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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 challenge. Here we show how the spatial distribution of surface abrasion can be visualized by observing the erosion of paint from bedrock surfaces in a natural bedrock gorge. If the paint is evenly applied, it creates a surface with relatively uniform erodibility, such that spatial variations in the erosion of this surface reflect variations in the erosivity of the flow and its entrained sediment. In our proof-of-concept study, this approach provided direct visual verification that the sediment tools effect was focused on upstream-facing surfaces. Further, it demonstrated strong cross-stream variations in bedrock erosion, even in this relatively narrow (5 m wide) gorge. The left side of the gorge experienced high sediment throughput with abundant lateral erosion on the painted wall up to 0.8 m 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 shielding the lower part of the wall. The erosion painting method provides a simple technique for qualitatively observing spatially distributed erosion in bedrock stream reaches, and 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 erosion in stream channels, with hydraulic shear detachment, plucking, and abrasion due to sediment impacts generally being the most efficient (Whipple et al., 2000; Sklar and Dietrich, 2004; Lamb et al., 2008). Bedrock topography together with the sediment tools and cover effects regulate the rate and spatial patterns 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) 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) 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).

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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 method gives insight into erosion processes during high-flow events.

2 Methods and proof-of-concept study

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 Ergenzinger, 2003), however, paint has been applied only rarely to study spatially distributed surface changes. Dietrich et al. (2005) and Surian et al. (2009) painted small patches on 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 the local spatial distribution of erosion on natural surfaces, as we illustrate here for bedrock surfaces.

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 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 these surfaces from defined vantage points. Repeat photographs from these vantage points were then used to document the removal of paint after erosive events. To compare specific details of interest over time, it was helpful to include retrievable features 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, the spatial pattern of erosion reflects the spatial pattern in the erosivity of the acting processes (i.e. their erosive strength or potential to erode). 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 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 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).

We repeatedly painted several patches of the gorge's bedrock surface during consecutive years and photo-documented the resulting spatial patterns of eroded paint, renewing the paint as needed. To visualize variations in erosion rates with height above the streambed, we painted several vertical stripes of 0.15 m width and 2.0 m height at two opposing straight and smooth bedrock walls (Figure 1 C and D). 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 altimeter positioned above the gorge. For analysis of the spatial distribution of bedrock erosion 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

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(Figure 1 C and D), both of which protrude from the streambed. We verified the plausibility of the photo-documented paint erosion patterns by comparing them to quantitative erosion analyses based on the repeated high-resolution TLS surveys of the gorge‘s bedrock surfaces (Beer et al., in review).

3 Results

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 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 paint was not renewed after the first period (Figure 2 B), and in the following three-week study period, a comparable 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 the one observed in the first period, revealing slow paint erosion above 0.8 m on the painted staff gauge (compare the right painted stripe in Figure 2 B and C). The qualitative erosion pattern of the staff gauge is consistent with the quantitative surface change detection data of Beer et al. (in review), which shows decreasing erosion rates with height over the streambed at this location (Figure 2 F and G present average erosion rates over the longer time frame of 04.06.2012 to 08.10.2013).

On the right gorge wall, both painted vertical stripes R1 and R2 (cf. Figure 1 D) consistently indicated stable, spatially localized zones of 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 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., 2013) were visually obvious on the boulder: (i) vertical erosion on planar surfaces (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 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 direction of streamflow and sediment flow. 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 proof-of-concept study illustrates how erosion painting can provide 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. 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). Hence, assuming that impacting grains that remove the paint will also abrade the underlying bedrock (which is reasonable from Figure 2, and from the impact marks in Figure 4 F), the erosion painting procedure can be considered as an indirect measure of bedrock erosion. However, it only serves as a qualitative indicator of erosion and does not allow quantitative inferences of bedrock change rates on 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 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 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 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. Any necessary permission should be requested especially for sensitive field areas.

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 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). Below 0.8 m the tools effect was strong enough to completely remove the paint during the first study period (Figure 2 A to 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 grains falling through the water column during flushings have likely driven lateral erosion (cf. Fuller, 2014; Beer et al., in review). At elevations greater than 0.8 m above the bed, the weaker tools effect due to lower

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sediment concentrations could be monitored 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.

