Reply to the comments of the three referees

We are grateful to Joel Johnson, Theodore Fuller, and the anonymous referee for their careful reading of our manuscript, their very encouraging comments, and their useful hints! In the following, we will reply to their major and minor comments by first quoting their words (in normal font) and then providing our response (in blue and italic font).

Please also find a change detection version of the whole manuscript (between the original submission and the revised version) at the end of this file.

Alexander Beer, James Kirchner, and Jens Turowski

A. Reply to the comments of Anonymous Referee #1

In the submitted manuscript Beer et al propose a new method for documenting spatial distributions in bedrock erosion via painting of bedrock surfaces. The authors suggest that paint is eroded by impacting sediment, such that areas of eroded paint correspond to areas of bedrock erosion, and compare their observations of eroded paint to repeat terrestrial laser scans.

To my knowledge, this is a new technique which has not been previously documented, and the authors show compelling results where the spatial patterns of eroded paint can be used to infer both variations in sediment impacts across a channel, as well as temporary aggradation of the sediment bed which can occur during floods. Erosion monitoring via painting appears to be a useful and easily applicable tool which can be of use in a variety of erosion studies, and as such, this manuscript deserves to be published. However, I have a few general comments which should be considered before published the final version.

Thank you for your kind evaluation of our work.

Major comments

1. The repeat photographs showing eroded paint do an excellent job of documenting erosion of paint via sediment impacts. However, I found the comparison with the TLS scans quite useful for making the connection that erosion of paint tracks with actual bedrock erosion. As this is intended to be a proof-of-concept methods paper, I think the paper could benefit from more comparisons between the TLS scans and photographs. For example, it could be useful to show some type of quantitative comparison between the eroded paint and documented bedrock erosion from the TLS scan (if the photos can be mapped over the TLS scans, then one could, for example, directly compare the areas of eroded paint with bedrock erosion from the TLS scans). For the paired TLS scan and eroded paint pair presented, it would be useful to show a TLS pair which corresponds to the photograph dates for painting (if such a TLS pair exists). Additionally, showing other TLS pairs which correspond to the eroded paint at different locations in the gorge would be worthwhile.

We are happy to hear that the reviewer agrees that the photo-comparison method is useful for easily demonstrating spatial erosion distribution. Unfortunately, no further direct comparative TLS data sets exist (specifically for the same period as the photographs), either because of low bedrock erosion rates, so that no clear pattern was visible (as noted in the text for the right gorge wall), or due to high bedrock erosion rates, so that all the paint was removed (as for the slab, Figure 4H). Direct quantitative comparison of paint erosion with TLS scans is problematic, because the paint is removed by amounts of erosion that are barely detectable by TLS, and, conversely, because erosion that can be easily measured by TLS would have removed the paint many times over.

We tried overlaying photos on TLS change detection data (and vice versa), but the resulting images were indecipherable due to the combination of the natural shading of the photos and the artificial shading of the TLS data. We think that the comparison of Figure 2B/C and 2F already shows that erosion painting clearly identifies the zones most affected by surface erosion. We also do not have directly comparable scans and paintings, since we painted much more often than we scanned.

Further (as outlined in more detail in the response to the second major comment below), this article on erosion painting is intended to provide both (i) a proof-of-concept study on the method and (ii) a discussion of its applicability, its advantages and its scientific potential, by highlighting specific results from its first application at our field site. Therefore, the focus of this article is not only on showing the comparability of the erosion patterns from TLS-based change detection and erosion painting. To more clearly indicate that this is not solely a proof-of-concept study, we will add to the beginning of the discussion: "In the following, we first assess the erosion painting method based on our proof-of-concept study. We then use this technique to draw inferences about spatial erosion processes at our study site, and discuss potential future applications in the geosciences.".

2. This appears to be a companion paper to a manuscript the authors have in review at JGR – Earth Surface. I have not seen this other manuscript in review, but from the citations listed here, this other paper appears to present more of the science and implications associated with documenting spatially-variable erosion, while this manuscript is focused more on methods. To that extent, there's large portions of the discussion section (e.g., section 4.2) as well as other parts of the paper that address some of the process implications and general science questions which may be more appropriate for the companion paper. Removing such sections from this paper would shorten the manuscript length and help to keep the focus on presenting a new method rather than discussion of science.

The present manuscript is not a companion paper to the one under review at JGR-ES, but an independent study with its own measurement technique and scientific results. The JGR paper presents the laser scans and their interpretation and does not mention the erosion

painting method at all. We point to the JGR paper for more detailed information on TLS data acquisition, processing and analysis for comparison with erosion painting.
In this ESurf paper, we not only address the scientific usefulness of the erosion painting method and outline potential areas of application, but we identify and discuss specific spatial patterns observed with this method in the field: (i) indirect visualisation of the tools effect (by the impact marks in the paint), (ii) consistent erosion patterns over different time periods, and (iii) strong variations in bedload transport across the study gorge. These are results that we could not obtain using the TLS scans. Hence, it would not be appropriate to move the discussion of these new observations and findings (e.g., section 4.2) to the JGR paper.

Minor comments

1. The authors frequently use the terminology which is either not explicitly defined or can have an ambiguous meaning. For example, the terms “tools effect” and “cover effect” should be defined since they won’t be obvious to all readers. Furthermore, I think it is more straightforward to simply describe the actual processes going on rather than using terminology, so in many places use of the term “tools effect” could be replaced, for example, with “sediment impacts”, and similarly “cover effect” could be replaced with something like “shielding of bedrock by deposited sediment.”
Often times erosion is mentioned, but it is unclear if this is meant to be erosion of paint or erosion of bedrock. Also, I think the authors use the term “erodibility” to refer to erosion of a material (i.e., bedrock erosion or erosion of paint), while “erosivity” refers to the ability of a sediment-laden flow to erode material, but I don’t think these terms were explicitly defined.

Thank you for pointing out these issues! We will clearly define these terms at their first use (tools and cover effects, erodibility and erosivity), and refrain from using them when direct description is more practical.

2. The writing in the paper is acceptable and the paper is readable, but there are many examples throughout the paper where the writing can be made more concise and superfluous information could be removed to reduce the overall manuscript length. I’ve indicated some of these in the technical comments below, but there are more throughout the paper.

In addition to responding to these technical comments below, we will the whole manuscript again to see where we can remove superfluous wording.

3. The documentation of aggradation during floods is cool and perhaps worth also highlighting in the abstract of the paper and emphasizing as an important benefit of this technique.

We agree and will gladly add a note to the abstract!

Line-by-line comments (no response needed)

Thank you very much for the thorough and helpful comments, we will gladly address them! Here are some responses to several of the line-by-line comments.

L13 – The 'several interacting processes' are not mentioned, which makes this sentence awkward.

Actually, in the further course of this sentence we name these processes (hydraulic shear detachment, plucking, abrasion, dissolution, and cavitation), but we will divide this sentence to be more clear: "Bedrock erosion in stream channels is driven by several interacting processes, of which the most efficient are hydraulic shear detachment of weak bedrock, plucking of bedrock blocks, and abrasion of small bedrock grains due to sediment impacts. Dissolution and cavitation can also be important contributors to bedrock erosion under specific conditions (Whipple et al., 2000; Sklar and Dietrich, 2004; Lamb et al., 2008; Vachtman and Laronne, 2013).".

Page 3 L8 – Here and also on L11-12 the writing is a bit ambiguous. I think you mean the highest flushing height recorded over the entire period was 2.6 m, the mean height averaged over all the events (including the time discharge was building up and waning down) was 1.3 m. Also, for the purposes of this methods, proof-of-concept paper, I'm not sure all this information is needed and some of it could be summarized in a table (and I imagine a lot of it is reported in the JGR paper), so some of it could be removed here to shorten the manuscript.

You are right, these sentences are a little hard to read. We therefore will move these values to a table in Figure 2 and shorten the sentences here, only stating that both flushing periods are comparable. However, as detailed above, this paper includes scientific results and interpretation (based on these numbers), and we therefore need to keep these data.

Page 4 L10-15 – I see the erosion painting method as a quantitative measure of the spatial distribution of sediment impacts, …

Thank you for that hint! We will gladly extend this section as follows: "Hence, erosion painting provides a semi-quantitative measure of the spatial distribution of sediment impact intensity, i.e. the erosivity of the streamflow. Assuming that impacting grains that remove the paint also abrade the underlying bedrock (which is reasonable from Figure 2 E, and from the impact marks in Figure 4 F), the erosion painting procedure can be further considered as an indirect measure of bedrock erosion.".

Page 5 L4-5 (and elsewhere) – I suggest reporting erosion rates in either mm/yr (instead of mm per 2 years, which is quite uncommon), and these should be instantaneous erosion rates based on the total time of flushing. Because the gorge's hydraulic regime is not natural, it makes more sense to me to normalize erosion rates by the total flushing time, as the flushing time can vary from year to year.

