Earth Surf. Dynam. Discuss.,
https://doi.org/10.5194/esurf-2020-54-AC1, 2021

Earth Surface Dynamics
Discussions
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Interactive comment on "Sediment size on talus slopes correlates with fracture spacing on bedrock cliffs: Implications for predicting initial sediment size distributions on hillslopes" *by* Joseph P. Verdian et al.

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Received and published: 4 January 2021

Interactive comment on "Sediment size on talus slopes correlates with fracture spacing on bedrock cliffs: Implications for predicting initial sediment size distributions on hillslopes" by Joseph P. Verdian et al. Anonymous Referee #1 Received and published: 4 August 2020

Referee Comment (overview): The problem of predicting sediment size distributions on hillslopes has seen recent interest in the geomorphology community. Sediment size, especially when larger than typical “soil” grain sizes, influences dynamics both on hillslopes and adjoining river channels that must carry hillslope-derived sediment. However, data regarding hillslope sediment size and dynamics is scarce. Important parameters such as initial sediment size distributions, as well as their subsequent evolution through transport and weathering through the hillslope system, are not well known. A common assumption is that fracture spacings can be used to estimate initial size distributions in hillslope sediment derived from bedrock outcrops. However, weathering of blocks in situ or immediately after detachment may alter the initial size distribution.

In order to test this, Verdian et. al present field measurements of fracture spacing in exposed rock walls and sediment size in immediately adjoining talus slopes at 5 different sites in California. They find that size distributions are not smaller than their respective rock wall fracture spacings (in fact, they are coarser) and conclude that weathering does not substantially alter the initial size distribution. However, they find that initial sizes and to some extent particle shape do depend on lithology. Finally, they propose a simple ratio of timescales that determines the importance of weathering in setting size distributions before detachment from parent material (bedrock or saprolite).

Given the scarcity of hillslope sediment size data, the data presented in this paper are useful for their own sake. The basic confirmation that fracture spacing sets initial size distributions is also useful for models of hillslope sediment transport. However, I find the scope of the paper and presentation and interpretation of the data to be misleading and confusing. Below I outline the main points that need to be addressed, along with suggestions for improvement.

Author Answer: We are grateful to Referee #1 for these thoughtful and constructive comments and suggestions. They are very useful for highlighting where we can improve our analyses, interpretations, and explanations. In our responses below, and associated changes to the manuscript, we have done our best to address each comment and concern.

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Main suggestions

Referee Comment 1: The primary claim of the paper is that pre-existing fractures in exposed bedrock cliffs set the initial size distributions of hillslope sediment. This is in contrast to the idea that weathering- either in situ or soon after sediment detachment- substantially alters sediment sizes. It is currently unclear in the paper 1) why we care about latent fracture spacing 2) how “initial” sediment size is defined 3) why initial sediment size in important.

Author Answer: This is a helpful comment because it shows that the original manuscript did not successfully communicate several essential elements of the work.

1) We care about fracture spacing because intersecting fractures create a set of blocks that represent a “latent” or potential set of sediment particles (note: fracture spacing is not latent, the sediment particles are). The term latent is useful to distinguish between the blocks within the bedrock and the sediment particles they could become once they are fully detached from the bedrock. The latent particle size distribution, set by the fracture spacing distribution, sets the size distribution of sediment particles when they are first detached from bedrock and entrained in the geomorphic transport system, in situations where bedrock has not been subject to substantial weathering prior to detachment. In those situations, the initial sediment size distribution can then be estimated directly from knowledge of bedrock fracture density, or predicted indirectly from the lithologic, tectonic, and topographic factors that influence the extent of bedrock fracturing. Where weathering not insignificant, the initial sediment size distribution will reflect both sets of factors, those that determine latent size and those, such as climate, minerology, and erosion rate, that determine the extent of rock weathering prior to particle detachment. Predicting initial sediment size thus requires understanding the controls on both latent size and subsequent modification by weathering, and the relative importance of each in a given geomorphic setting.

