Dear Editor, dear referees,

Thank you very much for handling our paper. We considered the comments as very constructive and have improved the paper accordingly.
The major changes include the improvement of the introduction with a clear explanation of how tectonics and climate operate to potentially influence the grain size pattern. Based on this, we phrased a distinct hypothesis to be tested. We also we improved the methods part by adding additional information about the sampling strategy and the data collection. We have used the Pearson's correlation coefficient to obtain statistically robust correlation between our grain size data and the morphological characteristics of the basins including mean basin slope, denudation rate and basin size, and shear stresses exerted by the streams. We found distinct correlations between the grain size pattern and these variables and have framed the discussion accordingly. Therefore, we found the grouping of basins into northern and southern domains no longer as useful and have thus re-structured the paper accordingly. In summary, the major changes include:

- Presentation of a clear outline of how tectonics and climate could influence the grain size pattern, and based on this, a formulation of a distinct hypthothesis
- Presentation of more details of how we have collected and analysed the data
- Testing through state-of-the art statistical methods whether basin shape, sediment flux and streams' shear stresses have a measurable control on the grain size pattern.

We have thus re-structured the discussion part accordingy.

Please find below a point-by-point response of how we have handled the suggestions and comments.
Thank you very much for your hard work.
On behalf of the co-authors

Camille Litty

Response to Editor

1. Clearer explanation and presentation on i) the processes which govern grain size distribution in river gravel bars; and ii) how these processes interact in this dataset to explain the observed patterns. The paper should to make clear what is known from the literature in the introduction, and then work these themes through the results and discussion in a systematic way. They key will be to better demonstrate the way in which they combine in this setting. Both reviewers press on this, and have specific recommendations to help here.

   <u>Processes govern grain size distribution and interaction</u>
   We have addressed this point by adding a new paragraph in the introduction, which explains how tectonics and earthquake occurrence should influence the grain size pattern, and what we expect based on this. In the same sense, we have discussed how this should imprint the grain size pattern. Based on this, we were able to phrase distinct hypotheses to be tested. In particular, earthquakes are expected to release large volumes of landslides to the trunk stream, which, in turn, is expected to yield in the supply of larger clasts. As such, we expected a positive correlation between the grain size pattern and the frequency of large earthquakes. We have tested these relationships and have not found a positive response. Introduction has been changed to address this hypothesis.
   In the same sense, the supply of larger volumes of sediment to the trunk stream is expected to shift the gravel front farther downstream, which, in turn, should be associated with a

coarsening of the material along the stream. Since we have 10Be-based sediment flux data, we were able to test these relationships and have indeed found a positive one. Introduction and the entire paper have been modified to address this point. Finally, climate could influence the grain size distribution through modifications of the streams' shear stresses. Since mean water discharge data of these streams are available, we were able to test these relationships. Again, introduction and text have been adjusted and modified to address this point.

2. A more robust analysis of the data and consideration of its limitations (see more detailed comments by both reviewers). These include a clearer explanation of sampling sites and how comparable these are between locations, uncertainties on grain size percentiles and some explanation on the method validation.

Data analysis

We have used the Pearson's correlation coefficient to obtain statistically robust correlation between our grain size data and the morphological characteristics of the basins including mean basin slope, denudation rate and basin size, and shear stresses exerted by the streams. We found distinct correlations between the grain size pattern and these variables and have framed the discussion accordingly.

Data collection

We have detailed our description about where we have collected the data, and why we have collected these sites. In particular, We selected river basins situated on the western margin of the Peruvian Andes, that were generally larger than 700 km^2. For these systems, 10Be-based basin-averaged denudation rates and water flux data are available, thus allowing us to explore possible controls on sediment flux and shear stresses on the grain size pattern. Sampling sites were situated in the main river valleys in the western Cordillera just before it gives way to the coastal margin. We selected the downstream end of these rivers because the grain size pattern at these sites is likely to record the ensemble of the main conditions and forces controlling the supply of material to the trunk stream farther upstream. We randomly selected c. five longitudinal bars where we collected our grain size dataset. Sampling sites are all accessible along the Pan-American Highway (see Table 1 for the coordinates of the sampling sites). We have added these statements in the revised version of our paper.

- I note you mention an addition of a paragraph on how tectonics can influence grain size and properties. It would be useful if the text here also included more in depth discussion on the role of fluvial transport (including abrasion) and the climatic factors (discharge, discharge intensity) that could influence. The reply doesn't indicate this has been included.

We apologize not to have been specific enough in our previous reply letter. While we cannot fully address the potential controls of discharge intensity on the grain size pattern with the available dataset, we were able to calculate water shear stresses for mean annual runoff magnitudes of these streams, and we did see positive correlations with the grain size data. We have thus discussed these aspects in full detail and also mentioned limitations in our analyses, which are set by the available information as note above.

We could not fully discuss the controls of abrasion on our grain size data, mainly because we lack a required high-resolution dataset. Nevertheless, since the bedrock lithology is nearly constant along strike, we do not consider that abrasion has a predictive power on our grain size pattern at the scale of the western Andean margin. We do note, however, that inferred shorter transport timescales in smaller and steeper basins is likely to decrease the timescale of abrasion, which would explain the sphericity pattern we have obtained. We have mentioned these issues in our revised article, but also added cautionary notes because data on these timescales are not available.

- There were some comments in the reply to Reviewer 1 which were unclear, mainly about the role of **transience**. They seemed to suggest there was additional downstream data than that presented – which if the case should be included. Nevertheless, this comment needs to be dealt with in the revision.

