Dear Editor, dear Referee,

Thank you very much for handling our paper once again. We have improved the paper according to the very constructive and helpful comments by yourself and the reviewer.

Following your suggestions, we have seen that values of the D50 are indeed nearly constant along the entire western Peruvian margin and range between 2 and 3 cm. The largest D50 with values up to 6 cm have been measured in streams that are either sourced in the Cordillera Negra where mean basin slope angles are larger than 20°, or in the Rio Ocoña and Rio Camaña rivers located at 16°-17°S, which have the largest mean annual discharge as they capture their waters from a broad area on the Altiplano. We thus suggest that the generally uniform grain size pattern has been perturbed where either mean basin slopes, or water fluxes exceed threshold conditions.

The major changes include the improvement of the discussion part with a focus on the comparison between the particularly larger D50 and the basins where hillslope gradients are steeper than 0.4 on the average (i.e., 20-22°), or where mean annual stream flows exceed the average values of the western Peruvian streams (10-40 m3/s) by a factor of 2. In addition, we have updated the Figures with more information about earthquake occurrence, and we have corrected the text following the Referee's recommendations. Finally, we have tuned down most of the inferences and interpretations, which were based on weak correlations only. We have thus re-structured the discussion part accordingly.
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

[1] Comments by section:

Editor's comments

Abstract:
We have tuned down the interferences and removed the statements, which lack a significant correlation. We have also removed the linkage to the earthquake occurrence, as this appears to be weakly introduced, as noted by the Editor.

Introduction:
We have improved the presentation of the past efforts in exploring the controls on the grain size pattern in streams. We made an effort to frame this section in a more global perspective, as required.

Results:
We have mentioned that the morphometric variables and related to this, information about sediment fluxes and water discharge are inter-related, as required.
We have removed the section, which discusses streams that have no gravel bars, since we have no information about where the gravel front is situated. We thus follow the recommendation by the editor not to spend too much space on an issue which lacks any data.

> We indeed consider earthquake intensity as an important variable, and magnitude thresholds > 5.5 might need to be exceeded for the release of large volumes of landslides, as noted by the Editor. However, Figure 1 by Keefer (1984) suggests that earthquakes with magnitudes 4.5 are are theoretically able to release landslides over an area >10 km^2, which is substantial. Therefore, we have decided to keep our threshold where we considered earthquakes with a magnitude M>4.5.
>
> We have completely rewritten the remaining part of the discussion following the recommendations by the Referee, thereby focusing on the pattern of the D_{50} as recommended.

Referee's comments

Tectonics and geological setting:

Section 1.1 provides some good information about the geological context, but more is needed. Firstly, I am confused about the boundaries of the tectonic domains. The authors describe a change in the degree of interseismic coupling between north and south, specifically with high coupling and high seismicity south of 13-16 °S, and low coupling and low seismicity to the north. The authors cite a paper by Nocquet et al. (2014), but this paper does not contain data as far south as 13-16 °S, and instead appears to place the gap in seismicity at 3-10 °S. Almost all of the catchments in this study area are south of 10 °S, so it needs to be clarified where this boundary is. I'm struggling to reconcile the data in Nocquet et al. (2014) with the statements in this section. This needs to be cleared up.

> Indeed, this paper by Nocquet does not contain data as far south as 13-16 °S. We have corrected this point and modified the tectonic section, plus we have expanded the figures showing the depth of the Nazca plate beneath the South American plate plus the frequency of earthquake occurrence over a broader scale.

Second, Fig. 3 shows a long-wavelength feature in the slope data (panel G), from 7 to 14 °S; what is this? It has quite a significant amplitude, with slopes almost doubling in the centre, but it isn't discussed. This could be significant – see my later suggestions.

> We have discussed this large wavelength pattern of mean basin slopes. Please see the revised version where we wrote: *The pattern of mean slopes per drainage basin reveals a distinct N-S trend (Table 1). The corresponding values increase from 20° to 25° going from 6°S to 10°S latitude (where they reach maximum values between 0.4 to 0.45 m/m) after which they decrease by nearly 50% to values ranging between 10° and 15°. These relationships have not been explored yet, but most likely reflect the extent to which streams have crossed the western escarpment and sourced their waters in the relatively flat plateau of the Puna region. Indeed, most of the western Peruvian streams have their water sources on this flat area and then cross the western escarpment, which yields relatively low mean basin slopes particularly for basins south of 12°S. Contrariwise, the basins around 11°-12°S latitudes (which are characterized by the steep slopes) have their sources in the relatively steep Cordillera Negra (Figure 1A), which is a relatively dry mountain range situated on the steep escarpment. Along these latitudes, the high Andes are constituted by the high and heavily glaciated Cordillera Blanca situated farther to the east (Figure 1A). This mountain range is drained by the Rio Santa, which flows parallel to the Andes strike within the valley of the Rio Santa, and then crosses the Cordillera Negra at a right angle (Figure 1A).*
>
> In this context: We agree that exceptionally larger D50 values of 4-6 cm were measured for basins situated between 11-12°S and 16-17°S where hillslope gradients are steeper than 0.4 on the average (i.e., 20-22°), or where mean annual stream flows exceed the average values of the

> western Peruvian streams (10-40 m3/s) by a factor of 2. We have changed the discussion part quite significantly based on the Referee's comment the reviewer have made.

Finally, what timescale do the historical earthquake records average over? Is this sufficient to compare with grain size data?

> The historical earthquakes that have been listed on the Figure 3 records earthquakes for at least the last century. In Peru, the older earthquakes that have been recorded by the USGS survey catalogue dates to the 28th of Sept. 1906, located in northern Peru. When it is know that sediments are evacuated on the basis of several years (one year in the Alps for example), more than a century should be a sufficiently long timescale.

