

1 Characterizing geologic and climatic controls on rockfall hazards 2 using an inventory and integrated kinematic and runout model: 3 Skagway, Alaska, USA

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10 Abstract

11 Rockfall is common in steep terrain and poses a hazard to nearby communities. While rockfall triggering mechanisms are
12 highly variable and difficult to quantify, the susceptibility of rock slopes to planar, wedge, or toppling failure can be readily
13 assessed using kinematic analysis. As such, valley slopes with favourable joint orientations exhibit high rockfall
14 susceptibility although the potential for rockfall runout to impact infrastructure and public safety depends on the morphology
15 of downslope terrain. Integrating rockfall susceptibility and runout models with maps of talus deposits accumulated from
16 past rockfall events is an effective combination of tools to inform mitigation but can be difficult to accomplish across
17 extensive areas. Here, we combine these methods with a rockfall inventory spanning 2005 to 2022 to assess geologic and
18 climate controls on rockfall activity in the steep and forested postglacial valleys proximal to Skagway, Alaska, where recent
19 rockfall activity has imperilled public safety, infrastructure, and tourism. The inventory reveals rockfall activity throughout
20 the year with peak activity in early spring that coincides with a rapid rise in minimum daily temperatures. Our field
21 investigations identified two steeply dipping orthogonal joint sets that favour toppling failure along NW-facing hillslopes in
22 the lower Skagway River valley as well as the NW-facing valleys that bound nearby Dyea Bay and Nahku Bay. We used
23 new and existing lidar data and 405 field-derived joint orientations to inform a kinematic toppling failure model that
24 identifies source zones upslope of abundant talus slopes that we mapped from field observations and lidar analyses. We
25 coupled the **predicted** source zones with RAMMS:Rockfall to simulate 197,800 rockfall runout events for scenarios with
26 varying block size and ground cover. The runout predictions highlight zones of low and high rockfall propagation
27 susceptibility that **isare** negatively correlated with hillslope roughness which results from the combined influence of joint
28 orientations that generate bedrock benches and the spatial pattern of glacial erosion. High-hazard segments of the ridgeline
29 exhibit distinct bedrock cliffs and slope-spanning talus slopes that result from the accumulation of rockfall activity over
30 millennia. Taken together, our findings illustrate past controls on rockfall location and timing to inform mitigative measures.

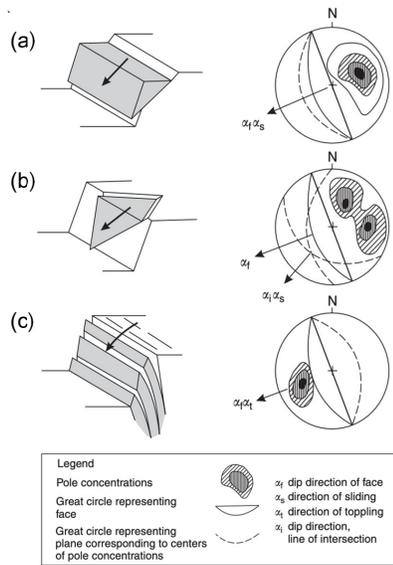
31 **1 Introduction**

32 In steep, rocky landscapes, the detachment and downslope movement of discrete rock fragments (i.e., rockfall) can occur
33 frequently and poses a significant hazard to proximal communities and infrastructure (Hungre et al., 2014). Rockfall activity
34 has been attributed to an array of highly disparate conditioning and triggering processes, including precipitation, frost
35 weathering, insolation, seismic activity, and slope modification (Collins and Stock, 2016; Rosser and Massey, 2022). In
36 Yosemite Valley, California, for example, rockfall triggers include rainfall events, snow melt, and freeze-thaw action that
37 can increase pressure along joints (Stock et al., 2011; Wieczorek and Jäger, 1996). Furthermore, rockfalls in Yosemite
38 Valley may also be triggered on warm summer days by cyclic solar heating, which can propagate exfoliation fractures and
39 lead to detachment (Collins and Stock, 2016). In the European Alps, warming and permafrost degradation have been
40 implicated in significant increases in rockfall activity (Allen and Huggel, 2013; Bajni et al., 2021; Bodin et al., 2015;
41 Paranunzio et al., 2015, 2016). Despite significant progress in characterizing rockfall triggering mechanisms, prediction of
42 rockfall timing and location has limited ability to inform warning systems (Rosser and Massey, 2022). Precursory rock
43 deformation can signal future activity (Abellán et al., 2010; Rosser et al., 2007; Royán et al., 2014), but current methods to
44 quantify precursor deformation across extensive areas composed of steep, high-relief surfaces are limited and oftentimes
45 rockfall occurs without prior deformation (Abellán et al., 2011). As a result, identifying rock slopes with the propensity to
46 generate rockfall, often referred to as rockfall source areas, is a key first step in mitigating rockfall hazards.

47
48 A wide array of methods has been proposed to assess the extent to which hillslopes are prone to rockfall activity. Delineating
49 potential source zones (e.g., Loye et al., 2009) can be accomplished from direct observation of past events, which assumes
50 the location of past detachments coincides with the likely location of future rockfall activity (Luckman, 1976; Matsuoka and
51 Sakai, 1999; Rapp, 1960; Whalley, 1984). Source zones can also be inferred from distinctive evidence such as talus and
52 scree deposits that have accumulated below cliff faces (Borella et al., 2019; Frattini et al., 2008; Moore et al., 2009; Stock
53 and Collins, 2014). Coupled assessment of rock slope morphology and the properties of potential source zones is another
54 common approach that uses digital elevation models (DEMs) for assessing source zones over large areas (Frattini et al.,
55 2008; Guzzetti et al., 2003; Messenzehl et al., 2017; Samodra et al., 2016), while more data-intensive and physically-based
56 deformation models can be used for slope-scale analyses (Matasci et al., 2018). In the absence of rock structure data, some
57 studies (e.g., Guerriero et al., 2024) have applied morphologic criteria (e.g., slope and curvature thresholds) to DEMs to
58 identify anomalous rock slope protrusions that are likely to experience rockfall events (Aksoy and Ercanoglu, 2006; Frattini
59 et al., 2008; Guzzetti et al., 2003; Marquinez et al., 2003; Sarro et al., 2024). Taken together, these studies suggest that the
60 approach to rockfall characterization is highly dependent on the availability of data, expansiveness of the study area, and the
61 desired level of confidence.

62

63 Because rockfall is typically localized along bedding planes, fractures, or joints, collectively referred to as discontinuities,
 64 susceptibility can also be evaluated by determining the geometry of these planes of weakness with respect to the slope and
 65 orientation of rock slopes. Kinematic analysis identifies blocks that can experience instability according to sliding, toppling,
 66 or wedge failure criteria as determined by the geometry of rock slopes and discontinuities (Fig. 1) (Bovis and Evans, 1996;
 67 Wyllie and Mah, 2004). Combining high-resolution DEMs with rock structure data can inform kinematic analyses and
 68 determine the relative likelihood (often defined as susceptibility) of different failure modes across extensive study areas
 69 (Grant et al., 2016; Günther, 2003; Kundu et al., 2023; Meentemeyer and Moody, 2000; Stock and Collins, 2014). Recent
 70 applications of kinematic analysis leverage lidar or photogrammetry to extract bedrock discontinuity data and test kinematic
 71 failure criteria on complex slope geometries, like overhanging rock quarries (Fanos and Pradhan, 2018; Gigli et al., 2022).
 72 Increasingly, the acquisition of discontinuity data is accomplished using automated analysis of point cloud data acquired
 73 from terrestrial laser scanning (TLS) (Matasci et al., 2018) or lidar or photogrammetry acquired from uncrewed aerial
 74 systems (UAS) (Utlu et al., 2023). These approaches are powerful but can be challenging to implement across large areas
 75 characterized by steep, rocky forested slopes where the details of rock structure are often obscured by vegetation.



76
 77 Figure 1. Schematic and corresponding stereonet representations of common rock slope failure modes: (a) planar sliding, (b)
 78 wedge, and (c) toppling. On the stereonet plots, the rock slope face orientation is represented by a solid black line, and poles

79 to planar discontinuities that meet conditions for failure are shown in shaded contours. Dashed lines represent planes of these
80 discontinuities. Modified from Wyllie and Mah (2004).

81
82 Initially, rock fragments move via creep, sliding, toppling, or falling before traveling downslope by following ballistic paths,
83 sliding, and rolling across rocky or talus slopes until stopping when sufficient energy dissipation has occurred via impacts
84 and/or friction (Caviezel et al., 2021). Computational rockfall runout models that account for the physics of these rockfall
85 processes can estimate the trajectories and kinetic energy of falling rocks to determine potential downslope impacts (Dorren
86 et al., 2007; Lu et al., 2021; Scheidl et al., 2020). Many DEM-based tools exist with a range of parameterization options to
87 perform physically-based rockfall simulations and predict the path of rocks over complex terrain and across variable land
88 cover (Lu et al., 2021; Moos et al., 2021). These models have been successfully employed to mitigate rockfall hazards with
89 diversion and attenuation structures, development setbacks, signage, or other means, in a variety of settings, including mines
90 and national parks (Guerriero et al., 2024; Klimeš et al., 2024; Stock and Collins, 2014; Stoffel et al., 2024). As a result, the
91 risk associated with rockfall activity can be reduced even though accurate prediction of triggering events remains elusive
92 (Rosser and Massey, 2022).

93
94 Although rockfall activity occurs in a wide range of geologic and climatic settings, it is particularly commonplace in post-
95 glacial landscapes owing to glacial erosion that alters near-surface stresses, fracture density, topographic variations from
96 glacial erosion, and changes in environmental conditions that occur in the wake of retreating glaciers (Ballantyne, 2002;
97 Leith et al., 2014). In particular, the spatial pattern of glacial erosion can align with the fabric of bedrock discontinuities and
98 set up failure-prone conditions across extensive areas. As such, relatively small changes in the orientation and geometry of
99 glacial valleys relative to the orientation of discontinuities can result in significant and systematic variations in rockfall
100 susceptibility. Although rockfall runout susceptibility is often simulated, the terrain characteristics that govern why and
101 where rockfall events tend to propagate long distances and pose risks downslope are seldom quantified. Rather most studies
102 focus on rockfall source areas whereas hillslope morphology and characteristics may impart a underappreciated role in
103 regulating runout pathways. As a result, geologic and geomorphic controls on rockfall hazard potential are typically not well
104 understood, which prevents us from addressing basic research and applied hypotheses such as how the magnitude and
105 frequency of events accumulate and contribute to mountain-scale erosion and how post-glacial slope morphology affects the
106 efficacy of mitigation efforts (Barlow et al., 2012; Corominas et al., 2014; Hales and Roering, 2007; Hungr et al., 1999;
107 Moore et al., 2009; Rosser and Massey, 2022).

108
109 Rockfall activity is common across much of Southeast Alaska but has been particularly acute in the Municipality of
110 Skagway, which is situated in a narrow, glacially carved valley herein referred to as the ‘Skagway River valley’ and hosts
111 vigorous cruise ship tourism from late spring to early fall. Indigenous knowledge of avalanches in the area has been

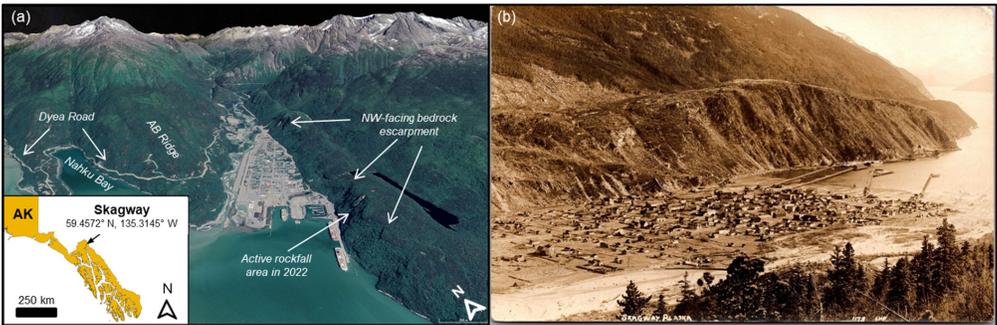
112 established (Thornton, 2010) and documentation of rockfall activity in Skagway by colonial settlers began in the late 1800s
113 when gold prospecting fuelled the establishment of the town. Following decades of sporadic activity, several large rockfall
114 events in summer 2022 impacted cruise docks along Skagway Harbor and generated renewed concern about the extent and
115 scope of rockfall hazards in the area. In particular, the extent and timing of past rockfall activity is not well known and the
116 susceptibility of rockfall initiation and runout in the area, and particularly along a ~5km long ridgeline that abuts the harbour,
117 town centre, and railroad, has not been characterized. This study area affords an opportunity to explore novel approaches to
118 combining kinematic and runout models to assess how glacial erosion and bedrock properties modulate the spatial pattern of
119 rockfall hazard. In this contribution, we summarize a rockfall inventory and geologic data that reflects the distribution and
120 timing of past rockfall activity, document rock structure data from field observations, and synthesize new and existing lidar
121 data from airborne and UAS platforms to inform an integrated kinematic analysis susceptibility and dynamic runout model.
122 Our findings establish the pervasive imprint of rockfall activity along slopes oriented to promote toppling failure and
123 demonstrates how slope morphology determines rockfall propagation susceptibility. We highlight how the pattern of glacial
124 erosion resulted in substantial rockfall erosion and cliff retreat along favourably oriented slopes while unfavourably oriented
125 slopes experienced minimal modification since glacial retreat. Our integrated mapping and modelling approach suggests that
126 postglacial feedbacks between rock structure and hillslope evolution can generate strong variability in potential rockfall
127 impacts and thus inform current mitigation efforts and anticipate future needs.

128 **2 Study area: Skagway, SE Alaska**

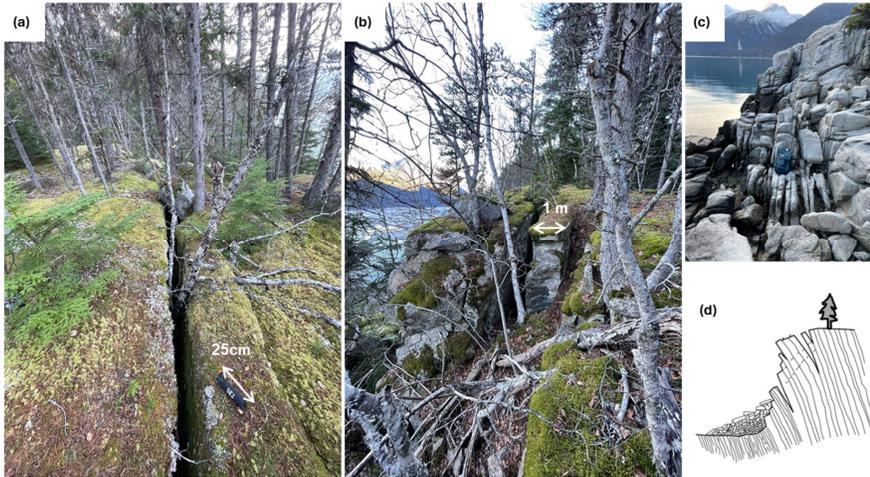
129 **2.1. Geology and glacial history**

130 Near the northern extent of the Alaska Panhandle, Skagway is situated in the Taiya Inlet atop deltaic and fluvial deposits
131 near the outlet of a deep fjord (Fig. 2). The surrounding terrain is steep and rugged, composed of Tertiary granodiorite of the
132 Coast Range Batholith, a belt of plutonic and metamorphic rocks that extends to northern Washington (Yehle and Lemke,
133 1972). Deformation in southeastern Alaska and southwest Yukon is governed by the subduction and translation of
134 the Pacific-Yakutat plates relative to the North American plate in the St. Elias region (Biegel et al., 2024). The Eastern
135 Denali Fault and the Chatham strait fault lineaments, both strike-slip fault systems, meet just south of Skagway (Choi et al.,
136 2021). Deformation associated with these structures appears to impart a significant influence on the orientation of glacial
137 valleys, as fjords in the area tend to be linear, striking north and northeasterly (Yehle and Lemke, 1972). A dam
138 reconnaissance study focused on West Creek, a drainage just 9 km northwest of Skagway, identified three joint sets in the
139 granodiorite bedrock, including two abundant sets with northeast-strike and vertical or steep dips to the south, and one less
140 abundant set with northwest-strike and a consistent vertical dip (Callahan and Wayland, 1965). That study also noted the
141 coincident orientation of topographic lineations in the area and the strike of joints interpreted to be splays from the Chatham
142 strait lineament, which is related to the nearly 3,000-km long Denali fault system. Spacing between the joints is variable,
143 ranging from 1 to 4 meters, and the joints do not exhibit slickensides or cataclastic fabric (Fig. 3a-c). Sheeting joints in

144 granodiorite observed near the tops of glaciated ridges are slightly curved or irregular, tend to parallel the ground surface,
145 and spaced from 1 to 2 meters apart at the surface. Regional studies of glacial history imply that the most recent episode of
146 major glacial retreat and valley exposure in Skagway occurred 10 to 12kya (Baichtal et al., 2021; Menounos et al., 2017) and
147 icefields persist today in nearby inland valleys. The steep slopes around Skagway are generally devoid of glacial till owing to
148 post-retreat erosion and deposition in valley floors in the form of alluvial fans and colluvial deposits.



