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Supporting Information for

Self-formed waterfall plunge pools in homogeneous rock

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Introduction

This supporting information contains text, one figure, and two tables. Text S1 provides methods for calculations of expected erosion rate upstream of the waterfall in our experiments. Figure S1 shows overlap in non-dimensional space (from the theory of *Scheingross and Lamb* [2016]) between the experiments detailed in the main text and natural waterfalls surveyed by *Scheingross and Lamb* [2016]. Tables S1 and S2 give the parameters for the experimental setup and tabulations of experimental data, respectively.

Text S1: Upstream erosion rate calculations

Comparing rates of fluvial bedrock incision upstream of waterfalls relative to plunge-pool vertical and lateral erosion allows evaluation of the ability for waterfalls to maintain their form during upstream retreat. Our experiments used a fixed, non-erodible bed upstream of the waterfall in order to keep waterfall drop height constant over the length of each experiment, and we instead use existing theory to estimate the magnitude of fluvial bedrock incision upstream of the waterfall for our experiments. We estimate incision using the total-load theory of *Lamb et al. [2008]*, a modified version of the saltation-abrasion model [*Sklar and Dietrich*, 2004], which predicts fluvial erosion as a function of the concentration of grains near the bed, particle impact velocity, fraction of exposed bedrock, and bedrock material properties, and has been experimentally tested [*Scheingross et al.*, 2014]. Erosion rate predictions require estimates of grain size, channel slope and width, flow depth, discharge, and sediment supply for which we used values from Table S1. For all calculations we set bedrock tensile strength to 0.32 MPa to match the tensile strength of the polyurethane foam in which plunge pools were formed. For Exp1, the total-load model predicts erosion rates of

3.8 x 10^{-4} m/hr, while for Exp2, the model predicts rates of 7.5 x 10^{-4} m/hr for the initial low sediment supply, and 3.7 x 10^{-3} m/hr for the high sediment supply.

Sustained upstream retreat via headwall undercutting requires that lateral plunge-pool erosion of the upstream pool wall outpaces vertical incision upstream of the waterfall, otherwise the waterfall will diminish in height with time. We compare the predicted upstream fluvial erosion rates to measured lateral erosion during the time when pools were alluviated, as this represents the period when pools are most likely to undercut the upstream pool wall. For this period, we calculate mean ratios of fluvial vertical incision to lateral plunge-pool erosion of 5.1 and 12.6 for Exp1 and Exp2, respectively, implying that waterfalls should diminish in height with time. Note that these calculations are based on lateral plunge-pool erosion over the entire pool walls, as it was not possible to separately quantify upstream and downstream plunge-pool wall erosion in the experiments. However, because lateral erosion tended to be focused on the downstream wall rather than the upstream wall, ratios of fluvial vertical incision to lateral headwall undercutting are likely higher than those reported above, and thus more strongly imply waterfalls diminish in height with time.

Sustained vertical drilling requires plunge-pool vertical incision to outpace upstream fluvial incision. For periods before the onset of sediment deposition, measured plunge-pool vertical incision are on average 38 and 23 times greater than upstream fluvial incision for Exp1 and Exp2, respectively, implying that vertical pool drilling, combined with keyholing and the lowering of the downstream plunge-pool lip, can be an efficient waterfall retreat mechanism in homogeneous rock.