Section 4.1.2. "Absence of gravels in rivers between 15.6 °S and 13.7 °S:
I'm not convinced by the arguments in this section. The authors propose that this sub-group of catchments lack gravel bars potentially because they have been lengthened by tectonic deformation, which resulted in a pulse of uplift and enhanced erosion, and the gravel-sand transition simultaneously migrated upstream into the catchments. Do the authors expect the gravel-sand transition to migrate upstream in response to enhanced erosion? This seems counterintuitive to me, and also contradicts the interpretations they make about grain size correlating (weakly) with sediment flux (e.g., Fig. 5a). Also, Fig. 4 shows the fining rates are fairly low in this landscape, with D50 only decreasing by a few mm over >100 km. How far upstream do the authors propose the gravel-sand transition has migrated in order to supply only sand at their sampling location? How much have these catchments supposedly been lengthened? As it stands, this section raises more questions than it answers.
I recommend the authors take a look at Lamb, M.P. and Venditti, J.V., 2016, The grain size gap and abrupt gravel-sand transitions in rivers due to suspension fallout, Geophysical Research Letters, 43, doi: 10.1002/2016GL068713. This paper discusses gravel-sand transitions and suggests they arise because of changes in bed shear velocity (the wash load hypothesis). Are there any reasons why these catchments might have different bed shear velocities? Perhaps the framework in this paper can help the authors develop a more robust argument, if they do want to invoke gravel-sand transitions here. At the moment this section seems contradictory and unintuitive.
A more minor point: this argument is repeated all over again in section 4.1.3 from lines 318-323, and this repetition is not needed.

> We removed this aspect of our analysis as this section was raising more questions than it answered and since the discussion about the lack of gravels was not the focus of the paper.

Section 4.1.4. "Supply control on the grain size pattern".
This section overstates some of the results. Lines 329-331: "the positive correlation between the size of the D50 and the morphometry of these basins" – there is no correlation between D50 and slope, so do the authors mean with catchment area? This is still a weak correlation, so I think this statement is over-selling the relationship. Especially given the authors then claim "environmental factors exert a major control on the pattern of the D50 encountered for the rivers in western Peru". These are weak correlations, not evidence for "major control".

> Yes, indeed, correlations are weak and our previous statements were a tentative effort to explain our dataset, but we have probably over-interpreted these weak correlations. Please see the revised manuscript where we wrote: *We consider the correlations between the grain size data (e.g., D_{50}) and the basins scale properties (basin area, mean basin denudation rates, water shear stresses, sediment fluxes) as not strong and convincing enough for the identification of potential controls of these variables on the grain size caliber.*

> Instead, we follow the recommendation by the Referee and focused on the pattern of the D_{50} only.

Also lines 332-335: “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” – there seems to be no correlation between D50 and mean slope, so how can this explain the grain size patterns? The relationships that can be drawn from the data are being overstated.

> Yes, these correlations are weak and relationships were overstated. Instead, we focus on the sections where the D50 were larger than on average. We have thus completely changed the discussion as recommended by the Referee.

Next, the sentence from lines 341-344 needs to be clearer. Are the authors suggesting that the catchments with coarser grain sizes experience El Niños and extreme rainfall events with a greater sensitivity than the catchments with finer grain sizes? I find this to be very unlikely, not to mention the lack of correlation between sediment flux, water discharge and any of the grain size percentiles.

> With a lack of correlation between sediment flux, water discharge and grain size distribution, this part was overselling our data. We have refocused our analysis on the pattern of the D_{50}. Please see also our responses above.

Finally, the paragraph from lines 345-364 isn’t very clear either. My understanding is that the authors propose the coarser-grained catchments are experiencing a downstream shift in the position of gravel fronts, due to greater sediment supply from hillslope sources. However Fig. 5a shows that catchments can have a large D50 with either a very low sediment flux or a very high sediment flux (the full range), and Table 3 shows that no grain size percentiles correlate with catchment slopes. The authors imply that denudation rates act as a proxy for the amount of hillslope-derived sediment, but this isn’t necessarily the case.
As this section was raising more questions than it answered and that it was not the focus of the paper, we removed this part.

> We have removed this entire section since it has opened more questions than it has offered answers. Please see also our response above.

Furthermore, it might be that slopes act to perturb sediment flux (and grain size) above thresholds, e.g., some threshold angle for landslides and debris flows. In this case a simple correlation (like Table 3) might not reveal whether there is a threshold-controlled grain size response to hillslope processes, because below the threshold you wouldn’t even expect a correlation.

> Yes this is what we state in this new version. This is summarized in the abstract: *Exceptionally large D50 values of 4-6 cm were measured for basins situated between 11-12°S and 16-17°S where hillslope gradients are steeper than 0.4 on the average (i.e., 20-22°), or where mean annual stream flows exceed the average values of the western Peruvian streams (10-40 m3/s) by a factor of 2. We suggest that the generally uniform grain size pattern has been perturbed where either mean basin slopes, or water fluxes exceed threshold conditions.*

Section 4.1.5. “Hydrological control on the grain size distribution”
Line 373-374. “grain sizes correlate with the shear stress values”. The relationships in Fig. 5b-c look quite tenuous to me.

> Yes indeed, correlations are week. *The mechanisms by which grain size can be mediated through a threshold effect upon transport are less well understood, but it has been known at least since the engineering work by Shields (1936), and particularly by Peter Meyer Müller*

> *(1948) that threshold conditions have to be exceeded upon the transport of grains in fluvial streams. As a consequence, at transport-limited conditions, sediment flux, and most likely also the caliber of the transported material, depends on the frequency and the magnitudes at which these thresholds are exceeded rather than on a mean value of water discharge (Dadson et al., 2003). This might be the reason why values of water shear stresses, that are calculated based on the annual mean of water flux, are not sufficiently strongly correlated with the D_{50} values to invoke a strong controls thereof.*

If you took away the one point with very large grain size the correlations might even become negative?