We have presented and discussed all available data. We were not able to identify any transient passage of sedimentary pulses through individual basins as we have not sufficient data on downstream patterns of grain size. However, we were able to address the issue of equilibrium versus transience at the scale of the entire Western Andean margin. We have mentioned this point at the very end of the paper where we wrote: *This suggest that the ensemble of erosional and sediment transport processes have reached an equilibrium at the scale of individual clasts, but also at the reach scale of rivers where the sedimentary architecture and the clast fabric of the channel fill has dynamically adjusted to water and sediment flux and their specific time scales. Accordingly, we see the western Peruvian margin as ideal laboratory to analyze the relationships between sediment supply and water runoff on the grain size pattern of the bedload, and we propose that the bedload caliber of these streams has reached an equilibrium to environmental conditions including water discharge, sediment flux and channel geometries.*

- Figure 3 is a good idea to provide an overview of the site characteristics and the data. However, the inclusion of data from an 'in review' publication is somewhat problematic. That secondary data seems to now be an important part of the discussion. It needs to be referred to without compromising ethics of submission, but if it is not published data the methods and approaches need to be explained herein.

The publication has now been accepted in Terra Nova

- Table 3 – This is a Pearson correlation matrix, and I guess that significance is $P<0.05$? It is good practice to provide P values for each r value (beneath). Note that the reply mentioned 'state of the art' statistical techniques. This is a standard technique, albeit a helpful one in this context to reveal some of the patterns.

We added a Table 4 of the p-values

- The graphical representation of the data is important in the community which reads ESurf. I recommend that relationships between some of the key variables are still presented as scatter plots in the revised version.

We have added a Figure 5 presenting some of the correlations to give a graphical representation of our data. 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.

- Please be **more specific when explaining how specific comments have been addressed (replies to Reviewer 2).** It is not that helpful to simply state comments have been addressed when the reviewer has raised a specific point which can be discussion in more detail in your reply.

We apologize not to have properly addressed these points. We have fully re-addressed this topic. We infer that a higher seismicity, which indicates a higher degree of tectonic processes at work, results in the release of large volumes of landslides, which in turn, would shift the bedload material to coarsen. We have thus explored possible correlations between our grain size data and the frequency of high-magnitude earthquakes, but have not found any correlations.

Likewise, high surface uplift rates are expected to steepen landscapes, thereby supplying coarser grained material to the trunk streams. We have taken the occurrence of raised Quaternary terraces as proxy for most recent surface uplift and have explored whether this correlates to grain size trends. We have not found any.

We acknowledge that we have not been sufficiently careful about these issues in our previous manuscript. We took the occasion to explain more carefully our approach during this revision.

- 'Contrariwise' is not a common word, and may not be clear to non-native (and indeed native English speakers). It is used on several occasions (i.e. it is overused). Other options include 'In contrast... 'On the other hand...'

We have changed the 'contrariwise' with 'in contrast' or 'on the other hand'

240: language here needs to be more precise with regard to the statistical nature of the relationships.

This part has been removed

241: 'frequency' Done

246: it wasn't clear how glacial melt plays a role here.

This part has been removed as we lack of data

247: for floods, runoff magnitude (e.g. Peak water discharge) and intensity are important parameters – these need to be teased apart and discussed. Are there any hydrological data or precipitation data which can be analysed from the study are to back these claims up?

We have added a paragraph on the hydrological control on the grain size distribution. We have taken the precipitation rates and water discharge data form Reber et al. in press and analysed the possible correlations with our grain size data. We have also calculated the shear stress exerted by the stream water. However we note that we lack of peak discharge data and maximum precipitation intensity data.

273: reference needed to support inference of fractures.

We had no indication of the size of the fabric network. We have removed this part of the discussion as we found more compelling evidence for correlations with other variables

279 – Clarify what mechanism - do you mean differential abrasion rates controlled by rock type – if so explain and cite relevant work.

L 351-354: In particular, the fining rate not only depends on the abrasion (Dingle et al., 2017) and the selective entrainment processes upon transport (Ashword and Ferguson, 1989), but also on the rate at which sediment is supplied to the rivers (e.g. McLaren, 1981; McLaren and Bowles, 1985).

288 and 289: 'correlation' => 'association'

ok

Figure 3 – horizontal lines are not needed here (same on other figures). Ensure '50','84' and '96' are subscript.

This has been made in fig 3, 4 and 5

Figure 3 B and Figure 6 B– what is the shaded area? Its not necessary.

These figures have been modified

Response to Referee #1

It lacks a clear explanation of how the different factors that are meant to influence grain size operate, both in the introduction and throughout the discussion. For example, it is stated that increased uplift will be expected the increase grain size, but the causal mechanism is not described.

We have addressed this point by adding a new paragraph in the introduction, which explains how tectonics and earthquake occurrence should influence the grain size pattern, and what we expect based on this. In the same sense, we have discussed how this should imprint the grain size pattern. Based on this, we were able to phrase distinct hypotheses to be tested.

There is also a difficulty in separating out the different mechanisms; for example, smaller basins seem to be correlated with lesser uplift, hence it is not obvious which of these two factors is more important.

This has been confusing, indeed. We thus have completely modified the analysis plus we have framed the discussion in a different way.

Another issue is that the paper seems to alternate between assuming that downstream fining is caused by abrasion and that it is caused by selective transport, without any explicit consideration of which process is likely to be more important, or the implications of one process being dominant. (A relevant paper for the discussion of abrasion processes is Sklar et al., 2006.)

It is true that we did not take into consideration the different processes. We have clarified this point and have been consistent in our interpretation.

Overall, I would have liked a greater sense of the underlying processes that control grain size, how they interact with each other, and the relative importance of the different factors.

This has been done. We have rephrased the discussion section, thereby addressing the interplay between the controls of the various variables more carefully.

I also have some queries about the way in which the data were collected and analysed. The authors do not state how the locations in the different river basins were selected (other than the presence of the highway).

This information has been added. In fact, we have sampled all streams where upstream basin sizes were larger than 700 km^2, and we have focussed our data collection at the downstream end where these rivers cross the tip of the mountain belt. This strategy allows us to explore how the ensemble of all processes in a basin relevant for the supply of material influences the grain size patter. This has been clarified in the revised version of the paper.

My concern is that they are attempting to compare grains sizes that are collected from different relative locations within the basin, and are therefore not comparing like with like. For example, if the basins all had the same rate of downstream fining but the samples were collected from different locations within the basins, then the analysis would show differences between the basins that are not actually there. The authors need to consider this as a possible source of variation within their results.