2) “Initial” sediment size is defined as the size of particles when they are first (or ini-

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tially) detached, or “released” from bedrock, and entrained in the geomorphic transport system. Sediment production is another term used for the concept that there is a threshold that separates intact rock from mobile sediment. When a sediment particle is first “produced”, it has a size; that is the initial size.

3) The initial size distribution is important for at least two key reasons. First, the initial size sets the upper limit for sediment size in a catchment; in the absence of flocculation or cementation, sediment particles can only become smaller. Second, the initial size sets the scale for particle size reduction by comminution processes during transport. Particle size reduction in transport is commonly modeled as a function of three factors: the initial size, a transport distance (or time in transport), and a rate constant. For example, the Sternberg equation for particle size reduction in fluvial transport can be written as D(x) = Do*exp(a*x) where Do is the initial size, x is transport distance, and a is the rate constant. Thus, initial size influences particle size throughout a catchment. Environments that produce relatively larger initial size distributions (for example, due to less fractured rock), should have relatively larger sediment size distributions throughout the catchment, all else equal. To the extent that sediment size influences other geomorphic processes and landform attributes (e.g. river incision into bedrock and channel slope), initial size will be an important contributing factor.

Changes to the manuscript: We have substantially rewritten the introduction to more clearly articulate these three main points.

Referee Comment 2: On one hand, I appreciate that the authors have taken the time to try to test this hypothesis with field data. The sediment size and fracture spacing data are vitally important for our understanding of hillslopes. On the other hand, it seems fairly obvious that boulders in a talus pile immediately next to a rock wall would have sediment sizes that correspond to the fracture spacing in that rock wall.

Author Answer: As we stated in the original manuscript, the (“fairly obvious”) expectation of a correspondence between fracture spacing in bedrock cliffs and talus size on adjacent slopes is both intuitively appealing and mechanistically based, yet has not been systematically tested across a range of lithologies and weathering environments. Two recent studies in relatively uniform rock types (Neely and DiBiase 2020; Sklar et al., 2020) have shown a correspondence between fracture spacing and the coarse mode of hillslope sediment size distributions. However, another recent study by Messenzehl et al. (2018) showed that this correspondence does not always occur. In their case talus size is roughly uniform across a suite of locations where fracture spacing ranges over an order of magnitude; importantly, measured talus size is always either larger than or approximately equal to the mean fracture spacing. Their data and interpretation support the hypothesis that talus production by frost-cracking can preferentially exploit a subset of pre-existing fractures with a characteristic spacing, presumably leaving other fractures intact within the blocks detached from the cliff wall. These two conflicting sets of results provide additional motivation for our study, which extends the available data across a more diverse set of rock types and wider range of fracture spacings.

Changes to the manuscript: In the revised introduction we provide more detail on the results of Messenzehl et al. (2018), and explain how they provide an alternative hypothesis of control on talus size by a physical weathering process.

Referee Comment 3: Fracture spacings are measured at the free boundary of the wall, where weathering processes can occur. Isn't it possible that the measured fracture spacings reflect a combination of latent and weathering derived fractures?

Author Answer: (As noted above, it is not the fractures that we consider to be latent, it is the fracture-bound blocks that have the potential to become sediment particles when detached.) Yes, physical weathering processes could create new fractures within rock exposed at the cliff face, which would be included in our measurements of fracture spacing. By making these measurements at sites where rapidly retreating cliff faces expose relatively unweathered rock, we sought to minimize, rather than eliminate, the contributions of weathering to the fracture spacing distributions. However, in these settings, we can reasonably assume that weathering has at most a minor influence, and that, if available, measurements of fracture spacing taken from drill cores at these sites would roughly reproduce the factor of 40 variation in median fracture spacing we observe at the rock face.

In our conceptual framework, we seek to distinguish the influence on the initial sediment size distribution of fracture-bound blocks, present in relatively unweathered rock at the base of the weathered zone, from the influence of weathering processes that can shift the initial sediment size distribution away from that of the fracture-block size distribution. Examples of such weathering processes include frost-cracking, as in the study by Messenzehl et al. (2018), and selective mineral dissolution that leads to disaggregation along crystal boundaries, which can produce a sand- or pea-gravel-sized initial distribution from crystalline rock that has a wide fracture spacing. Chemical weathering processes can also pre-condition rock by weakening it, such that it will produce initial sediment particles with sizes that reflect the scale of erosional detachment processes, such as the spacing between tree roots for sediment production by tree-throw or the size of animal limbs for sediment production by burrowing mammals. This study focuses on the end-member case where the influence of weathering is most likely to be limited to processes of detachment, rather than processes that significantly modify the rock at depth.