> Yes, we note that these correlations are weak and some might even break apart if the largest values (for e.g., shear stresses) are removed.

I think the text is overselling the data here, and this section is unsatisfying because [1] the plots in Fig. 5 are not conclusive, and [2] because the previous section suggested that grain size is limited by hillslope sediment supply. It's difficult to explain the data as both supply-limited and transport-limited at the same time. Also, the average particle size apparently isn't correlated with either water discharge or shear stress, so I'm really not convinced at all that it's possible to infer "a hydraulic control on grain size distribution of the Peruvian rivers" as the authors claim.

> We interpret the data to point towards transport limited conditions, where sediment flux, and most likely also the caliber of the transport material, depends on the frequency and the magnitudes at which thresholds upon transport are exceeded rather than on a mean value of water discharge (Dadson et al., 2003). This might be the reason why values of water shear stresses, that are calculated based on the annual mean of water flux, are not sufficiently strongly correlated with the D50 values to invoke a strong controls thereof. The hydraulic forcing has a control only when a threshold is exceeded. We have outlined these relationships and a possible interpretation.

Section 4.2. "Transport distance and slope angle controls on sphericity"

Lines 394-398. Recycling particles from a terrace surely won't make them more spherical, because while the particles are being stored they aren't being abraded. Lines 405-406. The authors propose that in catchments with steeper slopes, denudation rates will be faster and transport distances will be shorter. Table 3 shows no correlation between slope and denudation rate (or sediment flux). This may be because slopes influence denudation rates non-linearly (see my earlier comment about the potential role of thresholds in this landscape), but either way this section seems to contradict the author's use of correlations and their data. Furthermore, it is unclear to me how steeper slopes will reduce the transport distance of material. Residence time yes, but not distance.

> See 'Slope angle controls on sphericity': The relative poor positive correlation between the sphericity of the pebbles and distance from the escarpment edge prevents us from inferring a distinct control of this variable. We have thus corrected this point. Contrariwise, the positive Pearson correlation between the sphericity of the pebbles and the mean basin slope is quite high, thus pointing towards a significant control. This suggests that basins with steeper slopes, as is the case for the Cordillera Negra, produce rounder pebbles. We tentatively infer that time scales of transport and evacuation of material is likely to be shorter in steeper basins compared to shallower ones. This might influence the shape of pebbles as they tend to flatten in response to effects of abrasion and 3D heterogeneities of bedrock that becomes more obvious with time and transport distance (Sneed and Folk, 1958). We thus 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.

[2] Minor comments:

Lines 75-81. This sentence is very long and needs to be broken up. It also sounds like the authors expect grain size to be limited by all different factors at once. If "grain size… reflects the ensemble of mechanisms at work", then all of those mechanisms are limiting grain size together, e.g. the grain size characteristics are both supply-limited and transport-limited at the same time. The authors should think about whether this is really what they mean.

Line 92. Trujillo isn't marked on the map. As was suggested in the first round of review, it would be helpful to refer to towns that are marked on the map.

Trujillo has been added on the Figure 1.

Line 93. "…up to 100 km broad coastal forearc plain". Is this 100 km wide? Long?

It is a 100 km wide broad coastal forearc plain, this has been added.

Line 120. "Andean" should be changed to "Andes".

Done.

Line 140. As was pointed out in the first round of review, "strong precipitation rates" implies a high intensity of rainfall, which isn't the same as a greater overall amount. Consider "high precipitation rates" instead.

We have used high precipitation rates.

Line 144. "to reach" should be "from reaching".

Done

Line 148-149. Again, like in the first round of review, please be careful about equating El Niño with ENSO. El Niño is one state of the ENSO, but they're not the same thing.

We have carefully changed this.

Line 161. "We will use" – I recommend sticking to one tense here, present is probably best. See also line 163, "sampling sites were situated" – use the present tense, because the sites are still there.

The sentences have been checked to stick to only one tense.

Lines 164-166. Again, see my point for lines 75-81, which also applies here. Do the authors expect grain size to record all environmental "conditions and forces" at the same time? Put another way, is grain size simultaneously supply-limited and transport-limited?

We have changed that in the introduction

Line 187. Percentiles should be plural.

Done

Line 204. The authors refer to a paper by Reber et al. (in press) – I still think it would be good to briefly say how much time the discharge records cover (1 year, 100 years? Which years, i.e. are they biased by El Niño?), and in general terms where the stations are (e.g., near the catchment mouths or higher up in the catchments, are they are in similar places in each catchment?). It doesn't need to be a detailed account of every station, but very briefly the reader needs to know, in this paper, whether the data record a meaningful period of time and can be fairly compared between catchments. This only needs 1 or 2 sentences.

An explanation has been added to the text in the methods part: *The mean annual water fluxes were obtained by combining hydrological data reported by the Sistema Nacional de Informacion de Recursos Hidricos (2 to c. 20 years of record) and the TRMM-V6.3B43.2 precipitation database (Huffman et al., 2007).*

Lines 208-211. This sentence is really unclear. Sediment flux can indeed affect grain size fining rates, but why does this principle mean denudation rates are variable in this study area?

> We have considered the 10Be-based basin mean denudation rates (Reber et al., 2017; Table 1) as variable because in the supply-limited case, higher denudation rates could be associated with the supply of more coarse-grained material to the trunk stream, which in turn could result in larger clasts in these streams.

Line 232. “at 106 km river upstream” – this wording can be improved.

> The wording has been improved: *The D_{50} percentile of the b-axis decreases from 6.2 cm to a value of 5.2 cm c. 80 km farther downstream.*

Line 233. “for the Pacific coast” should be “from the Pacific coast”.

> Done.