This could indeed add a bias, however, we have selected streams where they cross the tip of the Andean mountain belt. Please see also comment above.

It would be useful to consider sample location as a function of total basin length, and also to normalise the distance to the knickpoint.

We have considered this variable (distance from edge of Western Escarpment). Please see revised version. We have not performed this normalization, but used other variables instead (e.g., shear stresses, basin-averaged denudation rates), which yield measures for flow strengths and sediment flux. Because grain size and fining trends potentially depend on these variables, we used these variables for our analysis and we have indeed found positive correlations with grain size patterns.

There is also the question as to whether these basins are in a form of equilibrium or whether the grain size might actually reflect transient processes such as a coarse sediment slug progressing through the basin. I think that you need more discussion of the literature on controls on downstream grain size; at present the relevant papers are only referred to in passing at the start of the introduction.

This might work for individual basins, such as exemplified for Majes, where the grain size decreases downstream. However, this does not work if all basins along the western Peruvian margin of the Andes are considered, because the D50, as an example, increases with downstream distance from the uppermost edge of the Western Escarpment. In fact, we would have expected the opposite where grain sizes decrease with increasing transport distance. However, we found positive correlations with grain size and mean basin slope, mean basin denudation rates and shear stresses of the streams. This suggests that supply of material (higher denudation rates) and water flow strengths have a large influence on the downstream fining trends within each basin. We have thus framed the discussion in this direction.

What were the channel morphologies

The channels have a braided pattern, and the morphology of the longitudinal stream profiles is characterized by two segments separated by a distinct knickzone. Please see revised version.

how large were the individual images ?

This has been clarified: Individual images are about 1 m^2.

how were grains selected within the images ?

Every pebble, which was entirely visible on the digital images, has been measured.

how representative are the selected bars ?

For these basins, sampling sites were situated in the trunk streams of these valleys where the streams cross the tip of the mountain belt, which is located near the Pacific Coast in most cases. We selected the downstream end of these streams because the grain size pattern at these sites is likely to record the ensemble of the main conditions and forces controlling the supply of material to the trunk stream in the upstream basin and thus the grain size caliber of these streams where they leave the Andes. In these streams, we randomly selected c. 5 longitudinal bars where we collected our grain size dataset. As such, we consider the selected bars as representative for the ensemble of supply and transport processes in the streams' basins.

how were grain outlines identified (automated or manual analysis) ?

From those photos, the intermediate b-axes and the long a-axes of around 500 pebbles were manually measured. We have added this information in the revised version.

was any attempt made to verify the grain size data produced,

No attempt has been made to verify the grain size data produced for this paper. Nonetheless, all the pebbles have been measured by the same operator. This yields the same bias for every sampling site, if there is any.

why were 500 extra grains used for grain shape

We have clarified this in the method part and what are the error bars on D50/D84/D95 (and hence are the identified differences significant)?

Uncertainties on the grain size percentiles are also about 3 mm. This value corresponds to the precision limits of the measurements with the software ImageJ and of the digital pictures' resolution. For the significance of the difference, correlations or trends have all been estimated through the Pearson correlation coefficient (p-value) and not anymore on a visual estimation as we have don before.

The lack of a clear hypothesis early on means that some of the analysis comes across as a bit of a fishing expedition, with lots of correlations on different data groupings being undertaken, and only the significant ones being presented. I think that you need to be more thorough about this analysis, for example through multiple or stepwise regression.

This has been done, and a hypothesis has been phrased. Please see also comment above.

Comments by line: 10: Overall the abstract could be more specific and provide some more evidence for the various claims.

We have addressed this point

53: To what extent are these different factors interrelated?

We have addressed this point by adding a new paragraph in the introduction

55: Make it clearer how this information about the general setting is related to the overall aim of understanding grain size.

Done

78: Be more explicit about why uplift produces larger clasts.

This has been specified

79: You describe both N-S and E-W variations; which are most important for your study?

N-S are more relevant; we have rephrased the introduction and clarified this point.

97: I'm surprised that erosion is nearly zero (line 89) given this high precipitation.

Abbühl et al. (2011, ESPL) have shown that the low denudation rates are due to the flat landscapes on the Altiplano.

122: Be more specific about uplift rates.

This has been changed accordingly

125: Is five sites enough to identify trends?

We have changed our data interpretation as there was no real reason to separate the basins into 2 groups (i.e. northern and southern domains). We have worked with all our dataset.

196: Calculate sorting parameters to quantify these trends.

No trend actually exists as there is no real change in the grain size from north to south, so we also did not introduce the sorting parameter.

176: Suggests that you are downstream of the gravel-sand transition? Does the transition occur in other basins?

This transition seems to not occur in the other basins. We have addressed this point in the discussion part.

195: It would be useful to calculate stream power, as this would enable you to look at the combined impact of slope, width and discharge.

Yes, indeed, but we have calculated shear stresses instead. We have done so and we do see correlation in between the grain size and the shear stress.

201: Is the relationship significant?

Indeed, we are not considering anymore the grouping (northern and southern domains) of basins.

209: Overall there are many competing ideas in the discussion, and it's not clear which are most important.

This has been confusing, indeed. We thus have completely modified this part of the analysis plus have framed the discussion in a different way.

216: This is the first mention of sediment sources; this needs to go earlier in the paper.

We now mention it earlier in the text. 'The upstream edges of this knickzone called the Western Escarpment also delineate the upper boundaries of the major sediment sources'

225: Note that rivers can also adjust to changes in uplift by changing other factors such as width, morphology and the amount of sediment cover.

Yes we have changed the part on the tectonic control on grain size

244: What is the mechanism that relates different flood characteristics to different grain sizes?

We have rephrased the entire discussion and have likewise changed this section.

257: What is your evidence?

Because we have only found a correlation between the D50 and the basins scale properties (basin area, denudation rates, mean slope, we infer that the mean grain size reflects the ensemble of a complex pattern of erosional processes operating in the Peruvian basins

273: How does the size of this fracture network compare to the grain sizes?

