modified after Trauerstein et al., 2013). The southern and northern group of basins represent catchments displaying differences in terms of their sizes and relationships with grain sizes (see Results). 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.
Figure 3: A: 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. B: Ratio between the intermediate axis and the long (a)-axis from north to south at the sampling sites presented in Figure 1.
Figure 4: Grain size results along the Majes River.
Figure 5: Grain size data. A: D50 versus distance from the uppermost edge of the western Escarpment (taken from Trauerstein et al., 2013). B: D96 versus distance from the uppermost edge of the western Escarpment. C: D50 versus gradient averaged over a 500 m-long reach. D: D96 versus gradient averaged over a 500 m-long reach. E: D50 versus mean annual runoff. F: D96 versus max annual runoff. We only present the plot of the river properties versus the D50 and D96. We found the same absence of correlation for the 84th percentile.
Figure 6: A: D50 versus the mean annual runoff normalized over the catchment area for the southern basins. B: D96 versus local gradient at the sampling site for the northern basins.