Line 312. “Infer” means to deduce something, but here the authors are speculating. I would change to “expect” or something similar.

> Done.

Line 313. “Increase *in* earthquake frequency”.

> Done.

Line 399. The 2016-2017 winter was not really an El Niño. There were restricted temperature anomalies that are sometimes called a “coastal El Niño”, but this is not the same as an actual El Niño, e.g., the Niño 3.4 box showed neutral anomalies. The warm water only pooled around southern Ecuador and northern Peru.

> We have changed our discussion part.

Lines 421-427. This really isn’t “unravelled” in this paper. Wouldn’t flattening the fabric of a clast reduce the c-axis, which isn’t measured here? Either way, there’s no explanation for the lack of correlation between slope and sediment flux or denudation rate, which seems counterintuitive given that sediment flux should relate to the residence time of clasts. This is more a hypothesis than a conclusion.

> Indeed. We have changed the interpretation: *The relative poor positive correlation between the sphericity of the pebbles and distance from the escarpment edge prevents us from inferring a distinct control of this variable. Contrariwise, the positive Pearson correlation between the sphericity of the pebbles and the mean basin slope is quite high, thus pointing towards a significant control. This suggests that basins with steeper slopes, as is the case for the Cordillera Negra, produce rounder pebbles. We tentatively infer that time scales of transport and evacuation of material is likely to be shorter in steeper basins compared to shallower ones. This might influence the shape of pebbles as they tend to flatten as effects of abrasion and 3D heterogeneities of bedrock that becomes more obvious with time and transport distance (Sneed and Folk, 1958). We thus 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.* Please see also our response above.

Line 427-428. “the ensemble of erosional and sediment transport processes have reached an equilibrium at the scale of individual clasts”. It’s not clear what this actually means.

> Yes, this was unclear and has been removed.

Lines 429-430. “the clast fabric of the channel fill has dynamically adjusted to water and sediment flux and their specific timescales”. This is also unclear. What timescales are being referred to here? What does it mean to say a “clast fabric has dynamically adjusted”?

We have removed this part.

Fig. 1. The latitude ticks are horizontal while the maps are actually rotated with respect to north, and I’m struggling to identify the latitudes of the catchments. The northernmost catchment looks to be around 9 °S on these maps, but plots at about 7 °S in Fig. 3. The coordinate system of the map could be clearer.

This has been shown in a clearer way on the figure 1

Fig. 1C. Around line 132 the authors describe a major N-S gradient in rainfall rates of ~1000 mm/yr. I can’t see evidence for this on the map, and the rainfall rates in the catchments look very uniform. If there is a major N-S gradient it’s hidden in the colour scale – consider using a different colour scheme that shows more variation between 0-1000 mm/yr. Also, the caption misspells “extent”.

There is a clear E-W trend but no clear N-S trend. The caption has been corrected

Fig. 2. The figure caption has an open bracket.

This has been corrected

Fig. 3. It’s unhelpful that the town names don’t match Fig. 1.

We have add the name of the city Camana in the figure 1

[3] General suggestions:

Here I am making some general suggestions to the authors, which they can take or leave as they like. I think a better way to interpret the grain size data would be to start with the D50 record in Fig. 3h and look at the spatial patterns. Most of the catchments have a uniform D50 of 2-3mm, and there are two places where there are peaks above this baseline. One is around 11-12 °S, and these catchments are the smaller ones between Lima and Huaraz that don’t seem to cross the western escarpment, while the others do. I suggested looking at this in my original review, and it still seems to me that this particular peak in grain size could be related to the catchments being shorter and steeper and not crossing the escarpment, but I’m not familiar enough with the area to develop this further. The authors should think about it, also because these catchments lie right in the centre of the long-wavelength feature visible in the slopes (Fig. 3g). If slopes are mediating grain size via a threshold effect, this could explain why the grain size peak is quite narrow and restricted to only the zone with the highest slopes and these shorter catchments in exactly this location.

The second peak is around 16-17 °S and coincides with a big spike in the mean annual water discharge. It could be that the correlation coefficients don’t show a relationship between grain size and water discharge because the authors are plotting loads of noise against itself (most of the catchments have a baseline discharge of 10-20 m3/s), but if they look across latitudes there seems to be an obvious response here. Where discharge jumps up to ~80 m3/s, D50 jumps up to ~6 mm.

Examining these two features in the grain size data would be a better way forward. They are similar in amplitude (D50 increasing by a factor of 2x to 3x, which is significant), but presumably result from different triggers – one to do with discharge (the zone where discharge spikes is where the rivers move coarser material), and the other potentially due to the catchments shortening, not crossing the escarpment, and having the greatest slopes. Both of these responses (to discharge and slopes) could be non-linear and involve thresholds, so the authors need to think about whether simple correlation coefficients are suitable for exploring this (I think not), and whether the relationships get obscured by just doing bulk correlations between all the other catchments as well, when actually the grain size responses are limited to just a few catchments.

If this is correct, then you have two cases where grain size is similarly perturbed (perhaps by thresholds), but as a result of very different perturbations. That's important, because many studies use grain size perturbations to infer climatic/tectonic forcings, but this would suggest both can have similar effects in the sedimentary record that might be difficult to tell apart. Furthermore, the positions of these grain size peaks make sense, suggesting that this is a robust data set that has been measured with great care in the field. The authors have done a great job putting the data set together, now they need to write a paper that does all their hard work justice.

> We are very grateful for this comment and have changed the paper accordingly, thereby following closely these recommendations. Our previous version was indeed an overstating of the relationships between week correlations.
> We have proceeded carefully with the acquisition of the grain size data and we are happy to read that the Referee considers the data as valuable contribution for the community.
> We hope this new version of the manuscript will indeed give justice to the work, which has been done.

