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2 **Controls on Ice Cliff Formation, Distribution and Characteristics on Debris-Covered**
3 **Glaciers**

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21 **Key Points:**

- 22 • We derived an unprecedented dataset of 37537 ice cliffs and their characteristics across
23 86 debris-covered glaciers in High Mountain Asia
- 24 • We find that 38.9% of the cliffs are stream-influenced, 19.5% pond-influenced and
25 19.7% are crevasses
- 26 • Ice cliff distribution can be predicted by velocity as an indicator of both the dynamics and
27 state of evolution of debris-covered glaciers
28

29 **Abstract**

30

31 Ice cliff distribution plays a major role in determining the melt of debris-covered glaciers but its
32 controls are largely unknown. We assembled a dataset of 37537 ice cliffs and determined their
33 characteristics across 86 debris-covered glaciers within High Mountain Asia (HMA). We
34 complemented this dataset with the analysis of 202 cliff formation events from multi-temporal
35 UAV observations for a subset of glaciers. We find that 38.9% of the cliffs are stream-
36 influenced, 19.5% pond-influenced and 19.7% are crevasses. Surface velocity is the main
37 predictor of cliff distribution at both local and glacier scale, indicating its dependence on the
38 dynamic state and hence evolution stage of debris-covered glacier tongues. Supraglacial ponds
39 contribute to maintaining cliffs in areas of thicker debris, but this is only possible if water
40 accumulates at the surface. Overall, total cliff density decreases exponentially with debris
41 thickness as soon as debris gets thicker than 10 cm.

42

43 **Plain Language Summary**

44

45 Debris-covered glaciers are common throughout the world's mountain ranges and are
46 characterised by the presence of steep ice cliffs among the debris-covered ice. It is well-known
47 that the cliffs are responsible for a large portion of the melt of these glaciers but the way they
48 form, and as a result the controls on their development and distribution across glaciers remains
49 poorly understood. Novel mapping approaches combined with high-resolution satellite and drone
50 products enabled us to disentangle some of these controls and to show that the ice cliffs are
51 generally formed and maintained by the surface hydrology (ponds or streams) or by the opening
52 of crevasses. As a result, they depend both at the local and glacier scale on the dynamic state of

53 the glaciers as well as the evolution stage of their debris cover. This provides a pathway to better
54 represent their contribution to glacier melt in predictive glacier models.

55

56 **1 Introduction**

57 Debris-covered glaciers are found in all mountain ranges (Scherler et al., 2018), and
58 supraglacial debris extents and thickness are expected to increase in a warming climate
59 (Compagno et al., 2022; Herreid & Pellicciotti, 2020; Stokes et al., 2007). However, despite
60 considerable recent advances, modelling the mass balances of these glaciers remains challenging
61 (Rounce et al., 2021). This is partly due to the presence of supraglacial ice cliffs, which melt up
62 to 20 times faster than the surrounding debris-covered ice, therefore compensating for the
63 relatively well constrained debris insulating effect (Anderson, Armstrong, Anderson, & Buri,
64 2021; Brun et al., 2018; E. S. Miles, Willis, et al., 2018; Reid & Brock, 2014; Sakai et al., 1998,
65 2002). In one catchment in High Mountain Asia (HMA) ice cliffs were shown to contribute 17+/-
66 4% of the melt of the debris-covered ice (Buri et al., 2021). This has major implications for the
67 mass balance of debris-covered glaciers (Pellicciotti et al., 2015) and their long-term evolution
68 (Ferguson & Vieli, 2021; Racoviteanu et al., 2022).

69

70 While models accurately simulate the energy and mass balance contribution of individual
71 ice cliffs (Buri et al., 2016; Kneib et al., 2022), their application at large spatial scales is limited
72 by our understanding of the controls of ice cliff distribution. Indeed, estimates of ice cliff density
73 are difficult to make (Anderson, Armstrong, Anderson, & Buri, 2021; Herreid & Pellicciotti,
74 2018; Kneib et al., 2020) and vary widely in time and space, between 1 and 15% of the debris-
75 covered area (e.g. Falaschi et al., 2021; Kneib et al., 2021; Loriaux & Ruiz, 2021; Sato et al.,
76 2021; Steiner et al., 2019; Watson et al., 2017). Remote sensing studies have shown that cliffs
77 are often associated with ponds (Steiner et al., 2019; Watson, Quincey, Carrivick, et al., 2017),
78 hinting at a preferential location of ice cliffs where lower glacier longitudinal gradient and
79 surface velocities promote surface ponding (Bolch et al., 2008; Quincey et al., 2007; Quincey &
80 Glasser, 2009; Racoviteanu et al., 2021; Reynolds, 2000; Sakai & Fujita, 2010; Salerno et al.,
81 2012). Other limited observations indicate that ice cliffs preferentially develop at the confluence

82 of glacial tributaries, in locations of high compressive strain rates, and areas of thinner debris
83 (Anderson, Armstrong, Anderson, & Buri, 2021; Anderson, Armstrong, Anderson, Scherler, et
84 al., 2021; Benn et al., 2012; Kraaijenbrink et al., 2016; Steiner et al., 2019; Watson, Quincey,
85 Carrivick, et al., 2017). However, the lack of consistent observations of cliff distribution makes it
86 difficult to include ice cliffs in predictive glacier models in a way that accounts for their spatial
87 distribution and temporal evolution.