We agree that reporting erosion rates in mm/2a is uncommon and will therefore present these rates in mm/a. We consider the measured erosion rates over the two years as realistic estimates of annual means for the man-made hydraulic regime at the Gornera, since the erosion values of the TLS measurements in Figure 2 F and G date from a period of around 200 erosive flushing events over two years with very different flushing behaviour (frequency, length, volumes etc., as outlined in Beer et al., in review). Hence, we consider it appropriate to report annual mean erosion rates instead of instantaneous values per flushing time.

We will mention this in the text: "Quantitative TLS-based spatial bedrock erosion measurements (over two years with more than 200 flushing events of various discharges, length and volumes; see Figure 2 E) confirmed the decrease in the tools effect with height above the bed, as qualitatively inferred from erosion painting.".

We doubt that erosion rates scale linearly with either the number of flushing events or the total flushing time, because (for example) flushing twice as often would entail half as much sediment being transported per flushing event (thus the number of events would double and the amount of sediment would remain the same). Likewise flushing twice as long would not change the total volume of sediment transported through the study reach (even though the total flushing time would double).

Page 5 L24-25 – I found it odd that shear detachment of paint by bubbles was mentioned here and not discussed. If this is to be brought up, the authors should discuss to the extent possible whether or not this mechanism led to erosion of the paint. My interpretation is that there are areas which were inundated with water but do not show erosion, such that the water alone is not able to erode the paint.

We will move the discussion of potential incorporation of air bubbles in the paint to the subsection "General assessment of the erosion painting technique". Actually, there were no indications of paint erosion patterns influenced by included air bubbles, but we will mention the need to ensure dry and clean conditions during painting to avoid this problem: "The paint should be applied carefully (e.g., avoiding wet and dusty rock, and leaving sufficient time for drying), since incorporated air bubbles or insufficient drying could lead to shear detachment of the paint by flowing water alone, without abrasion of the surface.".

Page 5 L32 – This is the only time in the manuscript where the possibility of varying sediment size is mentioned. If there is some data on this, it could be useful to mention earlier in the manuscript (this doesn't need to be in a lot of detail, but when describing the different flushing heights, one could also mention how the size of sediment supplied to the gorge could have changed).

Unfortunately, we do not have data on transported grain sizes, but due to the differences in flushing discharges, lengths, frequencies and volumes there may have been differences in transported grain sizes and sediment concentrations. We will address this in the section on the field site: "Due to the characteristics of the flushing operations (i.e. short, steep hydrographs and evacuation of previously accumulated sediment), the mean transported bedload grain size (D_{50}) likely varies considerably during each flushing event and between flushing events. The D_{50} of the natural streambed upstream of the hydropower water intake is ~4 cm at low flows, but it is unknown whether the average sediment load (including high flows) is finer or coarser than this.".

Page 7 L4-5 "who showed" should be "which shows"

Actually, both are possible, but we will streamline this sentence as follows: "Qualitative erosion patterns observable in the eroded paint generally coincided with the quantitative bedrock erosion analysis of (Beer et al., in review), consistently showing that erosion rates of local bedrock surfaces depend on their position in the streambed and their spatial exposure to the impact of erosive tools.".

Page 7 L11-13 – Abrasion mills can also be used to explore variations in "erosivity" by changing the flow velocity, the sediment size, or the sediment load, so I find this comparison a bit unfair or perhaps misleading.

Oh yes, correct, we did not consider that! Thank you for the hint! We will remove this erroneous notion in the text, but we will gladly build on your comment and mention that abrasion mills could be used to study the influence of streamflow erosivity on paint erosion: "Laboratory tests (e.g., using the erosion mills of Sklar and Dietrich,2001) could be used to explore the erodibility of different paints, the influence of applied paint thickness, and paint adhesion on different bedrock lithologies. Also the erosivity of the flow in the abrasion mill (i.e. its ability to erode the paint) could be studied by changing the mill's flow velocity or sediment loading. This analysis could serve as background for more semi-quantitative studies of natural flow erosivities.".

Page 7 L32 – Hasn't erosion of alluvium already been studied using paint in the Dietrich et al (2005) and Surian et al (2009) refs already cited? Or did you have something else in mind (if so, please elaborate).

Thank you for pointing this out! Dietrich et al., 2005 and Surian et al., 2009 studied changes of the upper sediment layer (or armour layer). However, we here mean studying the erosion depth of alluvium. Hence, we write instead: "Even erosion depths in (coarse) alluvium could *be studied, if a~suitable paint is infiltrated into the bed, complementing techniques like scour chains (Laronne et al., 1994; Liebault and Laronne, 2008) or injection of coloured sand profiles.".*

B. Reply to the comments of Joel Johnson

"Graffiti for science" by Beer et al. presents an interesting proof-of-concept study that nicely illustrates the utility of using paint to indicate spatial patterns of surface erosion or sediment transport. I recommend publication with minor revisions to clarify just a few points. While I think the idea of using paint to constrain erosion patterns is fairly straightforward, the case study and field site is sufficiently novel and detailed to warrant publication. I believe this work will inspire others to use the technique.

Thank you for your kind recognition of our work!

Comments

Page 1 line 9: I appreciate that the authors do not oversell their technique, but in some ways my initial reaction to this line is that "qualitative" sells their method a little short. True that they cannot quantitatively measure erosion rates with the technique (or at least not with much accuracy), but using paint can quantitatively give spatial pattern of surface impacts. I can live with calling the method qualitative, but would encourage selling it as potentially a way to quantify spatial patterns. Same comment would apply to some points in the discussion.

Thanks for your encouragement, will gladly take your hint! Actually, the painting technique does not really give a quantitative measure (it would need to be calibrated against independent measurements), but it could serve as a semi-quantitative measure of sediment impact intensities (i.e. showing regions with different partial paint removal). Hence, in the abstract we will state: "The erosion painting method provides a simple technique for mapping sediment impact intensities, and qualitatively observing spatially distributed erosion in bedrock stream reaches.".

In the chapter "General assessment of the erosion painting technique" we will discuss this writing: "The transient paint erosion on the higher parts of the staff gauge between Figure 2 A and C, and also the slight erosion zones above and below the zone of complete erosion in Figure 3 B, indicated regions with lower sediment impact frequencies. Hence, erosion painting provides a semi-quantitative measure of the spatial distribution of sediment impact intensity.".

Pg1line14: Not sure its worth separating out hydraulic shear detachment and plucking as separate processes. I could be wrong (didn't go back and check), but I don't remember any of the papers they reference for this point emphasizing hydraulic shear detachment in rock separate from plucking.

Correct; we will add another reference here that deals with hydraulic shear detachment as the dominant erosion process (Vachtman and Laronne, Geomorphology 2013: Hydraulic geometry of cohesive channels undergoing base level drop).

Pg1 line 24: The authors could consider referencing Johnson, Whipple, Sklar, GSA Bulletin 2010, "Contrasting bedrock incision rates from snowmelt and flash floods in the Henry Mountains, Utah", which monitored bedrock incision in a natural channel (albeit in a modified reach), and focused on spatial patterns of incision in relation to sediment transport and accumulation as well as hydrographs.

Thanks, we will gladly cite it.

Pg2 line 14: Maybe a little more detail on the paint. Was it housepaint? Latex based? Oil based? There are a great many types of paint with different properties that could be described as environmentally safe paint for outdoor use.

We will expand our description here to: "We used environmentally safe and water-insoluble latex-based dispersion paint to cover natural bedrock surfaces ...".

Pg3 line10: of 42 rather than 42 of?

Yes ☺, we will change this accordingly.

Pg3line11: say a bit more about the data gapâ˘A˘Twhich data set? Flow depths? Was it a sensor failure? Does the power company not have records of releases?

Actually, we only have a data gap in our flushing height measurements, but know of two flushing events from the hydropower discharge data (that were similar to the adjacent flushings). We will include the description of the flushings in a table added to Figure 2 to give a better overview and save space.

Pg3 line27: describe "vertical erosion on planar surfaces" a bit more; I don't think this is a specific enough description. Lots of surfaces oriented differently relative to flow are probably planar but don't have vertical erosion in this study.

To be more precise we will extend this as follows "… vertical erosion on planar surfaces in line with the streambed …".

Pg4 lines19-20: I realize references are given for erosion and erosivity, but I think it worth clarifying a bit more what is meant here. i.e., say something like the amount (length) of vertical erosion.

We will change and shorten this sentence for more clarity: "However, drawing quantitative inferences on erosion rates would require calibration against independent measurements, because the erodibility of the paint and the underlying bedrock will typically differ by large factors (see further discussion below).".

Pg4 line 23: Probably don't need to point out that permission could be needed to do graffiti …

We think it is better to mention this, since we would not want readers to think we were advocating indiscriminate use of graffiti.