We had no indication of the size of the fabric network. We have removed this part of the discussion as we found more compelling evidence for correlations with other variables.

287: This argument would be stronger if you presented the lithological characteristics of your grains, which you could identify from the photos. Or state that they are all identical within each basin. 300: Is this consistent with the geological variations?

A test of the inferred positive correlation between mean basin slope, bedrock lithology and particularly the occurrence of plutonic rocks, and the pebbles' sphericity would require a higher resolution topographic and geologic data, which are currently not available, we thus decided to remove this part, which also does not fit anymore in the discussion, as the grouping of basins into southern and northern domains is not considered anymore.

288: Note that you only have information on 2D grain shape not 3D.

Yes indeed, these are the a- and b-axis. So we are indeed missing the information about the third dimension to talk about the shape of the clasts. In this sense, the reviewer is correct. Nevertheless, we are still convinced that the 2D info contains valuable information about the shape of the clasts in the sense that preferential abrasion due to an inherited fabric (fractions, bedding, schistosity) returns elliptical rather than spherical clasts. We have thus kept this part of our analysis.

296: Which idea do you think is more correct?

This point has been addressed in the revised version of the text.

321: I'm still not entirely clear what you mean by a 'geomorphic' control.

It was indeed unclear, we have rephrased that. But what we wanted to say is that the geomorphic parameters (basin slopes, size, denudation) were controlling the grain size distribution

323: But much of the earlier discussion has referred to abrasion.

We have indeed been contradictory. However, we have substantially changed the paper and thus also the conclusions.

Table 1: Add an indication of where the site is relative to the knickpoint and within the basin.

This has been done in the method part

It would help to also present distances normalise by total basin length.

We did not normalize by the basin length because this is one of the parameters that we wanted to test as control on the grain size

Table 3: Give sorting values.

We have deleted table 3 as we do not group the basins into northern and southern basins

Figure 1: Add basin outlines to maps B and C.

This has been made

Figure 2: Add the channel.

This has been made

Response to Referee #2

The authors rule out a tectonic control by simply stating that greater surface uplift rates should result in larger clast sizes. Why?

We have fully re-addressed this topic. We infer that a higher seismicity, which indicates a higher degree of tectonic processes at work, results in the release of large volumes of landslides, which in turn, would shift the bedload material to coarsen. We have thus explored possible correlations between our grain size data and the frequency of high-magnitude earthquakes, but have not found any correlations.

Likewise, high surface uplift rates are expected to steepen landscapes, thereby supplying coarser grained material to the trunk streams. We have taken the occurrence of raised

Quaternary terraces as proxy for most recent surface uplift and have explored whether this correlates to grain size trends. We have not found any.

We acknowledge that we have not been sufficiently careful about these issues in our previous manuscript. We took the occasion to explain more carefully our approach during this revision. In particular, we wrote: *Among the various conditions, hillslope erosion and the supply of material to the strunk stream has been shown to mainly depend on: (i) tectonic uplift resulting in steepening of the entire landscape (Dadson et al., 2003; Safran et al., 2005; Wittmann et al., 2007; Ouimet et al., 2009), (ii) earthquakes and seismicity causing the release of large volumes of landslides (Dadson et al., 2003; McPhillips et al., 2014), (iii) precipitation rates and patterns, controlling the streams' runoff and shear stresses (Litty et al., 2016), and (iv) bedrock lithology where low erodibilty lithologies are sources of larger volumes of material (Korup and Schlunegger, 2009),. Because most of the bedload material of rivers has been derived from hillslopes bordering these rivers, as mapping and grain size analyses of modern rivers in the Swiss Alps have shown (Bekaddour et al., 2014; Litty and Schlunegger, 2017), it is very possible that the grain size distribution of modern rivers either reflect the seismic processes at work, or rather reveal the response to the climate conditions such as rainfall rates and the shear stresses of rivers.*

The mechanism underpinning this assumption (e.g., enhanced landsliding as a result of incision, etc) is very important if you want to look for tectonic signals in sedimentological data.

Yes indeed. However, we mainly focussed on the frequency of earthquakes, which should influence the occurrence of landslides and thus the grain size pattern of streams. We have selected this approach because earthquake data were available.

The Methods section requires more information about where the grain size were collected.

Improved and largely expanded.

'Along a highway' isn't very helpful – were the measurements made at equivalent locations in the longitudinal profiles of the catchments?

Yes indeed. We have outlined more carefully why we have selected our basins, and where we have done the measurements.

If you want to compare measurements from one catchment to another, it's important to demonstrate that the data come from comparable sampling sites.

Yes, indeed. We acknowledge that we have not properly explaine our sampling strategy and have now specified this point.

It would also be helpful to know where the discharge data were collected in the catchments. I appreciate that the coordinates are listed in Table 1, but some description is needed about whether the discharge data represent equivalent points in the catchments; i.e., if one catchment is sampled at the mouth and another at the headwaters, how can a meaningful comparison be made?

We have taken the discharge data from Reber et al., in press in Terra Nova. These authors provide the full information about the data source.

I have some major criticisms of the results. Uncertainties are needed on the grain size percentiles, because the scatter in Fig. 3a is larger than the trends the authors interpret.

The grain size data have too large a scatter, so interpretations of trends are indeed not possible. We have changed the manuscript accordingly. We have worked on statistical correlations using the Pearson's coefficient and no correlation has been found between the D50 and the latitude. Uncertainties on the grain size percentiles are also about 3 mm. This value corresponds to the precision limits of the measurements with the software ImageJ and of the digital pictures resolution.

The way the authors describe the grain size data from line 162 onwards implies a systematic variation from north to south, which is not really true.

Indeed, we have changed the analyses, and there is indeed not such a trend.

It should be clarified that the rates of grain size change from north to south refer to an average regression fitted to the data.

We have changed the analyses, and there is not such a trend.

The whole paragraph from line 171 is not really a description of results, and could be moved to the Discussion.