Changes to the manuscript: In the revised introduction we clearly define “latent size distribution” as the size distribution of fracture-bound blocks that would become sediment particles if particles are produced by detachment along those pre-existing fractures. We also clarify the distinction between weathering processes that contribute to the fracture spacing distribution at the surface, and weathering processes that have the effect of altering the initial sediment size distribution without affecting apparent fracture spacing.

Referee Comment 4: Either way, what is the functional importance of grain size set by latent fractures vs. a combination of latent and weathering?

Author Answer: Distinguishing the controls on initial sediment size is important for both understanding and modeling variations in sediment size across catchments. Whether initial size is controlled by fracture spacing acquired at depth, or by surficial weathering processes that tend to shift the initial size away from the fracture-determined latent size, has important implications for which landscape-scale boundary conditions are ultimately determining initial sediment size. Key controls on fracture spacing include rock strength and diagenetic origin, tectonic history, and topographic position. In contrast, weathering intensity and style will depend largely on climate, rock mineralogy, and erosion rate through its effect on residence time in the weathering zone. Our study is a small contribution to the larger problem of determining under what conditions fracture spacing is the dominant control.

Change to the manuscript: In the revised introduction we clarify this aspect of the study motivation.

Referee Comment 5: It is perhaps more interesting to find that talus material has not weathered since release from the wall. However, because there is no constraint on age of the talus pile, it is difficult to draw conclusions about the relevant weathering timescale. Further, the data presented in this paper do not have any relevance for subsequent weathering of sediment as it moves through the hillslope system and ultimately into channels. Other studies have found sediment size fining indicating a combination of selective transport and weathering. The authors contrast their findings with Neely and Dibiase 2020 and Sklar et al 2020, but these studies measured sediment sizes far away from their exposed bedrock sources. The authors should clarify that their findings have no bearing on sediment size evolution and transport long after detachment.

Author Answer: The Referee correctly notes that we did not measure the sizes of sediment other than on the talus slopes beneath the cliffs where sediment particles were produced, and thus do not present data that can be used to better understand the controls on rates of particle size reduction in transport long after detachment. However, we disagree with the statement that our measurements of initial sediment size have “no bearing” on sediment size evolution. As noted above, initial sediment size sets the scale for subsequent size reduction. Furthermore, initial size affects subsequent transport dynamics, which in turn can affect rates of size reduction.

Changes to the manuscript: We have revised the paragraph in the discussion where we compare our results with those of Neely and DiBiase (2020) and Sklar et al. (2020), to explicitly consider the potential role of size reduction in transport in explaining the differences in the offset between sediment size and fracture spacing among the three studies.

Referee Comment 6: Looking at Figures 3 and 4, I am not convinced that sediment sizes in the talus pile are indistinguishable from fracture spacing in the rock wall. In fact, they seem to be substantially larger at many of the sites. The authors explain that this may because block detachments occur along wider fracture spacings, and subsequent blocks thus contain some of the smaller fractures within them. This is interesting and a fine interpretation, but conflicts with the conclusion that fracture spacing can be used to predict initial sediment size on hillslopes. The authors point out that p values for their data are large enough to be “insignificant.” However, it is unclear how p values are calculated and whether they are meaningful for the data presented: “In each case, the increase in median particle diameter with increasing fracture spacing follows a trend with a slope that is statistically indistinguishable ($p>0.45$) from a 1:1 relationship in log-log space.” From figure 4 it looks like perhaps the slopes are equivalent, but particle sizes are substantially shifted from fracture spacing. The smallest offset between particle size and fracture spacing is 42%. Let me be clear: this is not a flaw in the data, but in the interpretation and presentation.