Quantitative spatial erosion measurements using TLS over a longer time frame (Figure 2 F) confirmed the decrease in the tools effect with height above the bed, as qualitatively observed from erosion painting. Mean erosion rates of 2 mm/2a near the bed gradually decreased to 1 mm/2a at 0.8 m height (Figure 2 G). Between heights of 1.0 m and 2.0 m erosion rates were more or less constant at 1 mm/2a, and at higher elevations they quickly approached zero (Figure 2 G). This pattern reflects the distribution of flushing heights (Figure 2 D and E) with only a few events exceeding water depths of 2 m and hence few erosive tools at those heights. During the longer time frame of the TLS study, the staff gauge 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 Figure 2 F, 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 bedrock erosion rates are indicated at the bottom of the staff gauge (cf. the yellow stripe pattern below 0.5 m in Figure 2 F), marking regions where paint was present during the first scan but had eroded before the second scan; thus the calculated erosion rates reflect the erosion of both the paint and the bedrock. These distortions of the TLS-based erosion patterns serve as a further proof-of-concept of the erosion painting technique, 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, since that profile is binned over the whole width of the analysed site (cf. Figure 2 F), and thus the influence of the paint is minimized.

At the right gorge wall, both stripes R1 and R2 were eroded only in 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 erosion (i.e. the sediment cover effect). The bedrock was eroded only near the top of this temporary cover in the restricted zone where moving particles (tools) were most abundant (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 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. 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 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 minor fluctuations of bed height and sediment transport at the right side of the gorge, even over differences in flushing durations, flushing heights (cf. Figure 3 C) and possibly also sediment concentrations and grain sizes. The paint erosion pattern on the right gorge wall (Figure 3 B and C) was not visible in the bedrock change detection study using repeated TLS (Beer et al., in review, the right wall is not shown there). Also, the right wall visually appeared very smooth and did not show any increased lateral erosion features at the zone of complete paint erosion. This indicates that paint erodibility was higher than bedrock erodibility and suggests that the bedrock erosion rates were too low to be detected in repeat TLS surveys there. 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), and on the spatial erosivity of the sediment-laden flow. Zones of focused erosion visually inferred from the distribution of impact marks and crestlines on the boulder were confirmed by the distribution of eroded paint, with the heavily impacted surfaces being paint-free and the crestlines forming sharp boundaries to 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 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 inclusion). However, the painted parts of the slab facing 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). 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).

Furthermore, a comparative view on the erosion patterns of all the painted stripes at both opposite bedrock walls (Figure 5 A left panel for the period of 06.06.2014 to 09.07.2014; cf. Figure 1 D) revealed strong cross-sectional differences in 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 the right gorge wall (Figure 5 C left panel), both stripes R1 and R2 showed a very restricted erosion band (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. Figure 5 A right panel): high sediment throughput on the left side, both in amount and velocity, and lower sediment transport 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 of only 5 m width was not expected from the straight channel geometry, from the local channel bed conditions at low flows (cf. Figure 5 A left panel), or from the reasonably homogeneous water surface across the gorge, as observed 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 (upstream of the gorge in Figure 1 B) that guided the sediment flow (cf. Beer et al., in review). Hence, the erosion painting technique was able to spatially illustrate 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 visualizing the spatial distribution of bedrock erosion and inferring the spatial distribution of sediment transport (i.e. the sediment tools and cover effects). Qualitative erosion patterns observable in the eroded paint generally coincided with the quantitative findings of Beer et al. (in review), who showed that erosion rate 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 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. Erosion painting provides an artificial surface (the paint) that has relatively uniform erodibility, and thus patterns of paint erosion should mostly reflect variations in erosivity of the flow 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 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 semi-quantitative studies of the erosivities of different flows. The choice of a particular paint (with known erodibility) would enable determining the threshold above which erosion 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 repeatedly paint entire walls, beds or cross-sections to study the spatial variations in streamflow erosivity due to varying sediment concentrations, or (ii) to paint below the sediment bed or below the current water line 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 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). 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), 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 alluvium could be studied if a suitable paint is used, complementing techniques like scour chains (Laronne et al., 1994; Liebault and Laronne, 2008) or injection of coloured sand profiles.

