Originally published as:

Scheingross, J., Lamb, M. P., Fuller, B. M. (2019): Self-formed bedrock waterfalls. - *Nature*, 567, pp. 229—233.

DOI: <http://doi.org/10.1038/s41586-019-0991-z>

Self-formed bedrock waterfalls

Joel S. Scheingross^{1,2†}, Michael P. Lamb¹, and Brian M. Fuller¹.

¹Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, CA, USA

²GFZ German Research Centre for Geosciences, Telegrafenberg, 14473 Potsdam, Germany

[†]Now at Department of Geological Sciences and Engineering, University of Nevada Reno, USA

Waterfalls are inspiring landforms that set the pace of landscape evolution as a result of bedrock incision¹⁻³. They communicate changes in sea level or tectonic uplift throughout landscapes^{3,4} or stall river incision, disconnecting landscapes from downstream perturbations^{1,5}. Here we use a physical experiment to show that waterfalls can form from a planar, homogenous bedrock bed in the absence of external perturbations. In our experiment, instabilities between flow hydraulics, sediment transport, and bedrock erosion lead to undulating bedforms, which grow to become waterfalls. We propose that it is plausible that the origin of some waterfalls in natural systems can be explained by this intrinsic formation process and suggest that investigations to distinguish self-formed from externally-forced waterfalls may help improve reconstruction of Earth history from landscapes.

Waterfalls are thought to form when rivers cross lithologic boundaries³, or through an external (allogenic) perturbation to riverbed topography such as sea-level change³, fault displacement^{6,7}, changes in tectonic uplift rates⁸, climate-induced changes in river incision rate^{4,7}, large landslides⁹, and glaciation¹⁰. For example, Niagara Falls formed because of recession of the Laurentide ice-sheet¹¹. Thus, waterfalls and steepened channel segments, or knickzones, are used to reconstruct perturbations in environmental forcing, such as climate and tectonism, over millions of years^{3,8,12}. However, mechanisms controlling waterfall formation are poorly understood because waterfalls form and evolve over geologic timescales, making constraints on

waterfall formation rare⁶. Many waterfalls lack a known origin; for example, waterfalls often occur in a series of steps within a knickzone, and it is often difficult to relate each waterfall to a specific external perturbation or lithologic control (Figure 1).

Here we propose that waterfalls can form autogenically; meaning, waterfalls form through internal feedbacks between water flow, sediment transport and bedrock incision, in the absence of external perturbations or lithologic controls. If autogenic waterfalls are common, their existence would change our interpretation of tectonic and climatic history recorded in river profiles. Autogenic feedbacks that lead to repeating topographic forms in riverbeds (i.e., bedforms) are common, but it is unknown whether similar feedbacks can cause waterfall formation in bedrock. For example, experiments have shown that incising, steep riverbeds rapidly develop repeating, undulating chutes and pools, known as cyclic steps¹³⁻¹⁶, that are self-organized^{17,18}. Cyclic steps are similar to waterfalls, but their step height is small relative to their wavelength, and they lack a freefalling jet that defines a waterfall^{15,19}. Workers have proposed that cyclic steps might develop into waterfalls^{13,20}; however, this hypothesis has not been tested. Instead, previous experiments have explored waterfall formation due to perturbations in external forcing - such as changes in base level, water discharge or sediment supply^{13,17,18,21} - or have used a layered or fractured substrate to promote waterfall formation^{22,23}. Moreover, most previous experiments used sediment substrates erodible by clear water alone^{13-15,17,18,21}, whereas natural bedrock channels wear by abrasion from particle impacts or plucking. New techniques using scaled concrete or foam are better quantitative analogs to bedrock²⁴, but experiments using these bedrock analogs have yet to explore waterfall formation.

Isolating the relative controls of climate, tectonics, lithology and autogenic dynamics on waterfall formation is challenging because bedrock riverbeds evolve over $>10^3$ yrs and they are

subject to autogenic dynamics and allogenic perturbations over varied timescales. To overcome this challenge, we used a physical experiment to test the hypothesis that bedrock waterfalls can form due to autogenic dynamics alone, in the absence of perturbations in external forcing or lithologic controls. The experiment was designed to simplify the natural environment in order to isolate autogenic processes, while maintaining dynamic scaling²⁵. Our experiment used a 7.3-m long by 30.5-cm wide riverbed tilted to 19.5% grade (Extended Data Figure 1). We used a synthetic bedrock of polyurethane foam, which simulates uniform bedrock (e.g., Figure 1) and lacks lithologic heterogeneities known to cause waterfall formation^{22,23}. Like natural rock, the foam resists erosion by water alone, and it follows the same erosion scaling law as natural rock under abrasion by particle impacts²⁴ (Methods). The bed was planar initially, and we used constant water discharge and supply of unimodal gravel (Methods), making the experiment free of perturbations in external forcing that are typically thought to cause waterfall formation^{3,4,8}. Hydraulics and sediment transport were scaled based on mountain rivers where waterfalls are common⁸, including Froude-transcritical and turbulent flow (Methods). Erosion-rate scaling suggests that riverbed evolution in our 3.7-hr experiment represents $\sim 10^2$ – 10^5 yrs of river incision for natural rivers that have flood intermittency and stronger substrates (Methods). Within the first hour of the experiment, impacts from bed load-transported gravel abraded a ~8-10-cm wide channel, and continued incision, in the absence of hillslope processes, led to the formation of a slot canyon (Extended Data Figure 2). Along the riverbed, decimeter-scale variations in erosion created repeating convex bedrock crests and concave depressions, which grew in amplitude to form cyclic steps, similar to previous experiments¹⁴⁻¹⁶. The cyclic steps migrated downstream due to sediment impacts on the upstream side of bedrock crests (Figure 2),