Author Answer: This is a helpful comment because it shows where the original manuscript lacked clarity regarding the inferences that can be drawn from the data. We did not make a blanket claim that talus particle sizes are statistically indistinguishable from fracture spacing. Rather, we used the term “indistinguishable” for specific, narrowly-focused hypothesis tests using the data.

First, it may be helpful to remind the Referee and potential readers that data do not have p-values, hypothesis tests do. The passage quoted in this comment describes our test of the null hypothesis that the degree of correspondence between fracture spacing and talus size does not vary with the magnitude of fracture spacing. In plain language, this hypothesis holds that where fracture spacing is relatively wide, talus size should be relatively large, and where spacing is relatively close, talus should be commensurately smaller. Unlike the previous work of Neely and DiBiase (2020) and Sklar et al. (2020), we can use our data to test this hypothesis because we made measurements at sites that encompass a wide range of fracture spacings. This is the same null hypothesis that was implicitly rejected by Messenzehl et al. (2018), because talus size did not vary in parallel with fracture spacing at their sites. One way to test this hypothesis is to use linear regression. Because fracture spacing and talus size vary over more than an order of magnitude from site to site, we log-transformed the median values of both variables. We then fit linear trends (for each particle axis) to the log-transformed data using ordinary least squares regression. This analysis produces best-fit estimates of the trend-line slopes and their associated confidence intervals. We would reject the null hypothesis if the trends deviated significantly from a 1-to-1 relationship. This is a two-tailed, one-sample test because the slope of the 1:1 line is exactly 1.0, it has no uncertainty associated with it, and we make no assumptions about whether the talus trend might steeper or less steep than 1.0. In this case, the p-value quantifies the probability that our median talus-size measurements were sampled from a population with an underlying 1-to-1 correspondence with fracture spacing. We would reject the null hypothesis if that probability were sufficiently low. However, for the three regressions (one for each axis), the lowest p-value was 0.45 (the other two were higher), far greater than the conventional threshold of 0.05. From this result, we make the inference that the correspondence we observe, on average, between fracture spacing and talus size, does not vary meaningfully with fracture spacing; it is scale invariant and therefore may also occur in other settings with fracture spacings that differ from our study sites. We use a similar statistical analysis to test for differences

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between talus size and fracture spacing in the spread of the distributions for each cliff-pair. We find that where the fracture spacing distribution has a narrow spread, so does the corresponding talus size distribution. More formally, we fail to reject (with $p > 0.67$) the null hypothesis that the spread in the talus sizes has a 1-to-1 scaling with the spread in fracture spacing across the range of fracture spacings measured. The results of these two hypothesis tests, taken together, provide strong support for the inference that the distributions of talus sizes at our sites are strongly influenced by the distributions of fracture spacings in the source rock. The corollary is that other factors, such as weathering processes that might impose a different distribution of initial particle sizes, are much less influential.

A second, and distinct issue, is the relationship between fracture spacing and the size of the three different talus particle axes measured. Even when fracture spacing and talus size are clearly correlated, the median fracture spacing may not match the median of any of the three axes, for a variety of possible reasons. In our data, the intermediate axis diameter comes closest, as we would expect, but is larger than the median fracture spacing, on average. Although this is clearly apparent in Figure 4, panel b, we report (in the Discussion) the results of a simple sign-test which rejects the null hypothesis that they are not different (with $p = 0.006$). Other statistical tests produce similar results: a paired-sample, 2-tailed t-test would reject the null hypothesis (with $p = 0.003$), as would the corresponding non-parametric Wilcoxon signed-rank test ($p = 0.002$). We certainly do not make the claim that the talus b-axis distributions are indistinguishable from the fracture spacing distributions.

One possible explanation for the systematic offset of b-axis size and fracture spacing may stem from the inherent limitations of using one-dimensional measures of size to characterize three-dimensional objects. Fracture spacing is an indirect measure of latent block volume, and axis diameter is an indirect measure for talus volume. Perhaps for this reason, Messenzehl et al. (2018) used their linear measurements of talus axes to estimate talus particle volumes; and used vertical and horizontal scanline measure-

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ments of fracture spacing to characterize fracture density in terms of joints per cubic meter of bedrock. However, when we convert our data in a similar manner, we obtain an almost identical result to the b-axis regression shown in Figure 4b. Thus, we conclude that the use of linear rather than volumetric metrics is unlikely to be the source of the difference between median b-axis and fracture-spacing data.