We have changed the analyses, so this paragraph has been removed.

However the final point (line 176) is very important and needs some explanation.

We have added an all paragraph on the gravel front in the discussion

Why are there catchments in the middle of the study area that apparently have much bigger grain size differences (only sand and no gravel) than the catchments examined in the paper?

We have discussed this point.

The authors are apparently aware of much larger grain size variability in the area but have ignored those catchments, and it is not clear to me why.

We have discussed this point.

There are some issues with Fig. 3. The data in panel A are compressed to the bottom of the graph and half the plot isn't used – please expand the data so the reader can better see the trends (the annotations can go above the graph).

In panel B, I am concerned that some of the data points are missing between 5-15 degrees latitude. Why are there only 6 points (compared to 11 in A)?

Figure 3 has been improved. The ratio b/a has not been measured at each sampling site so there are less data points in the ratio plot than in the percentiles one.

Also, which percentile has been used to calculate the a/b ratio?

There is no percentile used. We measured the length of the a-axis and the b-axis were per pebble. This gives us one value for the ratio. We repeated this for 500 pebbles, yielding a mean value per sampling site.

Next, it appears the coarsest grain sizes from the northern group of catchments are being exported from the shorter catchments that only drain west of the western escarpment. Those with larger upstream reaches crossing the western escarpment have equivalent grain sizes to the southern catchments. This difference is quite apparent by comparing Figs 1 and 3, and may invalidate the north/south grouping of catchments.

Yes indeed; we also realized that and have rewritten the discussion part of the paper.

The final part of the results contrasts Figs 5 and 6.

Yes indeed. We have completely changed this part of the analysis

The authors suggest that there are no correlations between grain size and the chosen parameters in Fig. 5, but that there are correlations when the catchments are grouped (Fig. 6).

We have changed this part of the analysis

This isn't really a comparison, because the two figures are showing different things. I cannot tell how Fig. 5e and 5f would compare to Fig. 6 if the same normalisation was performed on discharge.

Indeed, please note that we have changed this part of the analysis

Why was discharge normalised in Fig. 6a but not elsewhere in the paper?
And why have the authors chosen those particular grain size percentiles and variables in Fig. 6?

This has been changed and corrected. Indeed, this did not make sense.

It seems they have simply plotted everything against everything else and shown two unrelated correlations that are not particularly convincing and do not test a particular hypothesis.

We have framed our paper around a hypothesis. So this aspect has been changed. We have made a new figure showing the data from south to north and a correlation matrix using the Pearson's correlation coefficient to give statistically robust analyses.

I am confused about why the southern catchments should be characterised by comparing runoff normalised by area with D50, while the northern catchments should be characterised by their gradients as a function of D96.

We have changed this part of the analysis

The Discussion attempts to address some important questions about grain size patterns observed in river networks and how they might record various forcings. Unfortunately, it is inconclusive and unclear. The authors claim around line 219 that fluvial transport dominates the Majes basin – if so, why does the D50 not fine over a 100 km distance?

We have addressed this point.

In section 4.2, do the arguments here require that smaller rivers in smaller basins are moving coarser material? This needs to be clarified.

We have changed this part of the analysis

For section 4.3, what is the actual difference in climate between the northern and southern domains?

We have changed this part of the analysis; we no longer perform this grouping.

In Fig. 1c, apart from the wetter patch near Huaraz (which actually overlies a catchment exporting finer grain sizes!), the two areas look similar. I recommend the authors plot the runoff data and/or precipitation against latitude (following Fig. 3) if they want to argue there is a relationship here.

We have changed this part of the analysis

They need to show that the two domains are actually different and that climate correlates with grain size if they want to make that argument.

We changed this discussion accordingly

In section 4.4, the authors could clarify whether the smaller catchments in the northern group were glaciated as well, or only the larger ones? Because the coarsest data seems to only come from the smaller catchments, and this is an important difference that needs to be addressed.

We have clarify this point

These smaller catchments also drain proportionately more of the Coastal Batholith, which might indicate an erodibility control on grain size.

We have changed this part of the analysis and the discussion accordingly.

The arguments in this section are vague and undeveloped and jump from glaciers to lithology without offering any precise interpretations.

Yes, indeed. We have removed this part as it was non-conclusive.

- “Contrariwise” is an unusual word, and I recommend using something like “on the contrary” instead

We have learned this word from an English native speaker, so we have kept it.

- Refer to “El Niño”, not “the El Niño” or “the El Niño effect” (it is not an effect). Also, on line 114 you equate El Niño with ENSO – they are not exactly the same thing. El Niño is one phase of ENSO and brings particular weather patterns, but ENSO refers to the overall oscillation between El Niño, neutral, and La Niña states in the tropical Pacific

Yes, indeed. We have removed this part.

- “Strong precipitation rate” implies a high intensity of precipitation, which is quite different to a greater overall amount of precipitation

Yes indeed, and we have removed this part as our dataset is not precise enough. We mainly focus on the streams’ shear stresses.

- Lines 107-109. This is confusing – hot air cannot rise and is trapped against the foothills, but also cools at high altitude?

Yes, indeed. We have changed this sentence.

- Line 112. If you refer to Pisco, mark it on the map

It was referring to Piura which is outside of our study area so we have removed the sentence

- Line 143. The D96 is not the maximum particle size

This has been corrected

- Line 183. This sentence makes a big claim and needs to be supported by some key citations

Citations have been added to support the sentence.

- Line 293. Is the fracture spacing 10-20cm? Because this is the particle size range. I’m sure fracture spacing sets the sizes of large boulders, but I’m not convinced this mechanism applies to pebbles

Yes indeed. We have removed this part of the paper as it was non-conclusive.

- Line 295. The authors state that abrasion makes particles more spherical, and then say it doesn’t. Please clarify which it is

We have clarified this point. As particles are transported over longer distances, abrasion tends to equalize the length of the three axes, thus making a particle more spherical. While this concept is likely to be valid for pebbles with a homogenous fabric, it likely fails to describe abrasion and break-down of material with an inherited planar geologic fabric (such a gneisses and sediments).

