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1 **Knickpoint evolution in a supraglacial stream**

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Knickpoint evolution in a supraglacial stream

Despite numerous studies of knickpoints in bedrock and alluvial channels, no detailed description of knickpoint change on ice has been reported to date. This paper presents the first investigation of knickpoint evolution within a supraglacial stream. Repeat longitudinal profile surveys of a knickpoint on Vadrec del Forno, Switzerland reveal a step height increase of 115 mm and upstream migration of 0.26 m over three days during the 2017 ablation season. Rates and magnitudes of erosion vary spatially across the knickpoint in relation to differing discharge regimes. At high discharges ($\sim 0.013 \text{ m}^3 \text{ s}^{-1}$), erosion is focused at the step base; at low discharges ($\sim 0.003 \text{ m}^3 \text{ s}^{-1}$), erosion is focused on the reach upstream of the knickpoint, at the step lip and the step-riser face. This results in replacement of knickpoint morphology, driven by frictional thermal erosion and hydraulic action. Pool formation further influences step morphology, inducing secondary circulation and increased melt at the base of the step-riser, causing steepening. Results highlight the complexities of water flow over knickpoints, demonstrating that the stream power law does not accurately characterise changing knickpoint morphology or predict retreat rates. Although morphological similarities have been reported between supraglacial and bedrock/alluvial channels, knickpoints in non-ice-walled channels will not necessarily respond to discharge similarly to those in ice due to the different erosion processes involved.

Keywords: knickpoint; step; supraglacial; evolution; hydrodynamics; discharge

1. Introduction

Knickpoints are commonly observed features in the longitudinal profile of river channel systems. The term 'knickpoint' refers to channel reaches that exhibit a marked change in bed slope, and is used herein to refer to an individual step, comprising the local point of abrupt gradient change (the step lip) and the downstream channel-spanning steep segment (the 'step-riser'; Chartrand and Whiting 2000). Such changes in slope have been attributed to alterations in sediment supply (Brush and Wolman 1960) and base-level change resulting from eustatic, geological or tectonic perturbations (Haviv et al. 2010), with their presence increasing hydraulic resistance and dissipating energy (Leopold et al. 1960; Abrahams et al. 1995; Curran and Wohl 2003; Wilcox et al. 2011). Most knickpoints undergo upstream migration, governing

56 wider landscape changes through alteration of hillslope base level (Tucker and Whipple 2002;
57 Bigi et al. 2006; Whittaker and Boulton 2012). Three types of knickpoint retreat have been
58 identified by Gardner (1983) using flume experiments in cohesive, homogenous substrates: (i)
59 *parallel retreat* with retention of the original step morphology; (ii) *replacement* with alteration
60 of the original step morphology arising from erosion above the knickpoint lip and over the step
61 face; and (iii) *backward rotation* of the step towards the general channel slope, causing the
62 step-riser inclination to decrease. As adjustments in bedrock/alluvial channels typically occur
63 over decadal-to-millennial timescales, direct observations of upstream knickpoint retreat are
64 limited. Attempts have been made to predict knickpoint retreat rates in some landscapes using
65 the stream power incision model (Bishop et al. 2005; Crosby and Whipple 2006; Berlin and
66 Anderson 2007; Lague 2014). This model relates knickpoint retreat rate to catchment drainage
67 size, which acts as a proxy for discharge (Whipple and Tucker 1999; Crosby and Whipple
68 2006), assuming a constant flow regime. The stream power model, however, typically fails to
69 predict observations of knickpoint retreat due to poor characterisation of changing flow
70 regimes over a step (Dust and Wohl 2012), and the lack of consideration of sediment transport
71 processes (Jansen et al. 2011), the role of bedrock structure (Mackey et al. 2014), plunge-pool
72 dynamics (Scheingross and Lamb 2017) and the self-regulation of channel geometry (Baynes
73 et al. 2018).

74 Within bedrock channels, there is a lack of empirical data describing actively migrating
75 knickpoints (Cook et al. 2013), due to the typically slow retreat rates and difficulties in
76 identifying and isolating controlling intrinsic and extrinsic factors (Kephart 2013). Knickpoint
77 evolution mechanisms, therefore, remain poorly understood despite laboratory and flume
78 studies investigating drivers of change (e.g. Bennet et al. 2000; Grimaud et al. 2015; Lamb et
79 al. 2015; Baynes et al. 2018). However, knickpoint features have also been described in
80 supraglacial (e.g. Knighton 1981, 1985; Carver et al. 1994; St Germain and Moorman 2016)

81 and englacial channels (e.g. Pulina 1984; Holmlund 1988; Griselin 1992; Vatne 2001; Piccini
82 et al. 2002; Vatne and Refsnes 2003; Vatne and Irvine-Fynn 2016), where their formation is
83 considered to be related to intrinsic flow dynamics, in contrast to extrinsic factors commonly
84 cited for bedrock/alluvial systems (Phillips et al. 2010; Yokokawa et al. 2016). This gives rise
85 to a unique field environment that allows for isolation of hydrodynamic variables, since
86 ice-walled streams are typically devoid of sediment load (Leopold et al. 1960; Kostrzewski and
87 Zwoliński 1995; Karlstrom et al. 2013), and channel boundaries are close to the melting point.
88 These factors enable assessment of knickpoint evolution over shorter (hourly-to-diurnal)
89 timescales. Supraglacial streams are often considered to be analogous to bedrock channels, due
90 to their similarities in morphology and adjustment (Ewing 1970; Marston 1983; Knighton
91 1985; Karlstrom et al. 2013) and, thus, supraglacial investigations have been used to gain a
92 better empirical understanding of channel formation and evolution (Ferguson 1973).
93 Constraining supraglacial knickpoint evolution also has implications for understanding
94 englacial drainage systems, at least where conduits exist at atmospheric pressure, owing to
95 knickpoints forming a major component of vertical channel incision (Gulley et al. 2009; Vatne
96 and Irvine-Fynn 2016) and, thereby, underpinning meltwater transfer to a glacier's ice-bed
97 interface.

98 Currently, the potential of the supraglacial environment for examining knickpoint
99 formation and evolution processes has not yet been fulfilled. The majority of field-based
100 research on supraglacial streams was published several decades ago (e.g. Ewing 1970;
101 Pinchack 1972; Dozier 1974; Hambrey 1977), and focused on hydraulic geometry (e.g. Park
102 1981; Marston 1983; Kostrzewski and Zwoliński 1995; Brykała 1999) or meandering (e.g.
103 Knighton 1972; Ferguson 1973). Although the presence of knickpoints has been reported
104 (Dozier 1974), the only study to address this morphology in any detail examined its role in
105 inducing pulsating flow (St Germain and Moorman 2016). Despite a recent resurgence of

106 interest in supraglacial drainage, studies have predominantly used remotely sensed data (e.g.
107 Joughin et al. 2013; Lampkin and VanderBerg 2014; Rippin et al. 2015; Smith et al. 2015;
108 Karlstrom and Yang 2016; Yang et al. 2016) and, thus, do not account for a process-level
109 understanding of local hydraulics. Therefore, there is a need to elucidate the processes
110 responsible for morphological drainage evolution through field-based research (Gleason et al.
111 2016), and to advance existing numerical models (e.g. Karlstrom et al. 2013; Mantelli et al.
112 2015).