88

89 Ice cliff survival is inherently linked to debris stability, which is a function of local slope,
90 debris thickness and water content, as well as undercutting by streams or ponds (Moore, 2018).
91 The local slope can change in relatively short time scales with differential melt caused by
92 heterogeneous debris thicknesses (Moore, 2021; Nicholson et al., 2018; Sharp, 1949), which
93 results in the surface of debris-covered glaciers being particularly hummocky where the debris
94 gets thicker than 20-30 cm (Bartlett et al., 2020; King et al., 2020). Slope undercutting and
95 destabilisation by streams or ponds is expected to be one of the main triggers for ice cliff
96 formation (Mölg et al., 2019; Röhl, 2006, 2008; Sakai & Takeuchi, 2000) and survival (Benn et
97 al., 2001, 2012; Brun et al., 2016; Kneib et al., 2022; Sato et al., 2021; Watson, Quincey, Smith,
98 et al., 2017). Other hypothesised cliff formation mechanisms include crevasse opening (Reid &
99 Brock, 2014; Steiner et al., 2019) or the collapse of englacial conduits (Egli et al., 2021; Gulley
100 et al., 2009; Immerzeel et al., 2014; E. S. Miles, Watson, et al., 2018; K. E. Miles et al., 2020;
101 Sakai & Takeuchi, 2000), but these hypotheses have never been tested in a quantitative way.

102

103 In this study, we therefore 1) map ice cliffs across 86 glaciers in HMA, 2) determine their
104 physical characteristics, 3) attribute their distribution to potential local and glacier-wide
105 controlling factors. The findings are further corroborated by complementary observations on ice
106 cliff formation from high-resolution, multi-temporal Unoccupied Aerial Vehicle (UAV) data at
107 five of the studied glaciers (Text S1).

108

109 **2 Data and Methods**

110

111 We used 14 Pléiades stereo-images acquired between 2017 and 2021 to derive 2m-
112 resolution multi-spectral images and Digital Elevation Models (DEMs) covering 86 debris-
113 covered glaciers across HMA (Berthier et al., 2014; Shean et al., 2016; Fig. 1; Table S2), 70 of
114 which had more than 65% of their debris-covered area that could be classified after removal of
115 clouds, shadows and fresh-snow (Table S3). The DEMs were used to derive surface slope and
116 aspect, the glacier ‘hummockiness’, which we defined as the percentage of area for which the
117 Statistical Measure of Relief (SMR) calculated over a 8 m window was greater than 50 m (King
118 et al., 2020), as well as supraglacial channels (Schwanghart & Scherler, 2014; Text S2). The
119 multi-spectral images were used to manually update the glacier and debris outlines of the RGI
120 6.0 (Pfeffer et al., 2014; Scherler et al., 2018; Table S3). Glacier longitudinal gradient was
121 computed using the 30m resolution AW3D DEM (Dehecq et al., 2019; Tadono et al., 2014) and
122 combined with glacier ice thicknesses (Farinotti et al., 2019) to estimate driving stress over a
123 distance of two ice thicknesses. Distributed glacier velocity, compressive and tensile strain rates
124 were obtained from the global 50m resolution composite by Millan et al. (2022). We additionally
125 used the distributed debris thickness dataset of McCarthy et al. (2022) for all glaciers larger than
126 2 km² (64 glaciers, 47 of which have more than 65% of their debris-covered area that could be
127 classified). All these datasets were aggregated 1) in 500 m distance bins along the glacier
128 flowlines (Kienholz et al., 2014; King et al., 2020) and 2) for each glacier. Data gaps within the
129 bins were filled using a nearest neighbour interpolation.