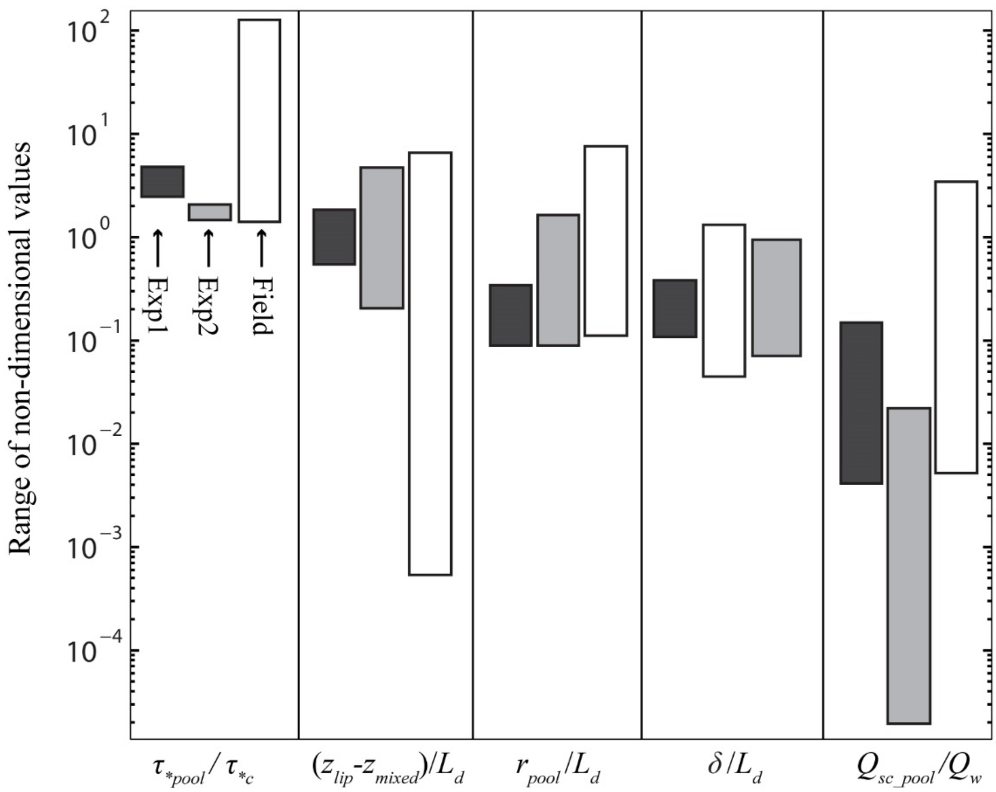

Figure S1. Range of non-dimensional variables which govern plunge-pool sediment-transport capacity in the *Scheingross and Lamb* [2016] theory for field-surveyed waterfalls (white boxes) [*Scheingross and Lamb*, 2016], Exp1 (dark gray boxes) and Exp2 (light gray boxes). Non-dimensional variables: τ_{*pool}/τ_{*c} - plunge-pool transport stage, $(z_{lip} - z_{mixed})/L_d$ – approximate plunge-pool depth to sediment (for deep pools) normalized by turbulent mixing length scale, r_{pool}/L_d – plunge-pool radius normalized by turbulent mixing length scale, δ/L_d - jet-descending region radius normalized by turbulent mixing length scale, and Q_{sc_pool}/Q_w – plunge-pool sediment-transport capacity normalized by water discharge. Note that we removed values of $Q_{sc\_pool}/Q_w = 0$ from both field and flume data for clarity.

Table S1. Summary of parameters for waterfall plunge-pool erosion experiments (attached on separate page)
Table S2. Measurements from plunge-pool erosion experiments (attached on separate page).

References

Lamb, M. P., W. E. Dietrich, and L. S. Sklar (2008), A model for fluvial bedrock incision by impacting suspended and bed load sediment, *Journal of Geophysical Research-Earth Surface*, *113*(F3), doi: 10.1029/2007jf000915.

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Sklar, L. S., and W. E. Dietrich (2004), A mechanistic model for river incision into bedrock by saltating bed load, *Water Resources Research*, *40*(6), doi: 10.1029/2003wr002496.

Table S1. Summary of parameters for waterfall plunge-pool erosion experiments[a]

Experiment ID	Water discharge (l/s)	Waterfall drop height (m)	Grain diameter (mm)	Sediment flux (g/s)	Flow depth at brink (cm)	Upstream flume slope (deg)	Downstream flume slope (deg)	Total run time (hr)
Exp1	0.58	0.42	2.4	9	1.3	2	10	113
Exp2	0.58	0.53	7	9 - 45	1.3	2	14.5	51

[a] All experiments used a commercially available, closed-cell polyurethane foam bedrock simulant (http://www.precisionboard.com), with 0.32 MPa tensile strength. In both experiments the upstream flume is 9.6 cm wide, 2.06 m long, is tilted to ~2 degrees, and has a fixed bed of 2.4 mm sub-rounded quartz grains. The downstream flume is 24 cm wide and 80 cm long, and in which we fixed a polyurethane foam block (~18 cm wide by 27 cm long).

