



1 **Characterizing rockfall hazard with an integrated kinematic analysis** 2 **and runout model: Skagway, Alaska, USA**

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9 **Abstract**

10 Rockfall is common in steep terrain and poses a hazard to nearby communities. While rockfall triggering mechanisms are
11 highly variable and difficult to quantify, the susceptibility of rock slopes to planar, wedge, or toppling failure can be readily
12 assessed using kinematic analysis. As such, valley slopes with favourable joint orientations exhibit high rockfall
13 susceptibility although the potential for rockfall runout to impact infrastructure and public safety depends on the morphology
14 of downslope terrain. Integrating rockfall susceptibility and runout models with maps of talus deposits accumulated from
15 past rockfall events is an effective combination of tools to inform mitigation but can be difficult to realize across extensive
16 areas. Here, we combine these methods with a historic rockfall inventory to assess rockfall hazard in the steep and forested
17 postglacial valleys proximal to Skagway, AK, where recent rockfall activity has imperilled public safety, infrastructure, and
18 tourism. Our field investigations identified two steeply dipping orthogonal joint sets that favour toppling failure along NW-
19 facing hillslopes in the lower Skagway River valley as well as the NW-facing valleys that bound nearby Dyea Bay and
20 Nahku Bay. We used new and existing lidar data and >300 field-derived joint orientations to inform a kinematic toppling
21 failure model that identifies likely zones of rock toppling. The predicted source zones are positioned upslope of abundant
22 talus slopes that we mapped from field observations and lidar analyses. Along the prominent ridgeline on the eastern margin
23 of Skagway, we used RAMMS:Rockfall to model nearly 200,000 rockfall runout events for four scenarios that account for
24 variations in clast size and ground cover. The runout predictions highlight distinct zones of low and high rockfall hazard
25 along the ridgeline that result from changes in hillslope morphology set by the combined influence of joint orientations and
26 the pattern of glacial erosion. High-hazard segments of the ridgeline exhibit distinct bedrock escarpments and slope-spanning
27 talus slopes that result from the accumulation of rockfall activity over millennia. Our findings reveal controls on past and
28 future rockfall activity and can be used to inform mitigative measures.



29 **1 Introduction**

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

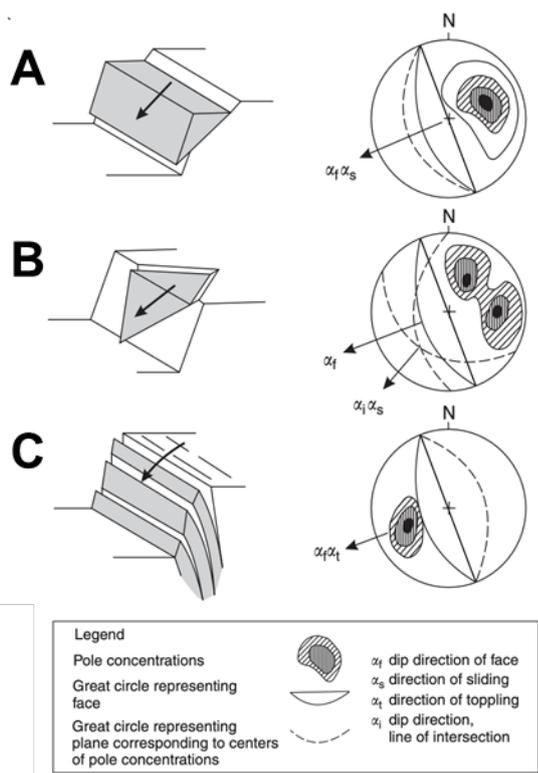
43
44 A wide array of methods has been proposed to assess the extent to which hillslopes are prone to rockfall activity. Delineating
45 potential source zones (e.g., Loye et al., 2009) can be accomplished from direct observation of past events, which assumes
46 the location of past detachments coincides with the location of future rockfall activity (Luckman, 1976; Matsuoka and Sakai,
47 1999; Rapp, 1960; Whalley, 1984). Source zones can also be inferred from distinctive evidence such as talus slope and scree
48 deposits that have accumulated below cliff faces (Borella et al., 2019; Frattini et al., 2008; Moore et al., 2009; Stock and
49 Collins, 2014). Coupled assessment of rock slope morphology and the properties of potential source zones is another
50 common approach that uses digital elevation models (DEMs) for assessing source zones over large areas (Frattini et al.,
51 2008; Guzzetti et al., 2003; Messenzehl et al., 2017; Samodra et al., 2016), while more data-intensive and physically-based
52 deformation models can be used for slope-scale analyses (Matasci et al., 2018). In absence of rock structure data, some
53 studies (e.g., Guerriero et al., 2024) have applied morphologic criteria (e.g., slope and curvature thresholds) to DEMs to
54 identify anomalous rock slope protrusions that are likely to experience rockfall events (Aksoy and Ercanoglu, 2006; Frattini
55 et al., 2008; Guzzetti et al., 2003; Marquínez et al., 2003; Sarro et al., 2024)