130

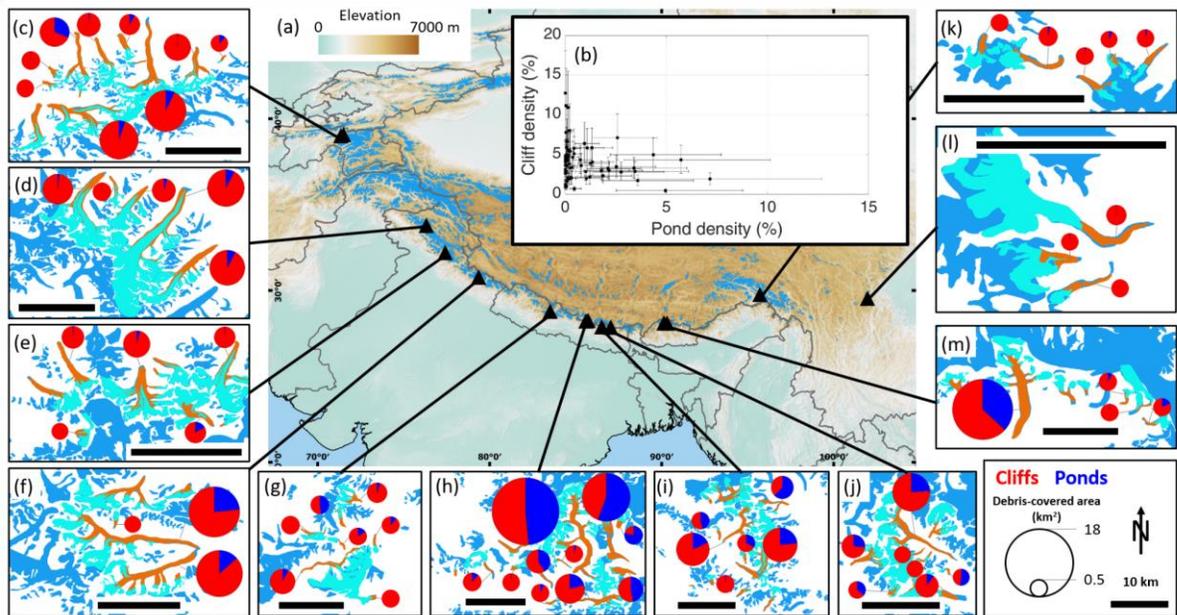
131 Ice cliffs and ponds were derived automatically in each Pléiades scene following the
132 Spectral Curvature method for cliffs, which is based solely on spectral characteristics (Kneib et
133 al., 2020), and the Normalized Difference Water Index (NDWI) for ponds (McFeeters, 1996; E.
134 S. Miles et al., 2017; Watson et al., 2016, 2018; Text S2). The ice cliffs are then implicitly
135 defined here as exposed ice in an otherwise debris-covered domain, therefore likely to undergo
136 ‘enhanced’ melt locally. Some of these features were clearly identifiable as crevasses due to their
137 elongated, straight or slightly curved shapes and these zones were outlined manually. Past

138 studies have only examined high-relief (several meters) ice cliffs, but here our interest is in all
 139 exposed ice in the debris-covered area, so we include smaller features common for thin-debris
 140 areas, such as crevasses, which similarly enhance surface ablation (Colgan et al., 2016).

141

142 Multi-temporal UAV data with a monitoring period longer than 2 years and with at least
 143 3 high-resolution (<1 m) DEMs and orthoimages were available at five of the studied glaciers
 144 distributed across HMA. This complementary data was used to identify ice cliff formation events
 145 and derive the characteristics of newly formed ice cliffs (Text S1).

146



147 **Figure 1:** (a) Map of HMA with each triangle representing one of the 14 Pléiades scenes
 148 (some scenes are very close to each other) and the boxes to the side (c-m) showing a zoomed
 149 view of the glaciers in these areas. The background is the GTOPO 30 arc seconds (~1 km) DEM,
 150 and the glacierised areas are indicated in blue. The inset boxes show the glacier RGI 6.0
 151 outlines in dark blue, the glaciers visible in the Pléiades images in turquoise and their debris-
 152 covered areas in brown. The pie charts are scaled to the absolute size of the debris-covered
 153 areas and show the relative proportion of ponds (dark blue) and cliffs (red) for each glacier for

154 *which more than 65% of their debris-covered area could be classified. (b) Cliff and pond density*
155 *of each of these glaciers. The bars show the uncertainties.*