and hydraulic jumps separated supercritical flow in chutes from subcritical flow in pools (Figure 3). Unlike previous work with sediment beds, some cyclic steps in our experiment developed into waterfalls starting between experiment time $2.1 < t < 3.1$ hr. Waterfalls formed as deeper pools trapped sediment that armored their bases against erosion, whereas vertical incision continued in the next pool downstream, causing the chute between the armored pool and its downstream neighbor to steepen (Figure 2; Extended Data Figures 3 and 4; Extended Data Table 1). The combination of deposition in the upstream pool and flattening of the pool's downstream lip created a smoothed reach over which water accelerated and detached at the steepened chute, forming a waterfall with a fully ventilated jet and plunge pool (Supplementary Videos 1 and 2). Two waterfalls formed with peak heights of 35 and 38 cm (~ 3.5 and six-fold the flow depth at the waterfall brink) (Extended Data Table 1). The escarpments had maximum slopes of 45° and 49° , similar to natural waterfalls in massive rock⁸ (Figure 1 and Extended Data Figures 5 and 6). In contrast to the cyclic steps, individual waterfalls showed negligible migration. Waterfalls persisted for ~ 20 min (representing $\sim 10^1$ – 10^4 yrs in natural rivers [Methods]) before erosion at the waterfall brink reduced the waterfall height causing flow reattachment to the riverbed (Extended Data Figure 3). As waterfalls were destroyed, the plunge-pool lip upstream of the waterfall steepened, leading, in one case, to a new proto-waterfall and plunge pool (Figure 2g). Our experiment had reach-averaged erosion rates $\sim$ two-fold higher than predicted for planar beds (Methods).

Autogenic waterfalls formed in our experiment due to feedbacks between water flow, sediment transport, and bedrock topography in the absence of rock fractures, bedding, or external perturbations to base level, water discharge or sediment supply. Autogenic waterfall formation is tied to the non-linear role of sediment in bedrock-bed stability, dynamics that may have been

absent in experiments with sediment beds erodible by water alone^{13,17,18,21}. In bedrock, zones of frequent, high-energy impacts erode rapidly, such as in shallow pools; however, spatial convergences in sediment flux, such as in deep pools, cause deposition and armoring of the riverbed. Waterfalls form when deposition in an upstream pool prevents erosion, while erosion downstream increases the vertical drop between adjacent pools. Waterfall jets can erode deep plunge pools, when unarmored, and outpace incision at the waterfall brink²⁰, thereby growing waterfall relief. However, drag in deeper pools reduces particle impact energy, slowing pool incision²⁰, and continued waterfall brink erosion eventually destroys the step (Figure 2; Extended Data Figures 3 and 4).

Unlike models of waterfalls migrating upstream¹¹, in our experiment waterfalls were stationary because the freefalling jet focused impacts on the plunge-pool floor rather than walls²⁰ (Supplementary Videos 1 and 2). Instead, our findings are consistent with escarpment retreat via a series of vertically-eroding waterfalls, in which waterfalls are repeatedly created and destroyed^{5,9,20}. In this model, flow acceleration towards the brink of an existing waterfall^{3,26} (Figure 2f) leads to the generation of cyclic steps upstream of the waterfall^{13,16,17}, which then grow via vertical plunge-pool erosion to form new waterfalls (Figure 2g). While there exists limited evidence of waterfall lifetimes, our scaled experiment suggests that individual autogenic waterfalls may persist up to 10^4 yrs, and continual creation of waterfalls would result in longer-lived escarpment retreat.