113 Here, we present repeat geometric measurements of a knickpoint within a supraglacial
114 stream on Vadrec del Forno, Switzerland, to characterise its morphological evolution in
115 response to hydrodynamic forcing. Measurement took place over three days during the 2017
116 ablation season. The results provide the first description and quantification of changing
117 knickpoint morphology on ice, and yield insight into the varying spatial focus of hydrological
118 erosion at differing discharges.

119 **2. Field site**

120 Vadrec del Forno is a 4.5 km long, temperate, Alpine valley glacier located in the Bregaglia
121 Range of Graubünden, southeast Switzerland (46°17'N, 9°40'E; Figure 1A). The glacier flows
122 north from the Italian border, comprising two accumulation basins that form a shallow gradient,
123 ~ 500 m wide tongue. The glacier elevation extended from ~ 2250 to 3200 m.a.s.l in 2016,
124 covering an area of 5 km². Across the ablation area, the predominant structural glaciological
125 feature is longitudinal foliation (Jennings et al. 2014), exerting a strong control over surface
126 meltwater drainage (cf. Hambrey 1977). This gives rise to relatively straight rills and streams
127 flowing parallel to the glacier flow direction, providing an excellent site for examining
128 hydrodynamics in straight channels unaffected by meander-induced secondary water
129 circulation.

130 **2.1 *Channel reach and knickpoint characteristics***

131 A straight 4.5 m long reach of a perennial stream containing a single transverse knickpoint was
132 selected for investigation on the west side of the ablation zone, ~ 0.85 km from the terminus
133 (Figure 1). Glaciologically, perennial streams are channels that persist and are repeatedly
134 reoccupied over inter-annual timescales, in contrast to annual streams that form and melt out
135 each year (Ewing 1970). Perennial streams, especially on non-temperate glaciers, can seed the
136 formation of englacial channels existing at atmospheric pressure (Gulley et al. 2009), therefore,
137 providing a better analogue for englacial drainage than annual streams. Here, the selected reach
138 was chosen for the presence of a knickpoint in isolation, with the absence of any distinct
139 elevation changes that may have influenced knickpoint evolution. This stream was a
140 distributary, bifurcating from a main channel 9 m above the reach, and appeared to exploit the
141 downglacier oriented longitudinal foliation. The reach had a low gradient (7°) and sinuosity
142 (1.005), and ranged in width from 0.14 to 0.66 m. Despite evidence of several transverse clear
143 ice bands cutting across the channel upstream of the knickpoint, there was negligible transverse
144 structural variability at, or downstream of the knickpoint, suggestive of a homogenous substrate
145 underlying the step itself, allowing patterns and rates of change to be attributed to
146 hydrodynamic variables. Although clastic debris was visible embedded in the channel bed
147 (Figure 1B), the stream flow was devoid of sediment bed load, with little to no transportation
148 of ice crystals over the measurement period.

149 The knickpoint was classified as a ‘break-in-gradient’ knickpoint type (after Haviv et
150 al. 2010), characterised by a gentle step lip and riser face with a channel-bed-supported sloping
151 jet (Figure 1C). Over the measurement period, this knickpoint accounted for between 15 and
152 32 % of the 0.68 m decrease in elevation along the longitudinal profile of the stream reach.
153 Initially, no pooling of water at the step base was observed; instead, a reverse bed slope was

154 recorded downstream of the knickpoint with detachment of flow from the channel bed and
155 water aeration at the downstream end of this reverse slope.

156 [Figure 1 near here]

157 **3. Methods**

158 Data was collected in the early ablation season, between, and inclusive of, the 6th and 9th July
159 2017. This short measurement period arose from considerable water flow reduction over the
160 knickpoint on the 9th July, as a result of upstream flow capture. Knickpoint and channel
161 cross-section measurements were completed between 08:00 and 12:00 before peak diurnal
162 discharge, with the exception of the 6th July when measurements were taken between 14:00
163 and 15:30 and excluded cross-section geometry. Using the assumption that peak discharge has
164 the greatest impact on changing channel morphology (Marston 1983; Carver et al. 1994),
165 geometric measurements are considered to reflect adjustments resulting from the previous
166 day's hydrodynamic forcing. Adjustment was assessed between each day's measurements,
167 giving three full days of change monitoring.

168 **3.1 *Knickpoint and channel geometry***

169 To measure knickpoint geometry, the majority of water flow over the step was temporarily
170 diverted to the main channel upstream of the reach, using sealed water-filled bags stacked at
171 the distributary diffluence. Water flow was diverted for ~ 20 minutes each day between 08:50
172 and 09:30. Once achieved, the horizontal distance of the step lip from a fixed reference point
173 was measured to determine upstream knickpoint recession. Daily central longitudinal profiles
174 of the step-riser were recorded using a contour gauge shaping tool, similar to techniques used
175 for quantifying surface roughness (McCarroll and Nesje 1996). The gauge maintains the shape
176 of a surface once moulded to it, allowing for replication with a quantified accuracy of 11 mm.
177 Careful gauge positioning onto laminated millimetre graph paper enabled tracing of the

178 lowermost edge using a whiteboard marker pen, with nadir photography using a 14-mpx
 179 Fujifilm Finepix JV200 digital camera allowing for extraction of profile coordinates. These
 180 profile coordinates were digitally plotted at centimetre resolution, using a Bezier spline
 181 interpolation to represent the step-riser (accurate to 5 mm).

182 Channel cross-section geometry was measured upstream and downstream of the
 183 knickpoint lip, to quantify vertical incision (Figure 1). Measurements were conducted from
 184 fixed reference points, established on the east stream bank. From these points, vertical depth
 185 measurements to the nearest 10 mm were recorded at 0.1 m intervals across the channel,
 186 relative to a taut tape measure anchored on the opposite bank. Vertical depth measurements
 187 and the 0.1 m measurement intervals were trigonometrically corrected to a horizontal plane,
 188 using the tape angle measured with a compass clinometer to $\pm 1^\circ$, with depth adjustment to the
 189 daily glacier surface elevation. The inevitable tape sag led to an uncertainty (C_{catenary}) that
 190 was quantified following Uren and Price (2005):

$$191 \quad C_{\text{catenary}} = \frac{w^2 D^3 (\cos 2\theta)}{24T^2}$$

192 (Equation 1)

193 where w is weight per unit length of tape, D is tape length, θ is the vertical angle between
 194 end-points and T is applied tension. Assuming modest tension of 10 N, (following Irvine-Fynn
 195 et al. (2014a)), for a tape length of 1.8 m and weight per unit length of 0.18 N m^{-1} , the maximum
 196 uncertainty was 1 mm. Within the horizontal plane, inevitable positional uncertainty in repeat
 197 surveys arises from ablation at the fixed reference points; however, this error is acceptable here,
 198 as cross-sections are not directly compared in absolute space.