156

157 **3 Results**

158 **3.1. Influence of supraglacial hydrology on ice cliff distribution**

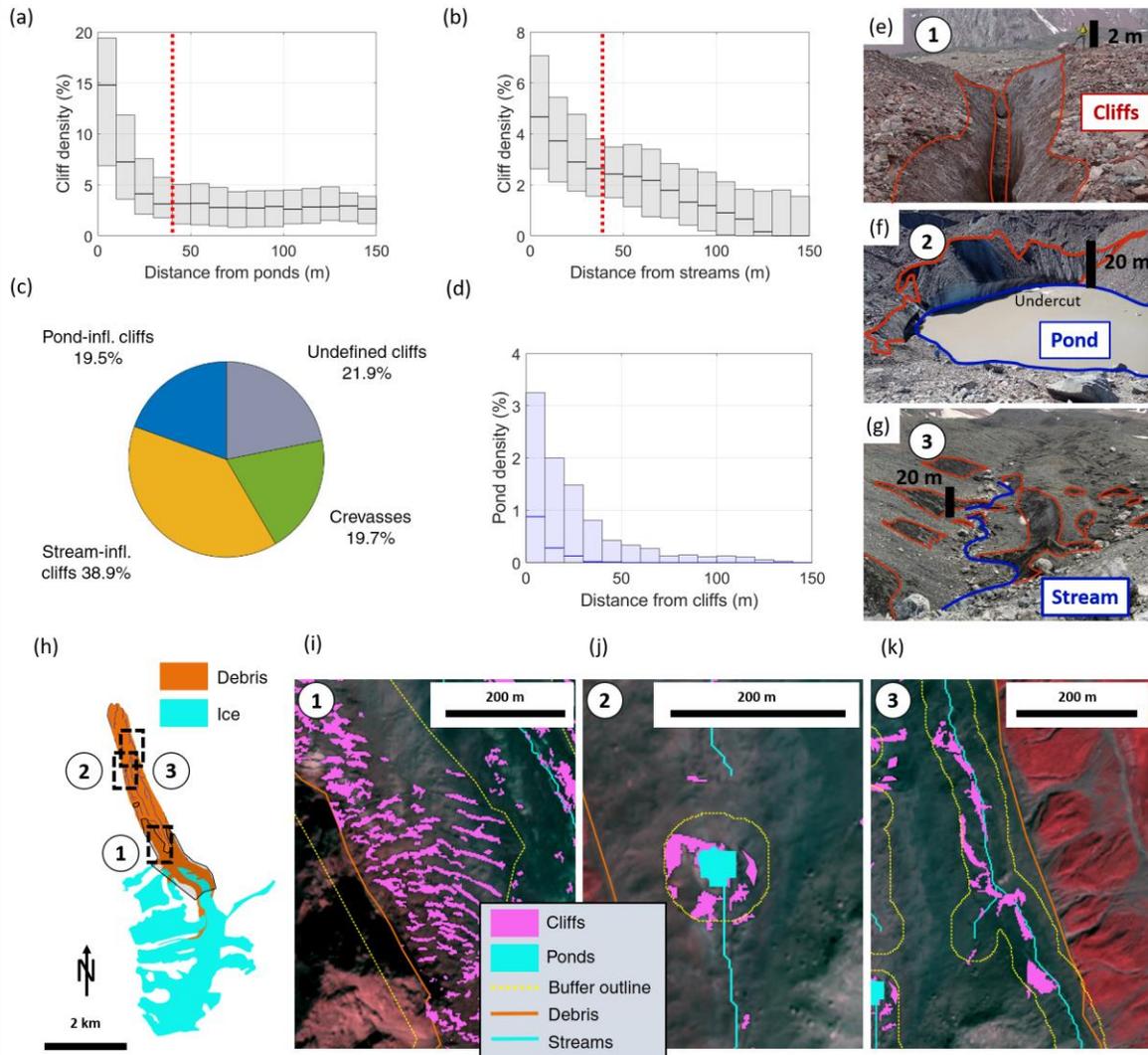
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160 Cliffs are preferentially located in the vicinity of ponds and streams, as their density
161 strongly decreases with distance from these hydrological features (Fig. 2a, b), and a large
162 majority of the ponds are related to at least one neighbouring cliff (Fig. 2d). This is further
163 confirmed by field observations (Fig. 2e-g) and multitemporal UAV observations showing that
164 the presence of streams or ponds is responsible for more than 79% of the newly-formed cliff area
165 (Fig. S2). This leads us to define a 40m-buffer around ponds and streams within which we
166 classify the cliff pixels as pond-influenced or stream-influenced (Fig. 2h). With this definition,
167 pond-influenced cliffs account for 19.5% and stream-influenced cliffs for 38.9% of the total cliff
168 area (Fig. 2c). In addition, crevasses represent 19.7% of the cliff area across all glaciers. They
169 are mostly located in the upper extents of the debris-covered areas but also appear lower down
170 glacier, at shear margins, and in the vicinity of proglacial lakes or lateral streams entering the
171 glacier (Fig. S6). The remaining cliffs are qualified as undefined. The stream mapping
172 parameters and choice of buffer size have little influence on this classification (Fig. 2h, S12).

173

174 The slope and density of ice cliffs vary between categories, while this is less the case for
175 aspect and size (Fig. S13). Crevasses are usually more densely distributed (15.2% of buffer area),
176 followed by the pond-influenced (6.7%), stream-influenced (4.3%) and undefined cliffs (2.1% of
177 remaining area, Fig. S13a). Despite a variety of glacier aspects (Table S3), there is a clear
178 preferential cliff aspect distribution in the NNW direction for all categories (Fig. S13d), while
179 the newly formed cliffs do not appear to have a preferential aspect (Sato et al., 2021; Fig. S4).