Our experiment suggests that self-formed waterfalls require a bedrock riverbed undergoing erosion by abrasion, and near Froude-critical flow (Froude number near unity). Near Froude-critical flow conditions are common to streams with slopes $>1\%$ grade^{13,27}, which dominate drainage networks in mountainous terrain, suggesting that autogenic waterfalls could be

widespread. However, more work is needed to identify the necessary conditions for self-formed waterfalls and fingerprint their attributes. Waterfalls in our experiment had drop heights 3-6-fold the flow depth, but this is unlikely to be diagnostic; the relative height likely depends on water discharge and sediment supply, which need to be systematically explored. Our experiment indicates that autogenic waterfalls should occur as a series of steps, with initial spacing set by the cyclic-step instability¹⁹. Waterfalls in series are common (Figure 1), and it is often difficult to link a specific external perturbation or rock heterogeneity to each individual waterfall, consistent with an autogenic interpretation. Conversely, the presence of a single, isolated waterfall (e.g., Niagara Falls) is inconsistent with autogenic formation, which requires cyclic steps as precursors to waterfalls.

In our experiment, the initial bed slope was imposed. In natural landscapes, steep riverbed slopes, capable of supercritical flow and autogenic waterfalls, might develop under steady external forcing or due to perturbations in forcing. For example, landscape evolution models under steady forcing evolve towards a topographic steady state with smooth, concave river profiles³. Knickzones and waterfalls only emerge in these models due to imposed lithologic variability or perturbations in external forcing³. Our experiment suggests, in contrast, that steeper riverbed reaches in steady state landscapes can develop waterfalls and intervening flatter reaches in the absence of external perturbations - dynamics absent in existing models³, including those used to invert topography for uplift history¹². A potential example is the Central Sierra Madre Block of the San Gabriel Mountains, California, which has been proposed as a topographic steady-state landscape²⁸ due to similar erosion rates across decadal-to-million year timescales^{1,28}, and uniform granitic rocks are not thought to impact landscape evolution¹. Rivers within this region (e.g., Rubio and Eaton Canyons, Figure 1b) have many waterfalls in series that lack

association with lithologic boundaries (Extended Data Figure 6), consistent with an autogenic origin.

Steep riverbeds also form through perturbations in external forcing, such that self-formed waterfalls might develop in concert with externally-forced knickzones. For example, previous workers have shown that a single perturbation in external forcing can cause the formation of multiple waterfalls^{5,8,9}. In addition, cyclic steps and proto-waterfalls are common upstream of waterfalls because supercritical flow develops as water accelerates towards the waterfall brink²⁶.

In Big Tujunga Creek catchment, CA, many tributaries, such as Fox Creek (Figure 1c), have a knickzone that has been linked to an increase in uplift rate⁸. Each knickzone is composed of numerous waterfalls that lack known origins, are consistent with autogenic formation, and have likely changed erosion rates of the broader knickzone in a manner that is inconsistent with fluvial incision models⁸. Bridalveil Creek in Yosemite Valley, California, provides another example where Bridalveil Falls formed along the steep glacially-carved valley walls following deglaciation¹⁰. Despite the allogenic origin of Bridalveil Falls, many additional waterfalls exist upstream of the main falls that are consistent with an autogenic origin (Extended Data Figure 5c). The upstream waterfalls developed in massive granitic rock, lack an association with jointing (Extended Data Figure 5b), are unaffected by base-level due to being upstream of the hanging valley, and are unlikely to have a glacial origin as they have been ice free since ~800 ka¹⁰. Individual waterfalls along Bridalveil Creek coalesce in a ~3-km long regional knickzone similar to those commonly attributed to perturbations in external forcing^{3,8,12} (Extended Data Figure 5c).

The generation of self-formed waterfalls illustrates the complex evolution of incising bedrock channels in response to constant forcing. The emergence of waterfalls is important for landscape

evolution because a series of waterfalls can change river incision rates²⁰ and river-profile concavity over kilometer scales⁸. Thus, autogenic waterfalls can affect bedrock erosion, sediment production, and hillslope gradients that drive landsliding², potentially driving oscillations in sediment flux²⁹. The existence of knickzones and waterfalls is often used to define landscape topographic disequilibrium with respect to external forcing³. In contrast, our experiment suggests that waterfalls may be able to emerge in landscapes with uniform lithology undergoing steady external forcing, which could lead to erroneous identification of changes in climate and tectonics from channel profile inversion. Autogenic waterfalls that emerge in response to externally-forced river steepening may change the rates that allogenic perturbations propagate through river networks, further obscuring climate and tectonic signals.