56
57 Because rockfall is typically localized along bedding planes, fractures, or joints, collectively referred to as discontinuities,
58 susceptibility can also be evaluated by determining the geometry of these planes of weakness with respect to the slope and
59 orientation of rock slopes. Kinematic analysis identifies blocks that can experience instability according to sliding, toppling,
60 or wedge failure criteria as determined by the geometry of rock slopes and discontinuities (Fig. 1) (Bovis and Evans, 1996;
61 Wyllie and Mah, 2004). Combining high-resolution DEMs with rock structure data can inform kinematic analyses and



62 determine the relative likelihood of different failure modes across expansive areas (Grant et al., 2016; Kundu et al., 2023;
 63 Stock and Collins, 2014). Recent applications of kinematic analysis leverage lidar or photogrammetry to extract bedrock
 64 discontinuity data and test kinematic failure criteria on complex slope geometries, like overhanging rock quarries (Fanos and
 65 Pradhan, 2018; Gigli et al., 2022). Increasingly, the acquisition of discontinuity data is accomplished using automated
 66 analysis of point cloud data acquired from terrestrial laser scanning (TLS) (Matasci et al., 2018) or lidar or photogrammetry
 67 acquired from uncrewed aerial systems (UAS) (Utlu et al., 2023). These approaches are powerful but can be challenging to
 68 implement across large areas characterized by steep, rocky forested slopes where the details of rock structure are often
 69 obscured by vegetation. As such, traditional, field-based means of bedrock structural characterization continue to be
 70 relevant.

71



72 Figure 1. Schematic representation of common rock slope failure modes: (a) planar sliding, (b) wedge, and (c) toppling. On
 73 the right of each diagram are stereonets, where the rock slope face is represented by a solid black line, and poles to planar
 74 discontinuities that meet conditions for failure in shaded contours. Dashed lines represent planes of these discontinuities.
 75 Modified from Wyllie and Mah (2004).

76

77 Initially, rock fragments move via creep, sliding, toppling, or falling before traveling downslope by following ballistic paths
 78 and rolling across rocky or talus slopes until sufficient energy dissipation has occurred via impacts or friction (Caviezel et



79 al., 2021). Computational rockfall runout models that account for the physics of these rockfall processes can estimate the
80 trajectories and kinetic energy of falling rocks to determine potential downslope impacts (Leine et al., 2014). Many DEM-
81 based tools exist with a range of parameterization options to perform physically-based rockfall simulations and predict the
82 path of rocks over complex terrain and across variable land cover (Lu et al., 2021; Moos et al., 2021). These models have
83 been successfully employed to mitigate rockfall hazard with diversion and attenuation structures, development setbacks,
84 signage, or other means, in a variety of settings, including mines and national parks (e.g., Stock and Collins, 2014) such that
85 rockfall risk can be reduced even though accurate prediction of triggering events remains elusive.

86
87 Although rockfall activity occurs in a wide range of geologic and climatic settings, it is particularly commonplace in post-
88 glacial landscapes owing to glacial erosion that alters near-surface stresses, fracture density, topographic variations from
89 glacial erosion, and changes in environmental conditions that occur in the wake of retreating glaciers (Ballantyne, 2002;
90 Leith et al., 2014). In particular, the spatial pattern of glacial erosion can follow the fabric or trend of bedrock discontinuities
91 and set up failure-prone conditions across extensive areas. As such, relatively small changes in the orientation and geometry
92 of glacial valleys relative to the orientation of discontinuities can result in significant and systematic variations in rockfall
93 susceptibility. Although it has been implied that the cumulative impact of small but frequent rockfalls in post-glacial settings
94 can match that associated with large-scale but less frequent catastrophic or progressive rock slope failure, data are currently
95 unavailable to rigorously test this notion (Barlow et al., 2012; Corominas et al., 2014; Hales and Roering, 2007; Hungr et al.,
96 1999; Moore et al., 2009; Rosser and Massey, 2022).