180



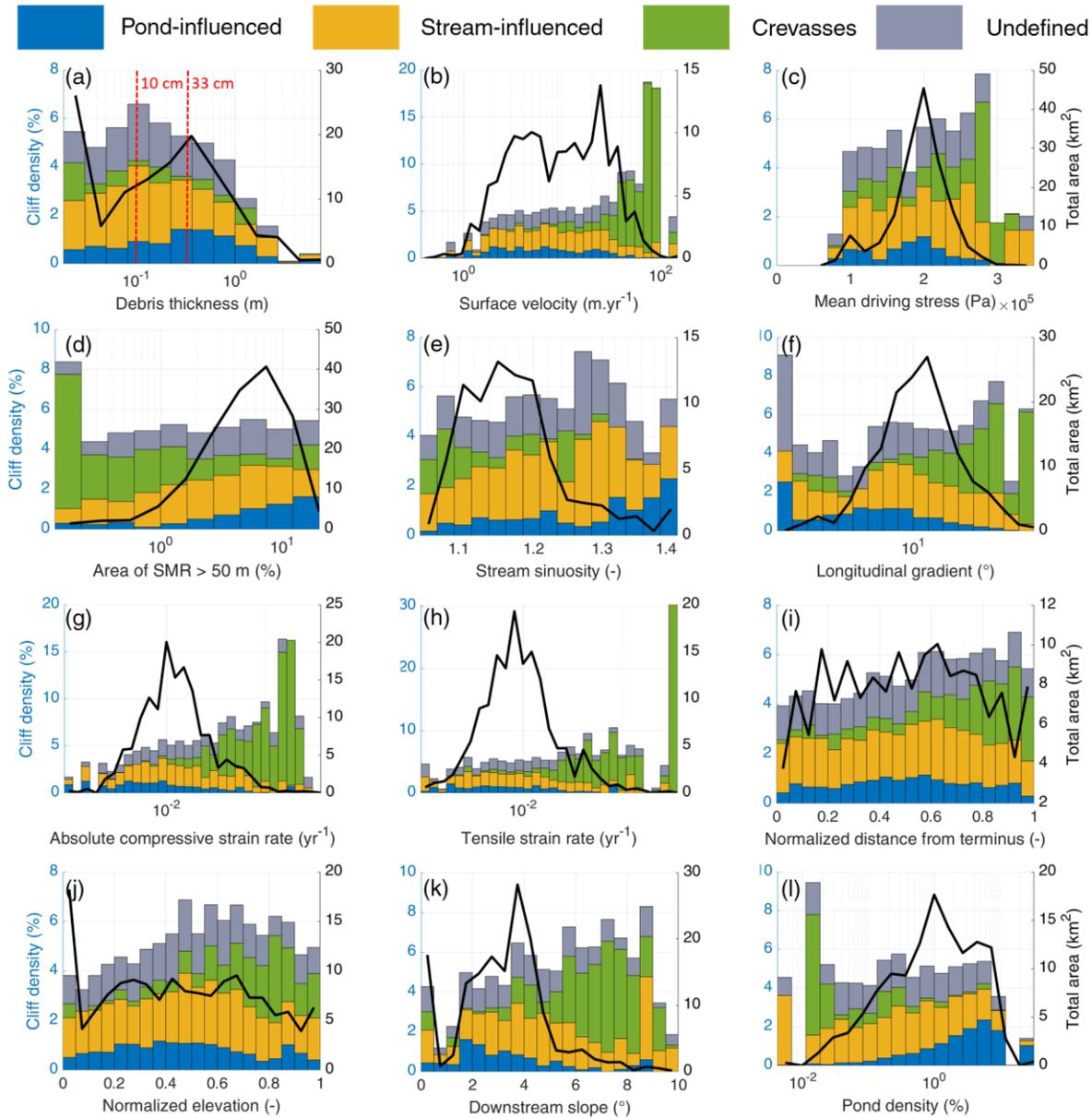
181
 182 **Figure 2:** Cliff density for all glaciers as a function of (a) distance from ponds after
 183 removal of the crevasses and (b) distance from streams, after removal of the pond-influenced
 184 cliffs. The box plots indicate the median, 25th and 75th percentiles of the cliff density within each
 185 10m bin for each glacier. The red dotted lines show the 40m buffers. (c) Area proportion of
 186 undefined, pond- and stream-influenced cliffs and crevasses across all debris-covered glaciers.
 187 (d) Pond density for all glaciers as a function of distance from cliffs. (h) Example of
 188 classification of ice cliffs from Kyzylsu Glacier, Tajikistan: 1/ crevassed-areas, 2/ pond-
 189 influenced cliffs and 3/ stream-influenced cliffs, with the pictures (e-g) and Pléiades view (i-k) of
 190 the corresponding zones. Image credit: Marin Kneib and Evan S. Miles. Background of (i-k) is
 191 the Pléiades false-colour multispectral image (19/09/2021). Pléiades © CNES 2021, Distribution
 192 AIRBUS DS.

193 **3.2. Controls on ice cliff distribution**

194

195 The variables associated with ice cliff distribution vary depending on the category of cliff
196 considered (Fig. 3, S15, Table S5). Stream-influenced and undefined cliffs follow a similar
197 distribution for all predictors (Fig. S15), which could indicate that a majority of the undefined
198 cliffs were formerly stream-influenced and backwasted away from the channels. 80% of stream-
199 influenced cliffs are located in areas with debris estimated to be thinner than 33 cm, while 45%
200 of the pond-influenced cliffs are located in areas with thicker debris (Fig. S15). This results in
201 the total cliff density decreasing exponentially ($Y = 5.8e^{-\frac{x}{2}}$, $R^2 = 0.73$) when debris gets thicker
202 than 10 cm (Fig. 3a, S16). Furthermore, crevasses and pond-influenced cliffs have a clearly
203 contrasting response to the different controls investigated. Indeed, 80% of the crevasses are
204 located in areas with surface velocities higher than the 13 m.yr⁻¹ threshold or in areas with debris
205 thinner than 20 cm (Fig. S15). Pond-influenced cliffs clearly depend on pond density, and are
206 thus preferentially located in non-dynamic areas with lower longitudinal gradient and velocity
207 and with thicker debris (Fig. 3, S15, S17).

