Title: New experiments to probe the role of fractures in bedrock on river erosion rate and processes

Summary:

Fournereau et al., performed a series of flume experiments to test the role of planar discontinuities in affecting the rates and spatial patterns of erosion in a bedrock-analog material (concrete). Planar discontinuities were produced from a network of BVOH plastic that dissolves or softens in cold water. The orientation and spacing of these materials inside the concrete was systematically adjusted, providing control on the spatial distribution and behavior of material properties of the eroded bed. An abrasion mill with rotating propeller was used to drive erosion with abrasive gravels. Erosion of the bed was measured both by weighing between 2 minutes of milling and by topographic differencing using 3D scans from close-range photogrammetry. The latter approach provides a map of where and how much erosion occurred on the bed over time. These topographic scans could be shared as digital data that records a time series of how erosion progressed through the bed material. This is a nice feature and produces a lasting dataset that could then be analyzed further.

The experiments show differences in the pattern and temporal evolution of erosion that occurred between concrete only and concrete + discontinuity experiments, but the overall amount of erosion remained similar. Removal of larger particles occurred when discontinuities were present and some of these fragments remained the flume cylinder, so their particle size distribution was measured after the experiments concluded. These fragments were interpreted as "plucked" blocks, as well as other areas in the topography where hot spots of erosion occurred. The relative proportion of erosion driven by plucked blocks and presumably detachment of smaller particles was estimated and shown to be a function of discontinuity spacing and in certain cases, orientation.

The experiments are rigorous and the hypothesis is tested appropriately. My main suggestions relate to the experimental apparatus and how the results are interpreted and presented with respect to field settings, which is challenging.

Main suggestions:

(1) Experimental design with respect to plucking mechanism

One potential issue with the experimental design -- combining the abrasion mill and a fractured bedrock media to quantify abrasion vs plucking erosion – is that it is not clear to what degree the mill produces flow conditions have been shown to drive plucking in fractured materials?

These flow conditions were generated and isolated in experiments with different flume geometries and shown to influence plucking of blocks:

Hydraulic jumps (Wilkenson et al., 2018) – the videos in the supplement are beautiful.

Flow constrictions (Saha et al., 2021) – a very large flume underlain by blocks

Knickpoints (Dubinski & Wohl, 2013) – also a larger flume underlain by blocks

Clemence 1988 – a student paper showing plucking at a knickpoint edge.

Protrusion/angle (Sidiki Koulibaly et al., 2024) – change block orientation & joint roughness

These are just suggestions of papers. They each include literature reviews of other works that should be considered in the topic.

Fractured bedrock tends towards these channel geometries (constrictions & knickpoints) in field settings due to heterogeneity in the rock strength fabric. Not sure if a reference is needed here, but a 600 m long scan of a bedrock river section in Taiwan shows channel widths narrowing from >100m to 40m over a distance of a few 10s of meters for example (Carr et al., 2023).

The experiments showed in their topography scans that more variable topography emerges depending on the fracture network. The variable topography likely generates flow features listed above as the experiments progress. The self-emergence of these features seems like a significant finding to me that is clearly shown from the experiments, and a large portion of the paper is dedicated to describing and quantifying changing patterns of erosion that result.

It seems challenging to explore the significance of the non-steady flow fields in relation to plucking, given the mill apparatus design. It's difficult to interpret whether the experiment is representing these phenomena as they would be developed in a field setting. I'm curious what the authors think about digging into this point? The topography scans do exist…

The types of conclusions that can be drawn from the work are maybe a bit limited when applying to field settings if the above paragraph can't be quantified – namely it's tough to conclude a lack of increasing erosion effectiveness from adding fractures in a field setting? The self-emergence of a rougher bed seems like a significant point that could maybe be expanded on.

(2) *Experimental design with respect to the 3D connectivity of the joint network*

The pre-seeded fractures do not contain an interconnected 3D network of joints. There are no subhorizontal fractures if I am understanding correctly? So blocks are not readily available for plucking – the 3rd joint set needs to form in-situ.