- Line 300. Yet the southernmost catchments in the southern grouping are very small, but show the roundest clasts. Is this not contradictory?

Yes, indeed. We have changed this part

- Fig. 5. These axes should be reversed

The figure has been removed and another figure with the same axis for every graphs

~~Multiple~~Environmental 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~~tectonic 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 where the rivers cross the tip of the mountain range, 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~~large scatter in the D_{50}, D_{84}, D_{96} values and in the ratio between the intermediate and the long axis. We have not found any correlations between the frequency of earthquakes and the grain size pattern, which suggests that the current seismic, and likewise tectonic, regime has no major controls on the supply of material on the hillslopes and the grain size pattern in the trunk stream. However, positive correlations between water shear stresses, mean basin denudation rates, mean basin slopes and basin sizes on nearly all grain size percentiles suggest a geomorphic control where larger denudation rates operating in larger basins, and steeper basins, paired with larger flow shear stresses, are capable of transporting more and coarser grained material. Furthermore, we use correlations between the clasts' sphericities and transport distances to infer a transport time control on the shape of the clasts. We thus suggest that the grain size distribution of gravel bars and the fabric of individual clasts has dynamically adjusted to water and sediment flux and their specific time scales.

1. INTRODUCTION

~~———~~The size and shape of ~~gravel bears~~gravels bear crucial information about (i) 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~~(ii) the mechanisms of sediment supply and provenance (Parker, 1991; Paola et al., 1992a, b; Attal and Lavé, 2006~~)~~), and ~~about~~(iii) 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).~~ and Ferguson, 1994). 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.~~ ; Allen et al., 2016). In addition, it has been proposed that the grain size distribution particularly of mountainous rivers reflect the erosional processes at work on the bordering hillslopes. This has recently been illustrated based on a study encompassing all major rivers in the Swiss Alps with sources in various litho-teconic units of the Central European Alps (Litty and Schlunegger, 2017). Among the various processes, the supply of material through landsliding (van den Berg and Schlunegger, 2012) and torrential floods in tributary rivers (Bekaddour et al., 2013) were proposed to have the greatest influence on the grain size distribution in these rivers (Allen et al., 2013), where tributary pulses of sediment supply alter the caliber of the trunk stream material. Accordingly, the nature of erosional processes on valley flanks are likely to have a measurable impact on the supply of material to the valleys’ trunk rivers, and thus on the sediment caliber in these streams.

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

The western margin of the Peruvian Andes represents a prime example where these mechanisms and related controls on the grain size distribution of river sediments can be explored. In particular, this mountain belt experiences intense and frequent earthquakes (Nocquet et al., 2014) in response to subduction of the oceanic Nazca plate beneath the continental South American plate at least since late Jurassic times (Isacks, 1988). Therefore, it is not surprising that erosion and the transfer of material from the hillslopes to the rivers has been considered to strongly depend on the occurrence of earthquakes, as measured ^{10}Be concentrations in pebbles suggest (McPhilipps et al., 2014). On the other hand, it has also been proposed that denudation in this part of the Andes is controlled by the distinct N-S and E-W precipitation rate gradients. These inferences have been made based on concentrations of in-situ cosmogenic ^{10}Be measured in river-born quartz (Abbühl et al., 2011; Carretier et al., 2015; Reber et al.,in press), and on morphometric analyses of the western Andean landscape (Montgomery et al., 2001). Because erosion has been related to either the occurrence of earthquakes and thus to tectonic processes (McPhillips et al., 2014) or rainfall rates (Abbühl et al., 2011; Carretier et al., 2015) and thus to the stream's mean annual runoff (Reber et al., in press), and since hillslope erosion and the supply of material to trunk streams is likely to influence, or at least to perturb, the caliber of the bedload material in mountainous streams (Bekaddour et al., 2013), it is possible that the grain size pattern in Peruvian trunk rivers reflects the ensemble of these mechanisms at work.

Here~~,~~ we present data on sediment grain properties from ~~streams~~rivers situated on the western margin of the Peruvian Andes (Figure 1A) in order to elucidate the possible effects of ~~precipitation, hydrological~~intrinsic factors such as morphometric properties~~, catchment morphometrics, tectonics and the El Niño on those sedimentological characteristics. We will show that differences in tectonic regime do not influence sediment~~ of the drainage basins, and extrinsic 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~~ (runoff and seismic activity) on sediment grain properties. To this extent, we collected grain size data from gravel bars of each stream along the entire western Andean margin of Peru that are derived from 21, over 700-km^2-large basins. Sampling sites were situated at the outlets of valleys close to the Pacific Coast.

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~~On the other hand, 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~~In contrast, 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).

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

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~~moisture to reach the coast. Only ~~around Piura, situated~~ in northern Peru ~~at~~around 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 the 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~~We selected river basins between 8°S and 18°S latitude situated on the western margin of the Peruvian Andes, because of the presence of marked N-S contrasts in precipitation rates and the presence of strong seismic activity due to the subduction of the Nazca plate (Table 1). Only the main river basins were selected, which were generally larger than 700 km^2. These basins have recently been analyzed for ^{10}Be-based catchment averaged denudation rates and mean annual water fluxes (Reber et al., in press). This allows us to explore whether sediment flux, which equals the product between ^{10}Be-based denudation rates and basin size, has a measurable impact on the grain size pattern. In addition, also for these streams, Reber et al. (in press) presented data on mean annual water discharge using the records of gauging stations and the TRMM-V6.3B43.2 precipitation dataset as basis (Huffman et al., 2007). We will use this information to explore the controls of water shear stresses on the caliber of the bedload material (see below).