Another possible explanation stems from the random orientation of the scan lines with respect to the joint sets exposed on the rock face. If a scan line traces diagonal transects across a set of prismatic rectangular blocks, where the latent a- and b- axes are exposed and the c-axes extend into the rock mass, then the measured fracture spacings would be systematically larger than the typical b-axis, by a factor that depends on the angle between the scan line and the joint set making up the b-axis fractures. However, if instead it is the a-axis that extends into the rock mass, then the scan line measurements would underestimate the b-axis. In the most general case, blocks are formed by three intersecting joint sets with non-perpendicular orientations, and thus are not rectangular prisms. In this case, the inter-fracture distance measured along any given scan line crossing a block could possibly range from near zero (near the tip of an acute-angled point) to greater than the a-axis length (for example if spanning the longest possible linear distance across a rectangular block face). An essential assumption in using the scan-line technique is that this variability can be overcome by a large sample size, resulting in an accurate if imprecise estimate of the central tendency and spread in the underlying population of fracture spacings. However, biased estimates can result at any single site, for the reasons outlined above.

A third possible explanation is not related to the geometry of measurement technique, but to mechanics of block detachment. As the referee notes, we interpret the offset between measured median b-axis and median fracture spacing to be at least partly due to incomplete exploitation of the full set of fractures by the rock detachment processes. This would result in some talus particles, particularly the larger ones, retaining some of the more closely-spaced fractures measured in the bedrock cliff face. This interpreta-

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tion is consistent with our observations in the field of fractured talus boulders, although some of those fractures could have been created or extended by stresses arising from the process of detachment from the cliff and deposition on the talus slope.

Finally, there is the question of how to predict initial sediment size. In environments where initial sediment size is dominantly controlled by the size of fracture-bound blocks at the surface of the source rock, relationships based on measurements or estimates of fracture spacing are likely to be a useful approach to predicting initial size. For example, if one assumes that our results can be generalized, one can write the following expression for the median b-axis (D50) as a function of the median fracture spacing measured by scan-line technique (F50): D50 = 1.42*F50, where the prefactor 1.42 accounts for the vertical offset of the b-axis regression line from the 1-to-1 line in Figure 4b. Whether this relationship accurately predicts talus particle sizes on other talus slopes beneath actively eroding bedrock cliffs could be explored with additional data. This simple expression serves to illustrate that fracture spacing can be used to predict talus particle size, in the case where there is a systematic offset to a scale-invariant correspondence between spacing and size.

Changes to the manuscript: In response to this comment, we have made a number of changes to the manuscript, including: - in the results section we expanded the explanation of the hypothesis tests applied to the data plotted in Figure 4; - in figure 2 we added a field photo showing talus boulders with fractures that can be interpreted as being inherited from the fractured bedrock of the cliff face above; - in the discussion section, we expanded the consideration of alternative explanations for the offset between the b-axis and fracture spacing; - in the discussion section, we added a paragraph, with additional relevant citations, discussing how measurements and model-based estimates of fracture spacing can be used to predict initial sediment size.

Referee Comment 7: Finally, it would be very helpful for the authors to more clearly outline the importance of this data. Even if fracture spacings perfectly matched sediment size in the talus piles, how is this helpful for future studies? Fracture spacing is

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very difficult to measure accurately, even in landscapes where clear, exposed bedrock exists. It is even more difficult in soil-mantled landscapes. The framework proposed in the paper is useful, if only because it points toward the difficulty and necessity for us to better understand rock and saprolite weathering and its role in producing initial sediment sizes. Perhaps one of the most interesting findings in this paper is the difference in grain size between lithologies. I think the paper would be much more interesting and useful if the authors amplified these findings. Overall, I think the findings in this paper are useful for advancing our fundamental understanding of hillslopes: but this does not come across clearly in the paper. I hope the authors can clarify the importance of their work.