~~Environmental~~Possible threshold controls on sediment grain properties of Peruvian coastal river basins

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ABSTRACT

Twenty-one coastal rivers located ~~on~~along the entire western Peruvian margin were analyzed to determine ~~the relationships between fluvial and tectonic processes and~~ possible controls on sediment grain properties. This represents one of the largest grain size dataset that has been collected over a large area. 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 of each drainage basin, sediment and water discharge together with flow shear stresses were determined and compared against measured grain properties. Grain size data show ~~a large scatter in the D_{50}, D_{84}, D_{96} values and in the ratio~~that the values for the D_{50} are nearly constant and range between 2-3 cm, while the values of the D_{96} range between 6 and 12 cm. The ratios between the intermediate and the long axis~~. We have not found any~~ range from 0.67 to 0.74. Linear 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~~all grain size percentiles and 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~~are small to non-existent. However exceptionally large D_{50} values of 4-6 cm were measured for basins~~,~~ situated between 11-12°S and 16-17°S latitude where hillslope gradients are steeper ~~basins, paired with larger flow shear stresses, are capable~~than on the average or where mean annual stream flows exceed the average values 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~~the western Peruvian streams by a factor of ~~the clasts~~2. We ~~thus~~ suggest that the generally uniform grain size ~~distribution of gravel bars and the fabric of individual clasts~~pattern has ~~dynamically adjusted to~~been perturbed where either mean basin slopes, or water ~~and sediment flux and their specific time scales~~fluxes exceed threshold conditions.

1. INTRODUCTION

The size and shape of 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), (ii) the mechanisms of sediment supply and provenance (Parker, 1991; Paola et al., 1992a, b; Attal and Lavé, 2006), and (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 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; 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~~mainly depends 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~~river discharge and shear stresses (D'Arcy et al., 2017; Litty et al., 2017~~),~~); and (iv) bedrock lithology where low erodibilty lithologies are sources of larger volumes of material (Korup and Schlunegger, 2009~~).~~ , Allen et al., 2015). Accordingly, the sediment caliber in these rivers could either reflect the nature of erosional processes in the headwaters and conditions thereof (such as lithology, slope angles, seismicity releasing landslides), which then corresponds to supply-limited conditions. Alternatively, if enough material is supplied to the streams, then the grain size pattern mainly depends on the runoff and related shear stresses in these rivers, which in turn corresponds to transport-limited conditions.

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~~ 2017), and on morphometric analyses of the western Andean landscape (Montgomery et al., 2001). ~~Because~~Accordingly, erosion along the western Peruvian Andes 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~~ 2017). Therefore, we hypothesize that hillslope erosion ~~and~~paired with the ~~supply of material to trunk~~ streams ~~is~~runoff are 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~~ have a measurable impact on the grain size pattern in the Peruvian ~~trunk rivers reflects the ensemble of these mechanisms at work~~streams.

Here we present data on sediment grain properties from rivers situated on the western margin of the Peruvian Andes (Figure 1A) in order to elucidate the possible effects of intrinsic factors such as morphometric properties of the drainage basins~~,~~ (mean slope, drainage area, stream lengths), and extrinsic properties (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. This represents one of the largest grain size datasets that have ever been collected over areas which have experienced different tectonic and climatic conditions.

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 wide, broad coastal forearc plain with Paleogene-Neogene and Quaternary sediments 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,~~a.s.l., where currently active volcanoes south of 14°S of latitude are related to a steep slab subduction. 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~~Paleogene sedimentary rocks (Figure 1B).

The tectonic conditions of the western Andes are characterized by strong N-S gradients in Quaternary uplift, seismicity and long-term subduction processes, which in turn seem controlled by a plethora of tectonic processes. The northern segment of the coastal Peruvian margin (i.e. to the north of 13°S latitude), hosts a coastal plain that shows little evidence for uplift, and the Nazca plate subducts at a low angle. Also in this region, the occurrence of large historical earthquakes at least along the coastal segment has been much less (Figure 2c). Only in northernmost Peru (4° to 6° S latitude) uplift of the coastal area is associated with subduction earthquakes (Bourgois et al., 2007). Further south, in the Cordillera Blanca area (around 12° S latitude) may have been uplifted due to upwelling of magma (McNulty and Farber, 2002). In particular, the coastal segment south of 13°S hosts raised Quaternary marine terraces (Regard et al., 2010), suggesting the occurrence of surface uplift at least during Quaternary times. Since the number and altitude of the terraces increases closer to the area where currently the Nazca ridge subducts, uplift of the coastal area in a radius of approximately 200 km around the ridge (roughly 12° to 14° S latitude) is attributed to ridge subduction (Sébrier et al., 1988; Macharé and Ortlieb, 1992). Between 15° and 18° S latitude, uplift is associated with bending of the Bolivian orocline (Noury et al., 2016). The area south of 12° S latitude is also the segment of the Andes where the number of earthquakes with magnitudes > 4 has been large relative to the segment farther north

(Figures 1 and 2c). In contrast, the northern segment of the coastal Peruvian margin (i.e., to the north of 13°S latitude), hosts a coastal plain that has been subsiding and the Nazca plate subducts at a low angle. Also in this region, the frequency of large historical earthquakes at least along the coastal segment has been much less (Figure 2c)

1.2 Morphology

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). The morphology of the longitudinal stream profiles is characterized by two segments separated by a distinct knickzone (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~~Cenozoic 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). ~~In contrast, little~~Little to nearly zero clastic material has been derived from the headwater reaches ~~in~~on 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).~~

The pattern of mean slopes per drainage basin reveals a distinct N-S trend (Table 1). The corresponding values increase from 20° to 25° going from 6°S to 10°S latitude (where they reach maximum values between 0.4 to 0.45 m/m) after which they decrease by nearly 50% to values ranging between 10° and 15°. These relationships have not been explored yet, but most likely reflect the extent to which streams have crossed the western escarpment and sourced their waters in the relatively flat plateau of the Puna region. Indeed, most of the western Peruvian streams have their water sources on this flat area and then cross the western escarpment, which yields relatively low mean basin slopes particularly for basins south of 12°S. Contrariwise, the basins around 11°-12°S latitudes (which are characterized by the steep slopes) have their sources in the relatively steep Cordillera Negra (Figure 1A), which is a relatively dry mountain range situated on the steep escarpment. Along these latitudes, the high Andes are constituted by the high and heavily glaciated Cordillera Blanca situated farther to the east (Figure 1A). This mountain range is drained by the Rio Santa, which flows parallel to the Andes strike within the valley of the Rio Santa , and then crosses the Cordillera Negra at a right angle (Figure 1A).