- 1 DiBiase, R. A., Whipple, K. X., Heimsath, A. M. & Ouimet, W. B. Landscape form and millennial erosion rates in the San Gabriel Mountains, CA. *Earth and Planetary Science Letters* **289**, 134-144, doi:10.1016/j.epsl.2009.10.036 (2010).
- 2 Weissel, J. K. & Seidl, M. A. in *Rivers over rock: Fluvial processes in bedrock channels Geophysical Monograph* (eds K. Tinkler & E. Wohl) (AGU, 1998).
- 3 Whipple, K. X., DiBiase, R. A. & Crosby, B. T. in *Treatise on Geomorphology* Vol. 9 (eds J. Shroder, Jr. & E. E. Wohl) (Academic Press, 2013).
- 4 Crosby, B. T. & Whipple, K. X. Knickpoint initiation and distribution within fluvial networks: 236 waterfalls in the Waipaoa River, North Island, New Zealand. *Geomorphology* **82**, 16-38, doi:10.1016/j.geomorph.2005.08.023 (2006).
- 5 Howard, A. D., Dietrich, W. E. & Seidl, M. A. Modeling fluvial erosion on regional to continental scales. *Journal of Geophysical Research-Solid Earth* **99**, 13971-13986, doi:10.1029/94JB00744 (1994).
- 6 Yanites, B. J., Tucker, G. E., Mueller, K. J. & Chen, Y. G. How rivers react to large earthquakes: Evidence from central Taiwan. *Geology* **38**, 639-642, doi:10.1130/G30883.1 (2010).
- 7 Malatesta, L. C. & Lamb, M. P. Formation of waterfalls by intermittent burial of active faults. *Geological Society of America Bulletin* **130**, doi:10.1130/B31743.1 (2018).
- 8 DiBiase, R. A., Whipple, K. X., Lamb, M. P. & Heimsath, A. M. The role of waterfalls and knickzones in controlling the style and pace of landscape adjustment in the western San Gabriel Mountains, California. *Geological Society of America Bulletin* **127**, 539-559, doi:10.1130/B31113.1 (2015).

- 199 9 Lamb, M. P., Howard, A. D., Dietrich, W. E. & Perron, J. T. Formation of amphitheater-
200 headed valleys by waterfall erosion after large-scale slumping on Hawai'i. *Geological*
201 *Society of America Bulletin* **119**, 805-822, doi:10.1130/b25986.1 (2007).
- 202 10 Matthes, F. E. in *USGS Professional Paper 160* (United States Government Printing
203 Office, Washington DC, 1930).
- 204 11 Gilbert, G. K. The history of the Niagara River, extracted from the sixth annual report to
205 the commissioners of the state reservation at Niagara, Albany, NY. (1890).
- 206 12 Roberts, G. G., White, N. J. & Shaw, B. An uplift history of Crete, Greece, from inverse
207 modeling of longitudinal river profiles. *Geomorphology* **198**, 177-188,
208 doi:10.1016/j.geomorph.2013.05.026 (2013).
- 209 13 Baynes, E. R. C., Lague, D. & Kermarrec, J. Supercritical river terraces generated by
210 hydraulic and geomorphic interactions. *Geology* **46**, 499-502, doi:10.1130/G40071.1
211 (2018).
- 212 14 Brooks, P. C. *Experimental study of erosional cyclic steps* Masters thesis, University of
213 Minnesota, (2001).
- 214 15 Taki, K. & Parker, G. Transportational cyclic steps created by flow over an erodible bed.
215 Part 1. Experiments. *Journal of Hydraulic Research* **43**, 488-501 (2005).
- 216 16 Yokokawa, M., Kotera, A. & Kyogoku, A. in *Advances in river sediment research* (eds
217 S. Fukuoka, H. Nakagawa, T. Sumi, & H. Zhang) (CRC Press, 2013).
- 218 17 Grimaud, J. L., Paola, C. & Voller, V. Experimental migration of knickpoints: influence
219 of style of base-level fall and bed lithology. *Earth Surf Dynam* **4**, 11-23,
220 doi:10.5194/esurf-4-11-2016 (2016).
- 221 18 Baynes, E. R. C. *et al.* River self-organisation inhibits discharge control on waterfall
222 migration. *Sci Rep-Uk* **8** (2018).
- 223 19 Izumi, N., Yokokawa, M. & Parker, G. Incisional cyclic steps of permanent form in
224 mixed bedrock-alluvial rivers. *Journal of Geophysical Research-Earth Surface* **122**, 130-
225 152, doi:10.1002/2016JF003847 (2017).
- 226 20 Scheingross, J. S. & Lamb, M. P. A mechanistic model of plunge pool erosion into
227 bedrock. *Journal of Geophysical Research-Earth Surface* **122**, 25,
228 doi:10.1002/2017JF004195 (2017).
- 229 21 Gardner, T. W. Experimental study of knickpoint and longitudinal profile evolution in
230 cohesive, homogenous material. *Geological Society of America Bulletin* **94**, 664-672,
231 doi:10.1130/0016-7606(1983)94<664:esokal>2.0.co;2 (1983).
- 232 22 Holland, W. N. & Pickup, G. Flume study of knickpoint development in stratified
233 sediment. *Geological Society of America Bulletin* **87**, 76-82, doi:10.1130/0016-
234 7606(1976)87<76:fsokdi>2.0.co;2 (1976).
- 235 23 Lamb, M. P. & Dietrich, W. E. The persistence of waterfalls in fractured rock.
236 *Geological Society of America Bulletin* **121**, 1123-1134, doi:10.1130/b26482.1 (2009).
- 237 24 Lamb, M. P., Finnegan, N. J., Scheingross, J. S. & Sklar, L. S. New insights into the
238 mechanics of fluvial bedrock erosion through flume experiments and theory.
239 *Geomorphology* **244**, 33-55, doi:10.1016/j.geomorph.2015.03.003 (2015).
- 240 25 Paola, C., Straub, K., Mohrig, D. & Reinhardt, L. The "unreasonable effectiveness" of
241 stratigraphic and geomorphic experiments. *Earth-Sci Rev* **97**, 1-43,
242 doi:10.1016/j.earscirev.2009.05.003 (2009).
- 243 26 Haviv, I. *et al.* Amplified erosion above waterfalls and oversteepened bedrock reaches.
244 *Journal of Geophysical Research-Earth Surface* **111**, doi:10.1029/2006jf000461 (2006).

