Supporting Information for

Stream hydrology controls on ice cliff generation, evolution, and survival on debris-covered glaciers

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Introduction

This supporting material contains text, video, figures, and tables, summarizing analysis of ITS_LIVE glacier velocity data (Text S1, Video 3, Figure S6), additional results of ice cliff DEM analysis (Figures S1-S3, S6), additional information on stream discharge measurements (Figures S4-S5, Table S1), and time lapse videos of stream avulsion events (Videos S1-S2).

Supplementary Text S1

We investigated the velocity history of Kennicott Glacier using the ITS_LIVE velocity dataset derived from LANDSAT and other records (A. S. Gardner et al., 2022; Alex S. Gardner et al., 2018). This allowed us to analyze changes in the glacier's velocity field from 1985-2020 (Supplementary Video S3). The glacier's lowermost reaches typically exhibit low velocity, tapering down to full stagnation in the lowermost 2.5 km. We observed two episodes of readvance, from 1988-1995 and 2018-2020, defined by an increase in velocity most dramatic on the western half of the glacier from 2.5-7 km up valley of the terminus.

The area coinciding with the strongest readvance was heavily crevassed in 2019-2020 (Supplementary Figure S4), with exposed ice faces that may evolve into ice cliffs. Thus for this area ice dynamics supersedes supraglacial hydrology as the dominant geomorphic driver of ice cliff formation and evolution.

Supplementary Videos

Supplementary Video 1 is a time lapse video of Avulsion #1 in action (described in Figure 4 of the main text). Frame interval is 30 minutes. Note the ablation stake in the foreground melting out of debris-covered ice.

Supplementary Video 2 is a time lapse video of Avulsion #2 in action (described in Figure 4 of the main text). Frame interval is 30 minutes.

Supplementary Video 3 is a data animation illustrating results from the ITS_LIVE glacier velocity dataset on Kennicott Glacier. This velocity data was generated using auto-RIFT (Alex S. Gardner et al., 2018) and provided by the NASA MEaSUREs ITS_LIVE project (A. S. Gardner et al., 2022). (a) Velocity field on Kennicott Glacier mapped through time. (b-f) Velocity profiles extracted from the map; y axis is in m yr^{-1} and x axis is in m. Red line indicates the current year while previous years are underplotted in progressively transparent black lines going into the past. Two readvances are observed in the vicinity of the (e) profile, circa 1988-1995 and 2018-2020.

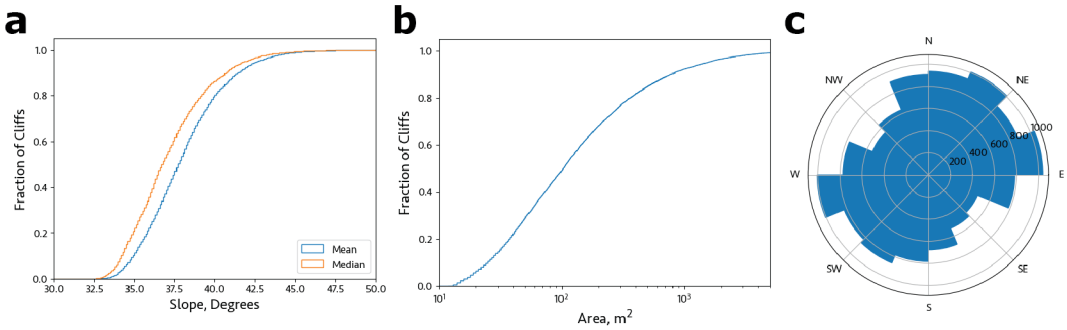

Figure S1: Cumulative statistics on ice cliff (a) surface slope, (b) geometric area, and (c) aspect.

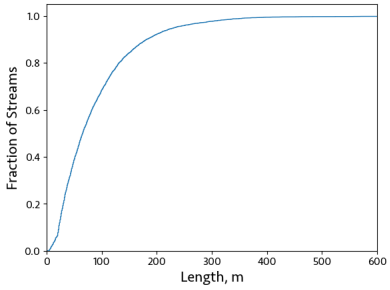

Figure S2: Statistics on predicted supraglacial stream channel length.