1.2 Climatic setting and runoff of streams

~~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 ~~(~~((Huffman et al., 2007; 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~~high 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 Andes form an orogenic barrier preventing Atlantic winds and moisture ~~to reach the coast. Only in northern Peru 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.~~from reaching the coast. 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~~Niño weather phenomenon ~~(ENSO)~~ (DeVries, 1987).

Mean annual discharge of streams along the western Peruvian margin has been reported by Reber et al. (2017). These authors calculated mean annual discharge values using the TRMM-V6.3B43.2 precipitation database by Huffman et al. (2007) as a basis. Reber et al. (2017, see their Table 3) corrected the theoretical values for water losses due to evaporation and irrigation using the gauging record of a minimum of 12 basins situated close to the Pacific ocean. For these areas hydrological data has been reported by the Sistema Nacional de Información de Recursos Hídricos (SNIRH). The hydrological data thus cover a time span of c. 12 years. The results show a pattern where mean annual ruonff of these streams ranges between c. 10-40 m^3/s. Rivers where mean annual runoff values are nearly 80 m^3/s comprise the Rio Santa at c. 9°S latitude (Figure 1A), which derives its water from glaciers in the Cordillera Blanca. Two other streams with high discharge values are situated at 16°-17°S (Rio Ocoña and Rio Camaña, Figure 1A) where the corresponding headwaters spread over a relatively large area across the Altiplano, thereby collecting more rain than the other basins.

2. SITE SELECTION AND METHODS

~~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~~are situated in the main river valleys in the western Cordillera between 8°S and 18°S latitude just before it gives way to the coastal margin. Only the 21 main river basins were selected, which were generally larger than 700 km^2. 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~~for simplicity because this yields comparable 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~~as the base level is the same for all streams. 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 the stream (Figure ~~2~~3; Table 2). The Majes basin has been chosen because of its easy accessibility in the upstream direction and because the morphology of this basin has been analyzed in a previous study (Steffen et al., 2010).

We randomly selected five longitudinal bars where we collected our grain size dataset. It has been shown that using a standard frame with fixed dimensions to assist gravel sampling reduces user-biased 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 at each longitudinal bar. Ten photos were taken from an approximately 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*-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).

The pebbles were characterized on the basis of their median (D_{50}), the D_{84} and the coarse (D_{96}) fractions. This means that 50%, 84% and 96% of the sampled fraction is finer grained than the 50^{th}, 84^{th} and 96^{th} ~~percentile~~percentiles 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).

Catchment-scale morphometric parameters and characteristics, including drainage area, mean slope angle ~~and~~ for each catchment, slope angle of the stream channel at the sampling site ~~(Table 1),~~ and distances from the sample sites to the upper edge of the Western Escarpment were extracted from the 90-m-resolution digital ~~-~~elevation model (DEM) 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 might 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~~2017), 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 DEM as a basis. In addition, stream channel~~ Stream channel widths ~~at each sampling site and at the time of the sampling campaign (May 2015)~~with an estimated error of 2 m were measured on satellite images ~~when~~where available, and on photos taken during the field ~~images~~campaign.

We were also interested in exploring whether sediment flux has a measurable impact on the grain size pattern because higher denudation rates could be associated with ~~uncertainties~~the supply of more coarse-grained material to the trunk stream This in turn could result in larger clasts in these streams and this could potentially cause gravel fronts to shift towards more distal sites (Dingle et al., 2017), thereby coarsening the sediment caliber at our sampling sites.These basins have recently been analyzed for ^{10}Be-based catchment averaged denudation rates and mean annual water fluxes (please see Reber et al., 2017, and information presented above). 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. ~~about 2 m. In addition, we~~ We have considered the ^{10}Be-based basin mean denudation rates (Reber et al., ~~in press~~2017; 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).~~higher denudation rates could be associated with the supply of more coarse-grained material to the trunk stream, which in turn could result in larger clasts in these streams. Furthermore, we also calculated mean basin sediment fluxes as a product between ^{10}Be-based denudation rates and basin size. We considered this variable because

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 Grain size

The results of the grain size 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 ~~for rivers along the entire western Peruvian margin~~ (Figure ~~3h~~2h; Table 1). Likewise, D_{84} values vary between 3 cm and 10.5 cm. The sizes for the D_{96} reveal the largest spread, ranging from 6 cm to 31 cm. ~~In addition, the~~The ratio between the lengths of the *b*-axis and *a*-axis (sphericity ratio) is nearly constant and varies between 0.67 and 0.74 (Figure ~~3i~~2i). Note that between 15.6°S and 13.7°S, no gravel bars are encountered in the rivers where they leave the mountain range, and only sand bars can be found. Therefore no results are exhibited for these latitudes (Figure ~~3h~~2h and ~~3i~~2i).