Sampling sites were situated in the main river valleys in the western Cordillera just before it gives way to the coastal margin. We selected the downstream end of these rivers because the grain size pattern at these sites is likely to record the ensemble of the main conditions and forces controlling the supply of material to the trunk stream farther upstream. We randomly selected c.

five longitudinal bars where we collected our grain size dataset. Sampling sites are all accessible along the Pan-American Highway (see Table 1 for the coordinates of the sampling sites). Additionally, the Majes basin (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; Table 2). The Majes basin has been chosen because of its easy accessibility in the upstream direction~~. For~~ and because the ~~other basins, sampling sites were mostly accessible along the Pan-American Highway (see Table 1 for the coordinates~~morphology of ~~the sampling sites~~this basin has been analyzed in a previous study (Steffen et al., 2010).

~~At each site, around ten digital images of about 1m^2 each 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~~selections 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 (c. 1 m) from the ground surface~~. Photos~~ at each longitudinal bar. Ten photos were taken from an approximately ~~10m^2~~10 m^2-large area to take potential spatial variabilities among the gravel bars into account. From those photos, the intermediate *b*-axes and the ratio of the *b*-axes and the long *a*-~~axes~~axis of around 500 randomly chosen pebbles were manually measured (Bunte and Abt, 2001b) and processed using the software program ImageJ (Rasband, 1997). 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). ~~Every pebbles which were entirely visible on the digital images have been measured.~~

The pebbles were characterized on the basis of their median (D_{50}), the ~~coarse (~~D_{84}~~)~~ and the ~~maximum~~coarse (D_{96}) fractions. This means that 50%, 84% and 96% of the sampled fraction is finer grained 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***~~ Catchment-scale morphometric ~~***properties. River discharge estimates***~~parameters and characteristics, including drainage area slope angle and slope at sampling site (Table 1), 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-resolution digital elevation model Shuttle Radar Topography Mission (SRTM~~) ~~~; Reuter et al., 2007). The distances from the sample sites to the upper edge of the Western Escarpment (Trauerstein et al., 2013) have been measured.

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

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

Here, $\rho=1000\ kg/m^3$ is the water density, g the gravitational acceleration, Q (m^3/s) is mean annual water discharge that we have taken from Reber et al. (in press), W (m) the channel width, and S (m/m) is the channel gradient. Channel gradients at the sampling sites were calculated using the 90-m ~~***resolution (NASA***~~ resolution DEM as a basis. In addition, stream channel widths at each sampling site and at the time of the sampling campaign (May 2015) were measured on satellite images when available, and on field images with uncertainties of about 2 m. In addition, we have considered the basin mean denudation rates (Reber et al., in press; Table 1~~).~~) as variable because larger denudation rates points towards a larger relative sediment flux, which in turn could influence downstream fining rates of grain sizes (Dingle et al., 2017).

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

3. RESULTS

~~***3.1 North-south pattern of grain sizes***~~

3.1 Grain size

The results of the grain size ~~measurement~~measurements 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~~for rivers along the entire western Peruvian margin (Figure ~~3A~~3h; Table 1). Likewise, D_{84} 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~~ratio between the lengths of 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.~~varies between 0.67 and 0.74 (Figure 3i). Note that ~~in the streams located~~ between 15.6°S and 13.7°S, no gravel bars are encountered ~~along the coast~~in the rivers where they leave the mountain range, and only sand bars can be found~~, and therefore~~. Therefore no results are exhibited for these latitudes (Figure ~~3A~~3h and ~~B~~3i).

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 the downstream hydraulic geometry of alluvial channels reflects the decrease of particle size within an equilibrated system involving stream flow, channel gradient, sediment supply and transport~~.~~ (e.g. Hoey and Ferguson, 1994; Fedele and Paola, 2007; Attal and Lavé, 2009). Sternberg (1875) formalized these relations and predicted an exponential decline in particle size in gravel bed rivers as a consequence of abrasion ~~as~~and selective transport where the gravel is transported downstream. The relation follows the form: $D_x = D_0\ e^{-\alpha x}$ (Sternberg, 1875). Here, the exponent α decreases from 0.3 for the largest percentile (i.e., the D_{96}) to c. 0.1 for the D_{50}~~.—~~ (Figure 4).

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).~~

Table 3 shows the Pearson correlation coefficients (r-value) between the grain sizes, the morphometric parameters and the characteristics of the basins. As was expected, the D_{50}, D_{84} and D_{96} all strongly correlate with each other (0.73 < r-value < 0.93), but the *b/a* ratios do not correlate with any of the 3 percentiles (-0.1 < r-value < 0.1). The D_{50} values positively (but weakly) correlate with the sizes of the catchment area (r-value = 0.31), the distances from the Western Escarpment (r-value = 0.35), the mean annual shear stress at the sampling site (r-value = 0.23), the denudation rates (r-value = 0.34) and the sediment fluxes (r-value = 0.42; Figure 5A).The sediment fluxes show the highest significance level; p-value = 0.05 (Table 4). The D_{84} and the D_{96} values correlate positively with the shear stress exerted by the water on an mean annual basis with r-value = 0.33 and 0.39 and p-value = 0.14 and 0.08 respectively (Figure 5B and C).

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

4. DISCUSSION

4.1 CONTROLS ON GRAIN SIZE

Downstream fining trends ~~at~~in the Majes ~~indicates~~basin indicate 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~~Accordingly, while the supply of hillslope-dervied material is likely to have been accomplished by mass wasting processes, the ~~Majes basin fluvial transport is the dominating process controlling the transport and~~ evacuation and transport of this sediment ~~from their sources~~ down to the Pacific Ocean has predominantly occurred through fluvial transport, as the exponential downstream fining of the grains implies.