Pg5 line9-17: I think briefly mention this explanation in the caption of figure2, and/or in the text where the figure is referenced, or at least say something like “relation between the change detection and painted areas is further explained in the discussion section”. When I looked at figure 2 I tried to figure out what was going on with the patterns of erosion on the surface, and was perplexed until getting to this paragraph.

We will add to the results section (where Figure 2F is cited first): ”Relationships between these bedrock surface changes and paint erosion are further detailed in the discussion section.”.

Pg5 lines 24-27: So do the authors think these issuesâˇA ˇTair bubbles in the paint, and painting on wet rock surfacesâˇA ˇTaffected their measurements? It’s a little unclear how much these factors may have influenced their results. Is it conjecture, or based on hindsight from their results?

We actually did not see any air bubbles in our paint, but we mention this as an issue that could hypothetically lead to bias in the paint erosion patterns. Hence, to be clearer on this issue and to nevertheless point to the potential problem of air bubble inclusion, we will move the discussion of this problem to the section “General assessment of the erosion painting technique”. There we will state: “The paint should be applied carefully (e.g., avoiding wet and dusty rock, and leaving sufficient time for drying), since incorporated air bubbles or insufficient drying could lead to shear detachment of the paint by flowing water alone, without abrasion of the surface.”.

Pg7 lines 9-12: I’m not sure how well this would necessarily work, because how well paint adheres to a surface is generally pretty sensitive to the surface characteristics. I would think that different rock types or compositions would typically have different “paintabilities”. Its kind of hard to get paint to stick well to quartz, for example. In any case this effect should be acknowledged.

Thank you for this hint! We will mention this when speaking about potential further studies with abrasion mills to provide the basis for more semi-quantitative studies of streamflow erosivities: “Laboratory tests (e.g., using the erosion mills of Sklar and Dietrich, 2001) could be used to explore the erodibility of different paints, the influence of applied paint thickness, and paint adhesion on different bedrock lithologies. Also the erosivity of the flow in the abrasion mill (i.e. its ability to erode the paint) could be studied by changing the mill's flow velocity or sediment loading. This analysis could serve as background for more semi-quantitative studies of natural flow erosivities.”.

Figure 2: In 2f and 2g, does “mm/2a” mean millimeters per two years? So is this not the amount of erosion measured between 4/6/2012 and 8/10/2013 (1 year and 4 months or so), but that amount of erosion, normalized up to two years? Please clarify what the 2 years means in this case.

Yes, these erosion rates are derived from bedrock change detection measurements (2 million point measurements at mm resolution) over the time span 04 June 2012 – 08 October 2013. Since nearly all flushing events in 2012 and 2013 occurred in between these two laser scanning dates, the measured values represent erosion over the two years. We will mention this fact in the figure caption and in the results section. As already noted in the reply to the Anonymous reviewer above, we will report the erosion values as means over the two years of measurement, i.e. in mm/a.

I realize the Lidar-based change detection measurements are not the main focus of the present work, but on the figure or in the main text I think some mention of uncertainty of these measurements is needed. Both uncertainty of the individual scans themselves, and also uncertainty in the differences.

We will give an explanation on this topic in the section “Process inferences from erosion painting at the Gornera”, as follows: “The uncertainty in the individual TLS change detection values was 2.2 mm over the biennial comparison, and thus was in the same order of magnitude as the detected change rates. However, the huge numbers of TLS measurements permit a stable general impression of surface changes, assuming their measurement errors are not spatially correlated (Beer et al., in review).”.

In 2e, it seems confusing to have the box and whisker plot rectangles not be centered over the time intervals that I think they’re supposed to represent.

We realized that it is more useful to give some statistical numbers on the flushing periods than showing additional boxplots. Hence, we will add a table with these numbers to the flushing height series in Figure 2 D and remove the boxplots (Figure 2 E).

In figure 5c, I presume the dark vertical lines on either side of the white painted area is the rock being wet? Clarify in caption what the dark areas are. Conceivably could be intrusions or something.

Thank you for pointing to this problem! Yes, the black stripes are wet rock sections; we will point this out in the figure caption.

C. Reply to the comments of Theodore Fuller

This is a welcome addition to the literature on erosion in bedrock channels. One of the primary contributions of the paper is the presentation of field-based evidence that supports several hypotheses of bedrock channel erosion. The field observations presented here support at least three existing hypotheses on bedrock erosion processes:
1) bedrock erosion rates are highly variable depending on the in-channel orientation of bedrock surfaces; 2) lateral bedrock erosion via tools is focused at the base of the channel wall; 3) suspended sediment is capable of bedrock erosion.

Thank you for your kind recognition and résumé of our study.

Comments

Field-based evidence of a substantial cross-channel gradient in sediment concentration during high, erosive channel flows is a valuable contribution to the literature. As such, I would like to see this explored in a little more detail (to the extent possible) perhaps by providing basic hydraulic conditions within and upstream of the gorge that might be driving this apparent concentration gradient.

Exploring the hydraulic conditions and the streambed's influence that drive this sediment routing certainly is worth a whole study (incorporating analysis of the various flushing events), but would go far beyond the scope of this paper. We do not have hard numbers on the hydraulics here, but in the discussion we will explain a bit more why we think the sediment is routed to the left side of the gorge: "Directly upstream of the inspected wall section (to the left of Figure 1 C), there are rock blocks of 2 m size in the streambed that leave a passage on the gorge's left side. This passage may channelize the sediment flow even when these blocks are submerged by the flushing water. Further, secondary currents due to turbulence induced by the boulders are also likely to have influenced the sediment distribution (Venditti et al., 2014). We do not have direct measurements of the spatial sediment transport distribution during the flushings, but the erosion painting technique was able to document the crucial influence of sediment routing in setting local erosion rates.".

As a proof-of-concept study, I would have liked to see a more detailed discussion of the methodology. The authors briefly mention some of the potential pitfalls of the method in the discussion section but do not really address how these pitfalls can be avoided. Maybe the authors have indeed provided the necessary level of detail for a proof-ofconcept study, perhaps the editor has a better feeling for the detailed required for such a study.

As answered to the Anonymous reviewer above, we will add some more discussion of problems with the painting technique in the subsection "General assessment of the erosion painting technique", stating: "The paint should be applied carefully (e.g., avoiding wet and dusty rock, and leaving sufficient time for drying), since incorporated air bubbles or *insufficient drying could lead to shear detachment of the paint by flowing water alone, without abrasion of the surface.".*

In light of the comment above, it might be prudent to focus a little less on the proofof-concept idea, particularly in the abstract and introduction sections, and more on the qualitative field-based evidence which lends support to several existing hypotheses. Again, I think perhaps the most exciting thing here is that you have FIELD-BASED evidence of patterns of bedrock erosion.

We agree, and we will avoid using the term "proof-of-concept" that often in the text, since we already discuss the findings of spatial bedrock erosion distribution and applicability of the technique in detail.

More detail of the field site would help the reader put the findings in context. Estimate of hydraulic conditions, grain size and mobility, primary lithology of channel boundaries: : :

We will add some info on the field site: "The local bedrock is serpentinite, and the bed sediment consists of both serpentinite and gneiss. […] Due to the characteristics of the flushing operations (i.e. short, steep hydrographs and evacuation of previously accumulated sediment), the mean transported bedload grain size (D_{50}) likely varies considerably during each flushing event and between flushing events. The D_{50} of the natural streambed upstream of the hydropower water intake is ~4 cm at low flows, but it is unknown whether the average sediment load (including high flows) is finer or coarser than this. The sediment bed surface in the gorge returns to roughly the same height following each flushing event, but it likely varies strongly during the flushings themselves (Beer et al., in review).".

Line-by-line comments submitted as a supplemental document using the Adobe comment tool within the manuscript.

Thank you for your thorough commenting! We will gladly address your comments, as detailed in the following.

Page 2 line 26: I realize the field site is described in detail in another paper but I think you should at least give a brief description of bedrock lithology and a D50 of the bedload material.

We will add additional info on the field site as detailed in the answer just given above.

Page 2 line 29: I think it should be made clear that the paint started at the sediment bed surface and not the bedrock bed surface. Do you know the thickness of the alluvial deposit?

We will add a note to the methods, indicating that stripe painting started at the surface of the sediment bed: "… we painted several vertical stripes of 0.15 m width and 2.0 m height on two opposing straight and smooth bedrock walls, starting at the sediment bed surface

(Figure 1C and D; we unfortunately could not paint below the sediment surface due standing water in the sediment body).".
We assume that the alluvial deposit is several meters thick, since we have observed local m-deep scouring of the sediment (through the ponding water).

Page 2 line 30: Do you have any sense of bed coverage during the actual flow events? Are all grain sizes mobile at flushing flows?

We will add a note indicating that sediment bed height was relatively constant between flushing periods, but likely varied strongly during flushings: "The sediment bed surface in the gorge returns to roughly the same height following each flushing event, but it likely varies strongly during the flushings themselves (Beer et al., in review).".
Few times we observed parts of the sediment bed in the gorge completely scoured (after longer flushing events). So we assume all sediment sizes (except the big boulders) are mobile during flushings .