Table S2. Measurements from plunge-pool erosion experiments[a]

Experiment ID	Time elapsed (hr)	Pool top width (cm)	Pool top length (cm)	r_{pool_lip} (cm)	r_{pool_avg} (cm)	S_f	h_{BR} (cm)	h_{sed} (cm)	V_{pool} (cm^3)	E_{vert} (m/hr)	E_{lat} (m/hr)	E_{vert} / E_{lat}	$E_{fluvial}$ / E_{lat}	E_{vert} / $E_{fluvial}$	Q_s (g/s)
Exp1	0.00	0.0	0.0	0.0	0[b]	N/A	0.0	-	N/A	N/A	N/A	N/A	N/A	N/A	9 ± 1
Exp1	0.17	2.5	3.3	1.5	1.1[b]	N/A	2.1	-	N/A	0.13	0.064	2.0	0.006	342	9 ± 1
Exp1	0.33	3.6	4.2	2.0	1.4[b]	N/A	2.2	-	N/A	0.0066	0.022	0.3	0.017	17	9 ± 1
Exp1	0.50	3.8	4.5	2.1	1.5[b]	N/A	3.0	-	N/A	0.046	0.0055	8.4	0.069	121	9 ± 1
Exp1	0.83	4.0	4.7	2.2	1.6[b]	N/A	4.0	-	N/A	0.029	0.0022	13.2	0.17	76	9 ± 1
Exp1	1.17	4.1	5.1	2.3	1.7[b]	N/A	5.0	-	N/A	0.029	0.0028	10.4	0.14	76	9 ± 1
Exp1	1.67	4.2	5.6	2.5	1.8[b]	N/A	5.9	-	N/A	0.019	0.0022	8.6	0.17	50	9 ± 1
Exp1	2.17	4.5	5.8	2.6	1.9[b]	N/A	6.9	-	N/A	0.021	0.0018	11.7	0.21	55	9 ± 1
Exp1	3.00	4.6	6.0	2.7	1.9[b]	N/A	7.9	-	N/A	0.012	0.00066	18.2	0.58	32	9 ± 1
Exp1	3.78	4.9	6.4	2.8	2.0[b]	N/A	8.7	-	N/A	0.0097	0.0016	6.1	0.24	26	9 ± 1
Exp1	4.58	5.3	6.4	2.9	2.1[b]	N/A	9.6	-	N/A	0.012	0.00092	13.0	0.41	32	9 ± 1
Exp1	5.50	5.4	6.5	3.0	2.2[b]	N/A	10.6	-	N/A	0.011	0.0004	27.5	0.95	29	9 ± 1
Exp1	6.50	5.6	7.5	3.3	2.4[b]	N/A	11.4	-	N/A	0.0083	0.0022	3.8	0.17	22	9 ± 1
Exp1	8.07	6.0	7.5	3.4	2.4[b]	N/A	12.4	-	N/A	0.0062	0.00047	13.2	0.81	16	9 ± 1
Exp1	8.83	6.1	7.5	3.4	2.5[b]	N/A	12.5	-	N/A	0.0012	0.00024	5	1.6	3.2	9 ± 1
Exp1	10.00	6.1	7.5	3.4	2.4[b]	N/A	13.5	-	N/A	0.0084	0[c]	N/A	N/A	22	9 ± 1
Exp1	13.00	6.2	7.5	3.4	2.5[b]	N/A	14.4	-	N/A	0.0029	6.1×10^{-5}	47.5	6.2	7.6	9 ± 1
Exp1	16.00	6.4	7.5	3.5	2.5[b]	N/A	15.3	-	N/A	0.0029	0.00012	24.2	3.2	7.6	9 ± 1
Exp1	20.00	6.5	7.5	3.5	2.3	1.5	16.2	-	261	0.0025	0[c]	N/A	N/A	6.6	9 ± 1
Exp1	24.00	6.7	7.5	3.6	2.4	1.5	16.2	-	289	0	0.00029	0	1.3	0	9 ± 1
Exp1	30.00	6.8	7.6	3.6	2.4	1.5	17.0	-	316	0.0013	8.9×10^{-5}	14.6	4.3	3.4	9 ± 1
Exp1	33.00	7.0	7.6	3.7	2.5	1.5	17.1	-	333	0.0003	0.00019	1.6	2.0	0.79	9 ± 1
Exp1	41.00	7.4	8.3	3.9	2.8	1.4	18.0	17.8	446	0.0012	0.00039	3.1	1.0	3.2	9 ± 1
Exp1	49.00	7.9	9.7	4.4	3.1	1.4	18.7	18.5	563	0.00088	0.00036	2.4	1.1	2.3	9 ± 1
Exp1	56.00	8.2	10.0	4.6	3.3	1.4	18.8	18	659	0.0001	0.00035	0.3	1.1	0.26	9 ± 1
Exp1	63.00	8.6	10.0	4.7	3.3	1.4	19.6	16.6	689	0.0011	9.0×10^{-6}	122.2	42	2.9	9 ± 1
Exp1	66.00	8.9	10.0	4.7	3.4	1.4	19.6	16.6	716	0	0.00022	0	1.7	0	9 ± 1
Exp1	72.00	9.1	10.0	4.8	3.5	1.4	19.6	15.6	740	0	9.7×10^{-5}	0	3.9	0	9 ± 1
Exp1	80.00	9.3	10.1	4.9	3.5	1.4	19.6	15	760	0	5.7×10^{-5}	0	6.7	0	9 ± 1

