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Dynamics

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Discussions

Interactive comment on "Impact of change in erosion rate and landscape steepness on hillslope and fluvial sediments grain size in the Feather River Basin (Sierra Nevada, California)" *by* M. Attal et al.

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esurf-2014-34: Response to reviewers' comments

Dear Editor,

We are very grateful to the two reviewers for their very constructive comments and suggestions. We had responded to the comments of reviewer 1 but will restate our responses here and provide updates on the actions taken in the revised manuscript which is now ready for resubmission. We respond to the general comments and then

more specifically to the line comments (line numbers refer to numbers in the Word document containing the revised manuscript).

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REVIEWER 1:

Firstly, the reviewer notes that the difference in grain size between landslide material and soil is unsurprising: "it is obvious to the casual observer that landslides contribute coarser material to rivers". We agree that this follows both conventional wisdom and the qualitative observations of anyone who ventures into the field. However, qualitative observations are not the same as quantitative data and we believe this is the first study that actually illustrates this point with actual grain size data for both soils and landslides in a similar parent rock in a given study area. The soil grain size data is probably the most novel, as highlighted by the reviewer. The reviewer would have liked more discussion about our observations in soils but we stress that a more detailed analysis of the soil properties, in particular their geochemistry, features in a companion paper (Yoo et al., Applied Geochemistry, 2011, referenced in the text). In the original submission, geochemical information of the soils was included as needed in the discussion sections. Still, in this revision, we included brief morphologic description of the soils with their soil taxonomy in the site description (section 2.1, line 170-175).

We acknowledge that the analysis of fluvial sediment data is "messier". It would have been splendid if we had found a much clearer signal but Mother Nature had decided otherwise. The three basins along which we decided to analyse the downstream evolution of fluvial sediment grain size ended up exhibiting different behaviours, in particular Bean Creek which shows no clear transition from steepened to relict landscape. We tried to reconcile the observations in all basins within the framework of flow competence and discussed the potential cause for the different behaviour in each basin. The reviewer's main criticism is: "how do you untangle the potentially dominant effect of hillslope sediment supply on channel grain size distributions?" We acknowledge that

this is difficult to assess and have therefore tried to be cautious in the paper. We say p.1066 line 8 "We therefore interpret the increase in sediment coarseness from the plateau to the steepened landscape as a result of an increase in both flow competence and the size of the sediment supplied from hillslopes to the channels". We believe that both factors are contributing to the downstream coarsening, for the following reasons:

(1) An increase in flow competence alone would not lead to the observed coarsening if sources were similar across the landscape. This is supported by the observation that there is a lack of coarse material on the plateau, as schematically illustrated in figure 12 (now fig. 11). For example, we found no clasts larger than cobble size at the plateau sites, whereas boulders were common at steepened landscape sites. This is a source effect. We have added line 521-524: "In addition, we find no coarse sediment available for transport along the studied rivers on the plateau: clasts larger than cobble-size are very rare on the plateau whereas boulders are widespread on the steepened landscape (e.g., see D100 data in Fig. 10 and Table A2)".

(2) There is a statistically significant increase in grain size with flow competence in Adams Creek (Fig. 11). This dataset includes two plateau sites and four steepened landscape sites across a range of ω'm values (our variable expressing competence) spanning two orders of magnitude. This suggests that flow competence plays a role in the evolution of grain size along the studied rivers: the coarsest transported sediment tends to occur at the sites with highest flow competence, which is consistent with our understanding of sediment transport in rivers. The rest of the data is noisy but is not incompatible with a general increase in grain size with flow competence. Isolating the influence of flow competence from the influence of sediment sources on the trends observed is however not possible with the data at hand. We have added at the end of the discussion (after discussing the rapid response of hillslopes), line 575-577: "This rapid response means that the increase in flow competence and change in sediment sources occur at a similar location along the rivers, making isolating the relative influences of these two controls on the grain size of the sediment transported by the rivers

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challenging".