149 Figure 2. Study area. (a) Oblique view looking N-NE into Skagway River valley, Alaska. Note active rockfall along the NW-
150 facing ridgeline and escarpment above the harbour and cruise ship docks. Use of Google Earth ©2025 permitted for non-
151 commercial use. (b) Oblique view from AB Ridge looking SE across Skagway towards the NW-facing ridgeline and
152 escarpment. This undated and uncredited historic image postdates the late 1890s construction of the current Skagway City Hall
153 and Museum (photo provided by A. Beierly). Local steep cliff faces with fresh bedrock exposure signify active rockfall. Note
154 the lack of vegetation and the sharp bedrock escarpment along the crest of the ridgeline and the abundance of active talus
155 slopes that connect to the harbour.



157 Figure 3. Images (a, b) of open joints and incipient toppling along the bedrock escarpment on the NW-facing ridgeline above
 158 Skagway Harbor. (c) Image of joint orientations along shore of Nahku Bay. (d) Schematic of toppling prone hillside with
 159 opening joints and talus accumulation modified from Wyllie and Mah (2004). Photos a, b, and c by Ian Wachino and Josh
 160 Roering.

161 2.2. Climate and vegetation

162 Currently, Skagway experiences a subarctic maritime climate, characterized by cool summers and cold, snowy winters.
 163 Current average summer temperatures range from 10 to 21°C, with occasional rainfall, and winter temperatures range from -
 164 12 to -1°C, with heavy snowfall, and freezing conditions (Western Regional Climate Center, 2025). High winds that funnel
 165 up the Taiya Inlet are common and for decades it was reported that Skagway's name originated from Lingít words describing
 166 north winds (Thornton, 2010) although recent research concludes that the name derives from a contraction of 'Áa
 167 Wushigagu Ye', which translates as "the Place with Solid Core Trees" (X. Twitchell, pers. comm, 2024). Compared to other
 168 areas in SE Alaska, Skagway receives relatively low annual precipitation (mean annual precipitation is 1.1m) owing to the
 169 rain shadow imposed by the bounding coastal ranges to the south (Daly et al., 2018). Atmospheric rivers account for nearly
 170 70% of annual rainfall in Skagway and intense precipitation associated with these phenomena occur with highest frequency
 171 and intensity from August to October (Nash et al., 2024). Skagway hosts a coastal rainforest of spruce (*Picea sitchensis*),
 172 pine (*Pinus contorta*), and cedar (*Chamaecyparis nootkatensis*) trees with dense underbrush at low elevations (under 1,000m
 173 above sea level) and high-alpine tundra above tree line (Harris and Farr, 1974). Historical photographs and descriptions
 174 suggest that forests covering the slopes perched above Skagway Harbor and township were disturbed through timber harvest
 175 and burning in the early 1900s (Wright et al., 2021).

176

177 **2.3. Historic rockfall activity**

178 Early Western descriptions of rockfall activity in Skagway tend to focus on impacts to the harbour and railroad, including a
179 series of events in 1901 that recorded burial of the tracks near the approach to the wharf (The Daily Alaskan, 1901). The
180 location of this event coincides with the steep rocky slopes above Skagway Harbor, which have generated numerous
181 rockfalls since that account (Fig. 2). A study of geologic hazards in Skagway noted the striking linearity of N- and NE-
182 oriented fjords and valleys and identified abundant actively eroding bedrock escarpments on a NW-facing ridgeline that
183 coincides with a zone of historic rockfall activity adjacent to the township and harbour (Yehle and Lemke, 1972).

184 Downslope of these escarpments are colluvial deposits, consisting of landslide deposits, including talus from historic rockfall
185 events. The abundance and extent of these deposits implies significant slope adjustment and retreat since glacial retreat and
186 the relative activity of the deposits is reflected by the relative abundance of vegetation cover (Ruffner and Abrams, 1998;
187 van Steijn, 2002). Across the valley on the western side of Skagway, these talus deposits are much less prevalent, and the
188 Yehle and Lemke (1975) maps do not indicate the presence of erosional escarpments.

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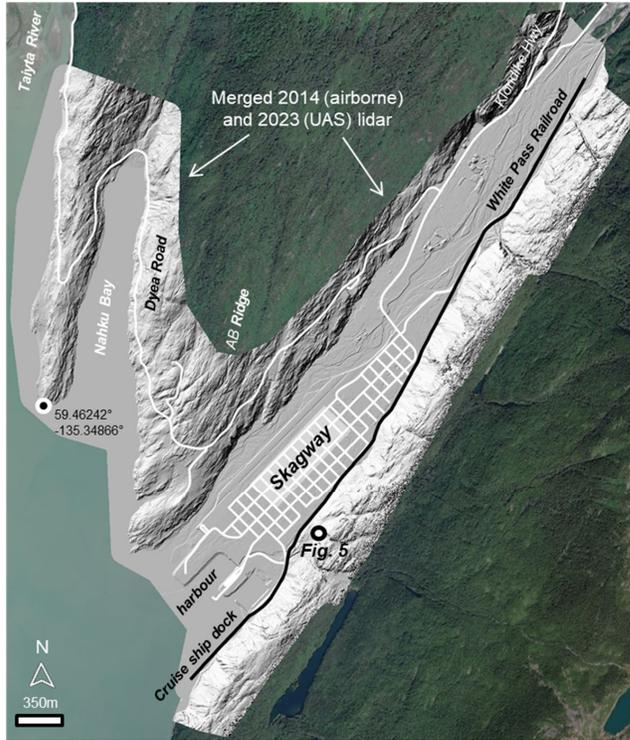
190 Rockfall hazard mitigation in the area is currently focused on the active rockfall source areas above the cruise ship dock in
191 Skagway Harbor. On June 23, 2022, rocks detached from the eastern ridgeline and impacted the cruise ship dock where
192 pedestrian traffic is frequent (Munson, 2022b). Two more rockfall events originating in the rocky slopes above the harbour
193 followed in rapid succession on August 3 and 5, 2022 (Munson, 2022a). Engineering efforts have been completed, which
194 include wrapping rock mesh covers over source areas, installing attenuator nets to block falling rocks, and scaling loose
195 rocks (Brennan and Whistler, 2022). Instrumentation has been installed to monitor the source area, including extensometers
196 installed at the top of the slope, which show that movement in the slide mass has increased from 4 cm per year to 6.5 cm per
197 year as of 2022 (Brennan and Whistler, 2022). Notably, the small section of rocky slopes above Skagway’s cruise ship dock
198 is a small fraction of the roughly 5-km long stretch of ridgeline that borders the eastern margin of Skagway. Rocky
199 escarpments and talus deposits have been noted along the entire ridge (Yehle and Lemke, 1972), including the “Cemetery
200 Slide”, a rockfall source area and runout zone stripped of vegetation by falling debris, which is similar to the active source
201 areas above the cruise ship dock. Although these zones of localized activity are well known, forest cover obscures the
202 geologic and topographic signature of past rockfall activity along the remainder of the ridge such that the pattern of relative
203 susceptibility and runout remains ambiguous.

204 **3 Methods**

205 **3.1. Overview**

206 Motivated by renewed rockfall activity, this study seeks to identify areas susceptible to rockfall initiation and runout within
207 the steep, post-glacial valleys around Skagway. Our analysis extends to the west of Skagway along Dyea Road to the Taiya

208 River, which hosts the Lingit settlement of Dyea and the Chilkoot Trailhead. Dyea Road is a well-travelled corridor that also
209 provides the opportunity to test our methodology across a wider range of topographic and structural configurations (Fig. 4).
210



211 Figure 4: Location map of Skagway, Nahku Bay, and Dyea Road showing a merged hillshade image of the 2014 airborne and
212 2023 UAS lidar bare earth data. White lines denote roads and the thick black line denotes a section of White Pass Railroad and
213 cruise ship dock used for our rockfall runout susceptibility analyses. The 2023 UAS lidar data was acquired along the ridge
214 southeast of the railroad while the 2014 airborne lidar accounted for the remainder of the study area imagery shown here.
215 Location of Figure 5 is shown by black/white filled dot. Background image from USGS NAIP (National Agriculture Imagery
216 Program).

217 3.2 Rockfall inventory

218 To investigate controls on rockfall timing, we accessed data generated for rockfall events between 2005 and 2022 from the
219 GeoEvent Slope Stability Database generated by the Alaska Department of Transportation & Public Facilities

220 (AKDOT&PF) Geotechnical Asset Management Program (Thompson, 2017). This database includes AKDOT&PF
221 maintenance and operations reports, including the location, date, event type (e.g., debris flows, rockfalls, landslides, snow
222 avalanches, flooding), relative magnitude, and cost, of slope processes that impact the Alaska highway system. Notably, this
223 database does not include information for activity along the White Pass Railroad that abuts the rockfall-prone ridgeline along
224 the eastern margin of Skagway. Nonetheless, it includes 866 rockfall event reports along segments of Skagway-Dyea Road
225 and Klondike Highway within our study area (Figure 4) that enabled us to assess climatic controls on rockfall activity. We
226 aggregated rockfall events according to Julian day to investigate seasonal trends in activity over the 17-yr record. For climate
227 context and comparison, we accessed Skagway Airport (PAGY) mean daily rainfall and mean daily maximum and minimum
228 temperature data for 2005 to 2025 (Horel et al., 2002).

229 **3.3 High-resolution topography: Airborne and UAS lidar**

230 Our analysis used two sources of lidar data to inform geomorphic and bedrock mapping, kinematic analysis, and runoff
231 modelling. We used a 2014 airborne lidar dataset with an average ground classified point density of 4.6 m⁻² acquired by the
232 Alaska Department of Geological and Geophysical Surveys (DGGS Staff, 2013) which includes low-elevation terrain in the
233 Skagway River valley, Nahku Bay, and part of Dyea valley (Macpherson et al., 2014). Because this lidar acquisition does not
234 span a significant portion of Skagway's rockfall-prone east ridge that abuts the township and harbour, we conducted a UAS
235 lidar survey in 2023 (Fig. 4). We acquired lidar data across the 2.3 km² area with peak elevations of 220 m near the cruise
236 ship docks and 320 m near the northern extent of the ridgeline (Roering et al., 2025). For the acquisition, the NSF RAPID
237 facility used a Trinity F90+ fixed wing drone with a Qube 240 lidar payload to fly ~120m above ground with 90% coverage
238 overlap. The surveyed area was slightly abbreviated due to a patch of extremely steep terrain where the UAS could not be
239 flown safely at distances sufficiently close to the ground surface to acquire data. The UAS survey produced a point cloud
240 containing 650 million total points with 200 million ground classified points, giving an average ground point density of 43
241 m⁻². We used the ground points to create a 1 m DEM using Cloud Compare (version 2.12.3) and combined it with the 2014
242 airborne lidar data to provide a continuous lidar coverage for our analyses (Fig. 4).

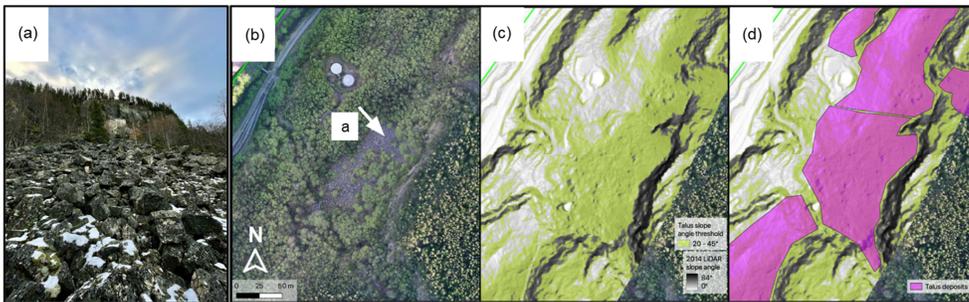
243 **3.4 Geomorphic mapping**

244 We used field observations, historic photographs, and slope thresholds and surface texture from the combined lidar DEM to
245 identify and map talus deposits that reflect the accumulation of rockfall deposits. These talus deposits include both forested
246 and unforested occurrences. To define the characteristic slope angles associated with active talus slopes we measured slope
247 angles from 20° to 45° that coincide with mapped talus deposits along the eastern ridge. Slopes steeper than 45° tend to
248 correspond with bedrock cliffs and outcrops, whereas slopes gentler than 20° often reflect relatively uneroded bedrock
249 surfaces or deposits from fluvial or other mass wasting processes. The relatively smooth texture of accumulated rockfall
250 deposits identified with hillshade and slopeshade layers (Burns and Madin, 2009) was also used to identify active talus
251 slopes as well as bedrock cliffs or outcrops that constitute a rockfall source area. Talus deposits occur on a wide range of

252 scales and for this analysis we focused on mapping patches of talus with area $>100\text{m}^2$ to ensure accuracy and highlight zones
253 of significant activity (Fig. 5). Specifically, we identified terrain that exhibits the relevant slope values as well as surface
254 textures consistent with talus deposits and then mapped polygons that enclose these zones when their areas exceeded 100m^2 .
255 The polygons were often separated by bedrock outcrops, gullies, and anthropogenic features.

256

257



258 Figure 5: Field images and lidar mapping of talus mantled slopes. (a) View looking SE along an exposed talus deposit with
259 boulder sized blocks at the base of a 40 m cliff known as Kirmse’s Cliff (lat: 59.45251, long: -135.31147). (b) Aerial imagery
260 from 2023 UAS survey showing a talus deposit and bedrock cliff, white arrow shows view direction for a, (c) Terrain within
261 the slope angle range of 20° - 45° colored in light green, and (d) map of talus polygons (pink) generated from lidar slope shade
262 and slope angle maps and orthoimagery. Hillshades in c and d derived from 2023 UAS lidar data. Background image from
263 USGS NAIP (National Agriculture Imagery Program).