Table S2. (continued)

Experiment ID	Time elapsed (hr)	Pool top width (cm)	Pool top length (cm)	r_{pool_lip} (cm)	r_{pool_avg} (cm)	S_f	h_{BR} (cm)	h_{sed} (cm)	V_{pool} (cm^3)	E_{vert} (m/hr)	E_{lat} (m/hr)	E_{vert} / E_{lat}	$E_{fluvial}$ / E_{lat}	E_{vert} / $E_{fluvial}$	Q_s (g/s)
Exp1	87.00	9.5	10.2	4.9	3.5	1.4	19.6	14.1	770	0	3.7×10^{-5}	0	10	0	9 ± 1
Exp1	97.00	9.8	10.4	5.1	3.7	1.4	19.6	14.1	819	0	0.00011	0	3.5	0	9 ± 1
Exp1	103.00	9.8	10.4	5.1	3.7	1.4	19.6	14.1	837	0	6.9×10^{-5}	0	5.5	0	9 ± 1
Exp1	113.03	9.8	10.4	5.1	3.8	1.3	19.6	14.1	880	0	9.4×10^{-5}	0	4.0	0	9 ± 1
Exp2	0.00	0	0	0	0	0	0	-	0	N/A	N/A	N/A	N/A	N/A	9 ± 1
Exp2	0.17	3.5	5	2.1	2.3	0.9	0.6	-	10	0.036	0.14	0.3	0.026	48	9 ± 1
Exp2	0.50	4.5	6	2.6	2.1	1.2	1.8	-	26	0.036	0[c]	N/A	N/A	48	9 ± 1
Exp2	1.00	5	6.7	2.9	2.2	1.4	3.3	-	48	0.03	0.0015	20.0	2.5	40	9 ± 1
Exp2	1.50	5.8	7	3.2	2.3	1.4	4.7	-	76	0.028	0.0023	12.2	1.6	37	9 ± 1
Exp2	2.00	6	7	3.3	2.4	1.4	5.3	-	92	0.012	0.0016	7.5	2.3	16	9 ± 1
Exp2	3.00	6	7	3.3	2.5	1.3	7	-	136	0.017	0.0014	12.1	2.6	23	9 ± 1
Exp2	4.00	6.5	7	3.4	2.6	1.3	7.7	-	166	0.007	0.0013	5.4	2.8	9.3	9 ± 1
Exp2	5.25	6.5	7.5	3.5	2.8	1.3	8.4	-	202	0.0056	0.0012	4.7	3.1	7.5	9 ± 1
Exp2	7.25	7	7.5	3.6	2.8	1.3	9.7	-	242	0.0065	0.00026	25.0	14	8.7	9 ± 1
Exp2	10.75	7.5	8	3.9	3.0	1.3	11	-	314	0.0037	0.00056	6.6	6.6	4.9	9 ± 1
Exp2	14.77	8.5	9.5	4.5	3.0	1.5	14.3	-	412	0.0082	3.5×10^{-5}	234.3	21	11	9 ± 1
Exp2	15.50	8.5	9.5	4.5	3.4	1.3	14.3	9.4	508	0	0.0046	0	0.80	0	45 ± 6
Exp2	16.67	11	10	5.3	3.9	1.3	14.3	5.3	682	0	0.0046	0	0.80	0	45 ± 6
Exp2	17.17	10.5	11	5.4	3.9	1.4	14.3	N/A	670	0	0	0	N/A	0	45 ± 6
Exp2	17.68	11	11	5.5	4.0	1.4	14.3	N/A	708	0	0.0021	0	1.8	0	45 ± 6
Exp2	18.80	11	11.5	5.6	4.1	1.4	14.3	5.6	750	0	0.001	0	3.7	0	45 ± 6
Exp2	19.92	11	12	5.8	4.1	1.4	14.3	N/A	760	0	0.00024	0	15	0	45 ± 6