97
98 Rockfall activity is common across much of Southeast Alaska but has been particularly acute in the Municipality of
99 Skagway, which is situated in a narrow, glacially carved valley herein referred to as the ‘Skagway River valley, and hosts
100 vigorous cruise ship tourism from late spring to early fall. Indigenous knowledge of avalanches in the area has been
101 established (Thornton, 2010) and western documentation of rockfall activity in Skagway began in the late 1800s when gold
102 prospecting fuelled the establishment of the town. Following decades of sporadic activity, several large rockfall events in
103 summer 2022 impacted cruise docks along Skagway Harbor and generated renewed concern about the extent and scope of
104 rockfall hazards in the area. In particular, the extent and timing of past rockfall activity is not well known and the
105 susceptibility of rockfall initiation and runout in the area, and particularly along a ~5km long ridgeline that abuts the harbour,
106 town centre, and railroad, has not been characterized. In this contribution, we summarize historic and geologic data that
107 reflects the distribution and timing of past rockfall activity, document rock structure data from field observations, and
108 synthesize new and existing lidar data from airborne and UAS platforms to inform a kinematic analysis susceptibility and
109 dynamic runout model for Skagway and the surrounding area. Our findings establish the pervasive imprint of rockfall
110 activity along slopes oriented to promote toppling failure. We highlight how the pattern of glacial erosion resulted in
111 substantial rockfall erosion and cliff retreat along favourably oriented slopes while unfavourably oriented slopes experienced

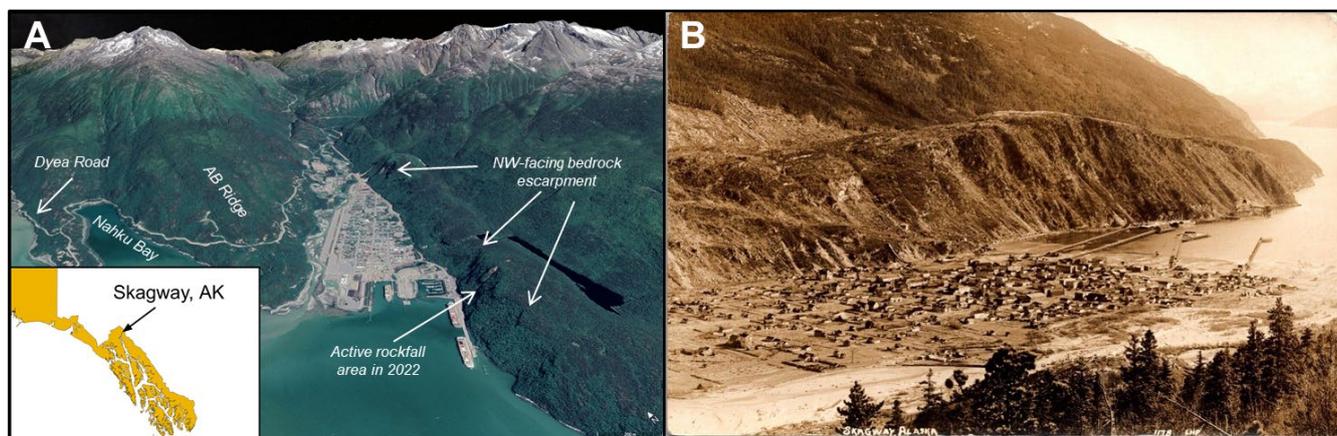


112 minimal modification since glacial retreat. Our coupled modeling reveals reveal high variability in potential impacts which
113 can inform mitigation efforts.

114 2 Study area: Skagway, SE Alaska

115 Near the northern extent of the Alaska panhandle, Skagway is situated in the Taiya Inlet atop deltaic and fluvial deposits
116 near the outlet of a deep fjord (Fig. 2). The surrounding terrain is steep and rugged, composed of Tertiary granodiorite of the
117 Coast Range Batholith, a belt of plutonic and metamorphic rocks that extends to northern Washington (Yehle and Lemke,
118 1972). Deformation in southeastern Alaska and southwest Yukon is governed by the subduction and translation of
119 the Pacific-Yakutat plates relative to the North American plate in the St. Elias region (Biegel et al., 2024). The Eastern
120 Denali Fault and the Chatham strait fault lineaments, both strike-slip fault systems, meet just south of Skagway (Choi et al.,
121 2021). Deformation associated with these structures appears to impart a significant influence on the orientation of glacial
122 valleys, as fjords in the area tend to be linear, striking north and northeasterly (Yehle and Lemke, 1972). A dam
123 reconnaissance study focused on West Creek, a drainage just 9 km northwest of Skagway identified three joint sets in the
124 granodiorite bedrock (Fig. 3c), two abundant sets with northeast-strike and vertical or steep dips to the south, and one less
125 abundant set with northwest-strike and a consistent vertical dip (Callahan and Wayland, 1965). The authors also noted the
126 coincident orientation of topographic lineations in the area and the strike of joints interpreted to be splays from the Chatham
127 strait lineament, which is related to the nearly 3,000-km long Denali fault system. Spacing between the joints is variable,
128 ranging from 1 to 4 meters, and the joints do not exhibit slickensides or cataclastic fabric (Fig. 3a,b). Sheeting joints in
129 granodiorite observed near the tops of glaciated ridges are slightly curved or irregular, tend to parallel the ground surface,
130 and spaced from 1 to 2 meters apart at the surface.