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~~c. 80 km farther downstream (Figures ~~2~~3 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 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

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~~three percentiles ($-0.1 <$ r-value < 0.1). Likewise, inter-correlation relationships also exist among other variables such as catchment area, distance from the western escarpment, sediment flux and water discharge (Table 3). 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). ~~3). The D_{84} and the D_{96} values correlate positively with the mean annual shear stress exerted by the water ~~on an mean annual basis~~flux with a r-value ~~=~~of 0.33 and 0.39 (Table 3). However, we note that these correlations are weak, and ~~p-value = 0.14~~some might break apart if the largest values for e.g. shear stresses (Table 3) are removed.

At a broader scale, values of the D_{50} are nearly constant between 2 and ~~0.08 respectively (Figure 5B~~3 cm (Table 3). The largest D_{50} with values of up to 6 cm are encountered in streams that are either sourced in the Cordillera Negra where mean basin slope angles are larger than 20°, or in the Rio Ocoña and ~~C).~~Rio Camaña rivers located at 16°-17°S, which have the largest mean annual discharge as they capture their waters from a broad area on the Altiplano.

The ratio of the intermediate axis over the long axis negatively correlates with the distance from the Western Escarpment (r-value = -0.33), albeit with a poor correlation, 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~~Table 3).

4. DISCUSSION

~~4.1~~

4.1 SLOPE ANGLE CONTROLS ON SPHERICITY

The poor negative correlation of -0.33 between the sphericity of the pebbles and distance from the escarpment edge (Table 3) prevents us from inferring a distinct control of this variable. On the other hand, the positive Pearson correlation of 0.63 between the sphericity of the pebbles and the mean basin slope is quite high (Table 3), thus pointing towards a significant control. This suggests that basins with steeper slopes produce rounder pebbles. 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). We tentatively infer that time scales of transport and evacuation of material are likely to be shorter in steeper basins compared to shallower ones. This might influence the shape of pebbles as they tend to flatten as effects of abrasion and 3D heterogeneities of bedrock that becomes more obvious with time and transport distance (Sneed and Folk, 1958). We thus 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.

4.2 CONTROLS ON GRAIN SIZE

Downstream fining trends in the Majes 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). ~~Accordingly~~So, while the supply of hillslope-dervied material is likely to have been accomplished by mass wasting processes, the evacuation and transport of this sediment down to the Pacific Ocean has ~~predominantly~~ occurred mainly through fluvial transport~~, as the exponential downstream fining of the grains implies.~~ .

~~*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~~impact

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 or intense rainfall 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~~expect a positive correlation between the frequency of large earthquakes and the grain size where an increase ~~of~~in earthquake frequency would induce an increase ~~of~~in landslide occurrence, thereby supplying coarser grained sediment from the hillslopes to the rivers. These relationships have been elaborated in multiples studies where positive relationships between landslide occurrence and the size of earthquakes have been documented (e.g., Keefer, 1984; 1994; Parker et al., 2011). ~~However, no~~We note here that a global-scale correlation ~~has been found between the seismicity and the grain size data when looking at~~between earthquake magnitudes and areas affected by landslides suggests that mass movements are triggered by earthquakes if a threshold magnitude of 5.5 is exceeded (Keefer, 1984). Here, we consider earthquakes with magnitudes >4.5 because Figure 1 by Keefer (1984) suggests that earthquakes with magnitudes as low as 4.5 are theoretically able to release landslides over an area larger than 10 km^2, which is already a large area. However, we do not see correlation between the number of recorded historical earthquakes larger than 4.5 Mw and the grain size data (Figure ~~3~~2c). We then ~~infer that seismic activity and particularly~~expect that the frequency of earthquakes larger than 4.5 Mw, and related to this, 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~~Possible threshold limits as controls 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). 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 Pisco valley at c. 13.7°S latitude, would positively contribute to this effect upon increasing the time scale of sediment evacuation.~~

~~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.~~

We consider the correlations between the grain size data and the basins scale properties (basin area, mean basin denudation rates, water shear stresses, sediment fluxes) as weak and unconvincing (Table 3). However, we recall that the D_{50} records a nearly uniform pattern with values that range between 2-3 cm along the studied western Peruvian margin. However, higher values of up to 6 cm are either measured in streams where mean slope angles of the bordering hillslopes in the upstream basin exceed 20° (between 11° and 12°S) or where water runoff values are nearly twice as large as the mean of all Peruvian streams (ranging between 10-40 m^3/s between 16° and 17°S; see Figure 3 and Table 3). Based on these observations, we tentatively interpret a supply control on the median grain size for the Cordillera Negra streams where slopes are mediating grain size through a threshold effect. In this case, these thresholds on the hillslopes are likely to be conditioned by the at-yield mechanical states of bedrock (Montgomery, 2001; Ouimet et al., 2009), where hillslopes with dip angles up to 20-25° can be sustained. Under these conditions, mass failure processes are likely to dominate the supply of material to the trunk stream, thereby increasing the caliber of the supplied material and causing the bedload material to coarsen. In the same sense, a threshold response to steeper slopes has been interpreted for the pattern of ^{10}Be-based denudation rates in the Andes (Reber et al., 2017) and in the Himalayas (Ouimet et al., 2009). In both cases, the relationships between denudation rates and mean basin slopes was considered to follow a non-linear diffusive mass transport model where denudation rates are proportional to mean basin slopes for low gradients, while these relationships become non-linear for slopes approaching a critical value. Reber et al. (2017) set this critical value to 27.5°, but the linear relationship of their dataset breaks apart for gradients larger than 0.4, which corresponds to an angle of c. 21°. At these conditions, hillslopes approach a threshold where slope angles are limited by the mechanical strength of bedrock (Montgomery, 2001; Schlunegger et al., 2013). Hillslope erosion is then mainly accomplished through mass failure processes, which in turn, is likely to supply more coarse-grained material to the trunk stream (see above), as modern examples have shown (Bekaddour et al., 2013). We note, however, that a confirmation of this hypothesis requires data about the spatial density and frequency of landslide occurrence along the western Peruvian Andes. This dataset, however, is not available yet, and its establishment warrants further investigations.