199 Bank full stage is unlikely within perennial supraglacial streams, as their existence
 200 depends on incision outpacing ablation, at least initially (Knighton 1981; Marston 1983).

201 Therefore, flow geometry dimensions of the ‘active channel’ (width, mean channel depth
 202 below the ice surface) were derived using water height at the channel thalweg (stage) at 10:00.
 203 This ‘active channel’ denotes the area that adjusts in relation to actively flowing water
 204 (Osterkamp and Hedman 1977), providing the best approximation of channel dimensions when
 205 the channel is most stable prior to peak discharge. Daily incision rates were determined using
 206 the difference between mean cross-section depths.

207 3.2 *Streamflow dynamics*

208 Stream discharge was measured at hourly intervals between 09:30 and 13:30. Following
 209 Hudson and Fraser (2002), discharge (Q) was estimated using salt dilution gauging:

210

$$211 \quad Q = \frac{k M}{(T_2 - T_1) \times (EC - EC_{bkgd})}$$

212

(Equation 2)

213 where M is mass of salt added in grams (here, 10 g pre-dissolved salt injected 11 m upstream
 214 of the detection point); $T_2 - T_1$ is tracer passage duration in seconds; $EC - EC_{bkgd}$ is mean
 215 electrical conductivity during the tracer passage, as measured with a REED SD-4307
 216 conductivity meter (0.1 μ S resolution, accurate to ± 2 % (REED 2015)); and k is the
 217 temperature-corrected proportionality constant, calculated as 1.5909 for 0 °C. Over the
 218 observed temperature range of 0.01 – 0.3 °C, variation in k was less than 1 % and negligible
 219 for discharge calculations. Measurements characterised the rising limb and beginning of the
 220 falling limb of diurnal discharge and, thus, captured daily peak discharge between 11:30 and
 221 12:30. An additional discharge reading was taken on the 6th July at 15:00, while it was not
 222 possible to derive discharge on the 9th July, as flow was too low to measure.

223 Flow velocity along the reach was calculated from the salt tracer travel time over the
224 thalweg distance and, following Knighton (1998), used with measurements of stage and flow
225 width to calculate Froude and Reynolds numbers (Fr and Re , respectively). Daily maximum
226 stream power per unit length over the knickpoint was estimated using the mean step gradient
227 and peak discharge. Detailed observations were also made regarding the nature of water flow
228 over the knickpoint, including defining the contact between the water and step-riser and
229 evidence of hydraulic jumps, backpooling and splashing of water in relation to the channel
230 morphology.

231 **3.3 Meteorological data**

232 In the absence of meteorological data at the glacier surface, hourly air temperature data over
233 the measurement period were obtained from the nearest MeteoSwiss automatic weather station,
234 located in Vicosoprano, 7 km from Vadrec del Forno. To interpolate these data to the local air
235 temperature at the study site, a relationship describing the lapse rate between Vicosoprano and
236 Vadrec del Forno was used, based on data from a HOBOware® weather station that had been
237 installed on the ice during July 2016. The calculated lapse rate ($r^2 = 0.72$, $p \leq 0.01$)
238 was $-0.009 \text{ }^\circ\text{C m}^{-1}$, giving a difference of $10.85 \text{ }^\circ\text{C}$ between the sites that was used to adjust the
239 2017 air temperature data. Hourly potential incident radiation at the glacier surface was
240 calculated following Irvine-Fynn et al. (2014b).

241 **4. Results**

242 **4.1 Knickpoint evolution**

243 The step lip migrated upstream by 0.26 m over three days from its initial 6th July position
244 (Figure 2), with the step-riser face steepening by 17° . Knickpoint recession rates were variable,
245 increasing from 0.01 m day^{-1} (6th - 7th July) to 0.08 m day^{-1} (7th - 8th July), with the greatest

246 recession of 0.17 m day^{-1} occurring between the 8th and 9th July, coincident with the greatest
247 change in step gradient (Table 1).

248 Step height increased by 115 mm with the greatest change of 88 mm occurring between
249 the 7th and 8th July. Between the 8th and 9th July, step height decreased by 18 mm. The reverse
250 bed slope at the step base was replaced with the formation of a pool towards midday on the 8th
251 July, with evidence of a hydraulic jump and backpooling.

252 [Figure 2 near here]

253 [Table 1 near here]

254 **4.2 Cross-section evolution**

255 Measured cross-sections (Figure 3) show that above the knickpoint, the channel was generally
256 wider and shallower than below the knickpoint. Over the measurement period, mean channel
257 depth above the knickpoint was 0.40 m, and 0.52 m below the knickpoint. The nature and rates
258 of morphological change were variable over both space and time, with disparity between the
259 cross-sections. Above the knickpoint, the channel cross-section was initially approximately
260 trapezoidal (Figure 3A; 7th July). This cross-section incised by 27 mm, developing a more
261 rounded, quasi-elliptical morphology (Figure 3A; 8th July), which further incised by 83 mm
262 and narrowed by 160 mm to form a more triangular morphology (Figure 3A; 9th July). Below
263 the knickpoint (Figure 3B), the channel maintained an approximately triangular cross-section,
264 with a stable width (Table 1) and incision of 73 mm over the first two days (6th - 7th, 7th - 8th
265 July). This profile subsequently widened by 80 mm and incised by 20 mm (8th - 9th July).

266 The channel upstream of the knickpoint incised 18 mm more than that below, with the
267 majority of vertical incision occurring between the 8th and 9th July above the step, and between
268 the 7th and 8th July below the step (Table 1; cross-section mean depths). However, the greatest
269 change in width was recorded between the 8th and 9th July for both cross-sections. As a result,

270 deepening and narrowing of the upstream cross-section coincided with a decrease in incision
271 and widening of the downstream cross-section.