It is hard to quantify how the fracture network develops/grows in near surface stress fields, particularly quantifying the openness of 3D joint networks in valley bottoms, because the horizontal fractures would be mostly buried. Fracture surveys on pinnacles, spires, and waterfall edges seem to indicate that blocks are detached by 3D joint sets with open apertures though.

Flow underneath the blocks along a subhorizontal fracture set is important for generating lift or hydraulic jacking from sediments infiltrating cracks (Hancock et al., 1998). The latter mechanism would not be possible in this experiment given the aperture of the fractures (~1 mm) and the size of the sediment used (10-20 mm). This demonstrates scaling issues between the flume experiment design and particle size distributions, which could be significant for driving erosion in natural streams. In the field, the fracture aperture can be wider than a portion of the particle size distribution.

(3) Strength of the joints?

I am not sure how to interpret the material used to form the joints, but I do find it very interesting. Is the material harder or softer than the concrete, and how does it change over time? Could this be calibrated with submersion experiments without any sediment? In either case, there are landscape examples where joint material is softer (as in an aperture) or harder than the surrounding rock mass (joints infilled with carbonate cement or vein material – qtz for example), so there is significance in putting in the heterogeneous material with a pre-defined orientation & spacing in either direction.

These complexities (1-3) may limit the scope of interpretations that can be made from the experiments when moving to natural landscapes/channels, but the research question addressed by the experiment is very difficult.

The experiment is performed rigorously and with reliable measurements of erosion patterns. The experiment setup may apply to certain field settings and the general observation of more spatially variable/rougher bed topography created from the joints is important.

General comment:

I'd recommend if possible that the authors include some pictures of the bed as the experiments progress? My understanding is these abrasion mills turn into a mess when they are running, but some photographs of the disks (if fractures formed in-situ) or wear of the BVOH might be insightful over time. Many flume studies include photographs or videos of the experiments progression, and I find this the be a big advantage to these experimental set ups.

Line by line comments – many of these are minor grammar suggestions – sorry… these are annoying:

Line 13: hillslope dynamics? Maybe "incision at the base of hillslopes" – if you have enough words to spare

Line 16: "However, there is no systematic study of the impact of fracture geometry and density on bedrock river erosion"

Slight wording changes suggested because this could be misinterpreted.

Maybe try:

"Systematic studies comparing fracture geometry and density and bedrock river erosion are needed."

Line 22: I'd remove "to our knowledge, this is the first study of its kind" --- if it's meant to shine, the work will shine on its own 😊

Lines 24-28 – any quantitative comparisons/statistics to report? In some of these lines (line 28) its not so clear whether this conclusion is based on the experiments or a general statement.

Line 29: Here is a place where it could be mentioned that erosion mode and location affects the roughness of the bed and presumably the flow field? Just a suggestion.

Line 40 – I like this point, but I would reword. Flume experiments also have their challenges upscaling to landscapes (which is usually a goal).

"Experimental approaches can be an attractive approach to address these questions due to slow timescales of erosion and numerous conflating factors that could affect bedrock strength in field settings."

Line 42: "demonstrated"

Line 43: "maximized"

Line 45: new paragraph?

Line 75 and others: unfortunately, the plural of "bedrock" is "bedrock".

Line 67-80 – In the context of fluvial erosion and bedrock fractures, there are fracture density measurements recorded in Snyder et al., 2003. I'll throw in a quick blurb here, but it's maybe not too important. In some ways DiBiase et al., 2018 or Neely & DiBiase, 2023 are making these comparisons between channel geometry, erosion, and fracture spacing, but the difficulty is that sediment size and bedrock fracture spacing co-vary in those sites (data from Neely & DiBiase, 2020), so the effect of one or the other is difficult to isolate – we interpreted that channels are mantled with sediment, so the fracture spacing effect is secondary to the cover effect. The flume approach is nice in this aspect -- the experiment can control the ratio between fracture spacing and sediment size in ways that might not be possible with field studies.