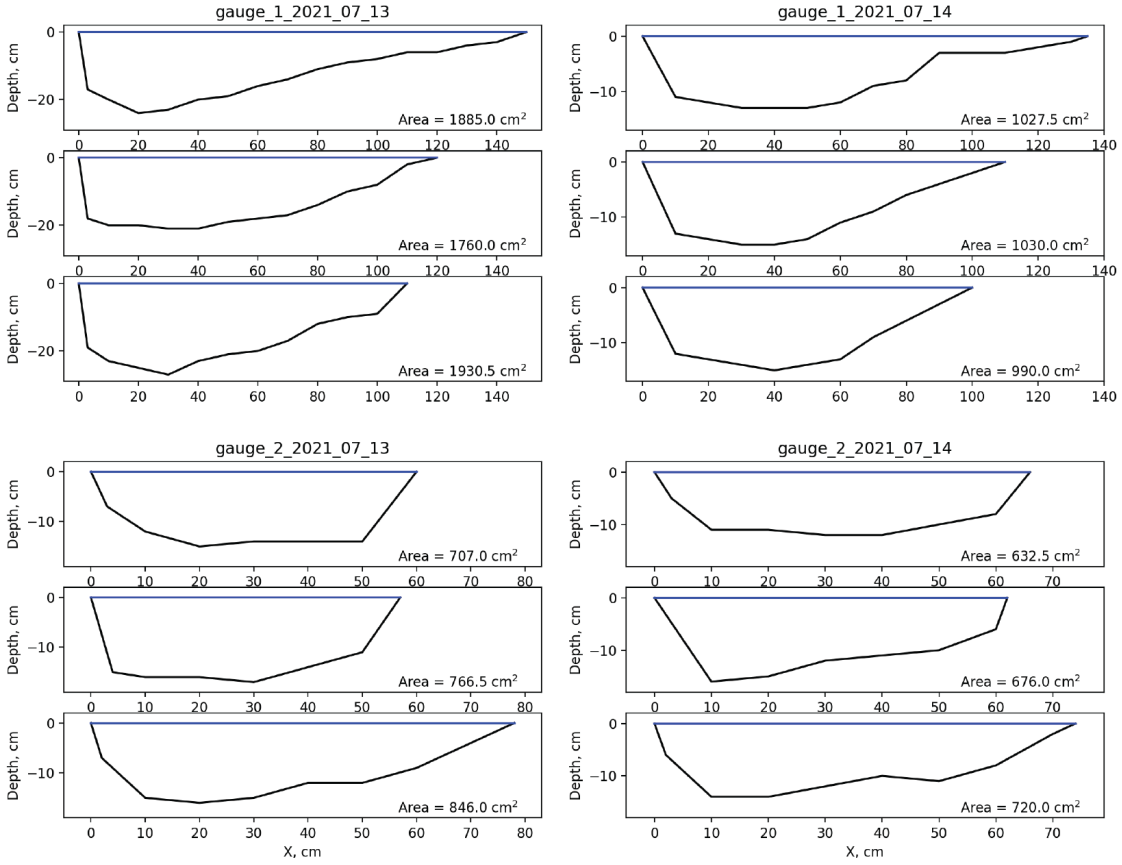

Figure S3: Measured channel cross-sections for stream gauges 1 & 2. The ice cliff face is located at 0 cm on each profile.