Page 2 line 31: Why is a reference for a 'water table' altimeter important? Maybe this is just my own misunderstanding of the term used here. Is water table equivalent to the open channel water surface?

We will change the term "water table altimeter" to "water surface altimeter" to make clear that this device monitored the height of the water surface in the gorge. Knowledge of this changing height is important for calculation of the submergence of the paint (Figures 2, 3 and 5).

Page 3 line 7: Sounds like fantastic field site for bedrock erosion studies with distinct sediment transport events.

This is the reason for our studies there ☺.

Page 3 line 8: Could specify that 'flushing height' is the same as flow depth (at least that is how I read this).

Yes, we mean "flow depth" by "flushing height". We will change the text here and elsewhere to avoid this term, and will name the y-axis of Fig.2D "flushing event flow height", since we refer to the height of water stage in the gorge during the flushings.

Page 3 line 17: At the risk of appearing to be a shameless plug for my own research, you could cite Fuller et al., 2016 (JGR-ES) which shows a similar result of decreasing erosion rates with height above the streambed.

☺ We will gladly cite Fuller et al., 2016, which was not yet published at the time we wrote this draft (so we originally referred to Fuller, 2014, PhD thesis).

Page 4 line 30: Fuller et al., 2016, which just came out in May, is a more easily accessible reference than the dissertation cited here. The hypothesis suggested by Fuller et al. is one of bed load particles being deflected into the channel walls rather than falling through the water column.

Ditto

Page 5 line 26: I am glad to see this discussed as I was wondering about this for much of the paper. I would make a note of how painting on wet rock and drying time could affect results in the methods section of the paper just so the reader doesn't have questions in his/her mind as they read through the results and discussion.

As detailed in the answers to both other reviewers above, we will better discuss problems with putting the paint on the rock in the section "General assessment of the erosion painting technique", stating: "The paint should be applied carefully (e.g., avoiding wet and dusty rock, and leaving sufficient time for drying), since incorporated air bubbles or insufficient drying could lead to shear detachment of the paint by flowing water alone, without abrasion of the surface.".

In the section on "Potential future applications of erosion painting" we will also note: "Laboratory tests (e.g., using the erosion mills of Sklar and Dietrich, 2001) could be used to explore the erodibility of different paints, the influence of applied paint thickness, and paint adhesion on different bedrock lithologies.".

Page 5 line 29: At the authors discretion in their encouragement of this method...I would advocate for excavating all the way to the bedrock bed and starting the vertical stripes at that elevation. I think it's possible that erosion could be occurring on the wall below the surface of the alluvial bed...though from a practical standpoint, unless a field site is highly regulated like the current site the base of the bedrock wall will likely be below base level flows.

We had the same idea of digging deeper in the sediment bed and painting the bedrock walls at lower elevations (below the sediment bed surface), since the sediment bed varies during the flushings. However, the water table in the sediment body is nearly flush with its surface and it was unfortunately not possible to paint below … We will mention this in the methods section: "To visualize variations of erosion with height above the streambed, we painted several vertical stripes of 0.15 m width and 2.0 m height on two opposing straight and smooth bedrock walls, starting at the sediment bed surface (Figure 1 C and D; we unfortunately could not paint below the sediment surface due the standing water in the sediment body).".

Page 6 line 29: Venditti et al., 2014 showed strong secondary flows, some oriented laterally toward the channel walls, as discharge enters a narrow bedrock canyon. You mention that the gorge measured here is only 30 m in length. Is it possible the type of flow described by Venditti et al., 2014 is contributing to the lateral transport of sediment particles? The Venditti paper should probably be referenced.

Yes, secondary currents will likely have conditioned sediment transport in the gorge; we will refer to Venditti et al., 2014. We will extend our discussion: "The driving mechanism of this laterally focused sediment transport was probably the coarse boulder bed of the channel upstream of the gorge (Figure 1 B) that likely deflected the sediment flow. Directly upstream of the inspected wall section (to the left of Figure 1 C), there are rock blocks of 2m size in the streambed that leave a passage on the gorge's left side. This passage may channelize the sediment flow even when these blocks are submerged by the flushing water. Further, secondary currents due to turbulence induced by the boulders are also likely to have influenced the sediment distribution (Venditti et al., 2014). We do not have direct measurements of the spatial sediment transport distribution during the flushings, but the erosion painting technique was able to document the crucial influence of sediment routing in setting local erosion rates.".

Page 7 line 3: when giving an example of the spatial distribution of sediment transport I would focus specifically on the cross-channel difference in sediment concentration that your results seem to support rather than generally mention the tools and cover effects.

We will extend our notes on what the erosion painting technique was able to show in this study (at the beginning of "Potential future applications of erosion painting") and state: "Our results demonstrate that erosion painting is a straightforward method for (i) visualizing the spatial distribution of bedrock erosion (i.e. variations with position and orientation), for (ii) inferring the spatial distribution of sediment transport (i.e. the sediment tools and cover effects), and for (iii) localising the transient elevation of the sedimentary streambed under some circumstances.".

Figure 2 comment 1: Interesting that even at heights above 2m where there were infrequent flows you still see erosion. If this is a real erosion signal and not just noise, it suggests erosion by some of the smaller particles in the distribution that may be in suspension. This would be field confirmation of the hypothesis put forth by Lamb et al., 2008 and Scheingross et al., 2014.

Thank you for your encouragement with interpretation of the erosion mode with height above the bed! The detailed discussion of the spatial change detection values (e.g., erosion up to three meters above the streambed) is already provided in Beer et al., in review, and we should not repeat it here. For consistency with Figure 2 A-C, we will only show the erosion profile up to 2.1m above the bed in Figure 2 G.

Figure 2 comment 2: Can you separate erosion according to discharge? If so, you could investigate the possible existence of an erosion threshold, like maybe no erosion occurs at the lower discharge events, maybe it is all due to the highest events. It could be that you don't have enough variation in flows due to controlled release events.

No, we sadly cannot separate erosion according to discharge (or flushing height). We always had several different flushing events (differing in discharge and likely sediment transport) in between the re-paintings. At the beginning and at the end of the summer, when there was much lower glacially driven discharge (and hence sediment transport), only a few small flushing events occurred in between the re-paintings and there was no paint erosion visible. In the summer with many high-flow events, we mostly had comparable erosion patterns (as detailed in Figure 3). So, we cannot determine a threshold of streamflow erosivity with our data. However, your hint is great, and we will gladly add this to the section on "Examples of advanced applications for field sites like the studied gorge would be (i) to more frequently check eroded paint patterns (e.g., after every erosive event) to find thresholds of paint erosion for constraining streamflow erosivity, (ii) to …".

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Graffiti for science - Erosion painting reveals spatially variable erosivity of sediment-laden flows

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Abstract. Spatially distributed detection of bedrock erosion is a ~~longstanding~~ long-standing challenge. Here we show how the spatial distribution of surface ~~abrasion can be visualized~~ erosion can be visualised and analysed by observing the erosion of paint from ~~bedrock surfaces in a natural bedrock gorge~~natural bedrock surfaces. If the paint is evenly applied, it creates a surface with relatively uniform erodibility, such that spatial ~~variations~~ variability in the erosion of ~~this surface reflect~~ the paint reflects variations in the erosivity of the flow and its entrained sediment. In ~~our~~ a proof-of-concept study, this approach provided direct visual verification that ~~the sediment tools effect was~~ sediment impacts were focused on upstream-facing surfaces in a natural bedrock gorge. Further, ~~it~~ erosion painting demonstrated strong cross-stream variations in bedrock erosion, even in ~~this~~ the relatively narrow (5 m wide) gorge that we studied. The left side of the gorge experienced high sediment throughput with abundant lateral erosion on the painted wall up to ~~0.8~~80 ~~m~~ cm above the bed, but the right side of the gorge only showed a narrow erosion band 15 - 40 cm above the bed~~due to the cover effect~~ , likely due to deposited sediment shielding the lower part of the wall. This erosion pattern therefore reveals spatial streambed aggradation that occurs during flood events in this channel. The erosion painting method provides a simple technique for mapping sediment impact intensities, and qualitatively observing spatially distributed erosion in bedrock stream reaches~~, and~~ . It can potentially find wide application in both laboratory and field studies.