264 3.5 Bedrock structure and discontinuities

265 To quantify the geometry of joints and discontinuities that contribute to rockfall initiation, we collected 405 structural
266 measurements (specifically, the strike and dip of planes that define the interfaces) at nearly 50 locations within the study area
267 and combined them to generate a ~~comprehensive-representative sample of discontinuities for our study area~~ **discontinuity**
268 **dataset** (Chaminé et al., 2015; Kundu et al., 2023). The steep, forested, and uneven terrain surrounding Skagway limits
269 access to outcrops ~~such that strict adherence to the~~ ~~and the~~ traditional ‘scanline’ method (Priest and Hudson, 1981) was
270 untenable. Furthermore, the significant forest cover and expansiveness of the study area precluded the use of ground-based
271 laser or SfM (structure from motion) methods for acquiring structural information. Instead, we traversed the base of outcrops
272 ~~throughout the study area~~ as an approximation of scanlines and measured the orientation of planar surfaces expressed in the
273 outcrop with FieldMoveClino, a digital compass-clinometer smartphone app (Oliinyk et al., 2020), which enabled rapid and
274 accurate data acquisition. Our measurements were acquired across a wide range of locations in the study area to characterize

275 spatial variations in discontinuity orientations [for implementation in a pixel-based kinematic analysis](#) (Günther et al., 2012).
276 In particular, we visited outcrops along the eastern, southern, and western corners of the study area to ensure that the full
277 range of relevant joint orientations was represented (Chaminé et al., 2015; Chiles and Marsily, 1993; Terzaghi, 1965; Zhou
278 et al., 2017). We identified joint clusters by converting the strike and dip of discontinuity planes to poles on stereonet ~~plots~~
279 and used [smoothed ~~contouring~~ Kamb contours with StereoNet v1.1](#) to separate ~~different~~ clusters (Cardozo and Allmendinger,
280 2013).

281 3.6 Kinematic analysis of rockfall susceptibility

282 To assess the spatial pattern of rockfall susceptibility across the study area, we adopted a kinematic analysis approach with
283 our discontinuity data and applied criteria for planar sliding and toppling failure within our combined lidar DEM. This
284 approach foregoes the mechanical complexity and extensive parameterization of more sophisticated analyses [that incorporate](#)
285 [three-dimensional stability models and joint filling, roughness, and persistence data](#). (e.g., Matasci et al., 2018) in order to
286 generate results that span an extensive area. [Rather, our analysis incorporates both topography and bedrock structure data](#)
287 [and thus provides insights beyond those provided by susceptibility criteria that are informed by simple thresholds defined by](#)
288 [slope angle alone](#). Kinematic analysis requires discontinuity data that is locally representative [in order determine rockfall](#)
289 [susceptibility at locations of interest](#) (Albarelli et al., 2021; Dorren et al., 2007; Günther et al., 2012). Traditionally,
290 discontinuity measurements are taken in the field, whereas many modern applications extract discontinuity orientations from
291 high-resolution point clouds of the rock slope face (Albarelli et al., 2021; Utlu et al., 2023). Field measurements remain a
292 reliable and relevant means to capture joint orientations (Kundu et al., 2023; Zhou et al., 2017), especially in locales where
293 terrestrial laser scans are not feasible due to hazardous terrain or where slope faces are obscured by vegetation.
294 As described below, the remarkable consistency of discontinuity orientations across the study area inspired this approach and
295 therefore we invoked the entire distribution of measured joint orientations at all locations to perform the kinematic analysis.
296 Specifically, we applied the stability criteria for each failure mode at each pixel in the merged lidar DEM by estimating the
297 fraction of the 405 joint orientations that are predicted to be unstable given the topographic aspect and slope angle of that
298 pixel. The failure criteria for planar and toppling failure are defined following Wyllie & Mah (2004) and described below.
299 Essentially, this approach is equivalent to locally performing a stereonet analysis of rock slope failure across our study area
300 and aggregating the results to identify potential rockfall failure modes and areas of high relative susceptibility. For the
301 analysis, we used a friction angle of 40°, consistent with measured values for jointed granodiorite similar to Skagway's
302 lithology (Alejano et al., 2019). To assess the accuracy of our modelled rockfall susceptibility maps, we visually compared
303 our predictions to the location of recent rockfall events in Skagway, as well as mapped bedrock cliffs and talus deposits,
304 which serve as a proxy for prior rockfall activity (Loye et al., 2009; Stock and Collins, 2014). In addition, we compared the
305 downslope direction of talus deposits with the aspect of topple-prone slopes to assess their relative correspondence.
306

307 Planar slides occur when the inclination of a bedrock slab exceeds the friction angle and it slides along a planar
 308 discontinuity. Toppling failures occur when discontinuities steeply dipping into the rock slope face form slabs or columns of
 309 rock that rotate forward along a fixed base (Fig. 1). Two types of toppling failures can occur that are influenced by the
 310 strength of the rock mass and the geometry of discontinuities. Flexural toppling, where slabs of rock bend forward until they
 311 break in flexure, is typical in shale and slate where orthogonal jointing is not well developed. Block toppling is common in
 312 crystalline bedrock with orthogonal joint sets, where two steeply dipping joint sets form the sides of blocks, and a third set of
 313 low angle, widely spaced joints form a basal failure plane. The active rockfall source area situated above Skagway's cruise
 314 ship dock has been described as a progressive toppling failure with a stair-stepped basal feature (Brennan and Whistler,
 315 2022). Topple failures observed in the field are consistent with this description, which is described by the block toppling
 316 failure mechanism. As a result, our analysis focuses on block toppling and planar sliding given that field observations and
 317 geotechnical reports do not identify wedge failures as a prevalent mechanism of rock slope instability. The challenge of
 318 implementing multiple discontinuity orientations required for wedge analyses across our entire study area also encouraged us
 319 to focus on block toppling and planar sliding in our analyses.

320
 321 The criteria for planar, wedge, or toppling failure is based on the orientation of discontinuities and their orientation relative
 322 to the rock slope face (Wyllie and Mah, 2004). The dip direction of the discontinuity (A) and rock slope (f) is given by α_A
 323 and α_f , respectively, and the dip angle of the discontinuity and rock slope, both relative to horizontal, is given by ψ_A and ψ_f ,
 324 respectively. The friction angle of the joint interfaces is given by ϕ .

325
 326 Accordingly, a rock slope is susceptible to planar sliding failure along a discontinuity if the following three conditions are
 327 simultaneously met:

328
$$|\alpha_A - \alpha_f| < 20^\circ ; \psi_A < \psi_f ; \psi_A > \phi \quad (1)$$

329 The first condition requires that the interfaces are aligned in a sufficiently similar orientation (in this case within 20°) while
 330 the second ensures that the discontinuity dip is shallower than the angle of the bedrock slope such that the discontinuity
 331 intersects or 'daylights'. The third and final condition demands that the interface slope angle exceeds the angle of friction. All
 332 three conditions must be met at a given location for planar sliding to be deemed likely.

333
 334 For block toppling failure, the following two conditions must be met simultaneously:

335
$$\alpha_f - 20^\circ < (\alpha_A \pm 180^\circ) < \alpha_f + 20^\circ ; (90^\circ - \psi_f) + \phi < \psi_A \quad (2)$$

336 The first condition asserts that the discontinuity must dip into the rock slope face and be parallel, or nearly parallel (e.g., within
337 20°), to the dip direction of the slope face. The second condition indicates that the discontinuity dip must exceed the friction
338 angle allowing for interlayer slip between the blocks. In our model, the maximum allowable dip direction deviation is $\pm 20^\circ$
339 for both planar slide and block toppling failure. Although this value is sometimes chosen to be $\pm 10^\circ$ for block toppling we
340 expanded the constraint to $\pm 20^\circ$ (Cruden, 1989; Gigli et al., 2022).

341
342 Using equations 1 and 2, we estimated the number of joints in our field-derived dataset ($n=405$) that are predicted to exhibit
343 planar and toppling failure, respectively, for each pixel in our merged lidar DEM. Also, by simultaneously accounting for
344 both modes of potential failure at a given location it is possible to assess the combined susceptibility to toppling and planar
345 sliding although we do not formally account for this possibility in our analysis. Our maps of planar and toppling failure are
346 then calculated as the percentage of joints that meet the conditions required for failure conditions at each pixel in our study
347 area. For example, a toppling failure index value of 0.21 for a given pixel in our DEM indicates that 21% of the joints in our
348 joint dataset satisfy the two conditions in equation 2. This approach provides a description of relative rockfall initiation
349 susceptibility across our study area.

350 3.7 Rockfall runout modelling with RAMMS

351 To model potential runout paths associated with rock slopes that have high rockfall susceptibility, as determined by our
352 kinematic analyses, we used the 3D rockfall simulation software RAMMS:Rockfall (<https://ramms.ch/ramms-rockfall/>) to
353 represent the sliding, bouncing, and rolling motion of blocks as well as the internal, gravitational, and contact forces of a
354 rigid body that can translate and rotate. This model accounts for the energy balance (including rotational momentum) of
355 falling rocks and has been used extensively at a range of scales for both applied and fundamental research studies (e.g.,
356 Caviezel et al., 2021; Kleinn et al., 2024; Leine et al., 2014; Lu et al., 2019; Ringenbach et al., 2023). The primary inputs
357 required for the RAMMS:Rockfall model include digital elevation data (i.e., DEM), the location of rockfall source areas,
358 specification of ground cover, and the shape and size of the falling blocks.

359
360 The model integration between our kinematic rockfall susceptibility analysis and the RAMMS:Rockfall simulations was
361 accomplished using the following workflow. First, we used our merged lidar DEM, which has a 1x1 m pixels (Fig 4) to
362 generate rockfall susceptibility index values for toppling and sliding failure and spans the area shown in Fig. 4. Given that
363 toppling instability dominates our study area, we ~~To identify potential source areas as we identified pixels in our maps of~~
364 with toppling susceptibility with values greater than 5%. Pixels with >5% toppling susceptibility demarcate rocky cliffs
365 situated above our mapped talus deposits as well as areas of recent rockfall activity in the Skagway Harbor (Fig. 5). To link
366 the susceptibility model to our runout model, the pixels with a >5% high toppling susceptibility were converted to polygons
367 and only polygons with area greater than 25 m² were retained to eliminate small, local high-relief features like boulders and
368 trees that can perpetrate the characteristic signature of rockfall source zones. Then, Rockfall source points for RAMMS

369 modelling were randomly distributed ~~aeross-within~~ the resulting polygon coverage with a density of 0.04 m² and a minimum
370 point spacing of 5 m. ~~The resulting 4,945 points serve as our rockfall initiation source point coverage and we used these~~
371 ~~points as input for RAMMS rockfall runout modelling.~~ This methodology follows convention used in other studies (Lu et al.,
372 2021) ~~and yielded 4,945 rockfall initiation points for each of our simulation scenarios and we generated an array of vector~~
373 ~~and raster output files described below.~~

374
375 The slopes east of Skagway are heavily forested, except in locations where falling debris has stripped vegetation, such as the
376 cruise ship dock and at the northern extent of the eastern ridge bordering Skagway. In RAMMS, we represented forested
377 areas as spruce alpine forests and trees were simulated in these areas using the 'dense forest' category in RAMMS, which is
378 defined by a stem density of 600 trees per hectare with a mean diameter of 30 cm. These parameters were chosen based on
379 our field observations and the typical density of mixed red alder coniferous stands in Southeast Alaska (Poage et al., 2007).
380 The effect of trees in the RAMMS rockfall runout module is to attenuate energy and reduce velocity, thus constituting a
381 significant impact on hazard potential. We mapped the distribution of trees by visually assessing the USGS NAIP imagery as
382 well as our UAS orthoimagery. The small amount of terrain (less than 5% of the study area) that exists outside these forested
383 areas was set to the fine talus cover category in RAMMS, which reflects negligible ground cover atop relatively fine-grained
384 talus deposits consistent with our field observations. We performed simulations with two land cover scenarios: 1) dense
385 forest and 2) fine talus cover, assigned across the entire simulation area to assess the potential role of timber harvest and fire
386 on rockfall runout and provide a conservative assessment of the hazard extent.

387
388 ~~Consistent with previous studies, w~~We estimated representative block size and shape by measuring the major axes of
389 randomly selected blocks in exposed talus piles (Hales and Roering, 2007; Messenzehl and Dikau, 2017; Pérez, 1998). To
390 estimate representative block sizes, the intermediate axis of 74 blocks was measured from field measurements and high-
391 resolution point clouds combined with orthoimagery (Fig. S1). We determined the mean intermediate axis size to be 1.08 m
392 while the 50th percentile was 0.66 m and the 95th percentile was 3.56 m. Blocks observed in the field are typically tabular and
393 the characteristic geometry of blocks was estimated by measuring the long, intermediate, and short axes of 10 blocks with
394 sufficient exposure to allow measurement using our UAS-derived point clouds. We applied the characteristic aspect ratio to
395 the 50th percentile and 95th percentile intermediate axis values from our measurements. The dimensions of the resulting rocks
396 used in the simulation were 0.94 m x 0.66 m x 0.37 m (medium, 50th percentile), and 5.10 m x 3.56 m x 1.99 m (large, 95th
397 percentile), which represent moderate and large block sizes, respectively. Given the tendency for large blocks to travel
398 longer distances, our 95th percentile blocks are intended to reflect the conservative (or long runout) scenario (Statham, 1976).
399 For these simulations, we assumed rock density of 2,700 kg m⁻³.

400
401 To simulate the range of potential rockfall impacts, we focused on four scenarios for RAMMS simulation with the following
402 parameterizations: 1) 50th percentile block with fine talus cover, 2) 50th percentile block with dense forest, 3) 95th percentile

403 blocks with fine talus cover, and 4) 50th percentile block with dense forest. To account for the stochastic nature of rockfall
404 release, we used RAMMS to select 1 of 10 randomly chosen block orientations to be released at each source point, yielding
405 49,450 individual rockfall runout paths for each of the four scenarios. Our results presented here focus on the two end-
406 member scenarios (50th percentile with dense forest cover and 95th percentile with fine-grained talus over) to illustrate the
407 extreme range of rockfall behaviour. In particular, the 50th percentile block size and dense forest represents the most typical
408 scenario whereas the 95th percentile and fine talus cover reflects an extreme case of large block detachments coupled with
409 slope clear conditions that would result from burning or extensive forest harvest.

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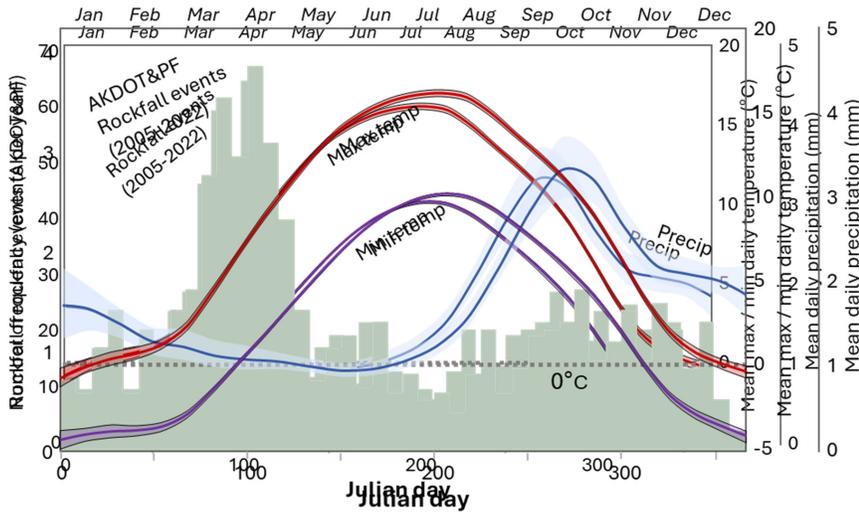
411 For our runout analysis, we focused on the eastern NW-facing ridgeline of the Skagway River valley to assess potential
412 impacts to the harbour and township. We used an array of analyses to investigate rockfall runout patterns and topographic
413 controls on the runout behaviour. First, to identify terrain with high likelihood of rockfall runout we used RAMMS to
414 calculate the number of rockfall events that traversed each pixel in our model domain for each of the scenarios. As such, the
415 cumulative number of rockfall passages at each pixel accounts for both the abundance of upslope source areas as well as the
416 tendency for topography to steer or direct rockfall into particular pathways. Second, we used RAMMS to create a “digital”
417 boundary (or barrier) coincident with the railroad tracks along the base of the ridgeline to record rockfalls that bypass the
418 boundary and have the potential to impact the harbour and township. Third, to estimate how topographic properties moderate
419 rockfall runout, we calculated local slope and terrain roughness across the simulation domain. Roughness was calculated as
420 the standard deviation of local slope values within a 5-m radius window. This approach has been successfully used to
421 differentiate the kinematics and age of landslide deposits (Booth et al., 2017; LaHusen et al., 2020) and in this case, we
422 choose the 5-m scale to be consistent with the scale of blocks, fractures, and bedrock landforms. Finally, we generated a 5.4-
423 km long transect coincident with the railroad within our simulation domain to quantify along-ridge variations in rockfall
424 passages, upslope source areas, slope angle, and terrain roughness.