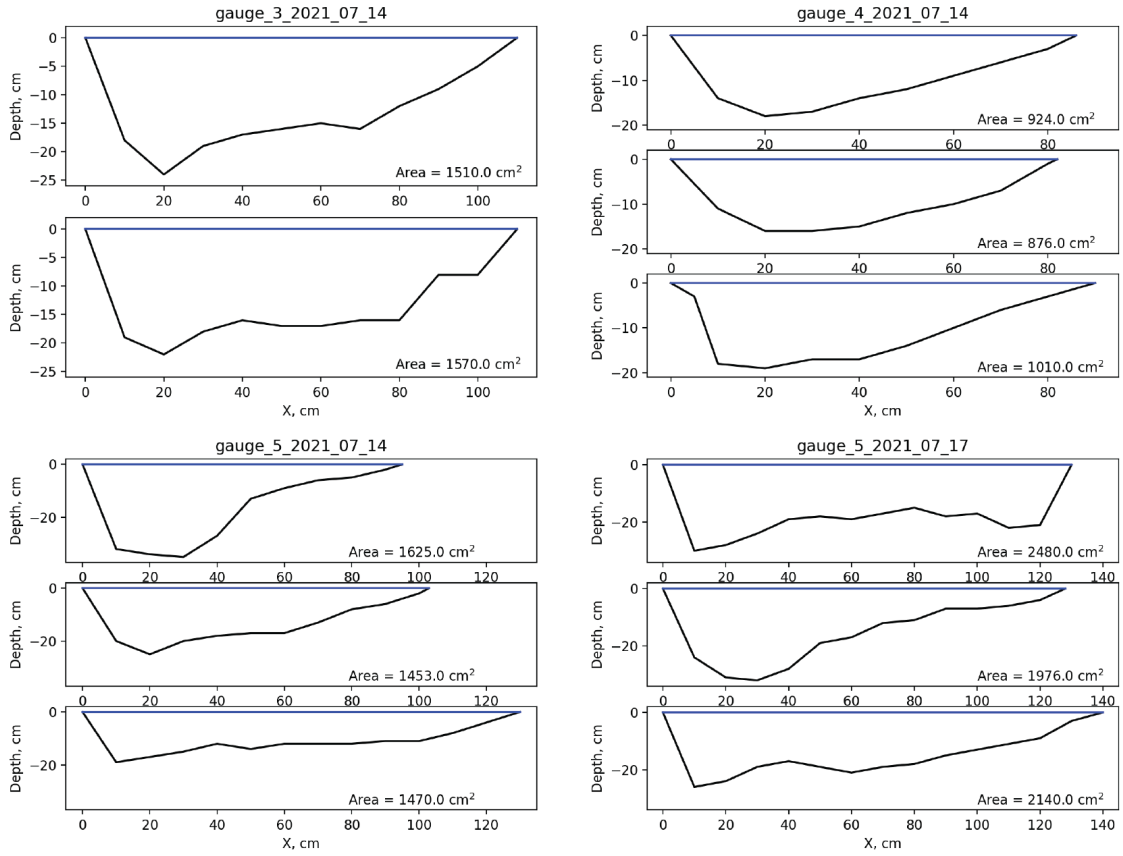

Figure S4: Measured channel cross-sections for stream gauges 3-5. The ice cliff face is located at 0 cm on each profile.

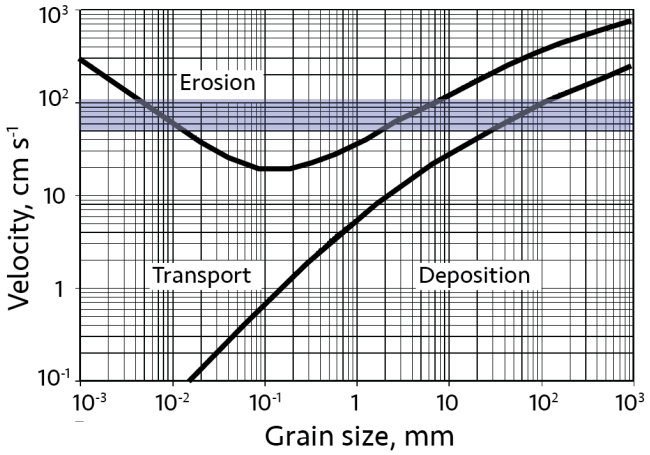

Figure S5: Hjulström curve (Hjulström, 1935) with velocities constrained from supraglacial stream discharge measurements overplotted in blue shading.