1 Introduction

Fluvial bedrock erosion is an important control on stream channel development (and thus on whole landscape evolution) in steep mountainous terrain and tectonically active regions. ~~Several interacting processes lead to bedrock~~ Bedrock erosion in stream channels ~~, with~~ is driven by several interacting processes, of which the most efficient are hydraulic shear detachment of weak bedrock, plucking of bedrock blocks, ~~plucking,~~ and abrasion of small bedrock grains due to sediment impacts~~generally being the most efficient (Whipple et al., 2000; Sklar and Dietrich, 2004; Lamb et al., 2008). Bedrock~~

~~topography~~ . Dissolution and cavitation can also be important contributors to bedrock erosion under specific conditions (Whipple et al., 2000; Sklar and Dietrich, 2004; Lamb et al., 2008; Vachtman and Laronne, 2013). Bedrock topographic features, together with the interplay of the sediment tools and cover effects (impacting sediment act as erosive tools while stationary sediment can protect surfaces against impacts), regulate the rate and spatial ~~patterns~~ pattern of local surface erosion (Gilbert, 1877; Sklar and Dietrich, 2004; Turowski et al., 2008; Johnson et al., 2009; Yanites et al., 2011; Cook et al., 2014; Beer et al., in review).

Spatially distributed measurements of natural bedrock erosion rates are valuable for understanding the underlying process physics, as well as for modelling landscape evolution and designing engineered structures. ~~Repeat measurements of local-scale (e.g. cross-stream)~~ Repeated measurements of local or reach-scale ~~(some 10s of meters along the stream)~~ rates of vertical erosion (i.e. channel incision), lateral erosion (channel widening) and downstream-directed erosion ~~(channel clearance)~~ of protruding bedrock surfaces are needed to better understand bedrock channel evolution. However, quantifying spatially distributed bedrock erosion rates in natural settings is challenging and few such measurements exist ~~(cf. Hartshorn et al., 2002; Turowski et al., 2008; Cook et al., 2014; Beer et al., in review)~~

(e.g., Hartshorn et al., 2002; Stock et al., 2005; Turowski et al., 2008; Johnson et al., 2010; Stephenson, 2013; Wilson et al., 2013

~~Here, we present an easy, inexpensive method for monitoring spatial patterns of bedrock erosion : erosion painting. We evaluate its applicability using a 3-year series of photographs of painted bedrock surfaces in a natural bedrock gorge in the Swiss Alps (for the field site cf. Beer et al., in review), and illustrate how this simple methodgives insight into erosion processes during high-flow events.~~

2 ~~Methods and proof-of-concept study~~

Documenting subtle topographic changes in bedrock surfaces has typically required sophisticated instruments and techniques, including photogrammetry, total stations, laser scanners, and erosion meters (Turowski and Cook, 2016). A much simpler, albeit more indirect method, has hardly been considered yet: painting. Paint is commonly used in fluvial geomorphology to visualize and track ~~particles. Besides colouring such tracers (e.g., single bedload pebbles to analyse sediment transport, overview by Hassan and Ergenz~~ ~~however, paint has been applied only rarely~~

tracer particles (e.g., single bedload pebbles to analyse sediment transport; see overview by Hassan and Ergenzinger, 2003). However, it has rarely been used to study spatially distributed surface changes. Dietrich et al. (2005) and Surian et al. (2009) painted small patches ~~on~~ of streambed sediments to study how sediment transport dynamics vary with channel characteristics. Gill and Lang (1983) applied several paint dots along shoreline bedrock platforms to get a general overview of erosion at large spatial scales. To our knowledge, however, paint has not been used to ~~visualize~~ analyse the local spatial distribution of erosion on natural ~~surfaces, as we illustrate here for bedrock surfaces~~bedrock surfaces.

Here, we explore an easy, inexpensive method for monitoring spatial patterns of bedrock erosion, which we term erosion painting. We evaluate its applicability using a 3-year series of photographs of painted bedrock surfaces in a natural bedrock gorge in the Swiss Alps, and illustrate how this simple method gives insight into sediment transport and erosion processes during high-flow events.

2 Methods

We present a proof-of-concept field study demonstrating the scientific potential of the following general approach. We used environmentally safe and water-insoluble ~~outdoor~~ latex-based dispersion paint to cover natural bedrock surfaces that were expected to show varying patterns of erosion (see below for a description of the field site), and ~~took pictures of~~ photographed these surfaces from defined vantage points ~~. Repeat photographs from these~~ regularly during visits to the sites. Comparisons of sequential photographs from the same vantage points were then used to document the removal of paint ~~after~~ by erosive events. To compare specific details of interest over time, it was helpful to include retrievable features (benchmarks) in the pictures. The observed pattern of eroded and remaining paint indicates the spatial distribution of erosion. More precisely, to the extent that the paint provides a uniformly erodible surface, we suggest that the spatial pattern of paint erosion reflects the spatial pattern in the erosivity of the ~~acting processes~~ flow and the sediment that it carries (i.e. their erosive strength or potential to erode the bedrock). For useful results to be obtained, this erosivity must be high enough to remove some of the paint, but also low enough that some paint remains.

The field site for this study was a ~~bedrock gorge reach~~ 30 m-long and 5 m-wide semi-alluvial bedrock gorge of the Gornera glacial meltwater stream above Zermatt, Switzerland (Figure 1). ~~In this gorge, we tested the bedrock erosion painting method in parallel with a quantitative bedrock erosion study using repeat terrestrial laser scanning TLS (Beer et al., in review). The 30 m-long semi-alluvial bedrock~~ The local bedrock is serpentinite, and the bed sediment consists of both serpentinite and gneiss. The gorge is regularly flushed with up to 3 m deep sediment-laden flows due to hydropower operations upstream (Figure 1 B). In between these flushing events of 15 - 30 min length each, there is negligible discharge in the gorge (Figure 1 C and D). Due to the characteristics of the flushing operations (i.e. short, steep hydrographs and evacuation of previously accumulated sediment), the mean transported bedload grain size (D_{50}) likely varies considerably during each flushing event and between flushing events. The D_{50} of the natural streambed upstream of the hydropower water intake is ∼4 cm at low flows, but it is unknown whether the average sediment load (including high flows) is finer or coarser than this. The sediment bed surface in the gorge returns to roughly the same height following each flushing event, but it likely varies strongly during the flushings themselves (Beer et al., in review).

We repeatedly painted several patches of the gorge's bedrock surface ~~during consecutive~~ over a period of 3 years and photo-documented the resulting spatial patterns of eroded paint, renewing the paint as needed. To visualize variations ~~in erosion rates~~ of erosion with height above the streambed, we painted several vertical stripes of 0.15 m width and 2.0 m height ~~at~~ on two opposing straight and smooth bedrock walls, starting at the sediment bed surface (Figure 1 C and D; we unfortunately could not paint below the sediment surface due to standing water in the sediment body). On the left gorge wall we connected two of these vertical stripes by horizontal lines to create a simple staff gauge, acting as a ~~-~~reference for a water ~~table~~ surface altimeter positioned above the gorge. For analysis of the spatial ~~distribution of bedrock erosion~~ bedrock erosion distribution across the streambed, we further painted a 2.5 m^2 wall section that laterally protruded into the streamflow, as well as the 20 m^2 top surface of a smooth bedrock boulder and the 3.2 m^2 smooth upstream face of a vertical bedrock slab (Figure 1 C and D), both of which ~~protrude~~ protruded from the streambed. We ~~verified the plausibility of the photo-documented paint erosion patterns by comparing them to~~ validated the inferred patterns of bedrock erosion by comparing photos of worn paint to contemporaneous quantitative erosion analyses based on ~~the~~ repeated high-resolution ~~TLS~~ terrestrial laser scanning surveys of the ~~gorge‘s bedrock surfaces (Beer et al., in review).~~ same surfaces (TLS; Beer et al., in review). We also compared paint erosion patterns on the opposing bedrock walls to draw inferences on spatial patterns of sediment transport during the flushings.

3 Results

Even over short periods (i.e. a few flushing events), paint erosion was visible over most of the studied bedrock gorge section. The painted stripes on the opposing smooth bedrock walls revealed different erosion patterns~~.~~: On the left gorge wall, the painted staff gauge (cf. Figure 1 D) was completely eroded up to 0.8 m above the streambed during a first study period of nearly one month with 44 flushing events ~~and a total flushing time of ∼26 h~~ (Figure 2 A ~~to~~and B). The ~~flushing heights during this first study period peaked at 2.6 m, with a mean flushing height of 1.3 m and an average event peak height of 2.1 m (Figure 2 D and E). The staff gauge~~staff gauge's paint was not renewed~~after the first period (Figure 2 B)~~, and in the following three-week study period, a comparable flushing series ~~42 of flushing events~~ ran through the gorge (Figure 2 D~~ and E; it is likely that there were three more flushings, but these cannot be verified due to a data gap~~). The ~~total flushing length in the second period was ∼22 h. Flushing heights peaked at 2.4 m, with a mean flushing height of 1.3 m and an average event peak height of 2.1 m (Figure 2 D and E). The~~ pattern of the eroded paint in the second period ~~differed only slightly from~~ changed only slightly compared to the one observed in the first period, revealing slow paint erosion above 0.8 m on the painted staff gauge (compare the right ~~painted~~ vertical paint stripe in Figure 2 B and C). The qualitative erosion pattern of the staff gauge's paint is consistent with the quantitative bedrock surface change detection ~~data~~ TLS-data of Beer et al. (in review), which ~~shows~~ show decreasing erosion rates with height over the streambed at this location (Figure 2 ~~F~~E and ~~G~~ F present average erosion rates over the longer time frame of ~~04.06.2012 to~~

08.10.2013). 04 June 2012 to 08 August 2013, with around 200 flushing events of varying lengths, varying flushed volumes and probably varying grain size distributions, comprising the bulk of the erosive events in both these years). Relationships between these bedrock surface changes and paint erosion are further detailed in the discussion section.