272 [Figure 3 near here]

273 **4.3 Streamflow dynamics**

274 Over the measurement period, discharge generally decreased (Table 1), with peak discharge on
275 the 8th July being an order of magnitude lower than on previous days, and water flow on the 9th
276 July being too low to measure. Water temperatures correlated positively with discharge
277 ($r = 0.83$, $n = 11$, $p \leq 0.01$). Expectedly, discharge also correlated positively with velocity
278 ($r = 0.82$, $n = 11$, $p \leq 0.01$) and stream power ($r = 0.99$, $n = 11$, $p < 0.01$) and, thus, stream
279 power was significantly lower on the 8th July than on previous days ($p \leq 0.01$). The reduced
280 discharge (8th and 9th July) was the result of upstream water capture, due to the main channel
281 incising at a faster rate than the studied distributary reach. However, linear regressions between
282 discharge and stream power with knickpoint retreat were not significant ($p > 0.05$).

283 Water flow over the knickpoint was continuously channel-bed-supported, with only
284 occasional observations of decoupled flow for a few seconds at a time. Water flow above and
285 below the knickpoint was mainly subcritical ($Fr < 1$) and was predominantly turbulent on the
286 6th and 7th July (high Re), with transitional flow on the 8th July (Table 1). As water neared the
287 step base, lateral flow interaction with the channel banks resulted in water being diverted
288 upwards and back towards the channel centre, causing flow convergence here and at the
289 beginning of the reverse bed slope. A submerged impinging jet was observed at the step base.
290 Downstream of the knickpoint, flow detachment from the channel bed occurred as the reverse
291 bed slope deflected water upward, causing visible aeration and spraying of the channel banks.
292 Immediately prior to midday on the 8th July, the effects of the reverse bed slope were less
293 obvious and a hydraulic jump was present at the step base, with evidence of backpooling.

294 5. Discussion

295 5.1 *Hydrodynamic forcing*

296 In the absence of an appreciable bed load, it is reasonable to assume that erosive forces are
297 predominantly hydrodynamic, with hydraulic action and melting driving supraglacial channel
298 change (Knighton 1981; Marston 1983; Kostrzewski and Zwoliński 1995; Isenko et al. 2005).
299 However, the results demonstrate that increased retreat rate was not associated with rising
300 discharge and stream power per unit length. This supports suggestions that the relationship
301 between discharge and knickpoint retreat rate is oversimplified (Baynes et al. 2018). Instead,
302 the results here show that greater knickpoint retreat occurred at lower discharges. The changing
303 step morphology indicates non-uniformity of erosion across the step, demonstrating the
304 complex interaction between discharge regime and knickpoint evolution (see Section 5.2).
305 Additionally, these data further demonstrate that the simplistic stream power incision model is
306 unlikely to adequately characterise retreating knickpoints (Howard et al. 1994; Scheingross
307 and Lamb 2017). This supports the work of St Germain and Moorman (2016), which
308 demonstrated that supraglacial step-pool morphologies do not necessarily form at high
309 discharge, contrary to assumptions by Vatne and Refsnes (2003) who regard high discharge as
310 a necessary factor for step formation in ice. Furthermore, this challenges the assumption that
311 the greatest channel change occurs at peak discharges in ice-walled channels (Marston 1983;
312 Carver et al. 1994), highlighting the need for measurements at increased temporal resolution to
313 better constrain the timing and rates of evolution.

314 As erosion reflects the balance between driving and resisting forces (Wohl 1998;
315 Hayakawa and Matsukura 2003), the role of ice substrate resistance in controlling knickpoint
316 migration rates must also be considered. The channel substrate comprised clear and bubbly ice
317 types, the former of which experiences preferential water erosion (Ewing 1970; Hambrey
318 1977), as exemplified by the undulating bed form troughs concordant with clear ice structures

319 upstream of the knickpoint (Figure 1B). The observed alternation in ice types through these
320 bed forms, had they extended downstream, could have explained the relative stability of the
321 step lip between the 6th and 7th July, with the subsequent increase in retreat rate being the result
322 of headward migration through clear ice to less resistant, bubbly ice upstream. However, the
323 absence of such structural features proximate to the knickpoint indicated a homogenous
324 substrate here, reflected by knickpoint migration via replacement. This implies that knickpoint
325 evolution was not structurally controlled during the measurement period, supporting the
326 argument that hydrodynamic forcing plays the dominant role in governing supraglacial step
327 evolution.

328 Within an ice-walled channel, thermal erosion is an additional contributing driver of
329 knickpoint retreat. Such heat energy transfer arises from several sources: sensible air
330 temperature and solar radiation, friction at the water-ice interface and turbulence-induced
331 friction within the water (Ewing 1970; Ferguson 1973; Marston 1983). Additional erosion can
332 arise from direct channel bed ablation through shallow water columns (Holmes 1955; Dozier
333 1974). Although direct ablation may have been possible in this study, given the maximum
334 recorded water depth of 0.1 m, this is not supported by the insignificant linear regression
335 between daily mean potential incident radiation and incision rates ($r = 0.027$, $p > 0.05$). Using
336 the 'Enter method', a multiple linear regression ($R^2 = 0.62$) demonstrates that discharge was
337 the only significant predictor of water temperature ($r = 0.75$, $p < 0.05$). This indicates that
338 frictional heat generated from viscous flow dissipation is the main component of thermal
339 erosion in this study, supporting research by Ferguson (1973), Parker (1975) and Marston
340 (1983) who estimated that this can account for 50 – 75 % of incision. The overall slope of the
341 stream reach here was 7°, with that of the knickpoint face being a minimum of 18°. As Pinchack
342 (1972) reported a requisite channel gradient of 11° to induce melt in a slightly wider stream

343 than reported here, this indicates that frictional heat potentially plays more of a role in erosion
344 locally, thereby contributing to knickpoint evolution.

345 **5.2 *Hydrological controls on supraglacial knickpoint evolution***

346 The notion that knickpoint retreat rate is primarily controlled by discharge (Seidl and Dietrich
347 1992; Howard et al. 1994; Bishop et al. 2005) is challenged by the supraglacial stream data
348 presented here. The greatest step retreat, gradient change and rate of upstream incision
349 (Cross-section A) were associated with low discharges, and the greatest increase in step height
350 and rate of downstream incision (Cross-section B) were associated with high discharges. To
351 explain these spatial and temporal variations, we propose a conceptual model of
352 process-morphology linkages to identify the hydrological controls on supraglacial knickpoint
353 evolution, whereby varying discharge regimes control spatial zones of erosion over the
354 step-riser and lead to pool formation (Figure 4). Three morphologically distinct zones of
355 erosion are identified, with differential rates and magnitudes of change at the step lip, riser face
356 and step base giving rise to knickpoint evolution via replacement of step morphology (Gardner
357 1983).