~~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-frecuency 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.~~*Absence of gravels in rivers between 15.6°S and 13.7 °S*

In the rivers located between 15.6°S and 13.7°S, no gravel bars are encountered where these rives leave the mountain range, and only sand bars can be found. This suggests that the transition from a gravel- to a sand-covered bed, i.e. the gravel front, is located along a more upstream reach of these rivers. This transition is generally rapid (Dingle et al., 2017) and often associated with a break in slope (Knighton, 1999). The gravel-sand transition has been interpreted to be controlled by either the elevation of the local base level, an excess of sand supply, and breakdown of fine gravels by abrasion (Dingle et al., 2017), or a combination of these parameters (Knighton, 1999). In our case, these rivers do not show any particular differences compared to the other rivers where coastal gravel bars have been found. In particular, there is no particular evidence why preferential breakdown of gravels along these rivers should be more efficient than in rivers farther north and south because the upstream morphometry and bedrock geology is similar. The other explanation would be an excess of sand supplied to these rivers. However, available information and geological maps do not display any major differences in bedrock lithologies along strike (Figure 1B), but we note that the resolution of the geological map does not provide enough detail about the weathering of the bedrock or the amount of regolith, which could be a source of sand. However, these rivers are situated in the segment where the buoyant Nazca Ridge is being subducted beneath the South American continental plate (Figure 3), which resulted in an uplift pulse of the forearc during Pliocene-Quaternary times, accompanied by enhanced erosion on the surface and at interface between the subducting and the hangingwall plate through tectonic shear (Hampel, 2002; Hampel et al., 2004). These effects are generally recorded in the morphology and sedimentary facies of the forearc (Hampel, 2002). Additionally, based on a detailed morphometric analysis of the region, Wipf et al. (2008) showed that this coastal uplift has rerouted and deflected the rivers in this area and has lengthened the downstream end of these rivers. It is thus possible that these tectonically-driven mechanisms caused the gravel front to step back farther into the mountain range, with the effect that the downstream terminations of these rivers only display sand bars. But we note that this interpretation warrants further detailed investigations, which includes a down-stream survey of the sediments in these rivers from the headwaters to the site where they discharge into the Pacific Ocean (similar to the analyses made along the Majes river, please see above).

Grain size and earthquake frequency

Landslides and debris flows represent the main processes of hillslope erosion and the main source of sediment in tectonically active orogens (Hovius et al., 1997; Korup et al., 2011). They are generally associated with triggers such as earthquakes and generally supply coarse and voluminous sediments to the trunk rivers (Dadson et al., 2003; McPhillips et al., 2014). In that sense we would infer a positive correlation between the frequency of large earthquakes and the grain size where an increase of earthquake frequency would induce an increase of landslide occurrence, thereby supplying coarser grained sediment from the hillslopes to the rivers. However, no correlation has been found between the seismicity and the grain size data when looking at the number of recorded historical earthquakes (Figure 3). We then infer that seismic activity and particularly the subduction mechanisms do not exert a measurable control on the grain size in the rivers of the western Peruvian Andes. Nevertheless, we do consider that the lack of gravels in rivers where the subduction of the buoyant Nazca ridge has caused uplift of the hangingwall plate was explained by a tectonic driving force (see section above). In particular, since this uplift caused a re-routing of these rivers (Wipf et al., 2006) and thus a lengthening of the river courses, the gravel front might have stepped back relative to the river mouth into the Pacific Ocean, as we have noted above.

Supply control on the grain size pattern

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

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

Hydrological control on the grain size distribution

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

4.2 TRANSPORT DISTANCE AND SLOPE ANGLE CONTROLS ON SPHERICITY

We consider a control of the transport distance on the sphericity of the pebbles. We indeed see a negative correlation between the sphericity and the distance from the Western Escarpment where the major sediment sources are situated, as provenance tracing investigations have shown (Litty et al., 2017). This suggests a decrease of the sphericity with a larger transport distance. As particles are transported over longer distances, we actually would expect abrasion (Dingle et al., 2017) to equalize the length of the three axes, thus making a particle more spherical. While this concept is likely to be valid for pebbles with a homogenous fabric, it likely fails to describe the abrasion and break-down of material with an inherited planar geologic fabric (such as gneisses and sediments). 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 multiple transport cycles of clasts that were temporarily stored in cut-and-fill terrace sequences, as e.g., put forward by Bekaddour et al. (2014) in their study about cut-and-fill terraces in the ~~catchment cannot be considered here~~Pisco valley at c. 13.7°S latitude, would positively contribute to this effect upon increasing the time scale of sediment evacuation.

~~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.~~

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

Conclusion

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

ACKNOWLEDGMENTS

This project is funded by the Swiss National Science Foundation (project Number 137516).

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~~FIGURE~~Wittmann, H., von Blanckenburg, F., Kruesmann, T., Norton, K. P., and Kubik, P. W., 2007. Relation between rock uplift and denudation from cosmogenic nuclides in river sediment in the Central Alps of Switzerland. Journal of Geophysical Research: Earth Surface, 112(F4).

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FIGURES AND TABLES 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~~ Results of the ~~basins characteristics~~statistical investigations, illustrated here as correlation matrix of the r-values. The valuess in bold show significant correlation between the ~~southern group of basins~~grain size data and the ~~northern group as showed in Figure~~ different catchment scale properties.

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~~ 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:**~~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 prole 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 (Reber et al. in press); f) Mean annual precipitation rates (Reber et al., in press); g) Mean annual water discharge (Reber et al., in press); h) Grain size results for the intermediate (b)-axis of the pebbles in the ~~streams~~rivers from north to south at the sampling sites presented in Figure 1~~. **B:**~~; i) Ratio between the intermediate axis

and the long (a)-axis ~~from north to south at the sampling sites presented in Figure 1.~~(modied after Reber et al., in press).

Figure 4: Grain size results along the Majes River.

Figure 5: ~~Grain~~Correlations between the grain size data~~.~~ and the river parameters. **A:** D_{50} versus ~~distance from the uppermost edge of the western Escarpment (taken from Trauerstein et al., 2013).~~sediment fluxes. **B:** D_{84} versus shear stress exerted by the water. **C:** D_{96} versus ~~distance from the uppermost edge of~~shear stress exerted by the ~~western Escarpment. **C:** D_{50} versus gradient averaged over a 500 m-long reach.~~water. **D:** ~~D_{96} versus gradient averaged over a 500 m-long reach. **E:** D_{50}~~ Ratio b/a versus mean ~~annual runoff. **F:** D_{96} versus maixum 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.~~ slope.