Line 81 – should plucking be included here? If the bedrock is already sectioned into blocks?

Figure 1 – I like this figure and it is nice to plot the control run in the context of the other studies with similar set ups.

Line 128: "center"

Line 170 – extra period.

Line 175 – interesting, this is a good idea.

Line 181, 185; in a few places in the manuscript would change "weighted" to "weighed"

Fig S2: interesting comparison, is the SfM of cumulative erosion always compared to the topography of the first point cloud? Or is erosion summed between successive differences as erosion proceeds? Just wondering if that could be a reason for the "drift" in cumulative erosion rates?

Figure 2 – Interesting to see the different spatial patterns in erosion and the emergence of the plucking holes

Line 199: "fractures"

Line 206: "eroded less" instead of "barely"

Line 212: in a propellor flume – not sure if there is a better word to describe the flume set up.

Figure 3 is very informative. I like panel d a lot. So if am reading this correctly, the largest local erosion rate is ~5 mm/min. Does this correspond to the size of a plucked block? Or are the blocks mostly wearing in place, in between the fractures? I guess with 10-20 mm impactors and 10-20 mm blocks, the impactors may not really be able to penetrate between the fractures?

Figure 4: Could it be more difficult to detect the small plucking events in the highest fracture density case?

I have a hard time understanding total dip angles? So two joint sets at 45 degrees would be 90 degrees?

Line 304: “Asymmetric”

Figure 5c, if more detail is needed to distinguish joint set orientations – i.e. same angle or different angle, consider using different symbols for the markers?

Figure 6 – I still have a bit of a hard time understanding the geometry by summing the dips together, maybe there is another way to display this. I think simply treating each combination of dips as a different column could be informative. Information about the fracture geometries gets lost by summing the fracture set dips together.

Line 319: I’m not sure, there are quite a bit of experiments that include fractures in the form of pluckable blocks? – maybe rephrase to be more specific about what is different about your experiment than some of the experiments listed earlier in the review.

Line 326: I really like the experiments, but it would be great to add some clarity here. Perhaps you can calibrate the material properties by submerging for regular intervals and measuring?

Line 328: “protruding from”

Line 331: “resistant”

Line 347: organization

Line 353: the geometries you are using seem like a good start to me?

Section 4.2 – I feel like something got disorganize here when explaining the methods of defining a “plucking event”. Could this be elaborated on in the methods section 2.3? So moving part of section 3.3 for the methods into section 2.3? It seems unusual to me that a plucking event could be defined as eroding material that is smaller than the fracture-bound blocks, but this is maybe an outcome of not having a sub-horizontal fracture set as well?

I see the fragment sizes plotted as a figure in the supplement. This is pretty interesting and does show more “platey” fragment sizes. Do the fragments cluster around the fracture spacing dimensions? I would expect the clasts corresponding to the densest fracture density to produce a cluster of fragments near 10mm a-axis, 10 mm b-axis, if the partings were occurring along the fractures?

I guess I am trying to untangle what went on inside the flume during detachment. The fragments are helpful but as you say they are an indirect measure. Glad you measured and held onto them!

Line 363: "implies"

Figure 7: Interesting plots that are getting at some of the geometry questions from before. So 10x10 mm is the spacing between the densest fracture network, but can produce plucked blocks that have a z-axis between 2.2 and 4 mm? The units of this are a bit hard to follow with the dimensionality of a and d, and the fit power law form.

Maybe plot without log transformation? If you are producing cubes, the relationship should be a square root form? So this is implying that slabs are formed (makes sense for plucking)?

Line 370: "ones?" fragments?

Discussion section – there is limited discussion linking the results to past work on the topic – either other flume experiments or contextualizing the results with bedrock erosion in the field. Maybe this can be developed a bit more?

It is important to discuss the data and the specifics of the experiment & design, but a section that zooms out to contextualize the study with past work/field settings would be encouraged – (by me)

Line 436: remove "the" before erosion rates

Line 437: "no fractures"

Line 442: I like this sentence for the implications of the work.