Author Answer: We agree that it is vital to clearly communicate the relevance of our results for future studies. Regarding the feasibility of obtaining fracture spacing measurements to predict initial sediment size, fracture spacing can be measured or estimated in a variety of ways. In soil-mantled landscapes, direct measurements of fracturing in bedrock can often be made where relatively unweathered bedrock is exposed in roadcuts or in outcrops such as along incising streams. Fracture spacing at depth can also be quantified using data obtained from drill cores, and a large literature exists reporting such measurements. Geophysical measurement techniques are also useful for characterizing sub-surface fracture density, and when calibrated by direct observations from cores and outcrops, may provide estimates of absolute fracture spacing. Fracture density can also be estimated from rock mechanical models, based on analysis of topographic and regional stresses. Application of these techniques will be important for exploring the utility of our time-scale-based conceptual framework for understanding the relative influences of fracturing and weathering in determining initial sediment size.

Our finding of a strong association between rock type and fracture spacing, and thus initial sediment size, also suggests a potentially fruitful avenue for future work. Our study was not designed to systematically test for the influence of rock type on fracture spacing, however a large literature exists on this broad topic, which might be mined for

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general relationships relevant for predicting hillslope sediment size. Overall, our results confirming the expected correspondence of fracture spacing and initial sediment size, for the end-member case of bedrock cliffs producing talus-sized sediment, provides a stronger foundation for future field and modeling studies that seek to understand the influence of tectonics, lithology and climate in controlling landscape-scale variation in hillslope sediment size.

Changes to the manuscript: We have expanded the discussion (and added several relevant citations) to more directly address the implications of this work for future studies, focusing particularly on approaches for quantifying fracture spacing in soil mantled landscapes and the potential to use variation in rock type as a proxy for differences in fracture spacing and thus latent sediment size.

Minor points

Referee Comment 8: Sediment shape: Figure 6 shows differences in sediment shape between lithologies. While this is useful information, the discussion around shape could be toned down. The authors contrast their findings with Domokos et al., 2015, stating that “there is no evidence in our data that initial particle shape varies with size, contrary to the predictions from previous work that smaller particles should be more block-like on average.” However, the particle shape-size trends in Domokos et al., 2015 saturate for grains around 50mm in length. Most of the data in this paper are at or above this range, so I wouldn’t expect them to see the shape-size trends. Perhaps a more interesting comparison is to look at differences between the average shape data presented here and the saturation values in Domokos (_0.425 for c:a and 0.675 for b:a). Further, I’m not sure that finding difference in mean shape values between lithologies can be directly compared with the probability distributions of shape parameters in Domokos et al.

Author answer: We agree that it is difficult to compare our data with those reported by Domokos et al. (2015), in part because of incomplete reporting of the methods they used to obtain their results. We accept the suggestions to tone down the implied criticism and to highlight the differences in saturation values.

Changes to the manuscript: We have revised the paragraph discussing the shape results as suggested.

Referee Comment 9: Ratio of timescales: The authors propose a framework in which the ratio between regolith residence time and particle detachment time determine initial sediment sizes. I think this framework is fine; however, the way it is presented assumes that regolith is necessary for weathering. I am still unconvinced that fracture spacing does not include effects from mechanical weathering (frost cracking, tree roots, thermal fluctuations, etc.). Perhaps the authors just need to clarify when the particle size clock starts (see next suggestion below). If it starts after particles are released from bedrock, then their framework makes sense. However if it starts when pure bedrock first begins to weather/crack, it may not be appropriate.

Author answer: As discussed above, we need to more clearly define how we conceptualize the potential role of some (but not all) weathering processes in shifting the initial sediment size distribution away from the size distribution of latent, fracture-bound blocks in bedrock. For the time scale of particle production, Tp, the “particle size clock” starts, during exhumation of the rock, when the boundary between intact rock (weathered or unweathered) and mobile regolith (whether remaining in contact with the bedrock or immediately removed by active transport) reaches outermost surface of the particle to be detached. This is implicit in the definition of Tp as the time required to detach a layer of particles of a given size. This is distinct from the two possibilities suggested by the Referee (after detachment or at a depth below any influence of weathering).