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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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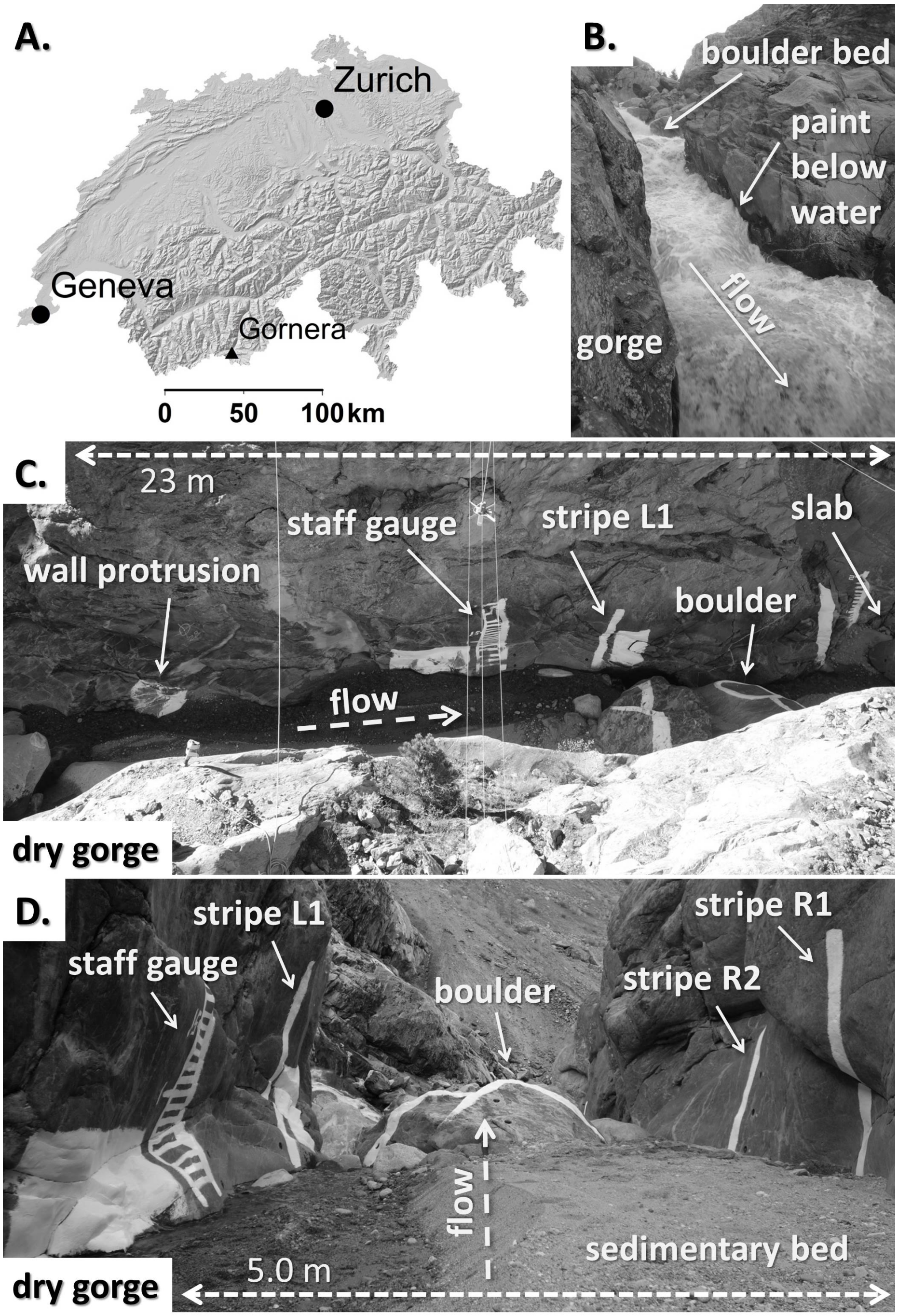

Figure 1. The demonstration field site for bedrock erosion painting: (A) The location of the Gornera proglacial stream, Switzerland, (B) lateral view of the bedrock gorge reach during flushing of the sediment retention basin upstream, (C) top view of the gorge reach during dry conditions, showing some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