On the right gorge wall, both painted vertical stripes R1 and R2 (cf. Figure 1 D) consistently and repeatedly indicated stable, spatially localized zones of paint erosion, as shown in Figure 3 for stripe R2. These zones of completely eroded paint were found roughly 15 - 40 cm above the streambed during dry conditions. Above and below this erosion band, the paint generally remained intact, but showed zones that were slightly eroded during periods with higher flushing frequencies or flushing intensities (compare the first and the second rows to the third row shown in Figure 3).

Interesting Characteristic spatial patterns of eroded paint were observed at the laterally protruding wall section, and at the boulder and slab protruding from the streambed (Figure 4, ; cf. Figure 1 C and D). The protruding wall section was predominantly eroded on its upstream-facing and upward-facing sides (Figure 4 A to B), i.e. on those faces most prone to sediment impacts. Typical features of a so-called UFCS-form evolution (Upstream Facing Convex Surface; cf. Richardson and Carling, 2005; Wilson et al., 20 were visually obvious The eroded paint on the boulder showed spatial patterns that are typical for the formation of upstream facing convex surfaces (UFCS; cf. Richardson and Carling, 2005; Wilson et al., 2013): (i) vertical erosion on planar surfaces in line with the streambed (i.e. incision; Figure 4 C to D), (ii) downstream-directed erosion on upstream-facing regions with abundant impact marks (Figure 4 E and F), (iii) no erosion on downstream-facing regions with nearly no impact marks (Figure 4 E and F), and (iv) a distinct crestline separating both regions (Figure 4 E and F). The vertical vertical-standing bedrock slab, which was overflowed by at least some of the flushings, revealed a spatially homogeneous pattern of downstream-directed erosion on its upstream face (Figure 4 G to H). Only a few small parts of the upstream face of the slab were not eroded, because they were oriented away from the general direction of streamflow and sediment flowtransport. Slab surfaces facing laterally, upward and downstream did not show any paint erosion over all three years studied (cf. the inset in Figure 4 H).

4 Discussion and Conclusions

4.1 General assessment of the erosion painting technique

Our In the following, we first assess the erosion painting method based on our proof-of-concept studyillustrates how erosion painting can provide . We then use this technique to draw inferences about spatial erosion processes at our study site, and discuss potential future applications in the geosciences.

4.1 General assessment of the erosion painting technique

This study illustrates erosion painting as a straightforward technique for visualizing the spatial distribution of the erosivity of sediment-laden flows. The paint remained on bedrock surfaces that were frequently submerged, showing that it could resist fluvial shear detachment and water dissolution (see the inset in Figure 4 H). In contrast, the paint was removed from surfaces where frequent sediment impacts were likely (e.g., Figures 2 C, 3 B and 4 B). This sediment-driven paint abrasion was clearly evident on surfaces where patchy paint still remained (cf. the slight erosion zones in Figure 3 B, and the upstream-facing part of the crestline in Figure 4 E~~ and F)~~). The transient paint erosion on the higher parts of the staff gauge between Figure 2 A and C, and also the slight erosion zones above and below the zone of complete erosion in Figure 3 B, indicated regions with lower sediment impact frequencies. Hence, ~~assuming~~ erosion painting provides a semi-quantitative measure of the spatial distribution of sediment impact intensity, i.e. the erosivity of the streamflow. Assuming that impacting grains that remove the paint ~~will~~ also abrade the underlying bedrock (which is reasonable from Figure 2 E, and from the impact marks in Figure 4 F), the erosion painting procedure can be further considered as an ~~-~~indirect measure of bedrock erosion. However, it ~~only serves as~~ is only a qualitative indicator of bedrock erosion and does not allow quantitative inferences of bedrock ~~change rateson the painted surface. Photo time series showing the remaining paint can provide an idea of the spatial distribution of erosivity. This is illustrated by the transient paint erosion on the higher parts of the staff gauge between Figure 2 A and C, and also by the slight erosion zones above and below the zone of complete erosion in Figure 3 B.~~ erosion rates.

Erosion painting is inexpensive, requires no fixed installations (apart from the paint itself), is straightforward to implement even in challenging locations, permits quick high-resolution field surveys (requiring only visual inspection of the surfaces and reference photographs), and can detect even low levels of streamflow erosivity. However, ~~it provides only qualitative indications of erosion and erosivity which might require further interpretation (cf. Hassan and Ergenzinger, 2003; Surian et al., 2009), and of course~~ drawing quantitative inferences on erosion rates would require calibration against independent measurements, because the erodibility of the paint and the underlying bedrock will typically differ by large factors (see further discussion below). Environmentally friendly paint should be used, and only small surface patches should be painted to ~~keep paint consumption small~~limit paint consumption and the visual impact of the technique. Any necessary permission should be requested~~especially~~ , particularly for sensitive field areas. The paint should be applied carefully (e.g., avoiding wet and dusty rock, and leaving sufficient time for drying), since incorporated air bubbles or insufficient drying could lead to shear detachment of the paint by flowing water alone, without abrasion of the surface.

4.2 Process inferences from erosion painting at the Gornera

The paint erosion pattern at the staff gauge (Figure 2 B and C) clearly indicated erosion by sediment impacts (i.e. the sediment tools effect), and its decreasing strength with height above the bed due to a decreasing concentration of abrasive tools ~~(as discussed by Beer et al., in review)~~ (as discussed by Fuller et al., 2016; Beer et al., in review). Below 0.8 m~~the tools effect~~, erosion was strong enough to completely remove the paint during the first study period (Figure 2 A ~~to~~and B). Paint erosion at this level also reflects the slight inclination of the wall, resulting in surfaces that face slightly upward. Here, erosive sediment impacts from deflected grains falling through the water column ~~during flushings~~ have likely driven lateral erosion ~~(cf. ?Beer et al., in review). At elevations greater than~~ (cf. Fuller et al., 2016; Beer et al., in review). Above 0.8 m~~above the bed, the weaker tools effect~~, fewer sediment impacts due to lower sediment concentrations could be ~~monitored~~ inferred from the incomplete removal of paint over both study periods (Figure 2 A ~~to~~- C), ~~because its spatial erosive energy (i.e. its erosivity) was low enough that the paint was not completely eroded~~indicating the low erosivity of the flow at these heights above the bed.

Quantitative ~~spatial erosion measurements using TLS over a longer time frame (~~TLS-based spatial bedrock erosion measurements (over two years with more than 200 flushing events of various discharges, length and volumes; see Figure 2 ~~F~~E) confirmed the decrease in ~~the tools effect~~ sediment impacts with height above the bed, as qualitatively ~~observed~~ inferred from erosion painting. The uncertainty in the individual TLS change detection values was 2.2 mm over the biennial comparison, and thus was in the same order of magnitude as the detected change rates. However, the huge numbers of TLS measurements permit a stable general impression of surface changes, assuming their measurement errors are not spatially correlated (Beer et al., in review). Mean erosion rates of ~~2~~1 mm/~~2a~~a near the bed gradually decreased to ~~1~~0.5 mm/~~2a~~a at 0.8 m height (Figure 2 ~~G~~F). Between heights of 1.0 m and 2.0 m erosion rates were more or less constant at ~~1~~0.5 mm/~~2a~~a, and at higher elevations they quickly approached zero (at 2.7 m, not shown in Figure 2 G). This bedrock erosion pattern reflects the distribution of flushing heights (Figure 2 D~~and E)with only a few events~~), with only brief flushing event peaks exceeding water depths of 2 m~~and hence~~, thus delivering few erosive tools ~~at those~~ to these heights. During the longer time frame of the TLS study, the staff gauge's paint was eroded and re-painted several times. Since successive layers of paint were not located exactly on top of one another, and some locations had more paint during the second scan than during the first, there ~~is apparent deposition visible in~~ appears to be an apparent positive surface change (Figure 2 ~~F~~E), which is simply the added thickness of the paint (cf. the blue stripes at heights between 1.0~~,~~ m and 2.0 m). Likewise, ~~apparent high~~ high apparent bedrock erosion rates are indicated at the bottom of the staff gauge (cf. the ~~yellow~~ vertical red stripe pattern below 0.5 m in Figure 2 ~~F~~E), marking regions where paint was present during the first scan but had eroded before the second scan~~; thus~~. Thus the calculated erosion rates in Figure 2 E reflect the erosion of both the paint and the bedrock. These distortions of the TLS-based erosion patterns ~~serve as~~ provide a further proof-of-concept of the erosion painting technique, by showing that removal of the paint corresponds to detectable rates of surface erosion. However, they do not distort the general pattern in the erosion profile ~~shown in~~ (Figure 2 ~~G~~F), since that profile is binned over the ~~whole~~ entire width of the analysed site (cf. Figure 2 ~~F~~E), and thus the influence of the paint is minimized.