358 At turbulent, high discharges, (here, 6th and 7th July), vertical incision is focused at the
359 step base. The reduced boundary resistance at high flows means that the impinging jet retains
360 energy over the step lip and face (Marston 1983; Wilcox and Wohl 2006; Comiti et al. 2009),
361 therefore, imparting greater hydraulic force to the step base. However, as the channel bed and
362 step face were not smoothly polished, channel roughness elements were limited to microscale
363 features, indicating that reduced boundary resistance is likely to have a negligible impact on
364 energy retention. At the step base, higher water temperatures associated with turbulence are
365 more likely to contribute to vertical incision, aided by the high degree of interaction between
366 the water jet and the channel bed. Incision rates at the step base exceed those at the lip, leading

367 to an increase in step height. Consequently, the knickpoint experiences considerable
368 steepening, which contradicts the more often observed backward rotation of the knickpoint in
369 homogenous bedrock and alluvial settings (Holland and Pickup 1976; Gardner 1983; Stein and
370 Julien 1993; Frankel et al. 2007).

371 [Figure 4 near here]

372 At low discharges with transitional flow, (here, 8th and 9th July), erosion is focused on
373 the reach immediately upstream of the knickpoint, the step lip and the step-riser face. At low
374 water depths, the microscale channel roughness has a greater influence on frictional energy
375 dissipation, increasing boundary resistance and resulting in accelerated melting of the bed
376 upstream of the step, and at the step lip where shear stress is highest (Gardner 1983). The lower
377 velocities associated with lower discharges act to increase the energy transfer time and, thus,
378 enhance melt at a given point (Thorsness and Hanratty 1979), with low turbulence inhibiting
379 energy dissipation within the flow itself. This occurs mainly above the step lip, where water
380 flow is slower than across the step-riser as a result of the gentler slope. Additionally, enhanced
381 erosion above the step lip is attributed to over-steepening (drawdown) of the water surface
382 profile as flow starts to accelerate over the increasing gradient (Gardner 1983; Haviv et al.
383 2006; Berlin and Anderson 2009). This enhanced energy transfer reduces the stream power of
384 the bed-supported jet (Chin 2003), resulting in less available energy to hydraulically erode the
385 step base and causing a decrease in step height.

386 The finding that low discharge has a dominant control on knickpoint migration
387 necessitates consideration of the potential methodological impact of temporary stream
388 diversion during low flows. The magnitude of knickpoint and channel adjustment was in the
389 order of centimetres to decimetres over 24 hours, with peak diurnal discharge only exceeding
390 $0.009 \text{ m}^3 \text{ s}^{-1}$ for a maximum of 3.5 hours over the measurement period. Low flow conditions
391 of $< 0.007 \text{ m}^3 \text{ s}^{-1}$ were recorded throughout the rest of the day, with flow diversion for 20

392 minutes accounting for < 2 % of this time, assuming continuous 24 hour flow. Consequently,
393 we suggest that flow diversion over such a short period had negligible impact on knickpoint
394 evolution; however, a portion of low flow channel adjustment may have been overlooked,
395 albeit small, as a result of this diversion. The estimated maximum discharge diverted to the
396 main channel ($\sim 0.005 \text{ m}^3 \text{ s}^{-1}$) is not expected to have resulted in a marked change in incision
397 rate or eventual channel capture over the timescales involved.

398 *5.2.1 Hydrological controls on pool development*

399 The lack of ice structural control over observed knickpoint evolution suggests that downstream
400 pool development on the 8th July was primarily controlled by step morphology adjustment in
401 response to discharge variations. Using the conceptual model described in Figure 4, an
402 explanation for pool formation can be proposed. At high discharges, localised erosion at the
403 step base leads to over-deepening. Water pools in this depression at low discharges, with the
404 reverse bed slope acting to further impede downstream flow. As pool development starts to
405 reduce the effect of the impinging jet on the channel bed (Wu and Rajaratnam 1998;
406 Zimmermann and Church 2001; Carling et al. 2005), the increased tailwater depth inhibits
407 vertical incision and results in a predominance of lateral erosion. In our study, this is
408 demonstrated by the coincident decrease in channel depth and increase in width below the
409 knickpoint between the 8th and 9th July. The pooled water creates a persistent contact with the
410 ice forming the lower section of the step-riser, causing erosion here (Figure 4), and resulting in
411 continued and accelerated steepening of the face at low discharge. Turbulent secondary
412 circulation back towards the step face and the formation of a hydraulic jump close to the step
413 base enhances this erosional zone. Pool development herein appears to conform
414 morphologically to the conceptual model proposed by Scheingross et al. (2017) to describe
415 abrasive plunge-pool evolution in homogenous bedrock. This suggests that in a homogenous

416 ice substrate and, even in the absence of sediment load, knickpoint retreat may be driven by
417 vertical drilling, a knickpoint migration process described by Howard et al. (1994) and Lamb
418 et al. (2007). This contrasts with classic waterfall erosion models that indicate knickpoint
419 migration owing to overlying caprock failure, following removal of an underlying substrate
420 (e.g. Gilbert 1890; Holland and Pickup 1976; Frankel et al. 2007). However, the lack of
421 undercutting herein may be due to the reduced discharge following pool formation, with
422 accelerated erosion of the upstream pool wall only being plausible in the case of continued
423 flow.

424 Although substrate characteristics influence the shape and recession rate of knickpoints
425 (Gardner 1983; Larue 2008; Phillips and Desloges 2014), our proposed model builds on the
426 concept that a mutual interaction exists between the shape of the heat transfer surface and the
427 variation in rates of heat transfer, the latter of which is determined by flow characteristics
428 (Gilpin et al. 1980). This advances the work of Vatne and Irvine-Fynn (2016), whose insights
429 from englacial knickpoint morphology indicated that step shape controls the type of water jet
430 and, thus, the location of energy expenditure and heat transfer across the knickpoint face. Our
431 model demonstrates that differing discharge regimes govern the location of erosion, a concept
432 that can be extended to knickpoint evolution in bedrock (Carling et al. 2005) and cohesive
433 sediment (Bennet et al. 2000), where varying degrees of surface erosion in relation to
434 hydrological forcing have also been recorded. However, the difference in erosive mechanisms
435 between supraglacial and bedrock/alluvial channels indicates that this model is not applicable
436 within the latter for determining the ways in which knickpoint morphology will adjust in
437 response to discharge alterations. Contrary to some previous assertions (e.g. Ewing 1970;
438 Marston 1983; Knighton 1985), this shows that the systems are not analogous to one another,
439 warranting further investigation into the differences between each environment and the
440 processes causing the formation and adjustment of similar channel morphologies.