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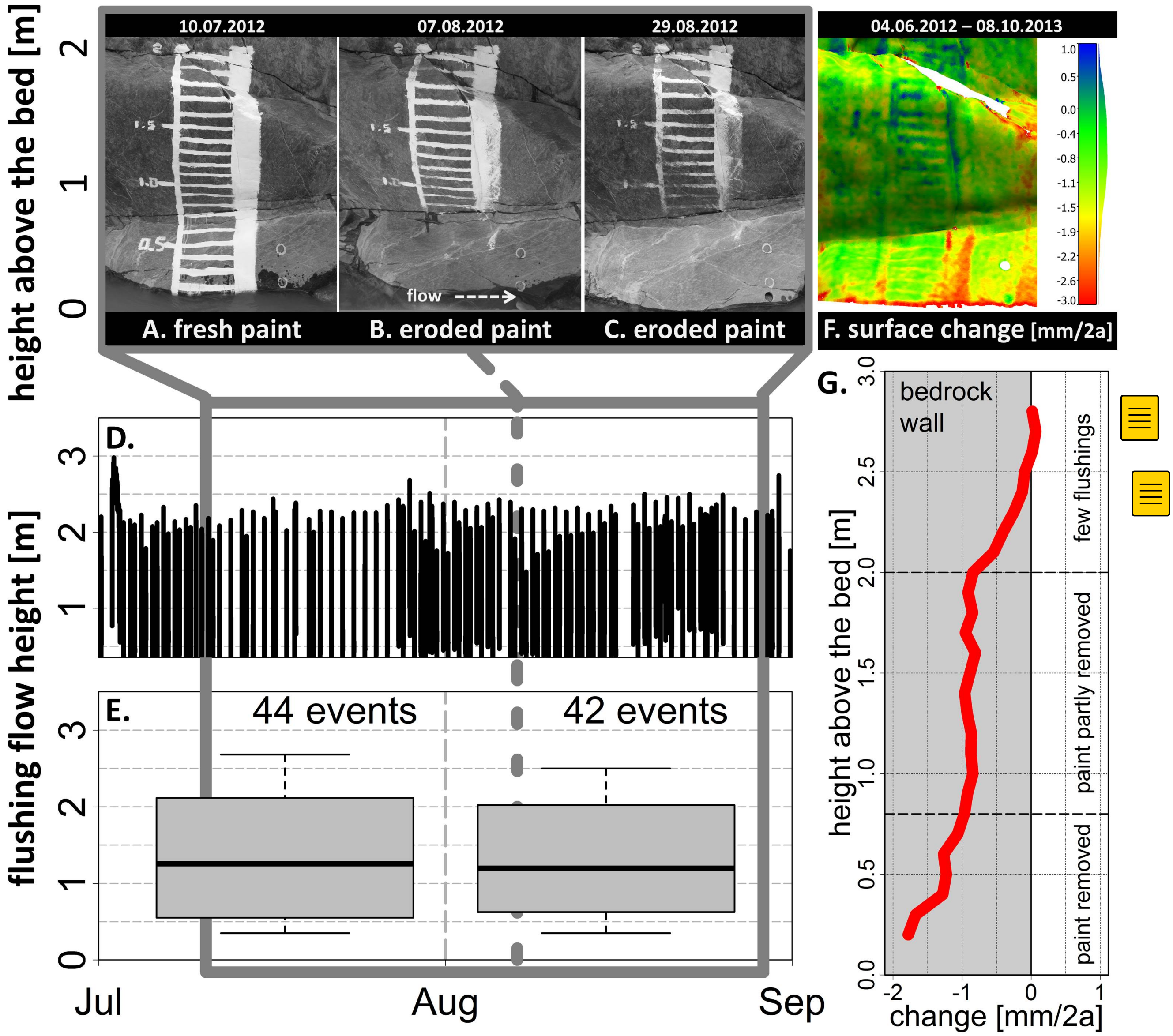