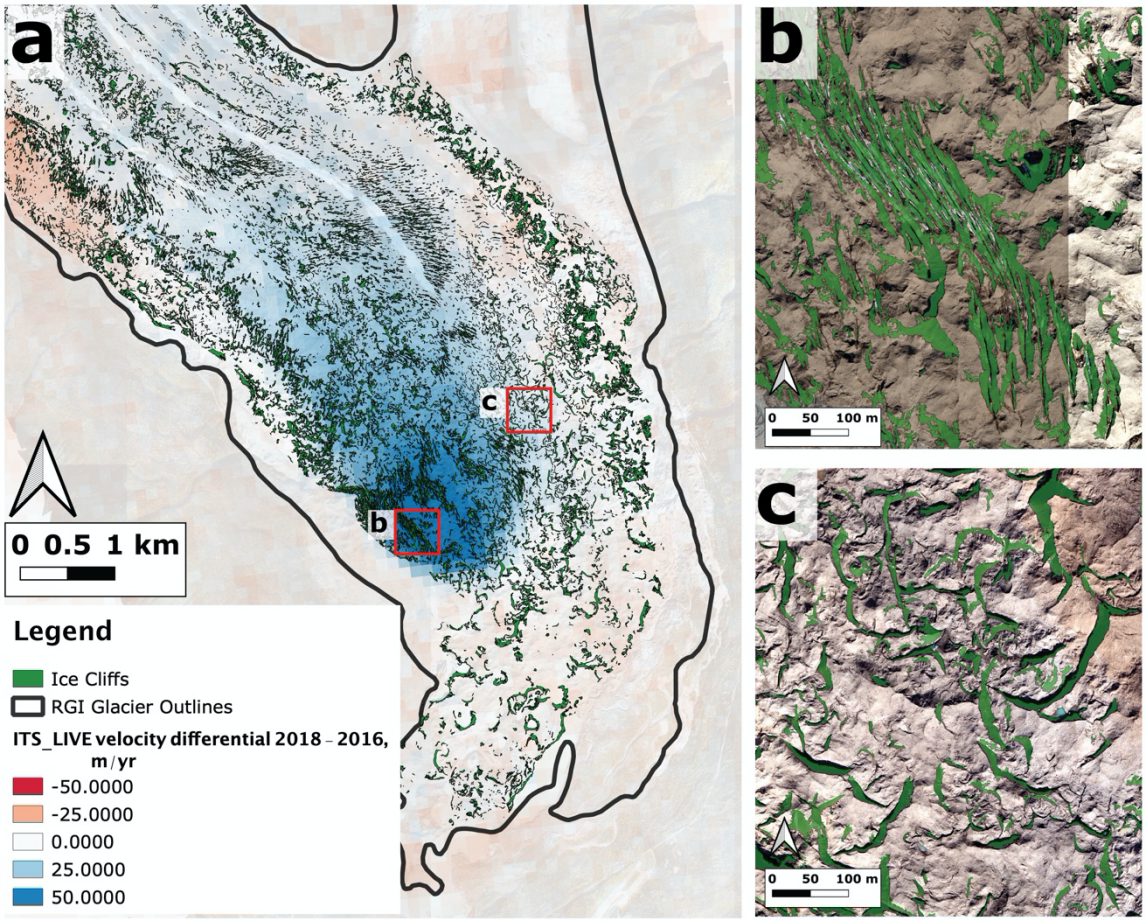

Figure S6: An illustration of the spatiotemporal importance of glacier dynamics to ice cliff generation and morphology. (a) Kennicott Glacier terminus with mapped difference in ITS_LIVE surface velocities between 2018 & 2016; positive values on the western terminus delineate the location of the 2018 readvance. (b) At the readvance front, crevasses are formed, exposing ice in repeated linear orientations. (c) Outside the readvance front, ice cliffs dominantly exhibit stream-influenced morphologies as described in this paper.

Gauge	Date	Time	Conditions	Length (m)	Datapoints	Latitude	Longitude	Z	Velocity (m/s)	Area (cm^2)	Flow (m^3/s)
1.1	July 13, 2021	~3:20-3:45 PM	Hot, sunny	8	8	61.4833	-142.9169	551.6	0.6	1700	0.102
1.2	July 14, 2021	2:32 PM	Cool, cloudy	8	6	61.4833	-142.9169	551.6	0.6	950	0.057
2.1	July 13, 2021	~3:50-4:15 PM	Hot, sunny	5	5	61.4836	-142.9161	553.5	1.1	700	0.077
2.2	July 14, 2021	~12:00 PM	Cool, cloudy	4	8	61.4836	-142.9161	553.5	0.9	611	0.055
3.1	July 14, 2021	~3:30 PM	Cool, cloudy	1.5	15	61.4822	-142.9144	530.5	0.8	1413	0.113
4.1	July 14, 2021	~4:00 PM	Cool, cloudy	6	8	61.4829	-142.9156	543.3	1.0	850	0.085
5.1	July 14, 2021	4:24 PM	Cool, cloudy	3	7	61.4828	-142.9154	544.9	0.9	1389	0.125
5.2	July 17, 2021	1:30-1:50 PM	Hot, sunny	2.5	7	61.4828	-142.9154	544.9	1.0	1850	0.185

Table S1: Summary of stream gauging experiments conducted on Kennicott Glacier for this study. Median velocity, channel cross-sectional area, and flow rates as constrained by the experiments are shown.