- 27 Palucis, M. C. & Lamb, M. P. What controls channel form in steep mountain streams?
Geophysical Research Letters **44**, 7245-7255, doi:10.1002/2017gl074198 (2017).
- 28 Lave, J. & Burbank, D. Denudation processes and rates in the Transverse Ranges,
southern California: Erosional response of a transitional landscape to external and
anthropogenic forcing. *Journal of Geophysical Research-Earth Surface* **109**,
doi:10.1029/2003jf000023 (2004).
- 29 Hasbargen, L. E. & Paola, C. Landscape instability in an experimental drainage basin.
Geology **28**, 1067-1070, doi:10.1130/0091-7613(2000)28<1067:Liaed>2.0.Co;2
(2000).

Supplementary Information is linked to the online version of the paper at

www.nature.com/nature.

Acknowledgements: We thank J. Preimesberger for assistance with preliminary experiments, R. DiBiase, W. Dietrich, N. Izumi, G. Parker, J. Prancevic, J. Turowski, and M. Yokokawa for discussion, and A. Wickert and two other referees for reviews. We acknowledge funding from the National Science Foundation (EAR-1147381 to M.P.L and a Graduate Research Fellowship to J.S.S.), NASA (12PGG120107 to M.P.L.), and the Alexander von Humboldt Foundation (postdoctoral fellowship to J.S.S.). This work includes data services provided by the OpenTopography Facility with support from the National Science Foundation under NSF Award Numbers 1557484, 1557319, and 1557330, and EAR-1043051.

Author Contributions: J.S.S. and M.P.L. designed the study and wrote the manuscript with input from B.F. J.S.S. and B.F. performed the experiment with input from M.P.L.

Author Information: Reprints and permissions information is available at

www.nature.com/reprints. The authors declare no competing financial interests. Correspondence and request for materials should be addressed to jscheingross@unr.edu.

Figure 1: Repeating waterfalls formed in relatively homogeneous rock. (a) Kohala Peninsula (Hawaii, USA), (b) and (c) Eaton Canyon (photo credit: Roman DiBiase) and Fox Creek (San

Gabriel Mountains, USA), (d) and (e) Dry Meadow (photo credit: Devon Santy) and Dinkey Creek (photo credit: Darin McQuoid) (Sierra Nevada, USA). Waterfall slopes range from ~45-90°.

Figure 2: Bedrock channel evolution. (a) Laser scan of bedrock profile evolution. (b) – (g) Detailed bedrock and water surface topographic profiles; gray shading shows sediment armoring. Light gray profiles spaced at ~0.3 hr intervals. Water surface profiles taken ~0.1 hr later than bedrock profiles; no water surface profile is available for (g). Raw data is provided in the Supplementary Information.

Fig. 3: Waterfall formation. (a) – (c) Upstream waterfall formation. (d) and (e) Detail of downstream waterfall jet. Note the surface on which the flume rests is titled 19.5% with respect to horizontal.

Methods

Water discharge, sediment supply, and grain size were selected so that the experiment initially had supercritical flow, while keeping sediment supply well below transport capacity to allow bedrock exposure. We fed unimodal, siliciclastic sediment at a constant rate of 0.5 ± 0.02 kg/s (mean $\pm$ standard deviation), with a median grain diameter of $D = 2.4$ cm to maximize erosion via high kinetic impact energy, and ensured large particle Reynolds numbers ($>5.0 \times 10^4$) typical of mountain streams. Water discharge was held constant at $Q_w = 14.2$ l/s, the initial reach-averaged Shields stress ($\tau^* \approx 0.11$) was in excess of the threshold of motion, and the gravel moved as bedload. Flow was fully turbulent (Reynolds numbers of 10^4 - 10^5). The initially high Froude number flow ($Fr \sim 4.5$ at $t = 0$) reduced to $Fr \sim 2$ by $t = 0.4$ hr, and flow was trans-critical by $t \sim 1.7$ hr due to cyclic step development. Base level was fixed 44 cm below the end of our

experimental test section (Extended Data Figure 1), allowing the channel upstream to erode freely over the duration of the experiment. Importantly, the cyclic steps and waterfalls emerged far upstream of the downstream boundary and were not influenced by base level.