Figure 2. The erosion pattern on the painted staff gauge at the left gorge wall (cf. Figure 1 C and D), indicated a region above the streambed in which the tools effect leads to accelerated lateral erosion: (A) the freshly painted staff gauge, (B) the eroded staff gauge after 44 flushing events, (C) the eroded staff gauge after an additional 42 flushing events, (D) time series of the flushing event heights, (E) boxplots of the flushing event heights in between the dates of the pictures, (F) at-a-point surface erosion 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), and (G) variation in bedrock erosion rates with height over the streambed. The vertical erosion profile in (G) is based on the mean values of horizontally binned at-a-point erosion rates given in (F). The grey background areas in (G) symbolize the region of the bedrock wall, with the change value of 0 mm/2a defining its original surface, and erosion penetrating into it. Note the different y-axes of the individual figures.

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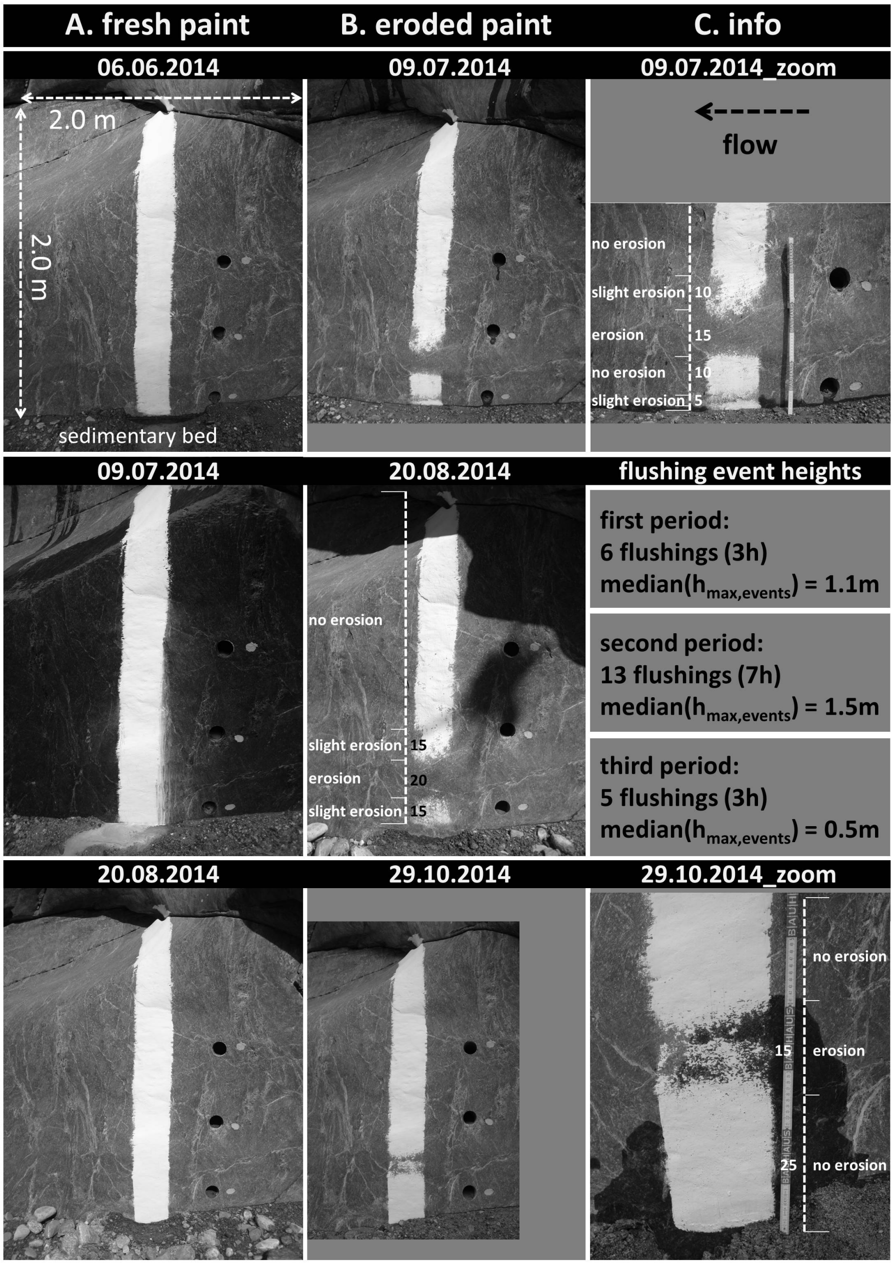

Figure 3. Painted stripe R2 on the right gorge wall (cf. Figure 1 D), indicating a zone of complete erosion ∼15 - 40 cm above the streambed, suggesting a temporary cover effect due to bed aggregation during flushings and a constrained tools effect on top, causing lateral erosion: Column (A) shows stripe 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 the erosion patterns along with information on the flushing events for each of the three periods.