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Line comments: P1051 Line 9: This is a sharp break. I would rewrite the end of section 1 to emphasize what the goals of the study are and perhaps keep the study area description in section 2.

–> We have rewritten the penultimate paragraph in introduction in order to make the reading more fluid and state the goals of the study more clearly (line 104-109). The paragraph now starts with: "This study proposes to bridge this gap by assessing the impact of increased erosion rates and associated slope steepening on sediment characteristics, both on hillslopes and in rivers. The study area is the Feather River basin (California) which comprises both low and high relief areas with erosion rates varying over an order of magnitude, from > 250 mm/ka in the steepest parts of the landscape to < 15 mm/ka on the low relief plateau (Riebe et al., 2000; Hurst et al., 2012)".

P 1059 Line 11: Perhaps describe the reach lengths in terms of # of channel widths?

–> We have added line 341: "which represents between five and 50 channel widths" after "100 m".

P 1062 Lines 3-5: I wanted to see a map of flow competence for the field area – perhaps add as another panel to figure 1? Also, why not just use specific stream power? It is easier to conceptualize (at least for me) and I suspect that changing the slope exponent from 1.15 to 1 will not fundamentally change the patterns/interpretations in figure 11.

–> Producing a map of flow competence would be challenging because it requires channel width measurements across the whole study area. Regarding the use of our competence variable ω'm rather than specific stream power: it is not clear in the literature that flow competence is related to specific stream power. Most studies relate competence to shear stress, but shear stress is difficult to quantify because of the co-variance between hydraulic radius and slope. Instead, we used an approach based

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on unit discharge which has been validated in previous studies. As the reviewer says, changing the slope exponent from 1.15 to 1 would not have a significant impact on our results.

P 1063 Lines 18-22: This sentence is difficult to unpack. Not much is said elsewhere in the manuscript about the difference in hillslope flux for relict vs. adjusting slopes. Perhaps this deserves a whole paragraph here.

—> We have added text to clarify this point which is of importance when considering the response of the landscape to change in erosion rates (both grain size and flux do increase). We have rephrased the section which now reads: "It is notable that sediment flux is directly related to erosion rates: a doubling of erosion rate will lead to a doubling of sediment flux to the river. An increase in erosion rate and hillslope steepness will therefore result in rivers being supplied with larger amounts of coarser sediment, making an increase in erosion rate more likely to influence fluvial sediment GSD than a simple change in source GSD".

P1063 Line 26: I suspect there is minimal to no salt weathering occurring in the Feather River sites!

—> The reviewer is correct. But this is just a generic statement about the processes that can affect particles during their time in soils.

P 1064 Lines 14-15: Units missing. I think you mean 0.51 meters right?

—> Oops, the units are meters indeed, thank you.

P 1064 Lines 14-19: Interesting to note that nearly similar soil thickness despite 2-fold increase in predicted erosion rates. . .

—> Yes, this was one of the many surprises the study area had to offer. We speculate in Yoo et al. (2011) that this is due to the buffering effect of tree throw: in the study area, trees manage to grow even in the steepest part of the landscape, thus preventing soil thinning with increasing erosion rate.

P 1067 Lines 15-17: Isn't the rapid hillslope response simply reflected in the lack of inner gorges?

—> This is an interesting point. Indeed, in many places in the steepened landscape, hillslopes are tightly coupled to the channel with no clear inner gorge. This supports the idea that hillslopes are responding rapidly to the change in rate of river downcutting. We have added this point in the last paragraph before conclusion and clarified our argument (which led to some confusion with reviewer 2). The paragraph now begins as follows line 563: "A series of observation suggests a rapid response of the hillslopes (in terms of source characteristics) to river steepening. Firstly, we observe that, only a few hundreds of meters downstream of the main topographic break in slope, fluvial sediment is significantly coarser than on the plateau and includes boulders that are typically absent on the plateau, as exemplified by the Adams Creek data (Fig. 9a). As rivers steepen and increase their competence in response to the increase in incision rate along the main stem of the Feather River, the adjacent hillslopes must steepen and respond rapidly to provide rivers with coarse sediment. Secondly, we note the absence of inner gorges in the steepened landscape, suggesting a tight coupling between the channel and hillslopes and a rapid response of hillslopes to an increase in the rate of river downcutting".