Changes to the manuscript: As noted previously, in the revised introduction we explain more carefully and completely our conceptualization of the potential role of weathering in altering the initial size distribution away from the latent size distribution of fracture-

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bound blocks, as distinct from the potential role of weathering processes in contributing to the fractures bounding latent sediment particles. We have also made changes in the discussion to clarify the definition of the particle production time scale.

Referee Comment 10: Definition of “latent” and “initial”: It’s currently a bit difficult to understand what the authors mean by “latent” and “initial.” A clear definition in the introduction would help a lot.

Author Answer: See our response to comment 1 above.

Changes to the manuscript: In the revised introduction we provide clear definitions of these two terms.

Referee Comment 11: Talus sampling: In line 139 the authors explain that spatially uniform sediment sampling along the talus slope should yield an accurate grain size distribution even with size selective entrainment. However, this assumes that size distributions change linearly downslope. The authors might want to simply point out this assumption.

Author Answer: A linear variation is not required for spatially uniform sampling to accurately characterize an attribute of a single population distributed non-uniformly in space. Consider the problem of sampling a stream bed to determine the median particle size representative of the entire bed. Lateral sorting processes, active throughout the channel, may distribute the different particles sizes across the bed in a highly nonlinear pattern of patches and gradients. The most straight-forward sampling approach in this case is a uniform grid, as detailed by Bunte and Abt (2001) in Chapter 6 of their comprehensive sediment sampling manual.

Changes to the manuscript: We have edited this passage to clarify this point, and have added a reference to Bunte and Abt (2001).

Referee Comment 12: Figure 3: The authors refer to parts of the figure by letter, but they’re not included in the figure.

Author answer: Thank you for catching this omission.

Changes to the manuscript: We have added letter labels to each panel in the revised version of Figure 3.

Referee Comment 13: Figure 4: A legend that identifies data points is needed. It is unnecessarily difficult to refer to figure 1 and remember the colors and shapes to understand figure 4.

Author Answer: We agree, a legend for figure 4 is helpful.

Changes to the manuscript: We have added a legend to the revised version of Figure 4.

Referee Comment 14: Missing references: The authors should also cite some missing recent relevant studies: Shobe et al., 2016, who explore hillslope sediment size controls on river incision; Glade et al., 2017, who show data for boulder size distributions in an exposed bedrock system; and Glade and Anderson, 2018, who discuss the implications of weathering vs. erosion rate timescales on hillslopes; Ward 2019, who discusses ratios between incision rate and cliff retreat timescales; Duszynski et al., 2019 who review scarp retreat mechanisms and the role of weathering.

Suggested references: Duszynski, Filip, Piotr Migon, and Mateusz C. Strzelecki. "Escarpment retreat in sedimentary tablelands and cuesta landscapes–Landforms, mechanisms and patterns." Earth-Science Reviews 196 (2019): 102890.

Glade, R. C., and R. S. Anderson. "Quasi-steady evolution of hillslopes in layered landscapes: An analytic approach." Journal of Geophysical Research: Earth Surface 123.1 (2018): 26-45.

Glade, Rachel C., Robert S. Anderson, and Gregory E. Tucker. "Block-controlled hillslope form and persistence of topography in rocky landscapes." Geology 45.4 (2017): 311-314.

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Shobe, Charles M., Gregory E. Tucker, and Robert S. Anderson. "Hillslope-derived blocks retard river incision." Geophysical Research Letters 43.10 (2016): 5070-5078.

Ward, Dylan J. "Dip, layer spacing, and incision rate controls on the formation of strike valleys, cuestas, and cliffbands in heterogeneous stratigraphy." Lithosphere 11.5 (2019): 697-707. Interactive comment on Earth Surf. Dynam. Discuss., https://doi.org/10.5194/esurf-2020-54, 2020. C6

Author Answer: Thank you for suggesting these additional references.

Changes to the manuscript: In the revised introduction we now cite Shobe et al. (2016) and Glade et al. (2017) as illustrations of the importance of initial sediment size to the geomorphic evolution of hillslopes and rivers, and in the discussion of weathering and sediment production time scales we cite the work of Glade and Anderson (2018).

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