Exp2	22.10	11.5	12	5.9	4.2	1.4	14.3	4.9	790	0	0.00037	0	10	0	45 ± 6
Exp2	24.37	11.5	12	5.9	4.4	1.3	14.3	5.4	858	0	0.00078	0	4.7	0	45 ± 6
Exp2	29.03	12	12	6.0	4.5	1.3	14.3	4.7	900	0	0.00023	0	16	0	45 ± 6
Exp2	33.65	12	13	6.3	4.6	1.4	14.3	4.9	946	0	0.00025	0	15	0	45 ± 6
Exp2	36.88	13	13	6.5	4.6	1.4	14.3	4.7	968	0	0.00016	0	23	0	45 ± 6
Exp2	43.83	12	13	6.3	4.8	1.3	14.3	4.1	1032	0	0.00022	0	17	0	45 ± 6
Exp2	45.65	13	12.5	6.4	4.8	1.3	14.3	4	1052	0	0.00025	0	15	0	45 ± 6
Exp2	51.00	12.5	13.5	6.5	5.0	1.3	14.3	4.4	1102	0	0.00021	0	18	0	45 ± 6

Table S2. (continued)

[a] Pool top width and pool top length refer to the cross-stream width and along-stream length measured at the top of the plunge pool (i.e., at $z = z_{lip}$). Markings of ' - ' in h_{sed} column denotes no sediment was deposited such that $h_{sed} = h_{BR}$; ' N/A ' indicates no measurements of depth to sediment were taken for the given experimental time. ' N/A ' in plunge-pool vertical and lateral erosion rate columns (E_{vert} and E_{lat}, respectively) indicate no measurement can be made for the initial pool geomety. Error on Q_s measurements reflect the the total range of measured sediment fluxes. Other variables: $E_{fluvial}$ - fluvial erosion rate upstream of waterfall predicted by *Lamb et al.* [2008], r_{pool_lip} - average plunge-pool radius at $z = z_{lip}$ from measurements of pool top width and length, S_f - shape factor ($S_f = r_{pool\_lip}/r_{pool\_avg}$), h_{BR} - plunge pool depth to bedrock, V_{pool} - plunge-pool volume, Q_s - sediment supply.

[b] r_{pool_avg} values back-calculated assuming $S_f = 1.38$.

[c] Measurements of plunge-pool lateral erosion that were discarded because differences in r_{pool_avg} result in non-physical negative erosion rates.