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426 4 Results

427 4.1 Rockfall inventory

428 The AKDOT&PF database includes 866 reports of rockfall-related maintenance and operation activities along the 10.3-km
429 long segment of Skagway-Dyee and Klondike Hwy within our study area between 2005 and 2022 (Fig. 6,7). This implies an
430 average rockfall frequency of 50 events per year, although this value is an overestimate because some of the reports are
431 redundant given that multiple days are reported in response to a single event. Among the events, 7 resulted in road closures
432 that lasted 3 days or longer in March 2012, October 2012, January 2014, March 2015, February 2016, September 2016, and
433 December 2020.



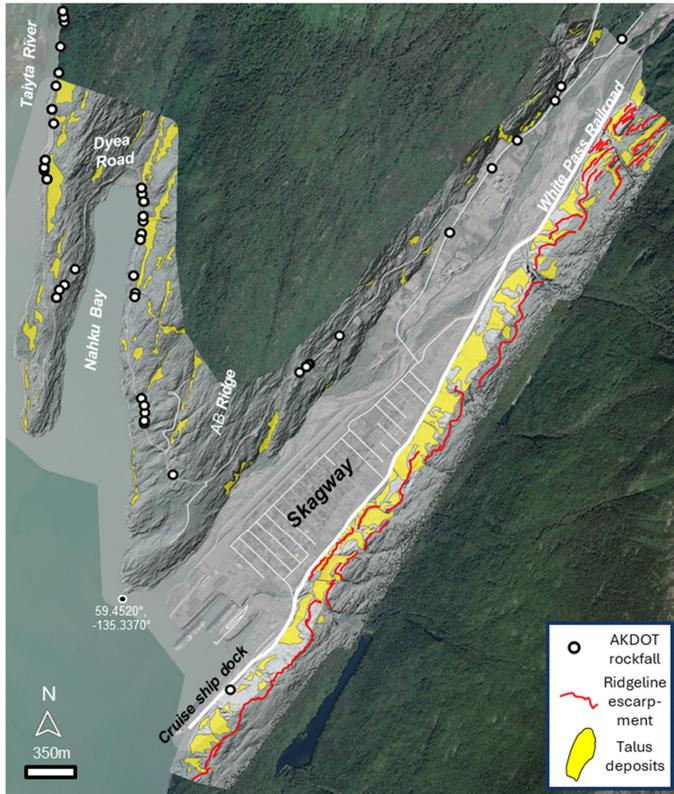
434
 435 Figure 6. Analysis of seasonal variation in rockfall activity-frequency and climate variables from the AKDOT&PF geoevent
 436 database (2005-2022) and daily mean precipitation and daily maximum and minimum temperature from the Skagway
 437 Airport (PAGY) for the period 2005-2025. The number of rockfall events (green bars) exhibits seasonal variations that don't
 438 obviously align with precipitation (blue) although maximum temperature (red) and minimum temperature (purple) increase
 439 significantly during the typical period of rockfall activity in March and April. The horizontal dashed grey line represents
 440 freezing. The confidence intervals for the climate data represent standard error of mean values over the period of record.
 441

442 According to our analysis, rockfall events peak in late March and April, occurring at a pace that is 4x greater than the
 443 remainder of the year (Fig. 6). This substantial uptick in activity corresponds with a seasonal increase in daily temperatures,
 444 particularly when the minimum daily temperature exceeds zero. This implies-temporal pattern is consistent with the well-
 445 documented observation that thawing of frozen rock slopes promotes the destabilization of blocks through the loss of tensile
 446 strength and increases in pore pressure from melting ice and snow (Birien et al., 2024; Imaizumi et al., 2025; Matsuoka,
 447 2019). In the fall, increased daily rainfall associated with atmospheric rivers with a detectable but small increase in activity.
 448 The mid-summer period of warm temperatures and dry conditions corresponds with the least active period. Some notable
 449 high impact rockfall events correspond with intense rainfall events, including December 2, 2020, when widespread events
 450 were preceded by over 3 inches of rainfall in the previous 24 hours.

451 **4.2 Geomorphic mapping**

452 The morphology of glaciated valleys around Skagway is variable owing to bedrock structure, differential glacial erosion, and
453 post-glacial landscape evolution (Fig. 4). These factors generate systematic variations in the abundance of bedrock cliffs that
454 serve as rockfall source areas as well as long, steep slopes that facilitate long rockfall runoff. On the east side of Skagway
455 River valley, our lidar DEM and field observations reveal a distinct northwest-facing bedrock escarpment that runs parallel
456 just below the crest of the ridgeline (Fig. 7). This feature is particularly distinct above the cruise ship dock, where the
457 ridgeline has high relief compared with sections to the north that abut the township. Below these bedrock escarpments, we
458 observe abundant talus deposits that extend continuously downslope to the base of the ridgeline and the valley floor (Fig. 7).
459 An undated historic photograph which postdates the 1899 construction of the current Museum and City Hall depicts the
460 eastern ridgeline in a state of minimal forest cover such that the escarpment and talus slopes above the harbour are clearly
461 visible (Fig. 2b). These observations imply substantial post-glacial erosion through lateral (southeastward) retreat of the
462 ridgeline as talus slopes convey bedrock downslope creating long and relatively smooth pathways for rockfall runoff. In
463 Figure 2b, the ridge on the left side of the image exhibits gentler slope angles ($<20^\circ$) and a benchy morphology which
464 implies less extensive post-glacial erosion and slope modification via rockfalls. Atop the ridge and east of the escarpment,
465 the ridgeline contains abundant evidence of unmodified glacial erosion features (Figure 4).

466
467 By contrast, the west side of the Skagway River valley has a very different morphology, in that it lacks a distinct escarpment
468 and instead exhibits consistent and gradual slopes that imply minimal post-glacial modification. Locally, we observe vertical
469 cliffs along the Skagway River, but otherwise the west side of the Skagway River valley consists of gentle rock slopes that
470 form prominent ridges and parallel the strike of the valley. We observe a similar pattern of bedrock escarpments and talus
471 deposits along the NW-facing slopes of two parallel ridgelines between Skagway and the Taiya River (Fig. 7).



473 Figure 7: Distribution of talus deposits (yellow polygons), AKDOT&PF rockfall geoevents (2005-2022) (white/black dots),
 474 and Eastern ridge bedrock escarpment (red lines). Note the abundance of talus deposits on the NW-facing ridgeline in Skagway
 475 and on NW-facing slopes in Nahku Bay and along Dyea Road. Background image from USGS NAIP (National Agriculture
 476 Imagery Program). Merged lidar hillshade image has 50% transparency.

477

478 Our lidar and field mapping revealed abundant talus slopes on northwest-facing ridgelines across our study area. More
 479 generally, talus deposits compose 12% of the 7.2 km² total mapped area (Fig. 7). Along the eastern ridgeline, we identified
 480 abundant talus slopes which collectively make up 25% of that ridgeline area. On the west side of the Skagway River valley,
 481 the southeast-facing ridgeline hosts sparse talus cover that constitutes only 3% of that side of the valley. Similarly, talus
 482 deposits on the southeast-facing ridgelines bordering Nahku Bay are much less abundant (1%) and smaller in area than on the

483 northwest-facing ridgeline that abuts the bay (11%). In summary, talus slopes are significantly more abundant on NW-facing
484 slopes across our study area and their location tends to correspond with AKDOT&PF geoevents along Dyea Road (Fig. 7).

485 **4.3 Bedrock structure and discontinuities**

486 To characterize the geometry of discontinuities with the potential to generate rockfalls, we collected 405 joint orientations
487 from 48 granodiorite outcrops across the study area (Fig. 8a, supplemental materials) and plotted the data as poles to planes
488 on an equal area stereonet with Kamb contours to identify dense clusters of poles which were then grouped into joint sets
489 (Fig. 8b-e). The clustering algorithm identified two dominant joint sets were identified in this survey (*J1* & *J2*), which are
490 steeply dipping and approximately orthogonal (Fig. 8e). The steeply dipping joints are conducive to toppling, which is the
491 most observed failure mode in Skagway. The most densely defined joint set is *J1*, which parallels the strike of the lower
492 Skagway River valley and the eastern ridgeline and predominantly dips to the southeast. The less densely defined joint set
493 (*J2*), is approximately orthogonal to *J1*, has near vertical dips, and strikes northwest.

494
495 In order to assess the consistency of rock structure, We subsampled the joint orientation data in three geographic zones at
496 the western, eastern, and southern corners of our study area ~~in order to assess the consistency of the rock structure~~. Joint
497 orientations from the western portion of the study area are remarkably similar to those observed in the eastern and southern
498 sections of our study area (Fig. 8b-d). Although some of the secondary and surface parallel joints were less prominent at
499 these locations, our finding of similar major joint orientations ~~This finding~~ supports our use of the same bedrock structure
500 data for kinematic analysis across the entire study area.

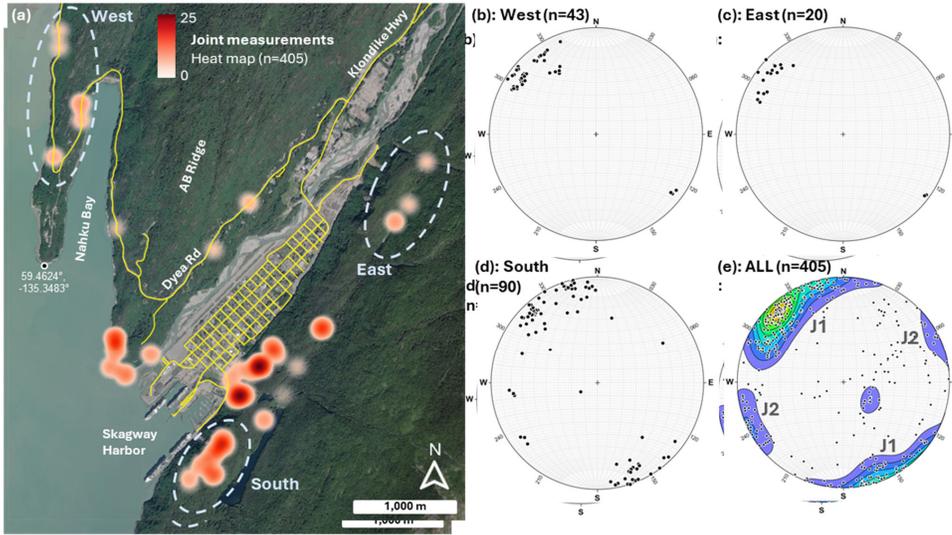


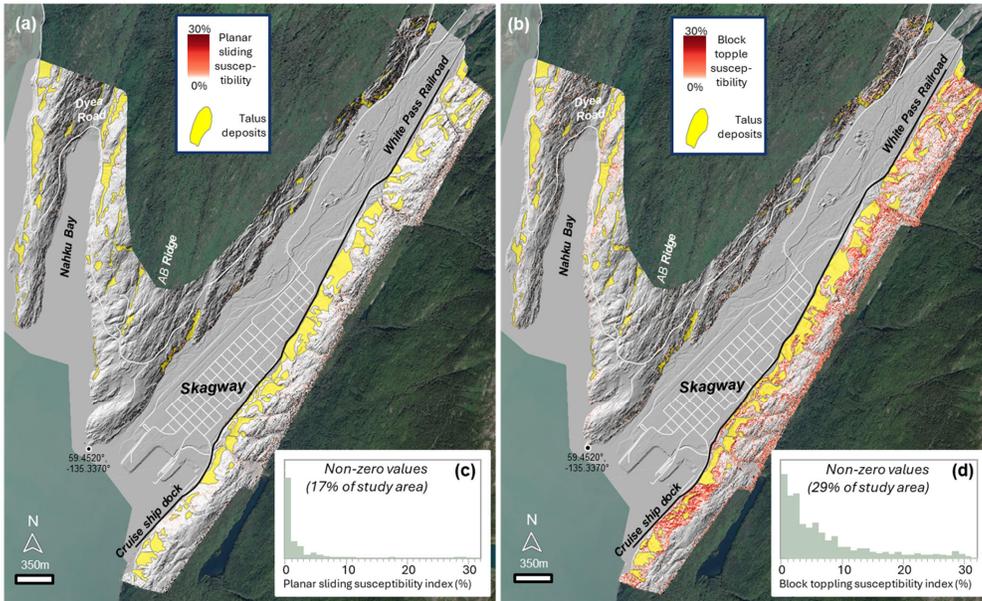
Figure 8: Joint survey data. (a) Location of 405 structural measurements from 48 outcrop locations with heat map showing relative abundance and dashed ellipses showing subsampled data shown in panels b-d. (b-e) Lower hemisphere equal area stereonet plots of joint measurements visualized as poles to planes for West (b), East (c), South (d), and ALL joint data (e). The plot in e shows Kamb contours to highlight dense clusters of poles (warm colors reflect high density and cool colors convey low density) and two dominant joint sets (J1 and J2) are labeled. Background image in (a) from USGS NAIP (National Agriculture Imagery Program).

4.4 Kinematic analysis of rockfall susceptibility

By combining equations 1 and 2 with our joint orientation data (Fig. 8) and merged lidar dataset (Fig. 4), we mapped susceptibility to planar sliding and block toppling, respectively, across our study area (Fig. 9a,b). Terrain susceptible to planar failure is sparse and 83% of the terrain has zero values of susceptibility such that none of the measured joint orientations satisfy the planar sliding criteria. Furthermore, the terrain with non-zero planar sliding susceptibility values has very low values with a small fraction exceeding 5% (Fig. 9c). By contrast, our analysis demonstrates that 29% of the terrain has non-zero values of block toppling susceptibility and a substantial fraction of the non-zero values exceed 5% (Fig. 9d). This result emerges because the abundance of consistently oriented joints with vertical or sub-vertical dips promotes block

517 toppling, which is supported by field observations. Furthermore, given the consistent orientation of sub-vertical joints across
518 our study area (Fig. 8), the primary control on rockfall susceptibility to toppling is the orientation and inclination of rock
519 faces according to equation 2. Along the ridge that borders the eastern margin of Skagway River valley, for example, the
520 glacially flattened bench at the ridge crest is not steep enough ($<20^\circ$) to meet topographic conditions for either failure mode
521 (Fig. 9a,b). Moving to the west side of the crest, however, the gentle ridgetop abruptly transitions to the steep escarpment
522 where overhanging, cliffy bedrock slopes are perched above extensive talus deposits (Fig. 7). In these locations, our analyses
523 show that a substantial portion ($>20\%$) of observed joints promote toppling failure (see deep red colours in Fig. 9b).
524 Furthermore downslope, we observe patchy zones of high toppling susceptibility, many of which are in close proximity to
525 Skagway township and harbour. Along the southeast-facing rock slopes that border the west side of Skagway, our analyses
526 show few and small patches of terrain with toppling susceptibility approximating 5%, indicating low susceptibility. This
527 asymmetric susceptibility pattern continues along the sub-parallel ridges west of Skagway along Dyea Road with west- and
528 northwest-facing ridgelines exhibiting abundant patches of terrain with high propensity for toppling failure and east- and
529 southeast-facing slopes showing negligible toppling susceptibility (Fig. 9b).