As a bedrock simulant, we installed an initially planar 76 cm thick bed of low-tensile strength ($\sigma_T = 0.32$ MPa) polyurethane foam (Extended Data Figure 1). This homogeneous foam quantitatively simulates massive rock in which waterfalls often form (Figure 1), and lacks fractures and bedding that are known to force waterfall formation^{2,22,23}. The foam follows the same tensile-strength versus erosion rate scaling observed in natural rock and concrete, allowing scaling of erosion rates between the laboratory and natural streams^{24,30}, and increased laboratory erosion rates due to the low-tensile strength foam. Eroded foam particles entered the wash load and did not contribute to channel erosion. Prior to the start of the experiment, we ran 20 hr of clear-water discharge with zero sediment supply (under otherwise identical conditions to the main experiment), observing no detectable erosion of the foam. In contrast, measurable erosion occurred within minutes of initiating sediment feed, indicating foam erosion occurred exclusively due to abrasion from particle impacts.

The water-surface elevation was measured along the channel thalweg at 1 mm horizontal spacing using a sub-mm vertical resolution laser scanner that illuminated the aerated water surface. The experiment was paused every 3 to 30 minutes to measure bedrock topography with the same laser scanner at resolutions of 1 mm in the along-stream direction and 2-10 mm in the cross-stream direction. Where sediment was deposited, we first scanned the bed with the sediment in place, then removed sediment by hand and scanned the bedrock surface, and finally replaced the sediment before resuming the experiment. The waterfall drop height was measured as the vertical distance between the point of jet detachment from the bedrock surface and the minimum

elevation of the downstream plunge-pool bedrock floor. Reach averaged erosion rates were calculated by differencing successive topographic scans and taking spatial averages. These rates were compared with theoretical predictions for a planar bed using a bedrock erosion model which accounts for erosion from bedload and suspended sediment³¹, with all values set to those in the experiment, and calibrated for the foam substrate³⁰.

In order to compare the timescale of erosion between the experiment and natural channels, we propose that the characteristic timescale to form autogenic waterfalls, T , scales with the time to vertically incise, at rate E , a distance equivalent to one channel depth, h , i.e., $T_{lab} \propto h_{lab} / E_{lab}$ and $T_{field} \propto h_{field} / E_{field}$, where subscripts ‘lab’ and ‘field’ refer to the laboratory and field conditions, respectively. We solved for T using average values from our experiment ($h_{lab} = 130$ mm, $E_{lab} = 100$ mm/hr) and a range of values appropriate for mountain rivers where waterfalls are common ($1 < h_{field} < 6$ m, $10^{-2} < E_{field} < 10^1$ mm/yr)^{32,33}. T_{field}/T_{lab} ranges from 10^5 - 10^8 ; the ratio is large mostly because of low tensile strength foam and the lack of flood intermittency in the lab.

Data Availability: All topographic and water surface profiles are available in the Supplementary Information.

- 30 Scheingross, J. S., Brun, F., Lo, D. Y., Omerdin, K. & Lamb, M. P. Experimental evidence for fluvial bedrock incision by suspended and bedload sediment. *Geology* **42**, 523-526, doi:10.1130/G35432.1 (2014).
- 31 Lamb, M. P., Dietrich, W. E. & Sklar, L. S. A model for fluvial bedrock incision by impacting suspended and bed load sediment. *Journal of Geophysical Research-Earth Surface* **113**, doi:10.1029/2007jf000915 (2008).
- 32 Finnegan, N. J., Roe, G., Montgomery, D. R. & Hallet, B. Controls on the channel width of rivers: Implications for modeling fluvial incision of bedrock. *Geology* **33**, 229-232 (2005).
- 33 Portenga, E. W. & Bierman, P. R. Understanding Earth's eroding surface with 10-Be. *GSA Today* **21**, doi:10.1130/G111A.1 (2011).
- 34 Yerkes, R. F. & Campbell, R. H. in *Open-File Report 2005-1019* (U.S. Geological Survey, 2005).

Extended Data Table 1: Elevation and erosion rates of waterfalls*

* Z_{brink} and Z_{pool} are the elevations of the plunge pool upstream brink and floor, respectively. E_{brink} and E_{pool} are the vertical lowering rate of the plunge pool upstream brink and floor, respectively.

Extended Data Figure 1: Experimental setup. (a) Schematic of experimental set up at $t = 0$ hr. Precut steps visible downstream of the test section extent eroded rapidly to the fixed base level and did not influence the experiment or the development of cyclic steps (which developed throughout the test section). (b) Photo of set up after completion of the experiment.