208



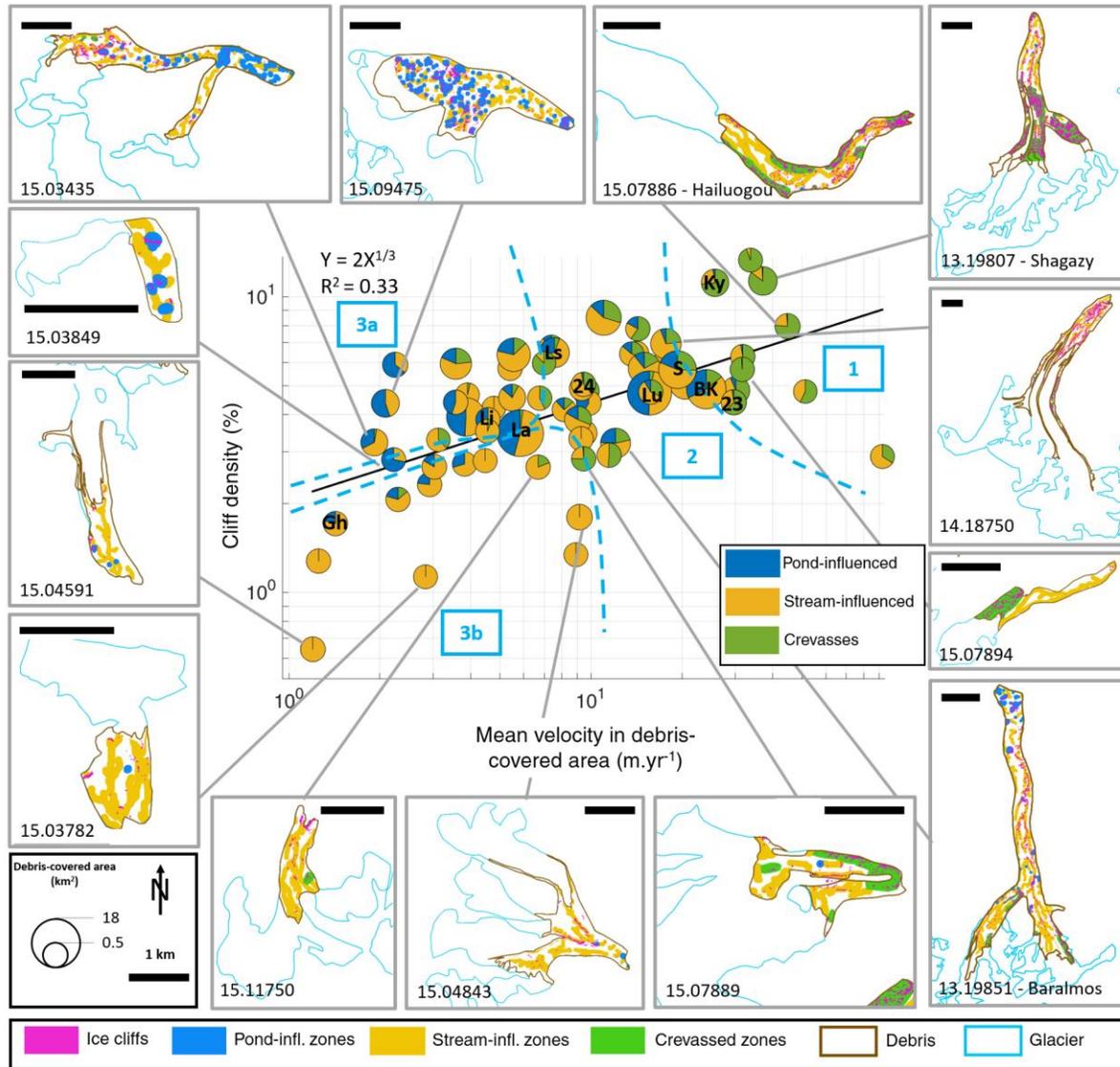
209
 210 **Figure 3:** Mean cliff density split by cliff category for all bins of all glaciers where more than
 211 65% of the debris-covered area could be classified as a function of (a) debris thickness, (b)
 212 surface velocity, (c) mean driving stress, (d) ‘hummockiness’, (e) stream sinuosity, (f)
 213 longitudinal gradient, (g) absolute compressive strain rate, (h) tensile strain rate, (i) normalized
 214 distance from terminus, (j) normalized elevation above terminus, (k) downstream slope to
 215 terminus and (l) pond density. The black line shows the area distribution of all the bins.

217 **3.2. Ice cliff dependence on glacier state**

218

219 When aggregating the metrics per glacier, a clear relationship between mean surface
220 velocity across the debris-covered area and cliff density becomes apparent (Fig. 4, S18). The
221 influence of climatic variables seems instead to be limited (Fig. S19). Cliff density decreases
222 with decreasing velocity, up to a point where the trajectory seems to bifurcate. The debris-
223 covered tongues with the highest cliff density and fastest velocity have a larger proportion of
224 crevasses (state 1, Fig. 4). At slower velocities ($<10 \text{ m.yr}^{-1}$), two trajectories are apparent: 1)
225 glaciers with a large proportion ($> \frac{1}{3}$) of pond-influenced cliffs and higher cliff densities (state
226 3a, Fig 4), and 2) glaciers with a majority of stream-influenced cliffs, which tend to have lower
227 cliff densities (state 3b, Fig. 4). The majority of the glaciers are found at an intermediary stage
228 between these three end-members, with a decreasing proportion of crevasses and an increasing
229 proportion of stream- and pond-influenced cliffs as velocity decreases (state 2, Fig. 4).

230



231
 232 **Figure 4:** Glacier-wide cliff density as a function of mean velocity in the debris-covered
 233 area for all glaciers where more than 65% of the debris-covered area could be classified. The
 234 proportion of undefined cliffs was not represented for readability. The boxes to the side show
 235 example maps of some of the glaciers with their surface classifications. Some additional
 236 reference glaciers are indicated in the main plot in black. The expression and R^2 of the black
 237 linear regression are indicated in the upper left corner. In light blue are shown four glacier
 238 clusters.