Figure 1: I would pair this with figure 3 as a two part overview figure, and eliminate the inset graphic currently with figure 3 (this is redundant since figure 4a serves much of the same purpose). As a general note, make sure that all labels and symbols can be read when printed out! I needed to zoom in significantly to see any details on many of the figures.

—> We thank the reviewer for this good suggestion, we have proceeded as suggested (reviewer 2 made a similar comment). The figures have been designed for the portrait format which is the final format in esurf. It is unfortunate that the review version is in landscape format.

Figure 2: You could easily add the hillslope length and relief to this figure to help clarify the meaning of those variables (i.e., that Sh is a hillslope-averaged quantity rather than local. . .)

–> Thank you, we have added this information to the diagram.

Figure 4: Enlarge Figure 4a, and perhaps color code the sample sites to make them visible. It's a little confusing to use circles for indicating the steepened channel reach, but it may work if the sample sites are color.

–> Thank you, we have coloured the steepened channel reach to clarify.

Figures 4b, 5, and 7 seem more like supplemental figures, but if they are included in the main text, perhaps combine them into one place?

–> We like to show the reader what the sites and samples look like. Combining all figures in one leads to a very large figure that does not fit in one page, so we have moved 4b to figure 5 ("soil sites") and kept figure 7 as it is ("fluvial sites").

Figure 6: This figure is a little tricky to interpret since the relative position of the profiles within the basin is unclear. Aside from Bean Creek, which looks like it drains to the NF Feather River, I suspect it would be easier to follow if you plotted all the tributary profiles alongside that of the MF Feather River.

–> We have tried to follow this suggestion but all the profiles end up overlapping, in particular Bean Creek that cuts across the others; in addition, this stretches the figure horizontally and makes the information less clear. We have therefore kept the original format but have added arrows in Fig. 1 to clarify where the different rivers connect to the Feather River.

Figure 8b: This figure is confusing because of the discontinuity across measurement methods. Personally, I would remove it since all this info is readily available in figure 8a.

–> We have been thinking about the different ways of displaying this information. What we can see in 8b but not in 8a is the difference between samples in the coarse sand / gravel fraction, with the proportion of fragments in this fraction increasing with erosion rate. Reviewer 2 also found that the gap between the curves obtained with the two different methods is confusing and wondered whether the data had been normalized properly. We have now double-checked the data and can confirm that the trends are correct. The caption now includes: "For both methods, the percent mass has been normalized to represent the value per 0.13 phi interval. Lines connecting the curves produced with the two methods (at 1 mm) have been removed for clarity; the peak at the transition is real: sediment in the fraction 1-2 mm is significantly more abundant than sediment in the fraction 0.5-1 mm". We believe this is an interesting observation that is not clear in Fig. 8a.

Figure 9: Plots a) and b) are basically showing the same thing. I think it would be clearer to just show 9a and remove 9b.

–> We think it is important to display the information in 9b for future studies of sediment transport in rivers that will incorporate grain size and sources of sediment. In particular, the fraction coarser than 1 mm is likely to be bedload whereas the fraction finer than 1 mm has the potential to travel in suspension. Similarly, Marshall and Sklar (2012) refer to the potential bedload fraction as "rock-fragments" in their global analysis of soil grain size, although they use a cut-off size of 2 mm.