Extended Data Figure 2: Experiment photographs showing canyon incision. (a) – (e) Progressive incision and canyon formation with time. Dashed line highlights the $x = 2.3$ m cross-section, arrow points downstream, 15 cm pen for scale. Photos were taken after removal of deposited sediment while the experiment was paused. (f) Field example of a canyon with similar morphology to our experiment from Pleasant Creek, Capitol Reef National Park, Utah, USA (photo credit: Bret Edge).

Extended Data Figure 3: Detail view of bedrock channel evolution. (a) – (f) Time-series of bedrock channel (black) and water surface (blue) profiles showing waterfall plunge-pool formation at $x \sim 4$ m. Gray lines show previous bedrock surfaces spaced at ~ 0.3 hr intervals and correspond to times shown in Figure 2a; gray shading denotes areas of deposited sediment. Note water surface profiles correspond to times ~ 0.1 hr later than bedrock profiles and no water surface profile is available corresponding to (f). Raw data is provided in the Supplementary Information (Supplementary Data 1).

Extended Data Figure 4: Relative vertical erosion rates at the waterfall brink (E_{brink}) and the waterfall plunge-pool floor (E_{floor}). (a) Erosion rate versus time for the upstream waterfall centered at $x = 4.3$ and (b) downstream waterfall centered at $x = 6.5$. During periods of waterfall formation ($2.4 < t < 3.1$ and $2.1 < t < 2.8$ hr for the upstream and downstream waterfall,

respectively) erosion at the pool floor outpaced that at the brink, causing an increase in waterfall height. As waterfall plunge pools deepened, their erosion rates slowed below that of the upstream brink, thereby decreasing waterfall height and destroying the original waterfall.

Extended Data Figure 5: Field examples of putative autogenic waterfalls formed in concert with externally-forced riverbed steepening. (a) Lidar shaded relief map of Yosemite Valley, California and (b) detailed view of potentially autogenic waterfalls upstream of Bridalveil Falls (data distributed via OpenTopography³⁵). Note waterfalls do not align with macroscale jointing or fractures visible in the Lidar. (c - e) Lidar-extracted long profiles above Bridalveil (c,d) and Upper Yosemite Falls (e). Colored dots show channel slopes above 30° calculated across a 3 pixel moving window (horizontal length scale of ~3 m). Waterfalls frequently occur at slopes <50°, similar to our experiment.

Extended Data Figure 6: Field examples of putative autogenic waterfalls formed in steady-state landscapes. (a) Shaded relief map of the Central Sierra Madre Block of the San Gabriel Mountains, California showing locations of Eaton and Rubio Canyons. (b) Simplified geologic map of Rubio and Eaton Canyons after ref [34], mixed intrusive rocks are dominated by Cretaceous and Triassic granitoids. (c,d) Detailed Lidar shaded relief maps showing potentially autogenic waterfalls in Eaton and Rubio Canyons (data courtesy of the National Center for Airborne Laser Mapping and available in the Supplementary Information [Supplementary Data 2]). (e,f) Lidar-extracted long profile for Eaton Canyon and Rubio Canyon with colored dots showing channel slopes above 30° calculated across a 3 pixel moving window (horizontal length scale of ~3 m).

35 Stock, G. Yosemite, CA: El Portal, Mariposa Grove, Yosemite Canyon & Tuolumne Meadows. National Center for Airborne Laser Mapping (NCALM), distributed by OpenTopography, doi: 10.5069/G9GQ6VP3 (2006)

Figure 1: Repeating waterfalls formed in relatively homogeneous rock. (a) Kohala Peninsula (Hawaii, USA), (b) and (c) Eaton Canyon (photo credit: Roman DiBiase) and Fox Creek (San Gabriel Mountains, USA), (d) and (e) Dry Meadow (photo credit: Devon Santy) and Dinkey Creek (photo credit: Darin McQuoid) (Sierra Nevada, USA). Waterfall slopes range from $\sim 45\text{-}90^\circ$.

Figure 2: Bedrock channel evolution. (a) Laser scan of bedrock profile evolution. (b) – (g) Detailed bedrock and water surface topographic profiles; gray shading shows sediment armoring. Light gray profiles spaced at ~0.3 hr intervals. Water surface profiles taken ~0.1 hr later than bedrock profiles; no water surface profile is available for (g). Raw data is provided in the Supplementary Information.

Formation of upstream waterfall

Figure 3: Waterfall formation. (a) – (c) Upstream waterfall formation. (d) and (e) Detail of downstream waterfall jet. Note the surface on which the flume rests is titled 19.5% with respect to horizontal.