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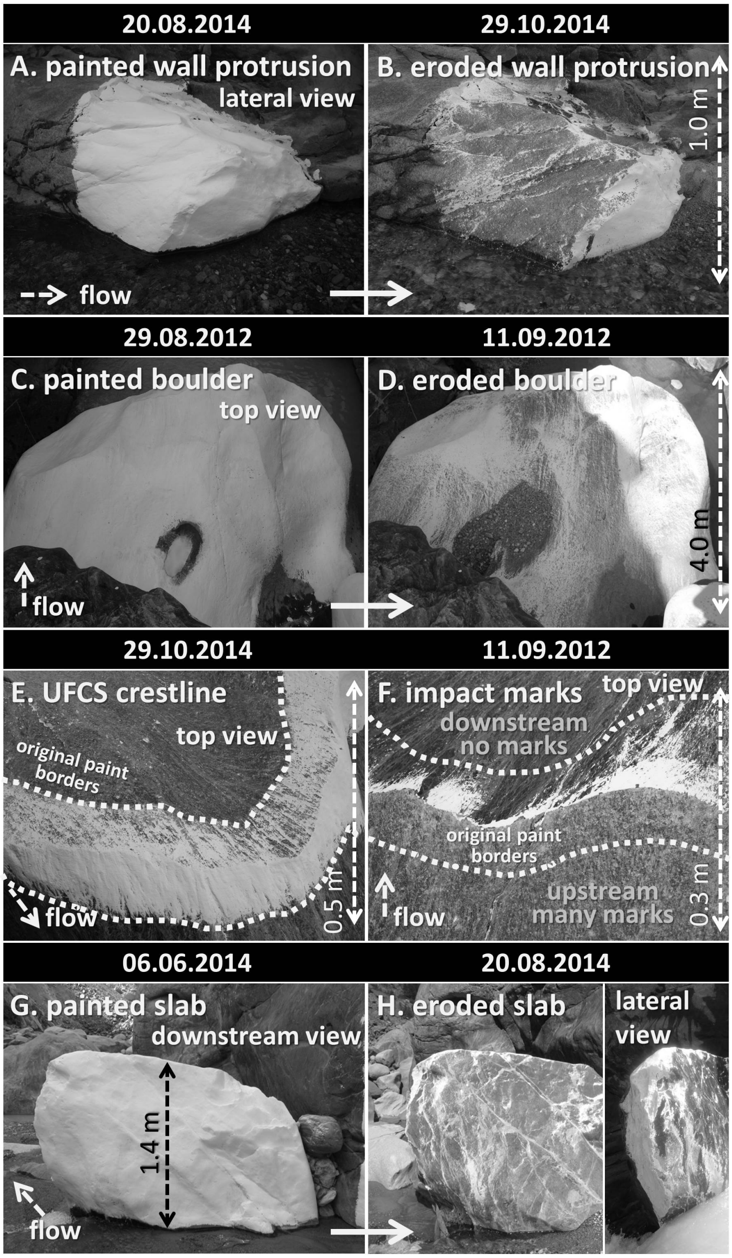

Figure 4. Patterns of eroded paint at several sites in the gorge, illustrating how erosion depends on local surface orientation: (A) lateral view of the painted protruding wall section, (B) eroded paint on that wall section, (C) top view of the painted boulder, (D) eroded paint on the boulder, (E) top view of a crestline on the boulder that was previously painted on both sides and now only shows erosion on the upstream-facing side, (F) demonstration of the 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 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 indicated in (E) and (F).