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REVIEWER 2:

This manuscript by Attal et al. discusses how hillslope processes determine the granulometry of the bedload fraction of river sediments through a transient landscape. The authors have chosen a very well confined study site that is well suited to study this thematic and have delivered extensive field observations of grain-size distributions from characteristic landscape features and river reaches. The main results of this study

are: 1) fluvial sediment granulometry mirrors the contiguous hillslope distribution; 2) grain-size in the source areas depends on the slope angle, which obviously controls the residence time and thus the exposure time of sediments to weathering; and 3) the hillslope response to base-level lowering is fast with respect to the river network. The authors have crafted a nice manuscript that is overall very clear and well supported by data and is well suited for publication in ESURF. I have only few minor comments that I believe can easily be incorporated, as well as few suggestions concerning the figures.

–> Thank you for these comments.

* My major criticism of this work is that the analyzed sediment deposits in the active river channel provide only a snap shot without any information on how and when these sediments have been deposited. I could imagine that some of the studied gravel bars have been deposited during unusual floods while others during high river stages in a rather continuous manner; the latter however are not special from a flood terminology point of view. This makes it difficult to relay grain-size with the flow competence of river reaches, since the depositional process is very little understood. - e.g. would the authors find the same results if this study was carried out a year earlier or later? - Last, the rather fine-grained material from the upstream low relief areas might leave the catchment predominantly in suspension and might be thus underrepresented in the analysis (?). I think it is fair to discuss this problematic in the manuscript more extensively and especially to highlight the fact that the analyzed sediments are immobile during sampling times. Maybe the authors have some more information on flood statistics of this area that could be included? It would help also if the authors could give more information on the climatology of the study area in order to understand how flushy/seasonal the system is.

–> This is a problem inherent to all studies of sediment in rivers that do not involve a bedload sampler (and bedload samplers do have problems too – how representative is the sediment sampled at one point at one time in a river in flood, and how does one samples bedload in a river in spate transporting boulder-size grains?!). We have now

clarified our assumptions in section 2.4, stating in particular that we are interested in the sediment transported by rivers during floods (including bedload). We completely agree that a lot of the fine sediment (finer than sand) is likely to be evacuated in suspension and that only a fraction of it will be trapped in the gravel bars. We have added information about the hydrology of the study area to illustrate that the fluvial system is seasonal and that sediment transport is likely to occur occasionally during floods triggered by storms. The beginning of the second paragraph in section 2.4 now starts line 309 as follows: "Large variations in ωm are expected along the rivers in the study area, in particular at the main topographic break in slope where both discharge and slope will increase downstream. In a situation where all grain sizes are potentially available for transport in the river, river sediment is expected to become coarser as ωm increases, which we will assess in the following. For simplicity, we assume that (1) sediment in gravel bars is representative of the sediment that is typically transported during floods; (2) sediment in all the gravel bars investigated has been mobilised during an event of similar magnitude; and (3) fluvial sediment transport and subsequent deposition in gravel bars occurred during floods resulting from storm events with no spatial variation in intensity across the entire study area. To maximise the validity of these assumptions, we consistently chose gravel bars that contained sediment that had been unambiguously transported by fluvial processes and that showed evidence of recent transport (i.e., we avoided bars with significant vegetation and/or moss cover). It is worth noticing that the climate in the study area is characterised by high seasonality, with 90 % of the precipitation falling between October and April during storms lasting from a few hours to up to 10 days [see data for Brush Creek hydrologic station (BRS) located in the headwaters of the Adams Creek basin at latitude 39.692 and longitude -121.339; data accessed on the 09/02/2015 on the California Data Exchange Center website at http://cdec.water.ca.gov/cgi-progs/stationInfo?station_id=BRS; maximum daily precipitation recorded since 1986 was 292 mm on the 1st January 1997]. This implies that generalised sediment transport in the study catchments is likely to happen suddenly and synchronously during storms. We thus consider that discharge scales with

drainage area A (e.g., Snyder et al., 2003)...". A final point: we do believe that our observations and interpretations would still stand had we carried out the work one or ten years earlier: the gravel bars may be located in different places and/or have different sizes, the absolute values of D50 and D84 would probably be different, but the general trends observed and the coarsening of the sediment downstream of the break in slope would still be there.