441 5.3 *Interactions between morphology and flow variability*

442 The zones of erosion outlined in Section 5.2 govern step and channel shape, and demonstrate
443 the effect of flow dynamics on knickpoint morphology. However, channel morphology also
444 controls flow dynamics over a step (e.g. Knighton 1981; Kostrzewski and Zwoliński 1995;
445 Milzow et al. 2006), determining these erosional zones. Here, this is exemplified by channel
446 narrowing over the knickpoint, confining water flow over the step-riser and resulting in water
447 overturning towards the channel centre with consequent flow convergence. This, in turn, gives
448 rise to the narrow cross-section at the step base, with water concentration driving vertical
449 incision. This feedback between channel morphology and hydraulics is complex, making it
450 difficult to identify clear cause-and-effect relationships (Wilcox et al. 2011).

451 In order to determine the importance of the erosional zones outlined here in controlling
452 knickpoint morphology and recession rates, knickpoint evolution was modelled (Figure 5)
453 using the daily ice melt rate as an equivalent erosional process for the stream power incision
454 model. Channel incision rates were derived from daily mean water temperature and velocity,
455 using relationships described in Isenko et al. (2005)'s Figure 2. Each knickpoint profile was
456 divided into linear millimetre-to-centimetre length segments based on changes in gradient
457 using Rhino3D[®] software (Robert McNeel & Associates 2017), with application of calculated
458 daily incision rates perpendicular to the local slope of each segment. Perpendicular offsetting
459 of each segment reflected changes in the horizontal and vertical plane, and better characterised
460 knickpoint retreat and morphological adjustment. A manually digitised curve joined the offset
461 segments to create a full modelled profile (Figure 5). As discharge prior to 08:00 was
462 consistently low ($< 0.005 \text{ m}^3 \text{ s}^{-1}$), it is assumed that stream flow is also low in the evening and
463 negligible overnight. This assumption is supported by the high snow line position in July 2017,
464 akin to that typically seen in late summer (Beat Kühnis, personal communication, July 2017).
465 Snowpack depletion reduces potential water storage at the glacier surface, the volume of

466 delayed runoff and the lag-time between peak melt and supraglacial discharge (see Willis et al.
467 2002). Here, the contribution of delayed runoff following peak ablation is likely to be minimal,
468 indicating that the stream did not experience continuous water flow over a 24-hour period.
469 Therefore, incision rates were applied for an 18-hour period to represent a maximum estimate
470 of change, as the mean water temperatures and velocities used encompassed the rising limb
471 and peak diurnal measurements.

472 [Figure 5 near here]

473 Comparison of the modelled profiles with observed knickpoint evolution emphasise
474 discrepancies between both the shape and rate of evolution (Figure 5). Modelled profiles
475 retained the original step morphology, overestimating vertical lowering (6th - 7th, 8th - 9th July)
476 and both overestimating (6th - 7th July) and underestimating headward recession at the step lip
477 (7th - 8th, 8th - 9th July). The inability of the model to accurately predict knickpoint evolution on
478 ice is likely due to the assumption of constant water temperature and velocity along the profile.
479 As the results herein demonstrate that differential zones of erosion arise at differing discharges,
480 this suggests that use of a constant-rate melt model for characterising step evolution is too
481 simplistic, similar to the stream power laws applied in bedrock/alluvial streams. The
482 complexities of changing flow dynamics across a knickpoint on ice must be further
483 investigated, to allow incorporation of these parameters and their feedback with the channel
484 boundary into numerical models.

485 **6. Conclusions**

486 Until now, there has been a limited process-level understanding of knickpoint evolution within
487 ice-walled channels, despite their importance in supraglacial and englacial incision processes.
488 Our study of a supraglacial knickpoint on Vadrec del Forno, Switzerland provides the first
489 detailed dataset of supraglacial knickpoint morphological change at a fine temporal resolution.
490 The results showed recession of 0.26 m over three days, with variable rates and magnitudes of

491 change, both spatially across the knickpoint and temporally over diurnal timescales. Low flow
492 rates coincided with the greatest step retreat, gradient change and rate of upstream incision,
493 and high flow rates coincided with the greatest increase in step height and rate of downstream
494 incision. Our conceptual model proposes that discharge variations control the zones of erosion
495 over the knickpoint, with low discharge focusing erosion on the reach upstream of the
496 knickpoint, the step lip and step-riser face, and high discharge focusing erosion at the
497 knickpoint base. Channel over-deepening at the knickpoint base led to pool formation, with the
498 increased tailwater depth inhibiting vertical incision and causing lateral erosion. This confirms
499 non-uniform water flow over the step, resulting in evolution through replacement of
500 morphology. Bed load absence within the stream indicates the hydrodynamic nature of
501 evolution, with the driving forces of hydraulic action and frictional thermal erosion governing
502 morphological change. The results indicate that peak discharge may not play as dominant a
503 role in drainage development on ice as previously considered, suggesting that the majority of
504 morphological adjustment in features such as knickpoints may occur prior to or following high
505 meltwater fluxes, either at a diurnal (supraglacial) or seasonal (englacial) scale.

506 The data presented here demonstrate that the relationships between discharge, stream
507 power and knickpoint retreat rate commonly used in bedrock/alluvial channels fails to capture
508 the intricacies and feedbacks of erosion processes driving knickpoint recession in ice-walled
509 channels. Our findings show that the considerable differences in erosive mechanisms between
510 supraglacial and bedrock/alluvial channels are likely to result in disparities in knickpoint
511 morphological adjustment in response to varying discharge regimes. The conceptual model
512 proposed herein has been developed from a relatively time-limited dataset, meaning that
513 ascertaining whether results provide a relevant representation of knickpoint evolution is
514 challenging. In order to test the wider application of the model, additional research within
515 supraglacial environments is required at a range of spatial scales, taking into consideration

516 channels of varying sizes, gradients and discharges. In particular, further investigation of
517 knickpoint erosion mechanisms in relation to variable flow regimes is essential, through
518 increasing the *temporal* and *spatial* resolution of flow measurements above, across and below
519 knickpoints.

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535 **Disclosure statement**

536 No potential conflict of interest was reported by the authors.

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561 JEK and TDLI-F developed the research question and context; JEK designed and conducted
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563 TDLI-F; TOH provided UAV imagery of the field site. All authors edited and revised the paper.