At the right gorge wall, both stripes R1 and R2 were eroded ~~only in~~ in only a restricted band situated more than 15 cm above the bed (~~cf.~~ Figure 3 for R2). This observation can be explained by the sediment bed aggrading up to this level during flushings, and thus shielding the lower levels of the wall from paint erosion (i.e. the sediment cover effect). The ~~bedrock~~ paint was eroded only near the top of this temporary cover in the restricted zone where moving ~~particles~~ sediment grains (tools) were most abundant ~~(Turowski et al., 2008)~~(see Turowski et al., 2008). Above and below this restricted zone of complete erosion, only small patchy areas of paint were removed (indicated as "slight erosion" zones; cf. Figure 3 B and C). This patchy erosion can be attributed to ~~two possible mechanisms: (i)~~ selective abrasion of the paint by less frequent sediment impacts than in the zones of full paint erosion~~, or (ii) shear detachment of~~. The lower patch of minimal erosion implies that the bed aggraded rapidly at the beginning of flushing events, and degraded rapidly at their ends, leaving little time for paint abrasion. The upper patch of minimal erosion implies rapidly decreasing sediment concentrations in the ~~paint by water discharge due to incorporated air bubbles in the paint, and /or insufficiently hardened paint at these positions, which could have led to weak adhesion of the paint~~ water column above the temporarily raised sediment bed, and thus generally low sediment transport rates at this location. ~~General care in applying the paint, e.g., by avoiding wet rock and leaving sufficient time for drying would help to exclude this second possibility.~~

Notably, the erosion pattern on the right gorge wall could be detected repeatedly (cf. the three date periods in Figure 3)~~. The lower edge of the stripes were not always painted exactly at the same height, due to varying sediment bed heights during each re-application of paint, but the position of the constrained eroded zone at the wall was more or less stable. This consistency suggests~~, and the zone of focused erosion on the wall occurred at a consistent height. This suggests that there were only minor fluctuations of bed height and sediment transport ~~at~~ on the right side of the gorge, ~~even over~~ despite differences in flushing durations, in flushing heights (cf. Figure 3 C)~~and possibly also~~, and probably also in sediment concentrations and grain sizes. The paint erosion pattern on the right gorge wall (Figure 3 B and C) was not visible in the TLS bedrock change detection study ~~using repeated TLS (Beer et al., in review, the right wall is not shown there)~~(Beer et al., in review, the right wall is not shown in). Also, the right wall ~~visually~~ appeared very smooth and did not show any ~~increased lateral erosion features at~~ visual evidence of increased abrasion in the zone of complete paint erosion~~. This indicates that paint erodibility was higher than bedrock erodibility and suggests that the bedrock~~, consistent with low transport rates in this location (as inferred in the previous paragraph). These observations suggest that bedrock erosion rates were too ~~low~~ slow to be detected ~~in repeat TLS surveysthere. Thus~~by the TLS surveys, despite visually obvious removal of the (much more erodible) paint. Thus, the erosion painting method may be able to qualitatively detect variations in erosion rates, even when these rates are too low to be measured quantitatively with more sophisticated techniques.

The erosion patterns of the painted surfaces ~~given~~ in Figure 4 illustrate how erosion depends on surface orientation and exposure to impacting particles ~~(the tools effect; cf. Beer et al., in review)~~ (the tools effect; Beer et al., in review), and on the spatial erosivity of the sediment-laden flow. Zones of focused ~~erosion~~ bedrock erosion, visually inferred from ~~the distribution of~~ both impact marks and crestlines on the boulder, were confirmed by the distribution of ~~eroded paint , with~~ paint erosion: the heavily impacted surfaces ~~being~~ were paint-free, and the crestlines ~~forming sharp boundaries to~~ formed sharp boundaries delimiting impact-free surfaces ~~with remaining paint (Figure 4 A to F, cf. Wilson et al., 2013; Wilson and Lave, 2014). The spatially eroded upstream-face~~ that were still paint-covered (Figure 4 A - F, cf. Wilson et al., 2013; Wilson and Lave, 2014). The paint-free upstream face of the slab (Figure 4 H) reflected abundant sediment impacts on this in-stream obstacle ~~(cf. Beer et al., in review, ; indeed, most of the few white areas in Figure 4 H appeared white even before painting due to quartz i~~ (cf. Beer et al., in review). Indeed, most of the few upstream-facing white areas visible in Figure 4 H appear white due to quartz inclusions rather than paint. However, the painted parts of the slab ~~facing~~ that faced laterally, upward, and downstream (cf. the inset in Figure 4 H) were protected from sediment impacts due to the diversion of sediment tools by the slab ~~(cf. Beer et al., in review)~~(Beer et al., in review). This indicates the crucial role of streambed topography in guiding streamflow and sediment flux ~~(cf. Johnson and Whipple, 2007, 2010; Cook et al., 2014; Beer et al., in review)~~ (Johnson and Whipple, 2007, 2010; Cook et al., 2014; Fuller et al., 2016; Beer et al., in review).

~~Furthermore, a~~A comparative view on the erosion patterns of all the painted stripes ~~at both~~ on the opposite bedrock walls (Figure 5 A left panel for the period of ~~06.06.2014 to 09.07.2014~~06 June 2014 to 09 July 2014; cf. Figure 1 D) revealed strong cross-sectional differences in the relative importance of the sediment tools and cover effects. Flushed discharge through the gorge carries substantial volumes of sediment that has previously accumulated in the upstream sediment retention basin (Beer et al., in review). Since both the staff gauge and ~~the~~ stripe L1 on the left wall were mostly eroded up to 0.7 m above the bed (at least for surfaces facing upstream; ~~cf.~~ Figure 5 B left panel), erosive tools likely abraded the whole left wall with diminishing intensity with height above the bed (Figure 5 B right panel). In contrast, ~~at~~ on the right gorge wall (Figure 5 C left panel), both stripes R1 and R2 showed a very restricted ~~erosion band~~ band of erosion (cf. Figure 3), suggesting that here the streambed aggraded up to the same level through multiple flushing events, with only a narrow erosion zone on top of it (Figure 5 C right panel).

Together, these interpretations indicate a strong difference in sediment ~~concentration along the gorge 's cross-section (cf.~~ transport concentration across the gorge (Figure 5 A right panel): ~~high sediment throughput~~ high-velocity transport of large volumes of sediment on the left side, ~~both in amount and velocity, and lower sediment transport~~ and slower transport of smaller volumes of sediment on the right side, where the sediment bed is elevated due to lower transport capacity. This large difference in sediment transport across ~~the channel section~~ a channel width of only 5 m ~~width was not expected~~ would not have been predicted from the straight channel geometry, from the ~~local channel bed conditions~~ flat channel bed cross-section at low flows (~~cf.~~ Figure 5 A left panel), ~~or~~ nor from the reasonably homogeneous water surface across the gorge during flushing events, as observed by eye, in videos, and in ~~videos and~~ pictures (cf. Figure 1 B). The driving mechanism of this laterally focused sediment transport was probably the coarse boulder bed of the ~~upstream channel (~~channel upstream of the gorge ~~in~~ (Figure 1 B) that ~~guided~~ likely deflected the sediment flow~~(cf. Beer et al., in review). Hence, the~~ . Directly upstream of the inspected wall section (to the left of Figure 1 C), there are rock blocks of 2 m size in the streambed that leave a passage on the gorge's left side. This passage may channelize the sediment flow even when these blocks are submerged by the flushing water. Further, secondary currents due to turbulence induced by the boulders are also likely to have influenced the sediment distribution (Venditti et al., 2014). We do not have direct measurements of the spatial sediment transport distribution during the flushings, but the erosion painting technique was able to ~~spatially illustrate~~ document the crucial influence of sediment routing in setting local erosion rates.

4.3 Potential future applications of erosion painting

Our results demonstrate that erosion painting is a straightforward ~~qualitative method for~~ method for (i) visualizing the spatial distribution of bedrock erosion ~~and~~ (i.e. variations with position and orientation), for (ii) inferring the spatial distribution of sediment transport (i.e. the sediment tools and cover effects), and for (iii) localising the transient elevation of the sedimentary streambed under some circumstances. Qualitative erosion patterns observable in the eroded paint generally coincided with the quantitative ~~findings~~ bedrock erosion analysis of Beer et al. (in review), ~~who showed that erosion rate~~ consistently showing that erosion rates of local bedrock surfaces depend on their position in the streambed and their spatial exposure to the impact of erosive tools.