* The leading research question(s) of this study has to be better highlighted. At the moment the elaborated introduction lets the reader only vaguely adumbrate what the goal of this study is.

−> We acknowledge that this was not very clear. Following the recommendation of the two reviewers, we have rewritten the penultimate paragraph in introduction in order to make the reading more fluid and state the goals of the study more clearly (line 104-109). The paragraph now starts with: "This study proposes to bridge this gap by assessing the impact of increased erosion rates and associated slope steepening on sediment characteristics, both on hillslopes and in rivers. The study area is the Feather River basin (California) which comprises both low and high relief areas with erosion rates varying over an order of magnitude, from > 250 mm/ka in the steepest parts of the landscape to < 15 mm/ka on the low relief plateau (Riebe et al., 2000; Hurst et al., 2012)".

* Considering that particle residence time is an essential argument for one of the major conclusions, the discussion of this parameter (page 1064, line 10 onwards) is coming a little out of the blue. It should be better introduced, explained in the method section and reported in the results.

−> The main objective of the study was to characterize sediment grain size distribution on hillslopes and in rivers and to document changes associated with differences in erosion rate. We introduce particle residence time in the discussion, when we try to interpret our observations in terms of processes. The residence time is a derived

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metric, which is calculated based on measured erosion rates (which were previously reported) and measured soil thicknesses (which were previously reported). We tested inserting sections on residence time earlier in the paper but felt it broke the flow of the narrative, and in addition we feel these do not belong in the methods and results since this is not a direct measurement but rather a derived metric based on preciously reported results.

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Minor comments: Page 1056, line 21: Table A1 is not exactly giving this information.

−> There is a "% mass largest clast" column in Table A1.

Page 1061, line 20 onwards: Is it necessary to apply such a complicated model? Or could the same conclusion be drawn from solely channel steepness or adjacent hillslope relief? This would make the findings intuitively simpler and would exclude a set of uncertainties, e.g. A=Q.

−> See response to next comment.

Page 1062, line 4 onwards: But this is intrinsic because the model is designed to work on slope and area. The conclusion should be that the model is a good predictor for landscape changes.... To derive this conclusion the model is not needed.

−> We compared grain size to flow competence because the theory predicts that grain size should increase with flow competence, which is a function of channel steepness and slope. This means that rivers of different sizes can be compared within the same framework. For example, Cascade Creek is a very large tributary of the Feather River. The sampling site on Cascade Creek on the plateau has the lowest slope of all sites (bar one). However it has the greatest flow competence of all plateau sites, due to its relatively high discharge, and it also has the coarsest sediment of all plateau sites, which may support the theory that grain size increases with flow competence.

Page 1065, line 1 onwards: It would be helpful to include some close-ups of the weath-

ering brim and pristine sediments in the manuscript.

–> We have added pictures on the figure with soil sites (now Fig. 4a).

Page 1065, line 10 to 22: It can also mean that the fines are just depleted because of higher transport capacities, flow velocities, etc.

–> Fair point, but we don't think this alone can explain coarsening. We have added line 512-515: "Depletion in fines could result in sediment coarsening but it cannot be the sole cause for coarsening in our case: the plateau sites would still be significantly finer than the steepened landscape sites in Adams Creek even after complete removal of their fraction finer than one, two or even ten mm (Fig. 9a)".

Page 1067, line 14: I do not understand this sentence.

–> We have rephrased line 561-562: "The cause of this distinct response of the Bean Creek basin to the rapid drop in relative base-level is unknown at that stage".

Page 1067, line 15: What is abnormal?