239 **4 Discussion and conclusions**

240 We have identified the presence of supraglacial streams and ponds, along with the
241 opening of crevasses, to be the main mechanisms responsible for ice cliff formation and
242 development. Newly-formed cliffs tend to be smaller in size and do not have any preferential
243 aspect (Kneib et al., 2021; Fig. S4, S5). Cliffs get reburied when they backwaste away from
244 these supraglacial features (Fig. 2a, b), with the strong control of solar radiation on cliff survival
245 resulting in the preferentially poleward orientation of the total ice cliff population (Buri &
246 Pellicciotti, 2018).

247

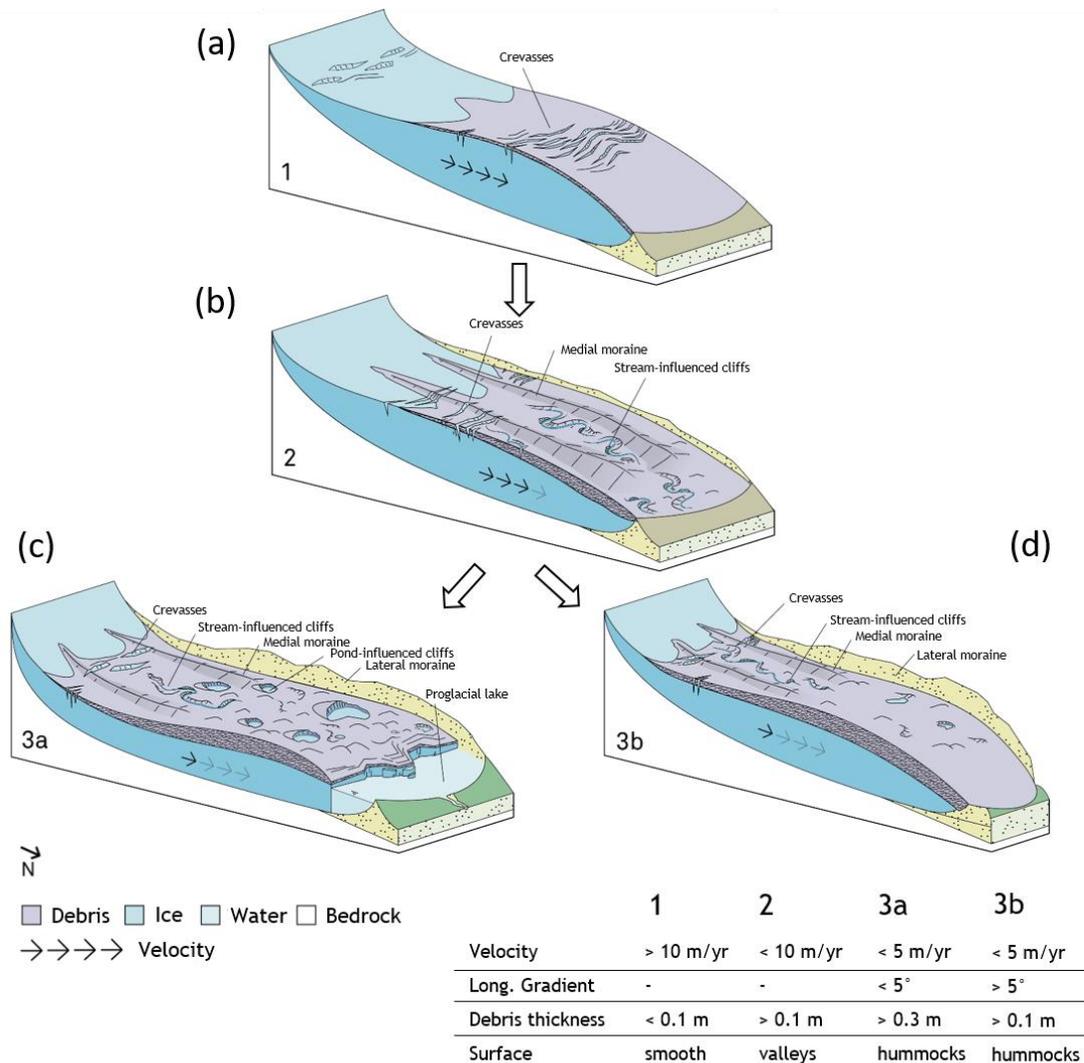
248 **4.1. Ice cliff distribution and glacier state**