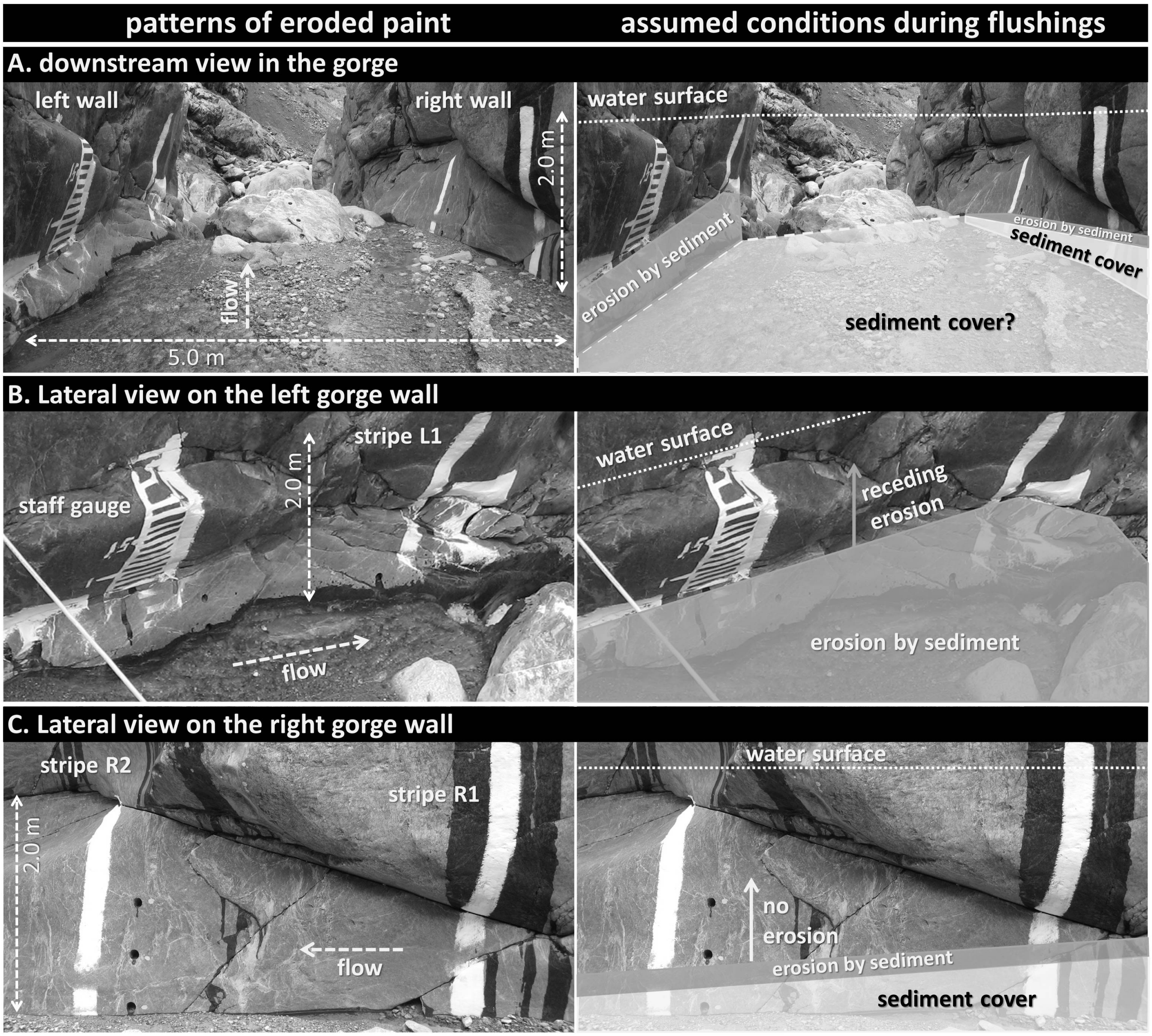

Figure 5. Erosion patterns on the painted stripes in the gorge (left column) reflect cross-stream variations in the tools and cover effects during flushings (right column): (A): downstream view into the gorge with four painted stripes visible (cf. Figure 1 D), (B) lateral view of the left bedrock wall, 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 to 09.07.2014.