–> We acknowledge this was unclear so rephrased the whole beginning of this paragraph. We have also included an observation from reviewer 1. The paragraph now begins as follows line 563: "A series of observation suggests a rapid response of the hillslopes (in terms of source characteristics) to river steepening. Firstly, we observe that, only a few hundreds of meters downstream of the main topographic break in slope, fluvial sediment is significantly coarser than on the plateau and includes boulders that are typically absent on the plateau, as exemplified by the Adams Creek data (Fig. 9a). As rivers steepen and increase their competence in response to the increase in incision rate along the main stem of the Feather River, the adjacent hillslopes must steepen and respond rapidly to provide rivers with coarse sediment. Secondly, we note the absence of inner gorges in the steepened landscape, suggesting a tight coupling between the channel and hillslopes and a rapid response of hillslopes to an increase in the rate of river downcutting".

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Page 1067, line 24: I do not understand how the authors know that the sediments have only been transported few 100m? And after 100m where do they go?

–> This was bad phrasing from us (the observation was a few 100m downstream of the break in slope, not the sediment transported!) We have rephrased this whole paragraph to avoid misunderstanding (see previous comment).

Table 1: Indicate what is t and p for completeness.

–> P-values and t values are statistical parameters that are commonly used to quantify the goodness of regressions. The p-value represents the probability that there is no relationship between variables; the t value is called the test statistic (now clarified in the table) and further characterizes the goodness of the fit as a function of the number of data points (tables showing the percentiles of the t Distribution as a function of degree of freedom, which is related to sample size, exist in the literature).

Figure 1: This could be combined with figure 2. Please include the basin outlines and river network.

–> The reviewer probably meant Fig. 3. Reviewer 1 also suggested combining Fig. 1 and 3 so we have proceeded as suggested.

Figure 2: The slope map would be easier to understand if slopes would be classified to few major classes and draped over a shaded relief. Sample locations need to be better highlighted as well as the river network. For orientation a flow direction indication of the MFFR would help.

–> Thank you for the recommendation. We have proceeded as suggested and added arrows indicating flow direction for all rivers.

Figure 5 upper panel: In the lower left part it looks like man made metal structures. Can these features have influenced your hillslope granulometry?

–> The railings have been installed after the landslide. We do not think they could have

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influenced the grain size of the sediment.

Figure 6: It would be helpful to include the development of the flow competence along the river channel in one of the panels.

–> Reviewer 1 also made a similar suggestion but we can quantify flow competence only at our sites because it depends on discharge, slope and channel width, the latter having been measured only at the measurement sites. The location where flow competence will certainly increase is at the break in slope, as both slope and discharge will increase downstream.

Figure 8b: I understand that it is difficult to combine different grain-size measuring technics. But still it would be helpful to normalize the laser measurements to the smallest sieve fraction in order to have one continuous curve. Somehow this must have been applied in panel a already. By looking at this figure, could the bimodal peaks contain any information of the sediment origin (mixing equilibrium, etc.) and how meaningful is a D50, D84, . . . , value for bi-modal distributions?

–> We have been thinking about the different ways of displaying this information. Reviewer 1 also found that the gap between the curves obtained with the two different methods is confusing. We have now double-checked the data (including the normalization) and can confirm that the trends are correct. The caption now includes: "For both methods, the percent mass has been normalized to represent the value per 0.13 phi interval. Lines connecting the curves produced with the two methods (at 1 mm) have been removed for clarity; the peak at the transition is real: sediment in the fraction 1-2 mm is significantly more abundant than sediment in the fraction 0.5-1 mm". We believe this is an interesting observation and now discuss it in the text, line 467-470: "The particle size distributions for this fraction tend to be bimodal, exhibiting a low at 0.5-1 mm; this is consistent with previous observations that rocks which weather to sand (e.g., granite, sandstone) will produce a distinct bimodal distribution compared to rocks which weather to clays (Wolcott, 1988; Marshall and Sklar, 2012)". We believe

the D50 and D84 values still adequately describe the grain size distribution of the sediment, though differences between samples may be amplified or dampened compared to a situation where the distribution is unimodal.

Figure 10: Differentiate the plateau and canyon part in the basins outline by shading. Zoom to the river section with data in plot a.

–> We have followed this advice.