In basins situated between 16°-17°S, mean basin slopes are clearly below threshold conditions, but the D_{50} is twice as large as in neighboring rivers. Interestingly, these streams have mean annual discharge values that are twice as large as the western Peruvian streams on the average. Similar to the Cordillera Negra, we relate the relationships at 16°-17°S to threshold controls. In this case, however, they are likely to be conditioned by transport. The mechanisms by which grain size can be mediated through a threshold effect upon transport are less well understood, but it has been known at least since the engineering work by Shields (1936), and particularly by Peter Meyer Müller (1948) that threshold conditions have to be exceeded and have a control on transport of grains in fluvial streams. As a consequence, at transport-limited conditions, sediment flux, and most likely also the caliber of the transported material, depends on the frequency and the magnitudes at which these thresholds are exceeded rather than on a mean value of water discharge (Dadson et al., 2003). This might be the reason why values of water shear stresses, that are calculated based on the annual mean of water flux, are not sufficiently strongly correlated with the D_{50} values to invoke a strong controls thereof (Table 3). However, the lack of information about discharge patterns prevents us from calculating the magnitude-frequency distribution of runoff. Nevertheless, we consider the occurrence of larger peak floods for streams that capture a large portion of their waters on the Altiplano Plateau. This might indeed be the case for the Rio Ocoña and Rio Camaña. We thus tentatively assign large peak floods for these streams, which might explain the larger D_{50} values encountered in their gravel bars. Although highly speculative, we support our statement by the highly seasonal character of preciptation occurrence particularly on the eastern Andean margin and the Altiplano Plateau, which is largely conditioned by the monsoonal Andean jet (see above). We note, however, that this statement warrants a high resolution hydrological dataset for the western Peruvian sreams, which is not available.

An exception from these relationships is presented by the Rio Santa (Figure 1A) where mean annual water discharge reaches a value of almost 80 m^3/s, but where the size of the D_{50} is low. We relate this to the possible supply-limited state of this stream, conditioned by the orogen-parallel valley of the Rio Santa between the Cordillera Blanca and the Cordillera Negra, which has acted as a subsiding graben since the past 5.4 Ma (Giovanni et al., 2010; Margirier et al., 2015) and which might thus have operated as a sediment trap. This interpretation is also consistent with the low ^{10}Be-based catchment averaged denudation rates measured for the Rio Santa basin, as noted by Reber et al. (2017).

Note that our inferences are largely based on the pattern of the D_{50}, and that the consideration of the larger percentiles might add alternative views on our interpretations. However, since all percentiles are inter-correlated, as the pattern of the Pearson correlation coefficients suggests (Table 3), we think that our general conclusions about the occurrence of thresholds upon the supply and transport of sediment will not change. Note also that either transport or supply control and related thresholds were identified by Reber et al. (2017) for their explanation of the 10Be-based datasets on basin-averaged denudation rates on the western Peruvian Andes. We tentatively interpret that the grain size pattern of the Peruvian streams follows these lines.

Conclusion

We ~~have conducted~~present a complete dataset about grain ~~size analysis of gravel bars in~~sizes for all major rivers that are situated on the western Andean margin of Peru ~~where they leave the mountain belt.~~. We ~~have~~did not ~~found~~find any correlations to the current seismic regimes, where a larger ~~seismicity~~occurrence of earthquakes with magnitudes larger than 4.5 Mw is expected to increase the supply of coarse-grained material. ~~Instead~~However, we found ~~positive correlations~~that the values for the D_{50} are nearly constant and range between ~~water shears stresses,~~ 2 and 3 cm. Exceptionally larger D_{50} values of 4-6 cm were measured for basins situated between 11-12°S and 16-17°S where hillslope gradients are steeper than average (i.e., 20-22°), and where mean ~~basin denudation rates,~~annual stream flows exceed the average values of the western Peruvian streams (10-40 m^3/s) by a factor of 2. We suggest that the generally uniform grain size pattern has been perturbed where either mean basin slopes ~~and basin sizes on nearly all grain size percentiles. We interpret these results as the combined effect of various geomorphic~~, or water fluxes exceed threshold 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~~ upon the supply and the 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 material. This might have implications for our understanding 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~~controls 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~~distribution of gravelly-based streams.

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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: Results of the statistical investigations, illustrated here as correlation matrix of the r-values. The valuess in bold show significant correlation between the grain size data and the 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~~

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).~~ The purple strip east of the trench axis corresponds to the swath over which the historical earthquake data, presented in Figure 3, The map also illustrates the location of the buoyant Nazca ridge, depth of the slab in dashed line, plus patterns of earthquake occurrence. **B:** Geological map of the western Peruvian Andes. **C:** Map of the precipitation rates showing the spatial ~~extend~~extent 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~~2: Topography of subducting Nazca plate, where slab depth data has been extracted from earthquake.usgs.gov/data/slab~~/.~~/ modified form Reber et al., 2017. 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~~2017); f) Mean annual precipitation rates (Reber et al., ~~in press~~2017); g) Mean annual water discharge (Reber et al., ~~in press~~2017); h) Grain size results for the intermediate (b)-axis of the pebbles in the rivers from north to south at the sampling sites presented in Figure 1; i) Ratio between the intermediate axis and the long (a)-axis (modied after Reber et al., ~~in press).~~2017). Exceptionally larger D_{50} values of 4-6 cm were measured for basins situated between 11-12°S and 16-17°S where hillslope gradients are steeper than 0.4 on the average (i.e., 20-22°), or where mean annual stream flows exceed the average values of the western Peruvian streams (10-40 m^3/s) by a factor of 2.

Figure 3: 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 4: Grain size results along the Majes River.

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