~~From a more local perspective, these~~ Local erosion rates depend on both the erodibility of the surface and ~~on~~ the erosivity of the sediment-laden flow that abrades it. A general challenge in surface erosion studies is that it is difficult to know whether spatial variations in erosion rates are driven by variations in erodibility ~~or erosivity~~of the surface or erosivity of the flow. Erosion painting provides an artificial surface (the paint) that has a relatively uniform erodibility, and thus patterns of paint erosion should mostly reflect variations in the erosivity of the ~~flow~~ streamflow and its entrained sediment. ~~Thus erosion painting presents a counterpart to techniques like erosion mills (cf. Sklar and Dietrich, 2001; Small et al., 2015), which provide a flow of known erosivity in order to measure the relative erodibility of different materials.~~ A further step would be to standardize the painting technique to a specified paint volume per unit area, thus better constraining the thickness (and therefore erodibility) of the paint layer. ~~The~~

Laboratory tests (e.g., using the erosion mills of Sklar and Dietrich, 2001) could be used to explore the erodibility of different paints~~and applied thicknesses could also be quantified by laboratory tests (e.g., using the erosion mills of Sklar and Dietrich, 2001), allowing~~ , the influence of applied paint thickness, and paint adhesion on different bedrock lithologies. Also, the erosivity of the flow in the abrasion mill (i.e. its ability to erode the paint) could be studied by changing the mill's flow velocity or sediment loading. This analysis could serve as background for more semi-quantitative studies of ~~the erosivitiesof different flows. The~~ natural flow erosivities. Further, the choice of a particular paint (with known erodibility) would ~~enable determining~~ allow one to specify the threshold above which ~~erosion~~ streamflow erosivity is detectable. Applying a series of layers of this paint, each with a different colour, would permit better quantitative constraints on erosion. Alternatively, one could apply a stack of paint layers with different colours and erodibilities (with each successive layer more erodible than the one below it) to handle a wide range of erosivities.

The simplicity of the erosion painting technique could lead to wide-ranging applications in geomorphology. Examples of advanced applications for field sites like the studied gorge would be (i) to more frequently check eroded paint patterns (e.g., after every erosive event) to find thresholds of paint erosion for constraining streamflow erosivity, (ii) to repeatedly paint entire walls, beds or cross-sections to study the spatial variations in streamflow erosivity due to varying sediment concentrations, or (~~ii~~iii) to paint below the sediment bed or below the ~~current water line~~ on-site water surface to determine how the sediment bed varies during flushings and whether erosion also occurs below the level of the dry bed.

Erosion painting should be applicable to topics and settings well beyond ~~our proof-of-concept~~ the framework of our study. The relative erodibility of paint by ~~water,~~ suspended sediment and bedload could be tested in the laboratory, e.g., in experiments similar to those of

~~Attal et al. (2006); Scheingross et al. (2014); Wilson and Lave (2014)~~ Attal et al. (2006), Scheingross et al. (2014), or Wilson and Lave (2014). Erosion painting could be used to more rigorously verify the generality of the observation that abrasion by bedload is dominant on stoss surfaces of bedrock, as seen here ~~(cf. Whipple et al., 2000; Wilson et al., 2013; Beer et al., in review)~~(cf. Whipple et al., 2000; Beer et al., in review), whereas abrasion by suspended load is more important on lee surfaces (Wilson et al., 2013). The interactions of streambed morphology and sediment routing could also be assessed (cf. Finnegan et al., 2007; Johnson and Whipple, 2007, 2010). Even erosion ~~of~~ depths in (coarse) alluvium could be studied, if a suitable paint is ~~used~~infiltrated into the bed, complementing techniques like scour chains (Laronne et al., 1994; Liebault and Laronne, 2008) or injection of coloured sand profiles.

Besides application in fluvial environments, erosion painting could also be used to visualize spatial distributions of erosion by ice (e.g., Herman et al., 2015) and wind (e.g., Perkins et al., 2015). Depending on the study topic, erosion painting could be accompanied by, or deliver additional qualitative supporting information for, quantitative surveys of surface change using more sophisticated instrumentation (e.g., TLS surveys, erosion sensors). For example, erosion painting could be used in pilot studies to provide a qualitative spatial view of local processes (e.g., for planning purposes). It could also enable straightforward comparisons between different sites used for longer-term monitoring, or provide spatial verification for local quantitative studies both in the field and in the laboratory.

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fig1_fieldsite.pdf

Figure 1. The demonstration field site for bedrock erosion painting: (A) The location of the Gornera proglacial stream, Switzerland, (B) lateral view of the bedrock gorge reach during flushing of the sediment retention basin upstream, (C) top view of the gorge reach during dry conditions, showing some eroded painted surfaces on the left wall and in the streambed, and (D) downstream view in ~~the dry~~ gorge reach ~~with~~ under dry conditions, showing some of the eroded painted surfaces. Only the paint areas that are indicated and named are used for analysis here.

fig2_gauge.pdf

Figure 2. The erosion pattern on the painted staff gauge at on the left gorge wall (cf. Figure 1 C and D) , indicated a region above the streambed in which the sediment tools effect leads to accelerated lateral erosion: (A) the freshly painted staff gauge, (B) the eroded staff gauge after a period of 44 flushing events, (C) the eroded staff gauge (not re-painted on 07 August 2012) after an additional 42period of 44 flushing events, (D) time series of the flushing event peak flow heights for both periods, (E) boxplots of the flushing event heights in between the dates of the pictures, (F) mean at-a-point surface erosion bedrock change detection values (more than 2 million points) from repeated terrestrial laser scanning over the two years 2012-2013 (for data and calculation cf. Beer et al., in review)2012 - 2013 (the timespan 04 June 2012 to 08 October 2013 includes nearly all flushing events in these years; for data and calculation see Beer et al., in review and (GF) variation in bedrock erosion rates with height over the streambed. For two flushings of the second painting period, no flushing height data exist (see the data gap in (D)), but the flushing discharge was comparable to the adjacent flushings. Paint erosion and additional paint coating at different positions in between the scanning dates led to some of the extreme change detection values in (E) that reflect the painted gauge pattern (see the text for details). The vertical erosion profile in (GF) is based on the mean values of horizontally binned at-a-point erosion rates given in (F), with a bin height of 0.1 m. This profile is only slightly distorted by the erroneous extreme change values from paint erosion (see (E)), due to the huge number of TLS measurements included. The grey background areas in (GF) symbolize the region of the bedrock wall, with the change value of 0 mm/2aa defining its original surface, and erosion penetrating into it. Note the different y-axes of the individual figures.

fig3_stripe.pdf

Figure 3. Painted stripe R2 on the right gorge wall (cf. Figure 1 D), indicating a zone of complete paint erosion at ∼15 - 40 cm above the streambed, suggesting a temporary sediment cover effect due to bed aggregation during flushings and a constrained sediment tools effect on top, causing lateral erosion: Column (A) shows stripe R2 freshly painted on three dates, column (B) shows the same stripe after 4-10 weeks of flushing events, and column (C) shows ~~zooms on~~ close-up views of the erosion ~~patterns~~ zone along with information on the flushing events for each of the three time periods. The dotted lines in column (B) locate the median of peak flushing heights per period (median $h_{peak,events}$)

fig4_obstacles.pdf

Figure 4. Patterns of eroded paint at several sites in the gorge (cf. Figure 1 C and D), illustrating how erosion depends on local surface orientation: (A) lateral view of the painted protruding wall section, (B) eroded paint on that wall section, (C) top view of the painted boulder, (D) eroded paint on ~~the~~ that boulder, (E) top view of a ~~crestline on the~~ boulder crestline that was previously painted on both sides and now only shows erosion on ~~the~~ its upstream-facing side, (F) ~~demonstration~~ close-up view of ~~the~~ a previously painted boulder crestline like in (E), demonstrating sediment impact marks on the upstream side and a lack of impact marks on the downstream side~~of a previously painted crestline like in (E)~~, (G) downstream view of the painted slab, and (H) the eroded paint on the upstream-facing side of that slab, with an additional lateral view of the painted margins of the slab facing upward, downward and laterally (inset on the right). Note the original borders of ~~paint~~ painting indicated in (E) and (F) by the dotted lines. Bedrock colour differences in (F) are due to the abundant impact marks upstream of the crestline.

fig5_gorge.pdf

Figure 5. Erosion patterns on the painted stripes in the gorge (left column) reflect likely cross-stream variations in the sediment tools and cover effects during flushings (as indicated by intepretive diagrams in the right column): (A)~~:~~ downstream view into the gorge with four painted stripes visible (cf. Figure 1 D), (B) lateral view of the left bedrock wall, and (C) lateral view of the right bedrock wall~~, as named in (A)~~. All pictures show paint erosion over the period of ~~06.06.2014~~ 06 June 2014 to ~~09.07.2014~~09 July 2014. The dark areas in (C) are wet rock sections due to seepage from above.