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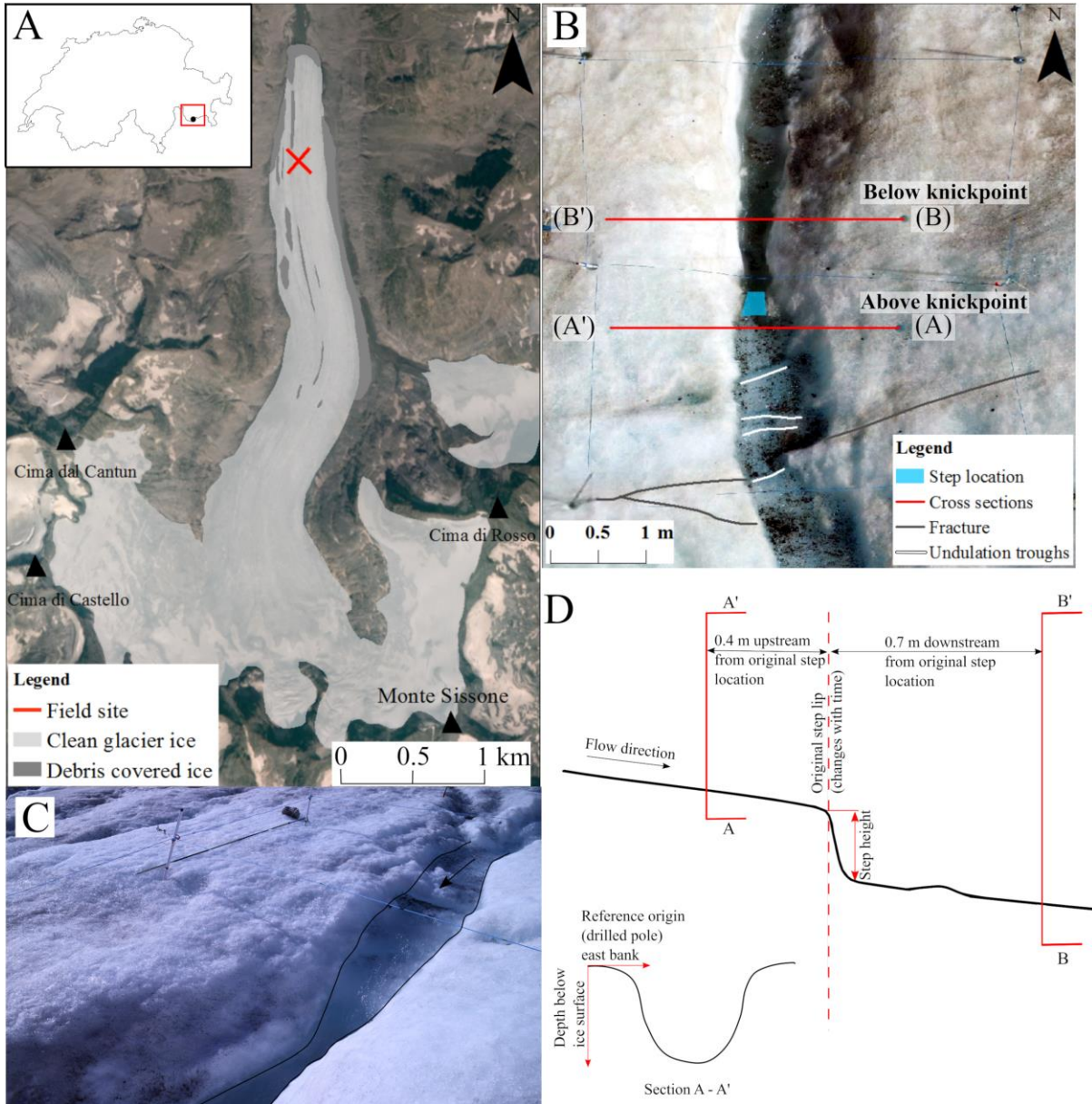
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770 flood in a step-pool channel. *Geomorphology*. 40(3-4):311-327.

771 **Table 1.** Summary of knickpoint and cross-section dimensions, flow parameters, and general interpolated weather trends for each day.

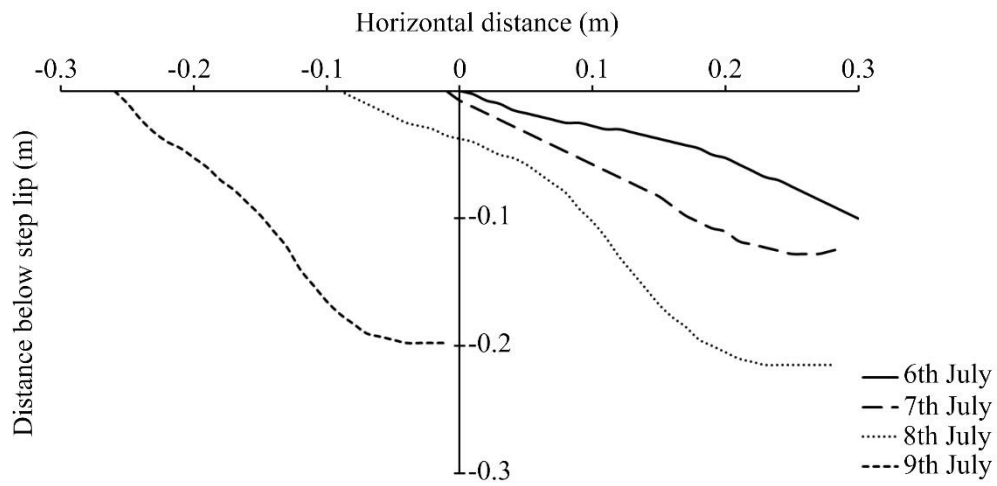
Day	Step height (mm)	Step gradient (°)	Cross-section above knickpoint		Cross-section below knickpoint		Peak discharge ($\text{m}^3 \text{s}^{-1}$)	Mean velocity (m s^{-1})	Maximum stream power per unit length (W m^{-1})	Mean water temperature ($^{\circ}\text{C}$)	Froude number range		Reynolds number range	Mean daily air temperature ($^{\circ}\text{C}$)	Mean daily potential incident radiation (W m^{-2})
			Mean depth (m)	Width (m)	Mean depth (m)	Width (m)					Above knickpoint	Below knickpoint			
6th July	100	18	-	-	-	-	0.013	0.75	46.81	0.3	1.08	0.76	4431	13.85	898
7th July	128	23	0.35	0.29	0.48	0.17	0.011	0.83	47.42	0.17	0.76 - 0.99	0.91 - 0.99	2836 - 6263	12.35	712
8th July	215	30	0.38	0.29	0.55	0.17	0.003	0.41	14.63	0.08	0.2 - 0.69	0.24 - 0.69	1004 - 3131	14.67	768
9th July	198	38	0.46	0.09	0.53	0.25	-	-	-	-	-	-	-	-	-