131



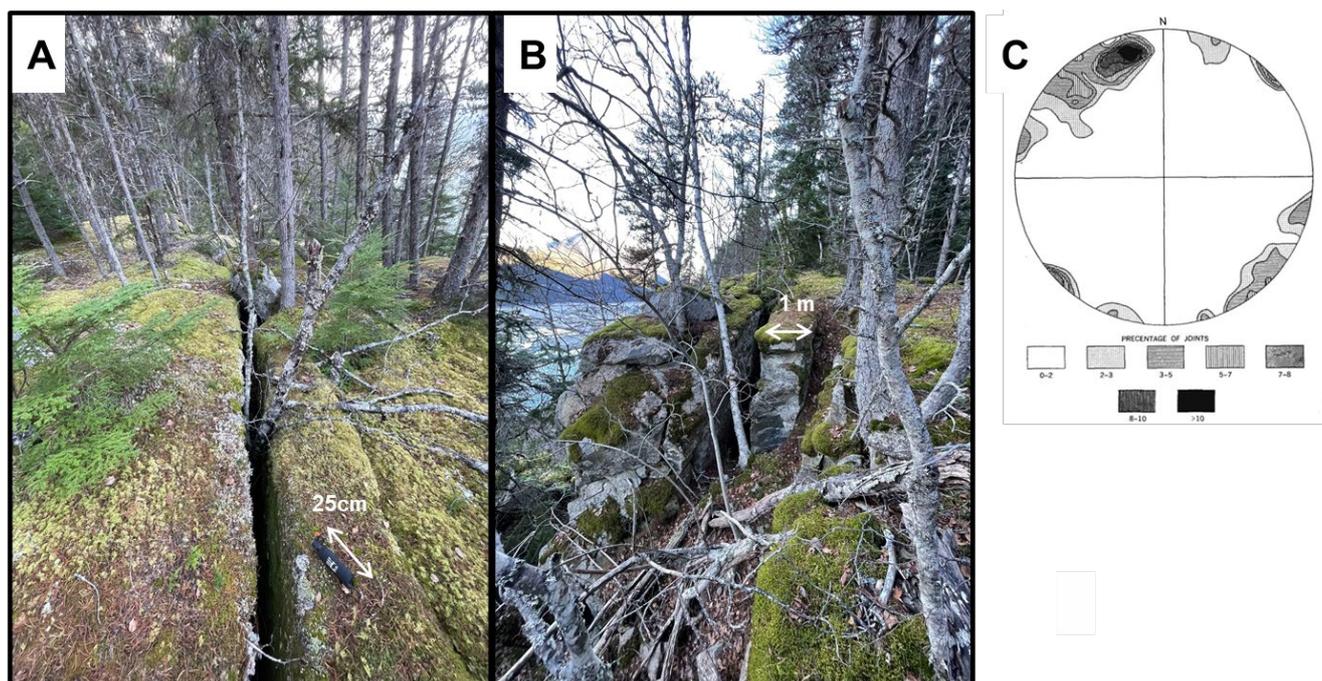
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133 Figure 2. Study area. (a) Oblique view looking N-NE into Skagway River valley, Alaska. Note active rockfall along the NW-
134 facing ridgeline and escarpment above the harbour and cruise ship docks. Use of Google Earth ©2025 permitted for non-
135 commercial use. (b) Oblique view from AB Ridge looking SE across Skagway towards the NW-facing ridgeline and
136 escarpment. This undated historic image (Wright et al., 2021) postdates the late 1890s construction of the current Skagway
137 City Hall and Museum. Note the lack of vegetation and the sharp bedrock escarpment along the crest of the ridgeline and the
138 abundance of active talus slopes that connect to the harbour.