530 ~~More generally, b~~By combining our talus deposit map with our toppling susceptibility map, we note a strong correspondence
531 such that zones with $>5\%$ toppling failure tend to occur just upslope of talus-mantled slopes (Fig. 9b). Using visual
532 validation (e.g., Albarelli et al., 2021)Furthermore, our maps show that zones with values of toppling susceptibility less than
533 5% tend to be more isolated and less clearly connected with talus deposits (Albarelli et al., 2021). As a result, the 5% (or
534 0.05) toppling susceptibility index value serves as an effective threshold for defining rockfall source areas.



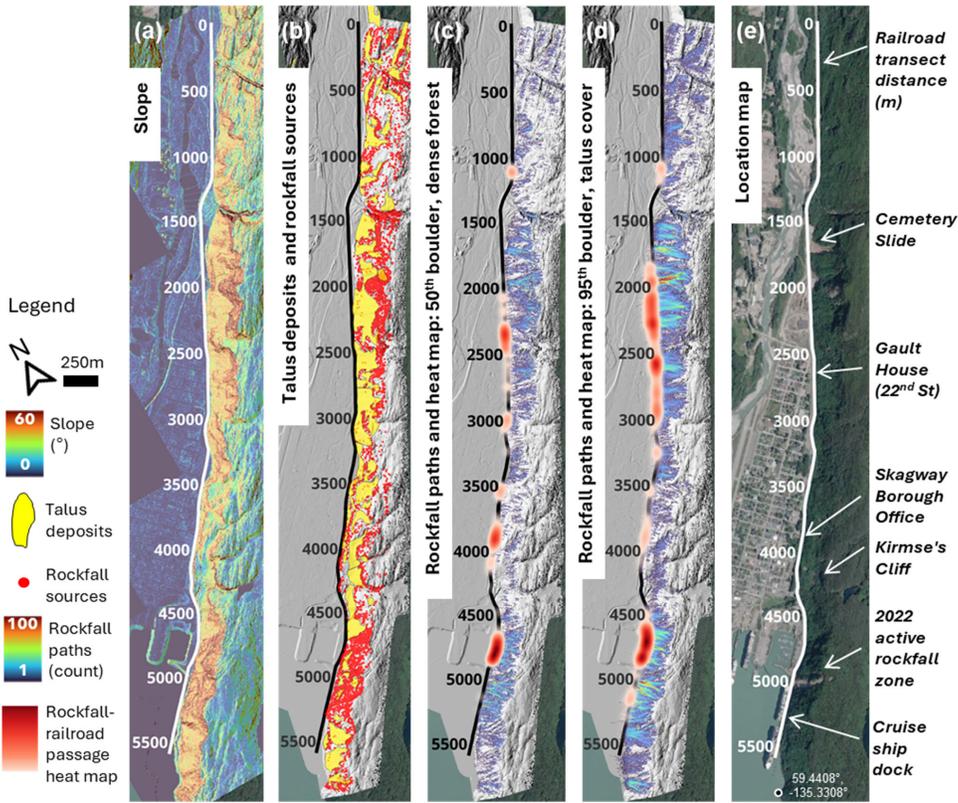
535 Figure 9: Maps of (a) planar sliding and (b) block toppling susceptibility indices using combined 2014 airborne and 2023
 536 UAS lidar datasets and joint orientation data. Histograms of (c) planar sliding and (d) block toppling susceptibility indices
 537 for non-zero values. The mapped and plotted values are the percentage of field-surveyed joints deemed unstable at each pixel
 538 according to equations 1 (planar sliding) and 2 (block toppling). Yellow polygons denote talus deposits. Note the abundance
 539 of toppling failure zones on NW-facing rock slopes that border Skagway and Nahku Bay as well as the correspondence
 540 between toppling susceptibility and talus deposits. Hillshade imagery derived from combined 2014 and 2023 lidar data.
 541 Background image from USGS NAIP (National Agriculture Imagery Program).

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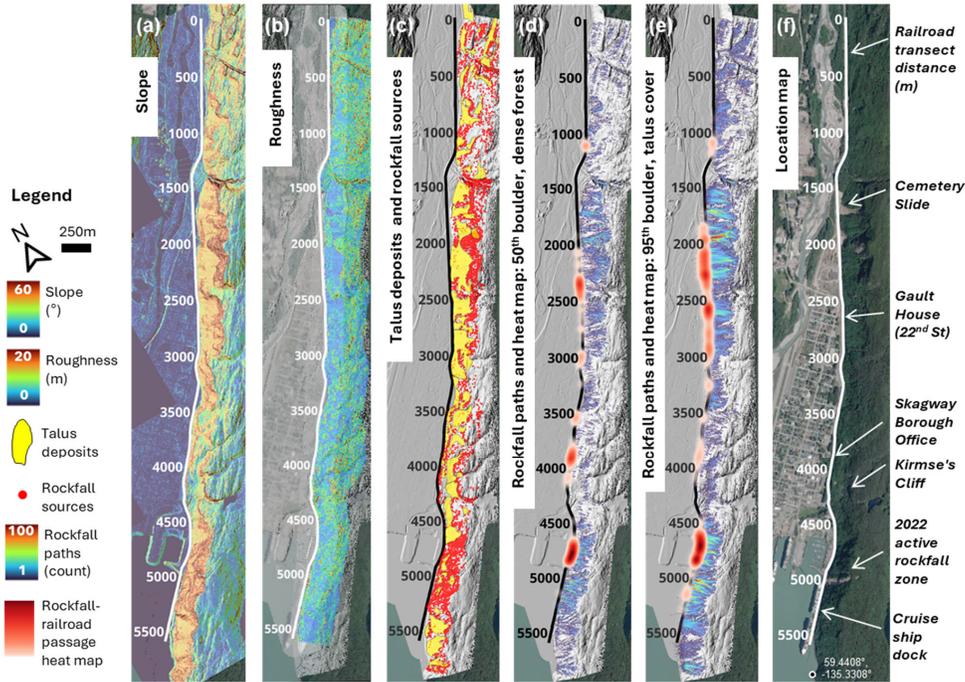
543 **4.5 Rockfall runout modelling using RAMMS**

544 Using zones of high toppling susceptibility (i.e., [susceptibility index](#) >5%) as source areas for rockfall initiation, we applied
 545 RAMMS to model the runout of 49,450 rockfall events for each of the four scenarios that account for differences in block
 546 size and ground cover. We applied the runout model along the ridge bordering the eastern margin of Skagway and used the
 547 5.4-km long section of the White Pass Railroad extended along the cruise ship dock to demarcate rockfall passages with
 548 potential impact to the harbour and township (Fig. 10a-f_e). The ridge is steeper in the southern (4500 to 5500 m on the
 549 railroad transect) and central (1500 to 3000 on the transect) sections where extensive bedrock cliffs protrude above [steep](#).

550 ~~low roughness talus deposits talus deposits~~(Fig 10a,b). These cliffs are identified as zones of high toppling susceptibility and
551 thus designated as rockfall source areas (Fig. 10b,10c). Our simulations showing the number of rockfall events that pass
552 through each pixel reveal distinct zones subject to high rockfall susceptibility as well as extensive downslope transport (Fig.
553 10e,d,d,e). For both the 50th block/dense forest and 95th block/fine talus scenarios shown here, the southern end of the
554 ridgeline above the harbour (between 4500 and 5500 on the transect) exhibits >10 specific chutes or paths of efficient
555 rockfall runout whereby initiation near the escarpment results in the concentration of rockfall runout along these paths and
556 conveyance to the cruise ship docks and/or harbour. Both scenarios exhibit a zone of events that pass across the railroad as
557 depicted by the heat map (Fig 10d,ee,d). In contrast, the central portion of the ridgeline (between 3000 and 4500m on the
558 transect) immediately adjacent to much of the township exhibits patchy and less frequent rockfall activity along gentle and
559 irregularly oriented bedrock steps and benches. Further north, our simulations reveal abundant long rockfall runout paths at
560 the northern extent of the township with concentrated activity near the Cemetery Slide area (between 1500 and 3000m on the
561 transect) with a high concentration of blocks predicted to pass across the railroad (Fig 10e,d). Finally, at the northernmost
562 extent of our simulation domain (from 0 to 1500m on the transect), the results show patchy and short rockfall transport paths
563 coincident with gentle, benchy topography. Taken together, these simulations demonstrate a large fraction of the ridge has
564 similar morphology and modelled rockfall runout behaviour as the zone of recent activity above the cruise ship dock.
565 Notably, the zone of extensive 2022 rockfall activity at 5000m along our transect is associated with abundant modelled
566 rockfall paths (Fig 10d,e). The fraction of these that are modelled to pass over the railroad is relatively low, however, owing
567 to retaining structures that are well-represented in the combined in lidar dataset (Fig. 4). While site-specific analysis and
568 mitigation plans are critical for addressing currently active rockfall areas (Munson, 2025), our regional approach highlights
569 that extensive portions of the ridgeline are highly susceptibility to rockfall activity that could impact the Skagway
570 community and transportation infrastructure.
571



572



573 Figure 10: Map of topography and rockfall models along the ridgeline that abuts Skagway township and Harbor. (a) Map of
 574 slope angle using merged 2014 airborne and 2023 UAS lidar, (b) Map of roughness defined as the standard deviation of slope
 575 angle within a 15-m radius (m), (c) Map of rockfall sources (red points) and talus deposits (yellow polygons), (e, dd, e) Maps
 576 of modeled rockfall paths for 2 scenarios with variable block size and land cover. The number of rockfall events that traverse
 577 each pixel is indicated by the color ramp. Heat map (red shades) denotes relative density of modeled rockfalls that pass over
 578 the railroad, (ef) Satellite image from USGS NAIP (National Agriculture Imagery Program) with annotated locations indicated.
 579 All maps include railroad transect demarcations. Hillshade images in (b-dc-c) derived from merged lidar datasets.

580

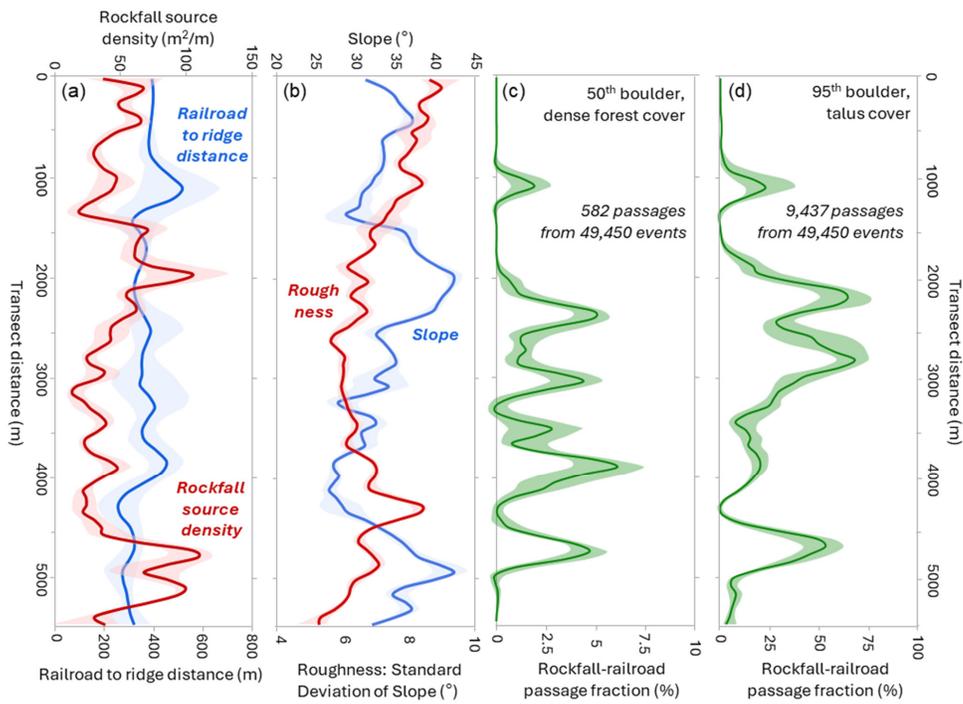
581 To assess controls on rockfall propagation susceptibility along the railroad transect, we tallied the number of simulated
 582 rockfall events that traverse the railroad track and quantified topographic properties of the ridge (Fig. 11). Although the
 583 railroad-to-ridge distance (or ridge width) is relatively consistent along the transect, the density of rockfall source areas
 584 (defined as the upslope area of rockfall susceptibility per length of railroad) varies substantially (Fig. 11a). The southern
 585 section of the ridge (4500 to 5400m) has a concentration of toppling source areas, which is ~4x higher than slopes in the

586 central section (2500 to 4000m) of our transect. Another zone of high source density occurs at ~2000m on the transect and
587 values to the northern extent are low to moderate in magnitude. Average slope angle along the ridge varies substantially with
588 high values ($>35^\circ$) in the southern (4500 to 5400m) and north-central (1500 to 2500m) sections and low values in the south-
589 central section (3000 to 4500m) (Fig. 11b). Average values of slope roughness (estimated as the standard deviation of slope
590 estimated for local windows with 5m radius) are relatively high in the southern section of the transect and low in the central
591 section before increasing monotonically to the north (Fig. 11b). Notably, our analysis shows that slope angle, rockfall source
592 density, and roughness exhibit distinctive patterns along the ridge enabling us to distinguish their influence on the modelled
593 runout pattern.

594

595 Although the relative pattern of simulated runout is consistent for the two scenarios shown here (Fig. 10d,e,f), our transect
596 analysis shows that only 1.2% of the simulated events for the 50th block/dense forest scenario result in passage across the
597 railroad whereas 19.1% of the 95th block/fine talus scenario events travel across the railroad (Fig. 11c,d). In several sections,
598 the passage fraction for the 95th block/fine talus scenario exceeds 50%, implying that the destabilization of a large block will
599 likely result in downslope impacts (Fig 11d). By contrast, the passage fractions for the 50th block/dense forest scenario rarely
600 exceed 4% such that unstable blocks have a low probability of impacting the valley (Fig 11c). This disparity reveals the
601 profound influence of block size and land cover on rockfall propagation susceptibility. Furthermore, the modelled runout
602 patterns reveal how slope morphology controls rockfall propagation. In both scenarios, sections of the ridge with high
603 passage fractions correspond with low roughness values and the zone of high roughness at 4000 to 4500m on the transect
604 corresponds with negligible rockfall passage (Fig 11b). By contrast, our analyses show that mean slope angle and rockfall
605 source density do not strongly correlate with the pattern of rockfall passage across the railroad.

606



607
 608 Figure 11: Plots of rockfall model variables and topographic properties along the railroad transect that bisects Skagway and
 609 the rockfall prone ridgeline (see Figure 10 for location). (a) Profile of rockfall source density ($\text{m}^2 \text{m}^{-1}$), which depicts the
 610 upslope area of toppling-prone terrain (normalized by distance along transect) calculated with equation 2 for terrain between
 611 the railroad and the ridge crest, and plot of the horizontal distance between the railroad and ridge crest, (b) Profile of average
 612 slope and roughness (estimated as standard deviation of local slope within a 5-m radius window) for terrain between railroad
 613 and the ridge crest, (c) Profile of modeled rockfall-railroad passage percentage for the scenario with 50th percentile block
 614 size and dense forest cover, and (d) Profile of modeled rockfall-railroad passage percentage for the scenario with 95th
 615 percentile block size and fine talus land cover. Shaded intervals convey standard deviation of values in all plots.