249

250 Velocity stands out as the main control on ice cliff density both at the local and glacier
251 scale (Fig. 3, 4). Interlinkages with other variables means that the cliff density also responds to
252 other local controls, and debris thickness especially, although each category of cliffs responds
253 differently (Fig. 3). The distribution of ice cliffs therefore depends on the glacier dynamics and
254 state. A dynamic debris-covered glacier (mean surface velocity $> 10 \text{ m.yr}^{-1}$, Fig. 4, 5a, S20a) is
255 usually characterised by thin debris and crevasses which comprise the majority of exposed ice
256 and drain supraglacial streams. Glacier slow-down results in reduced strain rates and the
257 migration of crevasses to the upper sections of the debris-covered area and their eventual
258 disappearance (Fig. 3j, S20b), the extension of stream-influenced cliffs through debris
259 destabilisation and thermo-erosional undercutting (Moore, 2018; Fig. 3a) and possibly the
260 emergence of pond-influenced cliffs. Ponds maintain cliffs in more stagnant zones of thicker
261 debris, also characterised by low longitudinal gradients and driving stress as well as increased
262 hummock prevalence (Benn et al., 2017; Steiner et al., 2019; Watson, Quincey, Carrivick, et al.,
263 2017; Fig. 5c). Such evolution has been observed on other glaciers: on Zmutt Glacier, where it
264 was linked to the development of supraglacial valleys driven by stream incision (Mölg et al.,
265 2020); and on Khumbu Glacier, where high relief zones characterised by growing cliffs and
266 ponds have developed as the glacier has slowed (King et al., 2020; Rowan et al., 2021). Our
267 large dataset enables us to show that this evolution holds across a large number of glaciers, and
268 to identify predictors of cliff type and distribution. The development of large pond-influenced

269 cliffs however requires the accumulation of water in surface depressions, which occurs for larger
 270 glaciers with lower longitudinal gradients (Fig. 4, 5c, S17). Most HMA glaciers in this stage of
 271 evolution are located in the Central and Eastern Himalaya (Benn et al., 2012, 2017; Racoviteanu
 272 et al., 2021; Watson et al., 2016; Watson, Quincey, Carrivick, et al., 2017; Fig. 1). However,
 273 some glaciers do not develop such drainage systems due to their relative steepness and small
 274 size, resulting in lower ice cliff densities (Fig. 4, 5d, S20d).

275
 276



277
 278 **Figure 5:** The four glacier evolution states, with their ice cliff distributions. State 1: fast
 279 flowing glacier with thin debris and extensive crevassing. State 2: advanced debris cover, with
 280 thicker debris and lower velocities enabling the development of supraglacial valleys and stream-

281 *influenced cliffs in the non-crevassed areas. State 3a: large stagnating debris-covered tongues,*
282 *characterised by hummocks, thick debris and ponds maintaining cliffs in these zones. State 3b:*
283 *stagnating tongues with thick debris, but high enough longitudinal gradient or low enough*
284 *surface meltwater to prevent the formation of ponds and therefore the survival of cliffs. Figure*
285 *credit: Martin Heynen.*

286

287 **4.2. Implications for glacier mass balance**

288

289 We have shown that ice cliff density and characteristics depend on the evolution state of the
290 debris-covered glacier (Fig. 5), which is controlled mainly by dynamics (velocity) and debris
291 thickness. Leveraging this new understanding of how glacier stage affects the presence of cliffs
292 on their surfaces, we have provided the distribution of each type of cliff on glaciers at different
293 stages of evolution (Fig. 3, 4, S20, Table S5). Future efforts should focus on testing the
294 framework developed here by substantially expanding the number of data points with particular
295 attention to include glaciers at distinct stages. Most of the debris-covered glaciers that have been
296 the object of detailed investigations belong to glacier states 2 and 3 and efforts should be made
297 to explore the whole range of evolution when targeting field studies. Already at this stage,
298 however, the relationships detailed in this study outline a framework to estimate ice cliff
299 distribution based on glacier flow characteristics, that are usually available in prognostic flow
300 models, and debris thickness, without having to map the cliffs. Combined with cliff melt
301 enhancement factors (E. S. Miles et al., 2022), this would allow long term estimation of the
302 contribution of ice cliffs to debris-covered glacier mass balance - representing a key modelling
303 advance.

304

305 Future work should also target the contribution of crevasses to glacier mass balance. Indeed,
306 these features would likely enhance melt even more than traditional stream- and pond-influenced
307 cliffs due to greater surface roughness at their location increasing turbulent fluxes, and additional
308 reflected shortwave contributions from the opposite crevasse walls (Cathles et al., 2011; Colgan
309 et al., 2016; W. T. Pfeffer & Bretherton, 1987; Purdie et al., 2022). Time-lapse images actually
310 show the upper walls of crevasses backwasting as traditional ice cliffs would (Fig. S21).

311 Furthermore, their longer-term evolution and influence on shaping the debris-covered glacier
312 surface remains unclear (Kirkbride & Deline, 2013).

313
314

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321 CNES ISIS Programme. We thank the team of the Centre for Research on Glaciers at the
322 Academy of Sciences of Tajikistan who enabled our 2021 fieldwork on Kyzylsu Glacier.

323

324 **Open Research**

325 The glacier, debris, crevasse, cliff and pond outlines will be made available on Zenodo. Other
326 datasets used include surface velocity from Millan et al. (2022), climate data from ERA5-Land
327 (Muñoz Sabater, 2019), RGI 6.0. glacier outlines (<https://nsidc.org/data/nsidc-0770/versions/6>), the
328 AW3D 30m DEM (Tadono et al., 2014) and ice thicknesses (Farinotti et al., 2019). Atmospherically-
329 corrected Sentinel-2 images prior to 2019 were obtained from CNES through the PEPS platform
330 (Hagolle et al., 2015). From 2019 and later they were processed directly in Google Earth Engine.

331

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