773

774 **Figure 1**

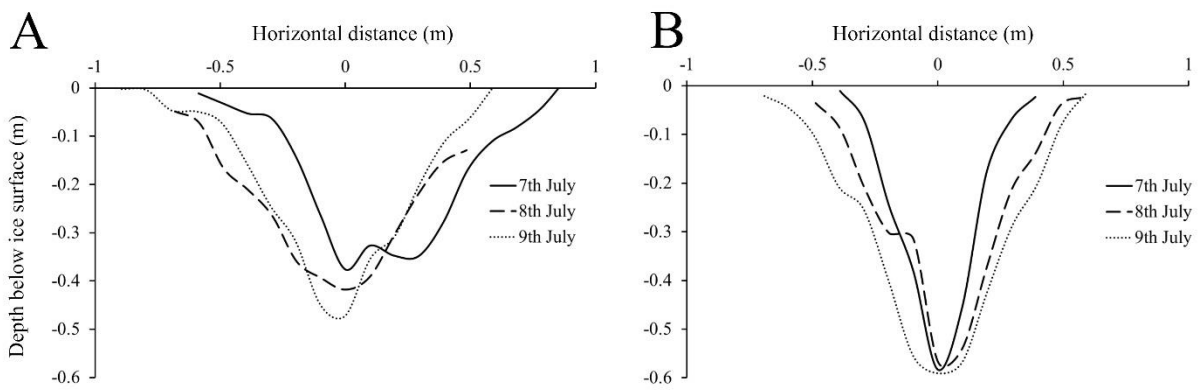
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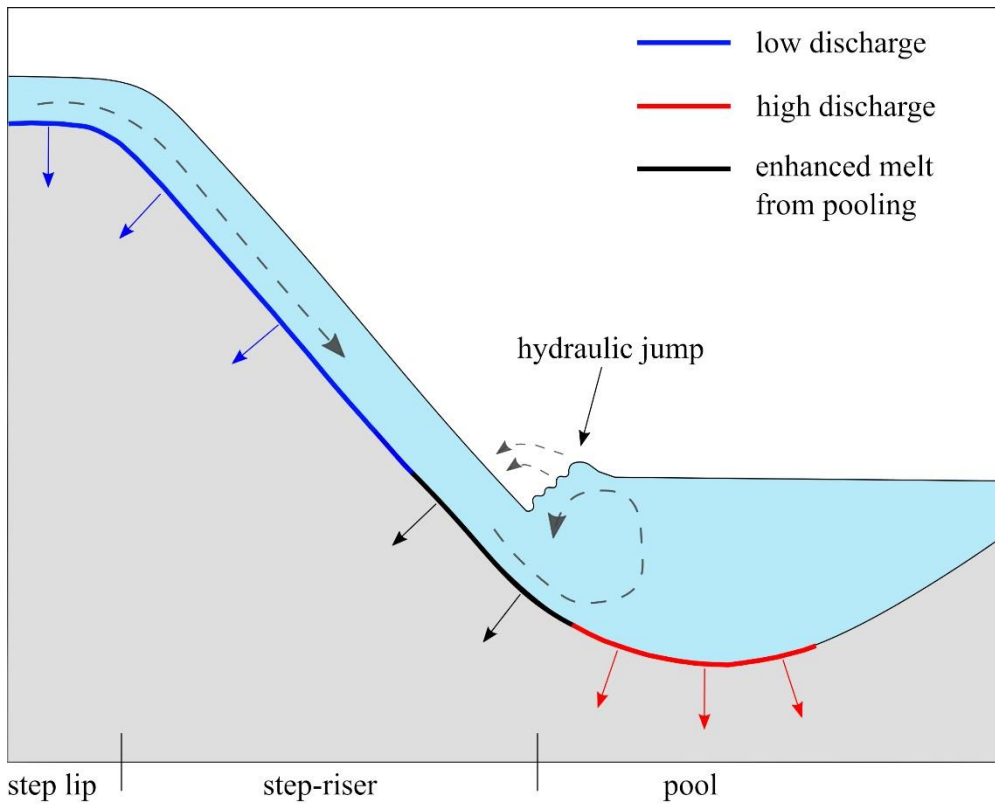
777 **Figure 2**

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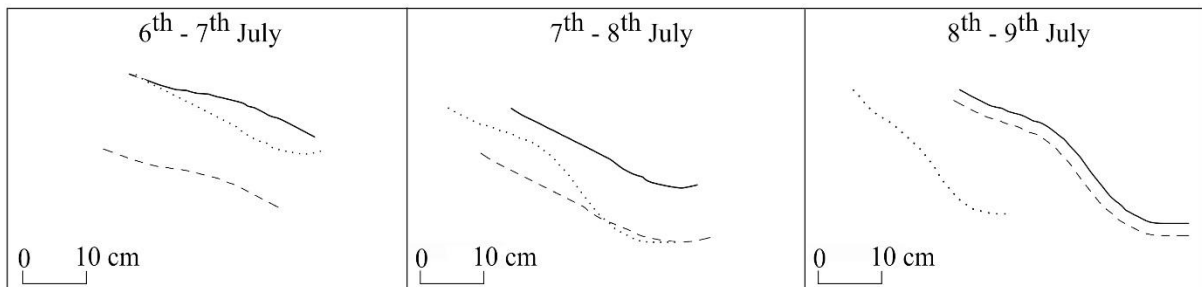
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780 **Figure 3**



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782 **Figure 4**



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784 **Figure 5.**

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790 **Figure 1.** (A) The red cross marks the field experiment location on Vadrec del Forno, with the
791 location of the glacier within Switzerland inset. RapidEye imagery obtained from PlanetTeam
792 (2017). (B) The stream reach planform, demonstrating the fracture and undulation troughs
793 upstream of the knickpoint. Longitudinal foliation within the stream vicinity is oriented
794 between 58° and 89° relative to north. Water and glacier flow is also to the north. Aerial
795 imagery obtained from an elevation of 30 m at a resolution of 0.02 m using a DJI Phantom 3
796 Series Standard quadcopter. (C) The step with the direction of water flow denoted by the black
797 arrow. The 2.3 m long crevasse probe lying horizontal on the far stream bank provides scale.
798 (D) Schematic longitudinal profile of the knickpoint, demonstrating the locations at which
799 cross-section geometry and step height was measured, with an example cross-section inset.

800 **Figure 2.** Central step-riser profiles for each day demonstrating the recession and morphology
801 of the step face immediately downstream of the step lip. The graph origin denotes the location
802 of the original step lip (6th July). To facilitate direct comparison, profiles have not been
803 corrected for vertical lowering.

804 **Figure 3.** Channel cross-sections measured on different days illustrating changes above (A)
805 and below (B) the knickpoint. The direction of flow is into the page. Cross-sections are
806 geometrically accurate relative to the glacier surface at the time of measurement, with the
807 x-axis denoting lateral distance from the thalweg.

808 **Figure 4.** Schematic illustration of the differing zones of erosion across the knickpoint at
809 varying discharges. The solid arrows denote the direction of boundary erosion and the dashed
810 arrows denote the direction of water flow.

811 **Figure 5.** Observed and modelled knickpoint evolution for each day, showing the original
812 knickpoint profile (as recorded on the start date), the end profile (as recorded on the end date)
813 and the modelled profile derived from 18-hour melt rates.

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