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616 **5 Discussion**

617 Although rainfall has been responsible for triggering some notable rockfall events in Skagway, a substantial seasonal
618 increase in rockfall events documented in the AKDOT&PF inventory occurred in late March and April. This period
619 corresponds to rapid increases in temperatures, particularly the minimum daily temperature, which implies that thawing of
620 ice, snow, and rock mass may contribute to increased activity (Fig. 6). This observation is consistent with many studies that
621 have documented thermal-driven rockfall activity in alpine environments in Europe and elsewhere; the proposed
622 mechanisms include active layer thaw, ice-filled fracture destabilization, and thermal stress cycles, with peak activity
623 typically occurring during spring and early summer months when temperatures rise above freezing (Draebing et al., 2022;
624 Gruber et al., 2004; Krautblatter et al., 2013; Matsuoka and Sakai, 1999; Mayer et al., 2024). Given that the low-elevation
625 rock slopes around Skagway are too warm to support permafrost, ice-filled fracture destabilization may be a relevant
626 mechanism. Field-based studies have noted cleft ice in rockfall scars which implies that ice segregation processes during
627 cold periods followed by warming and thaw-induced weakening can destabilize fractured rock masses (Huggel et al., 2012;
628 Ravelin et al., 2013). Dendrochronological studies in Switzerland reveal that 88% of rockfall scars occur between mid-
629 October and end of May, with peak activity in April when ice lenses formed from meltwater slowly infiltrate into fractures
630 (Stoffel et al., 2005). These studies highlight the critical role of spring thaw in destabilizing previously frozen rock masses
631 which may be relevant to the timing of rockfall activity in Skagway. Nonetheless, the specific timing of seasonal activity
632 remains challenging to predict, motivating efforts to determine the spatial pattern of rockfall initiation and propagation
633 susceptibility to mitigate hazard.

634
635 Taken together, our analyses of block toppling susceptibility and talus deposition maps demonstrate that rockfall source
636 areas and runout paths tend to be situated on northwest-facing rock slopes in the Skagway River valley, Nahku Bay, and
637 lower Taiya River valley. Our joint dataset suggests that this strong topographic control on rockfall activity owes to the
638 coincident alignment of glacial valleys and joint orientations, both of which are remarkably consistent in the area. The joints
639 measured in this study are consistent with the steeply dipping, orthogonal joint sets measured in a nearby (~15km northwest
640 of Skagway) structural survey in on a tributary to the Taiya River (Callahan and Wayland, 1965) and described in a
641 geotechnical assessment of the rock slopes above Skagway’s cruise ship dock (Brennan and Whistler, 2022). These high
642 angle joints are likely formed by the tensile component of shearing from the nearby Chatham Strait fault and Eastern Denali
643 fault systems. Rock slopes with orthogonal jointing are often predisposed to block toppling failure particularly where steep
644 orthogonal joints form the sides of toppling blocks and low angle joints act as the basal failure plane (Wyllie and Mah,
645 2004).

646
647 In their rockfall analysis, (Albarelli et al., (2021) state that “visual validation indicates that the areas of higher and moderate
648 rockfall susceptibility on the 3D model of the rocky slope are adjacent to rockfall source areas marked by the presence of

649 fallen blocks on the foot of the slope.” In adopting this approach, we note that toppling susceptibility index values >5% serve
650 to accurately differentiate terrain upslope of talus deposits (Fig. 9). The results of our kinematic analysis demonstrate that
651 rock slopes in the steep rugged terrain surrounding Skagway are highly susceptible to block toppling failure. The preference
652 for toppling failure is due to the steep inclination of joints, which are conducive to toppling failure as their near verticality
653 tends to preclude them from daylighting in rock slope faces, a necessary condition for planar sliding or wedge failure (Figure
654 1). The abundance of talus deposits situated just downslope of zones with high toppling susceptibility (Fig. 9b) is consistent
655 with other studies (Guerriero et al., 2024) and supports the utility of our modelling approach. ~~More advanced treatments that~~
656 ~~explicitly account for individual trees, land cover features, and source block geometry would improve the local accuracy of~~
657 ~~our simulations although the regional-scale results presented here are robust and helpful for informing mitigation efforts.~~
658

659 Consistent with previous studies (e.g., Loye et al., 2009), our rockfall susceptibility maps are consistent with the failure
660 mode and location of rock slope deformation observed in the field. On the uphill side of the prominent escarpment along the
661 eastern ridgeline in the lower Skagway River valley (Fig. 7), we observed numerous instances of detached parallel slabs of
662 rock separated by open tension cracks that extend downward for several meters (Fig. 3). These blocks appear to be
663 experiencing the early phases of toppling failure as vegetation and other environmental perturbations can contribute to crack
664 widening (Pawlik et al., 2016; Rempel et al., 2016). These observations also indicate that our predicted zones of toppling
665 failure are likely to continue propagating southeast with the active bedrock escarpment providing additional blocks to initiate
666 rockfall. More generally, these observations suggest that erosion and southeast-oriented lateral migration of the ridgeline has
667 been substantial since glacial retreat 10 to 12 kya. Approximate reconstruction of the ridge to its immediate post-glacial
668 geometry (Moore et al., 2009) implies that 10 to 100 meters of lateral erosion has occurred during the Holocene. The linear
669 character of the escarpment and pervasive indicators of active toppling also imply parallel retreat over geomorphic
670 timescales, which occurs given the favourable combination of dip and slope angle as well as erosion rate (Imaizumi et al.,
671 2015). As such, the unravelling and lateral retreat of the escarpment will likely continue until the interface encounters a
672 different configuration of slope and structural geometry.

673
674 As our simulations demonstrate, extensive rockfall activity and lateral divide migration does not occur along the entire ridge.
675 Rather, our results show large sections with patchy and localized talus deposits and benchy bedrock landforms that arises
676 because of variations in the depth and pattern of glacial erosion. Our novel roughness index serves as a proxy to reflect the
677 integrated effect of these slope properties on rockfall runout potential. Notably, our results show that zones with high
678 rockfall passage correspond with low roughness values upslope (Fig. 11), supporting the relevance of this morphologic
679 proxy for assessing rockfall propagation. Roughness can be assessed in numerous ways and the slope angle standard
680 deviation approach used here can be readily generated in GIS platforms (Booth et al., 2017). Our use of a 5-m radius for
681 calculating roughness implies that hillslope elements of this scale are relevant for regulating rockfall runout. Roughness
682 calculated for smaller length scales (~2 m) shows a very different spatial pattern that does not correspond with rockfall

683 [passage. More sophisticated approaches for estimating roughness, including wavelets \(e.g., Struble et al., 2021\), affords an](#)
684 [opportunity to dissect the scale dependence of hillslope properties that regulating runout behaviour \(Struble et al., 2021\).](#)

685
686 [In our study area, locations along the ridgeline illustrate morphologic controls on runout behaviour.](#) On Kirmse's Cliff (at
687 4200m on the transect, Fig. [10e10f](#)), for example, talus deposits extend upslope from the valley floor to vertical cliff faces
688 that terminate at the ridgeline (Fig. 5). In this area, toppling susceptibility is relatively high, but concentrated in a relatively
689 small area of vertical rock slope, and a forested talus deposit and benchy zone sits between the cliff and the valley floor (Fig.
690 [10b10c](#)). By contrast, several areas along the escarpment exhibit high potential for rockfall runout to reach the valley. At the
691 cruise ship dock (4500m on the transect), continuous, rockfall-prone slopes above the cruise ship dock span from the
692 escarpment to the base of the slope, resulting in a large area with high rockfall propagation susceptibility in close proximity
693 to harbour infrastructure. Similarly, from 1500 to 2000m on our railroad transect, a high-relief escarpment with steep vertical
694 bedrock outcrops near the crest exhibits a continuous steep slope to the valley floor (Fig. 10a). In this area, which is the
695 source area for the Cemetery Slide, rockfall susceptibility and long runout potential are high and we observed frequent
696 spalling and rolling rocks traversing the talus deposits during our field work (Fig. [10e4d,e](#)). In fact, The Daily Alaskan
697 reported a 1914 rockfall event just south of the Cemetery Slide at 2500m along the transect which coincides with our
698 simulations of high rockfall runout potential (Figs. [10d4e,e](#)). During that event, L. Gault noted “an avalanche of earth and
699 stone” that “leaped the railroad track...pounding against the fence.” Gault also noted that the railroad track served as a
700 “safety barrier” because “the force of the descent had been so much lessened.” Further afield in the northeast section of
701 Nahku Bay, another zone of high rockfall susceptibility is revealed by our analysis. Steep rocky slopes rise to an elevation of
702 250 m with close proximity to Dyea Road (Fig. 7). This area lacks a well-developed runout path, but it does coincide with
703 source areas for dozens of events in the AKDOT rockfall inventory that impacted Dyea Road. [More advanced runout](#)
704 [treatments that explicitly account for individual trees, land cover features, and source block geometry would improve the](#)
705 [local accuracy of our simulations although the regional-scale results presented here are robust and helpful for informing](#)
706 [mitigation efforts.](#)

707
708
709 Our analyses reveal distinctive zones of high rockfall initiation and runout (or propagation) susceptibility in the Skagway
710 region that result from the combination of glacial erosion that sets the morphology of bedrock slopes and the orientation of
711 joint sets that determine the geometry of potential bedrock failures. Most likely, the orientation and extent of glacial erosion
712 is not independent of the joints (Hooyer et al., 2012; Krabbendam and Glasser, 2011). Rather, we suspect that the nearly
713 parallel orientation of joints and the N-NE trending ridge along the eastern margin of the Skagway River valley arise due to
714 glacial erosion tracking discontinuities that facilitate erosion more readily than undeformed bedrock. This long-term
715 evolution implies feedbacks between rock structure and bedrock erosion processes from glaciers and rockfalls that support
716 strong gradients in rockfall activity. In assessing how these factors moderate the current hazard context, our findings

717 critically depend on the combination of kinematic modelling and runout susceptibility to provide constraints for identifying
718 areas at risk to inform mitigation efforts. Additional work is needed, however, to conduct a rigorous characterization of
719 rockfall risk in Skagway that includes estimation of occupation and usage of structures and transportation corridors to be
720 coupled with our results (e.g., Michoud et al., 2012).

721 **6 Conclusions**

722 ~~Our~~ Analysis of a rockfall inventory indicates a similar **strong preference for rockfalls** initiating on northwest-facing slopes
723 in the Skagway area. Combined with climate data, the inventory and reveal **also shows a seasonal peak in rockfall activity in**
724 late March and April that likely results from thawing of ice-filled joints and reduction of rock mass strength. ~~The Our~~
725 integrated kinematic analysis and the runout modelling presented here matches well with field observations and provides the
726 basis for a sophisticated approach in rockfall hazard assessment. The steeply dipping orthogonal joints in Skagway's rock
727 slopes are highly conducive to block toppling failure which has resulted in highly asymmetric rockfall susceptibility. Our
728 results highlight a distinct contrast in the morphology of Skagway River valley's eastern and western ridgelines, which is
729 primarily determined by the predisposition of northwest-facing slopes to block toppling failure along a densely fractured
730 joint set that dips steeply to the southeast. This is consistent with geomorphic evidence of extensive rockfall activity, where
731 talus deposits are more abundant and larger on the eastern side of the lower Skagway River valley than the west. This
732 structural control on rockfall activity is also evident in the east and west sides of Nahku Bay, situated to the west of
733 Skagway. ~~Our analysis of a rockfall inventory indicates a similar preference for initiating on northwest-facing slopes and~~
734 ~~reveal a seasonal peak in rockfall activity in late March and April that likely results from thawing of ice-filled joints and~~
735 ~~reduction of rock mass strength.~~ Our **integrated** simulations of rockfall **initiation and** runout show areas with high rockfall
736 **propagation** susceptibility that may merit further investigation and mitigation: 1) the ridgeline and slopes above the cruise
737 ship dock, 2) the high-relief topography at the north end of Skagway, and 3) the eastern ridgeline bordering Nahku Bay.
738 Recent rockfall source areas located in these regions are characterized by steep northwest-facing slopes that are highly
739 susceptible to block toppling failure and reach >200 m in elevation which facilitates long runout paths. Our results also
740 demonstrate that slope roughness over ~10m scales serves as a better predictor of rockfall propagation than slope angle and
741 the density of rockfall source areas. Our integrated modelling approach and field assessment provides a simple but robust
742 approach to assess rockfall hazard.

743 **7 Data availability**

744 All topographic data used for analyses are cited within the text. The structural data are available as Supplemental material.

745 **8 Author contribution**

746 IW and JR conceived and designed the study and IW and JR executed the study, RC provided on-site context, knowledge
747 and guidance, AP contributed to study design and fieldwork, IW and JR prepared the manuscript with contributions from all
748 other co-authors.

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758

759 **10 References**

- 760 Abellán, A., Calvet, J., Vilaplana, J. M., and Blanchard, J.: Detection and spatial prediction of rockfalls by means of terrestrial
761 laser scanner monitoring, *Geomorphology*, 119, 162–171, <https://doi.org/10.1016/j.geomorph.2010.03.016>, 2010.
- 762 Abellán, A., Vilaplana, J. M., Calvet, J., García-Sellés, D., and Asensio, E.: Rockfall monitoring by Terrestrial Laser Scanning
763 – case study of the basaltic rock face at Castellfollit de la Roca (Catalonia, Spain), *Natural Hazards and Earth System Sciences*,
764 11, 829–841, <https://doi.org/10.5194/nhess-11-829-2011>, 2011.
- 765 Aksoy, H. and Ercanoglu, M.: Determination of the rockfall source in an urban settlement area by using a rule-based fuzzy
766 evaluation, *Natural Hazards and Earth System Sciences*, 6, 941–954, <https://doi.org/10.5194/nhess-6-941-2006>, 2006.
- 767 Albarelli, D. S. N. A., Mavrouli, O. C., and Nyktas, P.: Identification of potential rockfall sources using UAV-derived point
768 cloud, *Bull Eng Geol Environ*, 80, 6539–6561, <https://doi.org/10.1007/s10064-021-02306-2>, 2021.
- 769 Alejano, L. R., Veiga, M., Pérez-Rey, I., Castro-Filgueira, U., Arzúa, J., and Castro-Caicedo, Á. J.: Analysis of a complex
770 slope failure in a granodiorite quarry bench, *Bull Eng Geol Environ*, 78, 1209–1224, [y](https://doi.org/10.1007/s10064-017-1160-
771 y), 2019.
- 772 Allen, S. and Huggel, C.: Extremely warm temperatures as a potential cause of recent high mountain rockfall, *Global and
773 Planetary Change*, 107, 59–69, <https://doi.org/10.1016/j.gloplacha.2013.04.007>, 2013.