Line 446: remove "or not"

Line 448-449: I would be careful about the last phrase, unless addressing the experimental design/questions earlier in the review.

Thank you for sharing your interesting work and it was a pleasure to read 😊

If you would like to discuss more or if you have any questions about this review, please do not hesitate to contact (abn5031@arizona.edu)

Referenced studies:

Carr, J.C., DiBiase, R.A., Yeh, E.C., Fisher, D.M. and Kirby, E., 2023. Rock properties and sediment caliber govern bedrock river morphology across the Taiwan Central Range. *Science Advances*, *9*(46), p.eadg6794. https://doi.org/10.1126/sciadv.adg6794

Clemence, K.T., 1988. 1987 Student Professional Paper: Undergraduate Division: Influence of Stratigraphy and Structure on Knickpoint Erosion. *Bulletin of the Association of Engineering Geologists*, *25*(1), pp.11-15. https://doi.org/10.2113/gseegeosci.xxv.1.11

Dubinski, I.M. and Wohl, E., 2013. Relationships between block quarrying, bed shear stress, and stream power: A physical model of block quarrying of a jointed bedrock channel. *Geomorphology*, *180*, pp.66-81. https://doi.org/10.1016/j.geomorph.2012.09.007

Hancock, G.S., Anderson, R.S., and Whipple, K.X., 1998, Beyond power: Bedrock river incision process and form: in Tinkler, K., and Wohl, E. E., eds., Rivers over rock: Fluvial processes in bedrock channels : Washington, D.C., American Geophysical Union, Geophysical Monograph 107, p. 35-60.

Koulibaly, A.S., Saeidi, A., Rouleau, A. and Quirion, M., 2024. Laboratory physical model for studying hydraulic erodibility of fractured rock mass. In *New Challenges in Rock Mechanics and Rock Engineering* (pp. 1416-1422). CRC Press.

Saha, R., Lee, J.S. and Hong, S.H., 2021. The impact of lateral flow contraction on the rock plucking process under sub-critical flow conditions. *Earth Surface Processes and Landforms*, *46*(14), pp.2902-2915. https://doi.org/10.1002/esp.5220

Snyder, N.P., Whipple, K.X., Tucker, G.E. and Merritts, D.J., 2003. Channel response to tectonic forcing: field analysis of stream morphology and hydrology in the Mendocino triple junction region, northern California. *Geomorphology*, *53*(1-2), pp.97-127. https://doi.org/10.1016/S0169-555X(02)00349-5

Wilkinson, C., Harbor, D.J., Helgans, E. and Kuehner, J.P., 2018. Plucking phenomena in nonuniform flow. *Geosphere*, *14*(5), pp.2157-2170. https://doi.org/10.1130/GES01623.1

Esurf review aspects:

1. Does the paper address relevant scientific questions within the scope of ESurf?

   Yes

2. Does the paper present novel concepts, ideas, tools, or data?

   Yes

3. Are substantial conclusions reached?

   Yes

4. Are the scientific methods and assumptions valid and clearly outlined?

   Yes

5. Are the results sufficient to support the interpretations and conclusions?

   Not necessarily – see review.

6. Is the description of experiments and calculations sufficiently complete and precise to allow their reproduction by fellow scientists (traceability of results)?

   I think so?

7. Do the authors give proper credit to related work and clearly indicate their own new/original contribution?

   Not necessarily – see review.

8. Does the title clearly reflect the contents of the paper?

   Yes

9. Does the abstract provide a concise and complete summary?

   Yes

10. Is the overall presentation well structured and clear?

    Yes

11. Is the language fluent and precise?

    Yes

12. Are mathematical formulae, symbols, abbreviations, and units correctly defined and used?

Yes

13. Should any parts of the paper (text, formulae, figures, tables) be clarified, reduced, combined, or eliminated?

    Yes

14. Are the number and quality of references appropriate?

    Not necessarily – see review.

15. Is the amount and quality of supplementary material appropriate?

    Yes