Extended Data Figure 1: Experimental setup. (a) Schematic of experimental set up at $t = 0$ hr. Precut steps visible downstream of the test section extent eroded rapidly to the fixed base level and did not influence the experiment or the development of cyclic steps (which developed throughout the test section). (b) Photo of set up after completion of the experiment.

Extended Data Figure 2: Experiment photographs showing canyon incision. (a) – (e) Progressive incision and canyon formation with time. Dashed line highlights the $x = 2.3$ m cross-section, arrow points downstream, 15 cm pen for scale. Photos were taken after removal of deposited sediment while the experiment was paused. (f) Field example of a canyon with similar morphology to our experiment from Pleasant Creek, Capitol Reef National Park, Utah, USA (photo credit: Bret Edge).

Extended Data Figure 3: Detail view of bedrock channel evolution. (a) – (f) Time-series of bedrock channel (black) and water surface (blue) profiles showing waterfall plunge-pool formation at $x \sim 4$ m. Gray lines show previous bedrock surfaces spaced at ~ 0.3 hr intervals and correspond to times shown in Figure 2a; gray shading denotes areas of deposited sediment. Note water surface profiles correspond to times ~ 0.1 hr later than bedrock profiles and no water surface profile is available corresponding to (f). Raw data is provided in the Supplementary Information (Supplementary Data 1).

Extended Data Figure 4: Relative vertical erosion rates at the waterfall brink (E_{brink}) and the waterfall plunge-pool floor (E_{floor}). (a) Erosion rate versus time for the upstream waterfall centered at $x = 4.3$ and (b) downstream waterfall centered at $x = 6.5$. During periods of waterfall formation ($2.4 < t < 3.1$ and $2.1 < t < 2.8$ hr for the upstream and downstream waterfall, respectively) erosion at the pool floor outpaced that at the brink, causing an increase in waterfall height. As waterfall plunge pools deepened, their erosion rates slowed below that of the upstream brink, thereby decreasing waterfall height and destroying the original waterfall.

Extended Data Figure 5: Field examples of putative autogenic waterfalls formed in concert with externally-forced riverbed steepening. (a) Lidar shaded relief map of Yosemite Valley, California and (b) detailed view of potentially autogenic waterfalls upstream of Bridalveil Falls (data distributed via OpenTopography35). Note waterfalls do not align with macroscale jointing or fractures visible in the Lidar. (c - e) Lidar-extracted long profiles above Bridalveil (c,d) and Upper Yosemite Falls (e). Colored dots show channel slopes above 30° calculated across a 3 pixel moving window (horizontal length scale of ~3 m). Waterfalls frequently occur at slopes <50°, similar to our experiment.

Extended Data Figure 6: Field examples of putative autogenic waterfalls formed in steady-state landscapes. (a) Shaded relief map of the Central Sierra Madre Block of the San Gabriel Mountains, California showing locations of Eaton and Rubio Canyons. (b) Simplified geologic map of Rubio and Eaton Canyons after ref [34], mixed intrusive rocks are dominated by Cretaceous and Triassic granitoids. (c,d) Detailed Lidar shaded relief maps showing potentially autogenic waterfalls in Eaton and Rubio Canyons (data courtesy of the National Center for Airborne Laser Mapping and available in the Supplementary Information [Supplementary Data 2]). (e,f) Lidar-extracted long profile for Eaton Canyon and Rubio Canyon with colored dots showing channel slopes above 30° calculated across a 3 pixel moving window (horizontal length scale of ~3 m).

Extended Data Table 1: Elevation and erosion rates of waterfall features

Experiment Time (hr)	Z_{brink} (m)	Z_{pool} (m)	$Z_{\text{brink}} - Z_{\text{pool}}$ (m)	E_{brink} (m/hr)	E_{pool} (m/hr)	$E_{\text{brink}}/E_{\text{pool}}$
<i>Upstream waterfall centered at $x = 4.2$</i>						
2.38	-0.82	-1.09	0.27			
2.71	-0.85	-1.18	0.33	0.10	0.29	0.36
3.05	-0.92	-1.27	0.35	0.21	0.27	0.77
3.38	-0.99	-1.29	0.30	0.21	0.06	3.74
3.70	-1.08	-1.34	0.26	0.28	0.15	1.93
<i>Downstream waterfall centered at $x = 6.5$</i>						
2.05	-1.24	-1.57	0.32			
2.38	-1.25	-1.62	0.37	0.03	0.17	0.18
2.71	-1.31	-1.69	0.38	0.15	0.19	0.81
3.05	-1.37	-1.71	0.34	0.20	0.08	2.50
3.38	-1.45	-1.72	0.27	0.23	0.01	19.50
3.70	-1.51	-1.72	0.21	0.19	0.00	

Z_{brink} and Z_{pool} are the elevations of the plunge pool upstream brink and floor, respectively. E_{brink} and E_{pool} are the vertical lowering rate of the plunge pool upstream brink and floor, respectively.