- 774 Baichtal, J. F., Lesnek, A. J., Carlson, R. J., Schmuck, N. S., Smith, J. L., Landwehr, D. J., and Briner, J. P.: Late Pleistocene
775 and early Holocene sea-level history and glacial retreat interpreted from shell-bearing marine deposits of southeastern Alaska,
776 USA, *Geosphere*, 17, 1590–1615, <https://doi.org/10.1130/GES02359.1>, 2021.
- 777 Bajni, G., Camera, C. A. S., and Apuani, T.: Deciphering meteorological influencing factors for Alpine rockfalls: a case study
778 in Aosta Valley, *Landslides*, 18, 3279–3298, <https://doi.org/10.1007/s10346-021-01697-3>, 2021.
- 779 Ballantyne, C. K.: A general model of paraglacial landscape response, *The Holocene*, 12, 371–376,
780 <https://doi.org/10.1191/0959683602hl553fa>, 2002.
- 781 Barlow, J., Lim, M., Rosser, N., Petley, D., Brain, M., Norman, E., and Geer, M.: Modeling cliff erosion using negative power
782 law scaling of rockfalls, *Geomorphology*, 139–140, 416–424, <https://doi.org/10.1016/j.geomorph.2011.11.006>, 2012.
- 783 Biegel, K. M., Gosselin, J. M., Dettmer, J., Colpron, M., Enkelmann, E., and Caine, J. S.: Earthquake Relocations Delineate a
784 Discrete Fault Network and Deformation Corridor Throughout Southeast Alaska and Southwest Yukon, *Tectonics*, 43,
785 e2023TC008140, <https://doi.org/10.1029/2023TC008140>, 2024.
- 786 Birien, T., Gauthier, F., and Meloche, F.: Global warming impacts on rockfall frequency and magnitude due to changing frost
787 distribution and frost cracking effectiveness, *Earth Surface Processes and Landforms*, 49, 3399–3418,
788 <https://doi.org/10.1002/esp.5913>, 2024.
- 789 Bodin, X., Schoeneich, P., Deline, P., Ravanel, L., Magnin, F., Krysiecki, J.-M., and Echelard, T.: Mountain permafrost and
790 associated geomorphological processes: recent changes in the French Alps, *Journal of Alpine Research | Revue de géographie
791 alpine*, <https://doi.org/10.4000/rga.2885>, 2015.
- 792 Booth, A. M., LaHusen, S. R., Duvall, A. R., and Montgomery, D. R.: Holocene history of deep-seated landsliding in the North
793 Fork Stillaguamish River valley from surface roughness analysis, radiocarbon dating, and numerical landscape evolution
794 modeling: Landsliding in the N. Fork Stillaguamish, *Journal of Geophysical Research: Earth Surface*, 122, 456–472,
795 <https://doi.org/10.1002/2016JF003934>, 2017.
- 796 Borella, J., Quigley, M., Krauss, Z., Lincoln, K., Attanayake, J., Stamp, L., Lanman, H., Levine, S., Hampton, S., and Gravley,
797 D.: Geologic and geomorphic controls on rockfall hazard: how well do past rockfalls predict future distributions?, *Natural
798 Hazards and Earth System Sciences*, 19, 2249–2280, <https://doi.org/10.5194/nhess-19-2249-2019>, 2019.
- 799 Bovis, M. J. and Evans, S. G.: Extensive deformations of rock slopes in southern Coast Mountains, southwest British
800 Columbia, Canada, *Engineering Geology*, 44, 163–182, [https://doi.org/10.1016/S0013-7952\(96\)00068-3](https://doi.org/10.1016/S0013-7952(96)00068-3), 1996.
- 801 Brennan, K. and Whistler, R.: Railroad dock landslide, initial site visit trip report, Skagway, Alaska,
802 Geotechnical/Environmental Report, No. 109508-001, Shannon & Wilson, Anchorage, AK, USA, 2022.
- 803 Burns, W. J. and Madin, I. P.: Protocol for Inventory Mapping of Landslide Deposits from Light Detection and Ranging (lidar)
804 Imagery, Oregon Department of Geology and Mineral Industries (DOGAMI) Special Paper 42, 36p., 2009.
- 805 Callahan and Wayland: Geologic reconnaissance of the West Creek damsite near Skagway, Alaska, *Geological Survey
806 Bulletin*, 1211-A, <https://doi.org/10.3133/b1211A>, 1965.
- 807 Cardozo, N. and Allmendinger, R. W.: Spherical projections with OSXStereonet, *Computers & Geosciences*, 51, 193–205,
808 <https://doi.org/10.1016/j.cageo.2012.07.021>, 2013.

- 809 Caviezel, A., Ringenbach, A., Demmel, S. E., Dinneen, C. E., Krebs, N., Bühler, Y., Christen, M., Meyrat, G., Stoffel, A.,
810 Hafner, E., Eberhard, L. A., Rickenbach, D. von, Simmler, K., Mayer, P., Niklaus, P. S., Birchler, T., Aebi, T., Cavigelli, L.,
811 Schaffner, M., Rickli, S., Schnetzler, C., Magno, M., Benini, L., and Bartelt, P.: The relevance of rock shape over mass—
812 implications for rockfall hazard assessments, *Nat Commun*, 12, 5546, <https://doi.org/10.1038/s41467-021-25794-y>, 2021.
- 813 Chaminé, H. I., Afonso, M. J., Ramos, L., and Pinheiro, R.: Scanline Sampling Techniques for Rock Engineering Surveys:
814 Insights from Intrinsic Geologic Variability and Uncertainty, in: *Engineering Geology for Society and Territory - Volume 6*,
815 Cham, 357–361, https://doi.org/10.1007/978-3-319-09060-3_61, 2015.
- 816 Chiles, J.-P. and Marsily, G.: Stochastic Models of Fracture Systems and Their Use in Flow and Transport Modeling, in: *Flow
817 and Contaminant Transport in Fractured Rock*, Academic Press, 169–236, <https://doi.org/10.1016/B978-0-12-083980-3.50008-5>, 1993.
- 819 Choi, M., Eaton, D. W., and Enkelmann, E.: Is the Eastern Denali fault still active?, *Geology*, 49, 662–666,
820 <https://doi.org/10.1130/G48461.1>, 2021.
- 821 Collins, B. D. and Stock, G. M.: Rockfall triggering by cyclic thermal stressing of exfoliation fractures, *Nature Geoscience*, 9,
822 395–400, <https://doi.org/10.1038/ngeo2686>, 2016.
- 823 Corominas, J., van Westen, C., Frattini, P., Cascini, L., Malet, J.-P., Fotopoulou, S., Catani, F., Van Den Eeckhaut, M.,
824 Mavrouli, O., Agliardi, F., Pitilakis, K., Winter, M. G., Pastor, M., Ferlisi, S., Tofani, V., Hervás, J., and Smith, J. T.:
825 Recommendations for the quantitative analysis of landslide risk, *Bull Eng Geol Environ*, 73, 209–263,
826 <https://doi.org/10.1007/s10064-013-0538-8>, 2014.
- 827 Cruden, D. M.: Limits to common toppling, *Can. Geotech. J.*, 26, 737–742, <https://doi.org/10.1139/t89-085>, 1989.
- 828 Daly, C., Smith, J., and Halbleib, M.: 1981-2010 High-Resolution Temperature and Precipitation Maps for Alaska Final
829 Report, Oregon State University, Corvallis, Oregon, 2018.
- 830 DGGS Staff: LiDAR Datasets of Alaska, Alaska Division of Geological & Geophysical Surveys,
831 <https://doi.org/10.14509/25239>, 2013.
- 832 Dorren, L., Berger, F., Jonsson, M., Krautblatter, M., Mölk, M., Stoffel, M., and Wehrli, A.: State of the art in rockfall – forest
833 interactions, *Schweizerische Zeitschrift für Forstwesen*, 158, 128–141, <https://doi.org/10.3188/szf.2007.0128>, 2007.
- 834 Draebing, D., Mayer, T., Jacobs, B., and McColl, S. T.: Alpine rockwall erosion patterns follow elevation-dependent climate
835 trajectories, *Commun Earth Environ*, 3, 1–12, <https://doi.org/10.1038/s43247-022-00348-2>, 2022.
- 836 Fanos, A. and Pradhan, B.: Laser Scanning Systems and Techniques in Rockfall Source Identification and Risk Assessment:
837 A Critical Review, *Earth Systems and Environment*, 2, <https://doi.org/10.1007/s41748-018-0046-x>, 2018.
- 838 Frattini, P., Crosta, G., Carrara, A., and Agliardi, F.: Assessment of rockfall susceptibility by integrating statistical and
839 physically-based approaches, *Geomorphology*, 94, 419–437, <https://doi.org/10.1016/j.geomorph.2006.10.037>, 2008.
- 840 Gigli, G., Lombardi, L., Carlà, T., Beni, T., and Casagli, N.: A method for full three-dimensional kinematic analysis of steep
841 rock walls based on high-resolution point cloud data, *International Journal of Rock Mechanics and Mining Sciences*, 157,
842 105178, <https://doi.org/10.1016/j.ijrmmms.2022.105178>, 2022.
- 843 Grant, A., Wartman, J., and Abou-Jaoude, G.: Multimodal method for coseismic landslide hazard assessment, *Engineering
844 Geology*, 212, 146–160, <https://doi.org/10.1016/j.enggeo.2016.08.005>, 2016.

845 Gruber, S., Hoelzle, M., and Haeblerli, W.: Permafrost thaw and destabilization of Alpine rock walls in the hot summer of
846 2003, *Geophysical Research Letters*, 31, <https://doi.org/10.1029/2004GL020051>, 2004.

847 Guerriero, L., Annibali Corona, M., Di Martire, D., Francioni, M., Limongiello, M., Tufano, R., and Calcaterra, D.: Rockfall
848 susceptibility analysis of the “San Michele Arcangelo” historic trail (Central Italy) based on virtual outcrops and multiple
849 propagation models, *Bull Eng Geol Environ*, 83, 263, <https://doi.org/10.1007/s10064-024-03764-0>, 2024.

850 Günther, A.: SLOPEMAP: programs for automated mapping of geometrical and kinematical properties of hard rock hill slopes,
851 *Computers & Geosciences*, 29, 865–875, [https://doi.org/10.1016/S0098-3004\(03\)00086-4](https://doi.org/10.1016/S0098-3004(03)00086-4), 2003.

852 Günther, A., Wienhöfer, J., and Konietzky, H.: Automated mapping of rock slope geometry, kinematics and stability with
853 RSS-GIS, *Nat Hazards*, 61, 29–49, <https://doi.org/10.1007/s11069-011-9771-2>, 2012.

854 Guzzetti, F., Reichenbach, P., and Wieczorek, G. F.: Rockfall hazard and risk assessment in the Yosemite Valley, California,
855 USA, *Natural Hazards and Earth System Sciences*, 3, 491–503, <https://doi.org/10.5194/nhess-3-491-2003>, 2003.

856 Hales, T. C. and Roering, J. J.: Climatic controls on frost cracking and implications for the evolution of bedrock landscapes,
857 *Journal of Geophysical Research*, 112, <https://doi.org/10.1029/2006JF000616>, 2007.

858 Harris, A. S. and Farr, W. A.: The forest ecosystem of southeast Alaska: 7. Forest ecology and timber management., Gen.
859 Tech. Rep. PNW-GTR-025. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research
860 Station. 116 p, 025, 1974.

861 Hooyer, T. S., Cohen, D., and Iverson, N. R.: Control of glacial quarrying by bedrock joints, *Geomorphology*, 153–154, 91–
862 101, <https://doi.org/10.1016/j.geomorph.2012.02.012>, 2012.

863 Horel, J., Splitt, M., Dunn, L., Pechmann, J., White, B., Ciliberti, C., Lazarus, S., Slemmer, J., Zaff, D., and Burks, J.:
864 MESOWEST: COOPERATIVE MESONETS IN THE WESTERN UNITED STATES, 2002.

865 Huggel, C., Allen, S., Deline, P., Fischer, L., Noetzli, J., and Raveland, L.: Ice thawing, mountains falling—are alpine rock
866 slope failures increasing?, *Geology Today*, 28, 98–104, <https://doi.org/10.1111/j.1365-2451.2012.00836.x>, 2012.

867 Hungr, O., Evans, S. G., and Hazzard, J.: Magnitude and frequency of rock falls and rock slides along the main transportation
868 corridors of southwestern British Columbia, *Can. Geotech. J.*, 36, 224–238, <https://doi.org/10.1139/t98-106>, 1999.

869 Hungr, O., Leroueil, S., and Picarelli, L.: The Varnes classification of landslide types, an update, *Landslides*, 11, 167–194,
870 <https://doi.org/10.1007/s10346-013-0436-y>, 2014.

871 Imaizumi, F., Nishii, R., Murakami, W., and Daimaru, H.: Parallel retreat of rock slopes underlain by alternation of strata,
872 *Geomorphology*, 238, 27–36, <https://doi.org/10.1016/j.geomorph.2015.02.030>, 2015.

873 Imaizumi, F., Matsuoka, N., Hayakawa, Y. S., Samikshya, D., and Stoffel, M.: Linkages between abundant rockfall and debris-
874 flow activity at Täschgufer, Swiss Alps, *Geomorphology*, 110009, <https://doi.org/10.1016/j.geomorph.2025.110009>, 2025.

875 Kleinn, J., Christen, M., and Bartelt, P.: Probabilistic event-based rockfall modelling for deriving continuous intensity-
876 frequency curves in the impact area, *Interpraevent 2024. Conference proceedings*, 648–652, 2024.

877 Klimeš, J., Kılınar, J., Kopačková-Strnadová, V., Pánek, T., McColl, S., and Jelének, J.: Landslides in the glaciated mountains
878 of the Cordillera Blanca, Peru—types, spatial distribution, and conditioning factors, *Landslides*,
879 <https://doi.org/10.1007/s10346-024-02387-6>, 2024.

- 880 Krabbendam, M. and Glasser, N. F.: Glacial erosion and bedrock properties in NW Scotland: Abrasion and plucking, hardness
881 and joint spacing, *Geomorphology*, 130, 374–383, <https://doi.org/10.1016/j.geomorph.2011.04.022>, 2011.
- 882 Krautblatter, M., Funk, D., and Günzel, F. K.: Why permafrost rocks become unstable: a rock–ice-mechanical model in time
883 and space, *Earth Surface Processes and Landforms*, 38, 876–887, <https://doi.org/10.1002/esp.3374>, 2013.
- 884 Kundu, J., Sarkar, K., Ghaderpour, E., Mugnozza, G. S., and Mazzanti, P.: A GIS-Based Kinematic Analysis for Jointed Rock
885 Slope Stability: An Application to Himalayan Slopes, *Land*, 12, <https://doi.org/10.3390/land12020402>, 2023.
- 886 LaHusen, S. R., Duvall, A. R., Booth, A. M., Grant, A., Mishkin, B. A., Montgomery, D. R., Struble, W., Roering, J. J., and
887 Wartman, J.: Rainfall triggers more deep-seated landslides than Cascadia earthquakes in the Oregon Coast Range, USA,
888 *Science Advances*, 6, eaba6790, <https://doi.org/10.1126/sciadv.aba6790>, 2020.
- 889 Leine, R. I., Schweizer, A., Christen, M., Glover, J., Bartelt, P., and Gerber, W.: Simulation of rockfall trajectories with
890 consideration of rock shape, *Multibody Syst Dyn*, 32, 241–271, <https://doi.org/10.1007/s11044-013-9393-4>, 2014.
- 891 Leith, K., Moore, J. R., Amann, F., and Loew, S.: In situ stress control on microcrack generation and macroscopic extensional
892 fracture in exhuming bedrock: FRACTURE GENERATION IN EXHUMING BEDROCK, *Journal of Geophysical Research:*
893 *Solid Earth*, 119, 594–615, <https://doi.org/10.1002/2012JB009801>, 2014.
- 894 Loye, A., Jaboyedoff, M., and Pedrazzini, A.: Identification of potential rockfall source areas at a regional scale using a DEM-
895 based geomorphometric analysis, *Nat. Hazards Earth Syst. Sci.*, 9, 1643–1653, <https://doi.org/10.5194/nhess-9-1643-2009>,
896 2009.
- 897 Lu, G., Caviezel, A., Christen, M., Demmel, S. E., Ringenbach, A., Bühler, Y., Dinneen, C. E., Gerber, W., and Bartelt, P.:
898 Modelling rockfall impact with scarring in compactable soils, *Landslides*, 16, 2353–2367, <https://doi.org/10.1007/s10346-019-01238-z>, 2019.
- 900 Lu, G., Ringenbach, A., Caviezel, A., Sanchez, M., Christen, M., and Bartelt, P.: Mitigation effects of trees on rockfall hazards:
901 does rock shape matter?, *Landslides*, 18, 59–77, <https://doi.org/10.1007/s10346-020-01418-2>, 2021.
- 902 Luckman, B. H.: Rockfalls and rockfall inventory data: Some observations from surprise valley, Jasper National Park, Canada,
903 *Earth Surface Processes*, 1, 287–298, <https://doi.org/10.1002/esp.3290010309>, 1976.
- 904 Macpherson, A. E., Nicolsky, D. J., and Suleimani, E. N.: Digital elevation models of Skagway and Haines, Alaska:
905 Procedures, data sources, and quality assessment, *Alaska Division of Geological & Geophysical Surveys*,
906 <https://doi.org/10.14509/29143>, 2014.
- 907 Marquínez, J., Menéndez Duarte, R., Farias, P., and Jiménez Sánchez, M.: Predictive GIS-Based Model of Rockfall Activity
908 in Mountain Cliffs, *Natural Hazards*, 30, 341–360, <https://doi.org/10.1023/B:NHAZ.0000007170.21649.e1>, 2003.
- 909 Matasci, B., Stock, G. M., Jaboyedoff, M., Carrea, D., Collins, B. D., Guérin, A., Matasci, G., and Raveland, L.: Assessing
910 rockfall susceptibility in steep and overhanging slopes using three-dimensional analysis of failure mechanisms, *Landslides*,
911 15, 859–878, <https://doi.org/10.1007/s10346-017-0911-y>, 2018.
- 912 Matsuoka, N.: A multi-method monitoring of timing, magnitude and origin of rockfall activity in the Japanese Alps,
913 *Geomorphology*, 336, 65–76, <https://doi.org/10.1016/j.geomorph.2019.03.023>, 2019.
- 914 Matsuoka, N. and Sakai, H.: Rockfall activity from an alpine cliff during thawing periods, *Geomorphology*, 28, 309–328,
915 [https://doi.org/10.1016/S0169-555X\(98\)00116-0](https://doi.org/10.1016/S0169-555X(98)00116-0), 1999.

- 916 Mayer, T., Deprez, M., Schröer, L., Cnudde, V., and Draebing, D.: Quantifying frost-weathering-induced damage in alpine
917 rocks, *The Cryosphere*, 18, 2847–2864, <https://doi.org/10.5194/tc-18-2847-2024>, 2024.
- 918 Meentemeyer, R. K. and Moody, A.: Automated mapping of conformity between topographic and geological surfaces,
919 *Computers & Geosciences*, 26, 815–829, [https://doi.org/10.1016/S0098-3004\(00\)00011-X](https://doi.org/10.1016/S0098-3004(00)00011-X), 2000.
- 920 Menounos, B., Goehring, B. M., Osborn, G., Margold, M., Ward, B., Bond, J., Clarke, G. K. C., Clague, J. J., Lakeman, T.,
921 Koch, J., Caffee, M. W., Gosse, J., Stroeven, A. P., Seguinot, J., and Heyman, J.: Cordilleran Ice Sheet mass loss preceded
922 climate reversals near the Pleistocene Termination, *Science*, 358, 781–784, <https://doi.org/10.1126/science.aan3001>, 2017.
- 923 Messenzehl, K. and Dikau, R.: Structural and thermal controls of rockfall frequency and magnitude within rockwall–talus
924 systems (Swiss Alps), *Earth Surface Processes and Landforms*, 42, 1963–1981, <https://doi.org/10.1002/esp.4155>, 2017.
- 925 Messenzehl, K., Meyer, H., Otto, J.-C., Hoffmann, T., and Dikau, R.: Regional-scale controls on the spatial activity of rockfalls
926 (Turtmann Valley, Swiss Alps) — A multivariate modeling approach, *Geomorphology*, 287, 29–45,
927 <https://doi.org/10.1016/j.geomorph.2016.01.008>, 2017.
- 928 Michoud, C., Derron, M.-H., Horton, P., Jaboyedoff, M., Baillifard, F.-J., Loye, A., Nicolet, P., Pedrazzini, A., and Queyrel,
929 A.: Rockfall hazard and risk assessments along roads at a regional scale: example in Swiss Alps, *Natural Hazards and Earth
930 System Sciences*, 12, 615–629, <https://doi.org/10.5194/nhess-12-615-2012>, 2012.
- 931 Moore, J. R., Sanders, J. W., Dietrich, W. E., and Glaser, S. D.: Influence of rock mass strength on the erosion rate of alpine
932 cliffs, *Earth Surface Processes and Landforms*, 34, 1339–1352, <https://doi.org/10.1002/esp.1821>, 2009.
- 933 Moos, C., Khelidj, N., Guisan, A., Lischke, H., and Randin, C. F.: A quantitative assessment of rockfall influence on forest
934 structure in the Swiss Alps, *Eur J Forest Res*, 140, 91–104, <https://doi.org/10.1007/s10342-020-01317-0>, 2021.
- 935 Munson, M.: Railroad Dock landslides continue, declaration of emergency in place, *The Skagway News*, 12th August, 2022a.
- 936 Munson, M.: Rockslide at cruise ship dock – Skagway’s Railroad Dock has limited use, *The Skagway News*, 23rd June, 2022b.
- 937 Munson, M.: Skagway gets first look at possible plans for expensive and complicated rock fall mitigation, *KTOO*, 2025.
- 938 Nash, D., Rutz, J. J., and Jacobs, A.: Atmospheric Rivers in Southeast Alaska: Meteorological Conditions Associated With
939 Extreme Precipitation, *Journal of Geophysical Research: Atmospheres*, 129, e2023JD039294,
940 <https://doi.org/10.1029/2023JD039294>, 2024.
- 941 Oliinyk, M., Bubniak, I., and Vikhot, Y.: Using Move software by geological field works, *International Conference of Young
942 Professionals «GeoTerrace-2020»*, 1–5, <https://doi.org/10.3997/2214-4609.20205706>, 2020.
- 943 Paranunzio, R., Laio, F., Nigrelli, G., and Chiarle, M.: A method to reveal climatic variables triggering slope failures at high
944 elevation, *Nat Hazards*, 76, 1039–1061, <https://doi.org/10.1007/s11069-014-1532-6>, 2015.
- 945 Paranunzio, R., Laio, F., Chiarle, M., Nigrelli, G., and Guzzetti, F.: Climate anomalies associated with the occurrence of
946 rockfalls at high-elevation in the Italian Alps, *Natural Hazards and Earth System Sciences*, 16, 2085–2106,
947 <https://doi.org/10.5194/nhess-16-2085-2016>, 2016.
- 948 Pawlik, Ł., Phillips, J. D., and Šamonil, P.: Roots, rock, and regolith: Biomechanical and biochemical weathering by trees and
949 its impact on hillslopes—A critical literature review, *Earth-Science Reviews*, 159, 142–159,
950 <https://doi.org/10.1016/j.earscirev.2016.06.002>, 2016.

- 951 Pérez, F.: Talus fabric, clast morphology, and botanical indicators of slope processes on the Chaos Crags (California
952 Cascades), U.S.A., *gpq*, 52, 47–68, <https://doi.org/10.7202/004861ar>, 1998.
- 953 Poage, N. J., Marshall, D. D., and McClellan, M. H.: Maximum Stand-Density Index of 40 Western Hemlock–Sitka Spruce
954 Stands in Southeast Alaska, *Western Journal of Applied Forestry*, 22, 99–104, <https://doi.org/10.1093/wjaf/22.2.99>, 2007.
- 955 Priest, S. D. and Hudson, J. A.: Estimation of discontinuity spacing and trace length using scanline surveys, *International
956 Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts*, 18, 183–197, [https://doi.org/10.1016/0148-
9062\(81\)90973-6](https://doi.org/10.1016/0148-
957 9062(81)90973-6), 1981.
- 958 Rapp, A.: Talus slopes and mountain walls at Tempelfjorden, Spitsbergen : a geomorphological study of the denudation of
959 slopes in an Arctic locality, *Skriftter, Norsk Polarinstittut*, 119, 1960.
- 960 Ravelin, L., Deline, P., Lambiel, C., and Vincent, C.: Instability of a High Alpine Rock Ridge: the Lower Arête Des
961 Cosmiques, Mont Blanc Massif, France, *Geografiska Annaler: Series A, Physical Geography*, 95, 51–66,
962 <https://doi.org/10.1111/geoa.12000>, 2013.
- 963 Rempel, A. W., Marshall, J. A., and Roering, J. J.: Modeling relative frost weathering rates at geomorphic scales, *Earth and
964 Planetary Science Letters*, 453, 87–95, <https://doi.org/10.1016/j.epsl.2016.08.019>, 2016.
- 965 Ringenbach, A., Bebi, P., Bartelt, P., Rigling, A., Christen, M., Bühler, Y., Stoffel, A., and Caviezel, A.: Shape still matters:
966 rockfall interactions with trees and deadwood in a mountain forest uncover a new facet of rock shape dependency, *Earth
967 Surface Dynamics*, 11, 779–801, <https://doi.org/10.5194/esurf-11-779-2023>, 2023.
- 968 Roering, J. J., Dedinsky, K., Grilliot, M., Wachino, I. D., and Cash, R.: Skagway Landslide Hazard, RAPID Facility,
969 <https://doi.org/doi.org/10.17603/ds2-2e3p-yn12>, 2025.
- 970 Rosser, N. and Massey, C.: Rockfall hazard and risk, in: *Landslide Hazards, Risks, and Disasters*, Elsevier, 581–622,
971 <https://doi.org/10.1016/B978-0-12-818464-6.00013-5>, 2022.
- 972 Rosser, N., Lim, M., Petley, D., Dunning, S., and Allison, R.: Patterns of precursory rockfall prior to slope failure, *Journal of
973 Geophysical Research: Earth Surface*, 112, <https://doi.org/10.1029/2006JF000642>, 2007.
- 974 Royán, M. J., Abellán, A., Jaboyedoff, M., Vilaplana, J. M., and Calvet, J.: Spatio-temporal analysis of rockfall pre-failure
975 deformation using Terrestrial LiDAR, *Landslides*, 11, 697–709, <https://doi.org/10.1007/s10346-013-0442-0>, 2014.
- 976 Ruffner, C. M. and Abrams, M. D.: Relating land-use history and climate to the dendroecology of a 326-year-old *Quercus
977 prinus* talus slope forest, *Can. J. For. Res.*, 28, 347–358, <https://doi.org/10.1139/x97-220>, 1998.
- 978 Samodra, G., Chen, G., Sartohadi, J., Hadmoko, D. S., Kasama, K., and Setiawan, M. A.: Rockfall susceptibility zoning based
979 on back analysis of rockfall deposit inventory in Gunung Kelir, Java, *Landslides*, 13, 805–819, [https://doi.org/10.1007/s10346-
016-0713-7](https://doi.org/10.1007/s10346-
980 016-0713-7), 2016.
- 981 Sarro, R., Rossi, M., Reichenbach, P., and Mateos, R. M.: From rockfall source areas identification to susceptibility zonation:
982 a proposed workflow tested in El Hierro (Canary Islands, Spain), *Natural Hazards and Earth System Sciences Discussions*, 1–
983 30, <https://doi.org/10.5194/nhess-2024-85>, 2024.
- 984 Scheidl, C., Heiser, M., Vospernik, S., Lauss, E., Perzl, F., Kofler, A., Kleemayr, K., Bettella, F., Lingua, E., Garbarino, M.,
985 Skudnik, M., Trappmann, D., and Berger, F.: Assessing the protective role of alpine forests against rockfall at regional scale,
986 *Eur J Forest Res*, 139, 969–980, <https://doi.org/10.1007/s10342-020-01299-z>, 2020.

- 987 Statham, I.: A scree slope rockfall model, *Earth Surface Processes*, 1, 43–62, <https://doi.org/10.1002/esp.3290010106>, 1976.
- 988 van Steijn, H.: Long-term landform evolution: evidence from talus studies, *Earth Surface Processes and Landforms*, 27, 1189–
989 1199, <https://doi.org/10.1002/esp.420>, 2002.
- 990 Stock, G. M. and Collins, B. D.: Quantitative Rockfall hazard and risk assessment for Yosemite Valley, Yosemite National
991 Park, California, USGS Scientific Investigations Report 2014-5129, 2014.
- 992 Stock, G. M., Bawden, G. W., Green, J. K., Hanson, E., Downing, G., Collins, B. D., Bond, S., and Leslar, M.: High-resolution
993 three-dimensional imaging and analysis of rock falls in Yosemite Valley, California, *Geosphere*, 7, 573–581,
994 <https://doi.org/10.1130/GES00617.1>, 2011.
- 995 Stoffel, M., Lièvre, I., and Monbaron, M.: Seasonal timing of rockfall activity on a forested slope at Täschgufer (Swiss Alps)
996 - a dendrochronological approach, *Zeitschrift für Geomorphologie*, 89–106, 2005.
- 997 Stoffel, M., Trappmann, D. G., Coullie, M. I., Ballesteros Cánovas, J. A., and Corona, C.: Rockfall from an increasingly
998 unstable mountain slope driven by climate warming, *Nat. Geosci.*, 1–6, <https://doi.org/10.1038/s41561-024-01390-9>, 2024.
- 999 Struble, W. T., Roering, J. J., Dorsey, R. J., and Bendick, R.: Characteristic Scales of Drainage Reorganization in Cascadia,
1000 *Geophysical Research Letters*, 48, e2020GL091413, <https://doi.org/10.1029/2020GL091413>, 2021.
- 1001 Terzaghi, R. D.: Sources of Error in Joint Surveys, *Géotechnique*, 15, 287–304, <https://doi.org/10.1680/geot.1965.15.3.287>,
1002 1965.
- 1003 The Daily Alaskan: SLIDE: Hill again caves in near Moore’s Wharf, *The Daily Alaskan*, 20th October, 1, 1901.
- 1004 Thompson, P.: Alaska Department of Transportation & Public Facilities (AKDOT) Geotechnical Asset Management Program,
1005 Technical Report STP000S(802)(B), Juneau, AK, 2017.
- 1006 Thornton, T. F.: *Our Grandparents’ Names on the Land/Haa Leelk’w Has Aani Saax’u*, University of Washington Press,
1007 Seattle, WA, 256 pp., 2010.
- 1008 Utlu, M., Öztürk, M. Z., Şimşek, M., and Akgümüş, M. F.: Evaluation of rockfall hazard based on UAV technology and 3D
1009 Rockfall Simulations, *International Journal of Environment and Geoinformatics*, 10, 1–16,
1010 <https://doi.org/doi.%252010.30897/ijgeo.10323768>, 2023.
- 1011 Western Regional Climate Center: <https://wrcc.dri.edu>, last access: 14 August 2025.
- 1012 Whalley, B.: Rockfalls, in: *Slope Instability*, Wiley, Chichester, UK, 217–256, 1984.
- 1013 Wiczorek, G. F. and Jäger, S.: Triggering mechanisms and depositional rates of postglacial slope-movement processes in the
1014 Yosemite Valley, California, *Geomorphology*, 15, 17–31, [https://doi.org/10.1016/0169-555X\(95\)00112-1](https://doi.org/10.1016/0169-555X(95)00112-1), 1996.
- 1015 Wright, B. E., Plumb, P., Wright, J., and Biles, F. E.: Historical photographs from U.S. Forest Service research and
1016 development activities in Alaska, <https://doi.org/10.2737/RDS-2021-0084>, 2021.
- 1017 Wyllie, D. C. and Mah, C. W.: *Rock Slope Engineering*, 4th ed., Spon, 456 pp., 2004.
- 1018 Yehle, L. A. and Lemke, R. W.: Reconnaissance engineering geology of the Skagway area, Alaska with emphasis on evaluation
1019 of earthquake and other geologic hazards, USGS Open File Report, 1972.

1020 Zhou, X., Chen, J., Chen, Y., Song, S., Shi, M., and Zhan, J.: Bayesian-based probabilistic kinematic analysis of discontinuity-
1021 controlled rock slope instabilities, *Bull Eng Geol Environ*, 76, 1249–1262, <https://doi.org/10.1007/s10064-016-0972-5>, 2017.

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