139
140 Regional studies of glacial history imply that the most recent episode of major glacial retreat and valley exposure in
141 Skagway occurred 10 to 12kya (Baichtal et al., 2021; Menounos et al., 2017) and icefields persist today in nearby inland
142 valleys. The steep slopes around Skagway are generally devoid of glacial till owing to post-retreat erosion and deposition in
143 valley floors in the form of alluvial fans and colluvial deposits.

144



145

146

147 Figure 3. Images (a) and (b) of open joints and incipient toppling along the bedrock escarpment on the NW-facing ridgeline
148 above Skagway Harbor. Equal-area, lower hemisphere stereonet with 1% area contours of 60 joints measured near Dyea, west
149 of Skagway. Photos in a and b by Ian Madin and Josh Roering. Modified from Callahan and Wayland, 1965. See Fig. 4 for
150 location.

151

152 Currently, Skagway experiences a subarctic maritime climate, characterized by cool summers and cold, snowy winters and
153 current average summer temperatures range from 10 to 21°C, with occasional rainfall, and winter temperatures range from -



154 12 to -1°C , with heavy snowfall, and freezing conditions. High winds that funnel up the Taiya Inlet are common and for
155 decades it was reported that Skagway's name originated from Tlingit words describing north winds (Thornton, 2010)
156 although recent research concludes that the name derives from a contraction of 'Wushigagu Ye', which translates as "the
157 Place with Solid Core Trees" (X. Twitchell, pers. comm, 2024). Compared to other areas in SE Alaska, Skagway receives
158 low precipitation (mean annual precipitation is 1.1m) owing to the rain shadow imposed by the bounding coastal ranges to
159 the south. Atmospheric rivers account for nearly 70% of annual rainfall in Skagway and intense precipitation associated with
160 these phenomena occur with highest frequency and intensity from August to October (Nash et al., 2024). Skagway hosts a
161 coastal rainforest of spruce, pine, and cedar trees with dense underbrush at low elevations (under 1,000m above sea level)
162 and high-alpine tundra above tree line. Historical photographs and descriptions suggest that forests covering the slopes
163 perched above Skagway Harbor and township were disturbed timber through harvest and burning in the early 1900s (Wright
164 et al., 2021).

165
166 Early Western descriptions of rockfall activity in Skagway tend to focus on impacts to the harbour and railroad, including a
167 series of events in 1901 that recorded burial of the tracks near the approach to the wharf (The Daily Alaskan, 1901). The
168 location of this event coincides with the steep rocky slopes above Skagway Harbor, which have generated numerous
169 rockfalls since that account (Fig. 2). A study of geologic hazards in Skagway noted the striking linearity of N- and NE-
170 oriented fjords and valleys and identified abundant actively eroding bedrock escarpments on a NW-facing ridgeline that runs
171 along the eastern margin of Skagway that coincides with a zone of historic rockfall activity (Yehle and Lemke, 1972).
172 Downslope of these escarpments are colluvial deposits, consisting of landslide deposits, including talus from historic rockfall
173 events. The abundance and extent of these deposits implies significant slope adjustment and retreat since glacial retreat and
174 the relative activity of the deposits is based on the abundance or absence of vegetation cover. Across the valley on the
175 western side of Skagway, these talus deposits are much less prevalent, and the Yehle and Lemke (1975) maps do not indicate
176 the presence of erosional escarpments. On June 23, 2022, rocks detached from the eastern ridgeline and impacted the cruise
177 ship dock where pedestrian traffic is frequent (Munson, 2022b). Two more rockfall events originating in the rocky slopes
178 above the harbour followed in rapid succession on August 3 and 5, 2022 (Munson, 2022a).

179
180 Rockfall hazard mitigation in the area is currently focused on the active rockfall source areas above the cruise ship dock in
181 Skagway Harbor. Engineering efforts have been completed, which include wrapping rock mesh covers over source areas,
182 installing attenuator nets to block falling rocks, and scaling loose rocks (Brennan and Whistler, 2022). Instrumentation has
183 been installed to monitor the source area, including extensometers installed at the top of the slope, which show that
184 movement in the slide mass has increased from 4 cm per year to 6.5 cm per year as of 2022 (Brennan and Whistler, 2022).
185 Notably, the small section of rocky slopes above Skagway's cruise ship dock, where the engineered mitigation and
186 monitoring efforts are focused, is a small fraction of the roughly 5-km long stretch of ridgeline that borders the eastern
187 margin of Skagway. Rocky escarpments and talus deposits have been noted along the entire ridge (Yehle and Lemke, 1972),

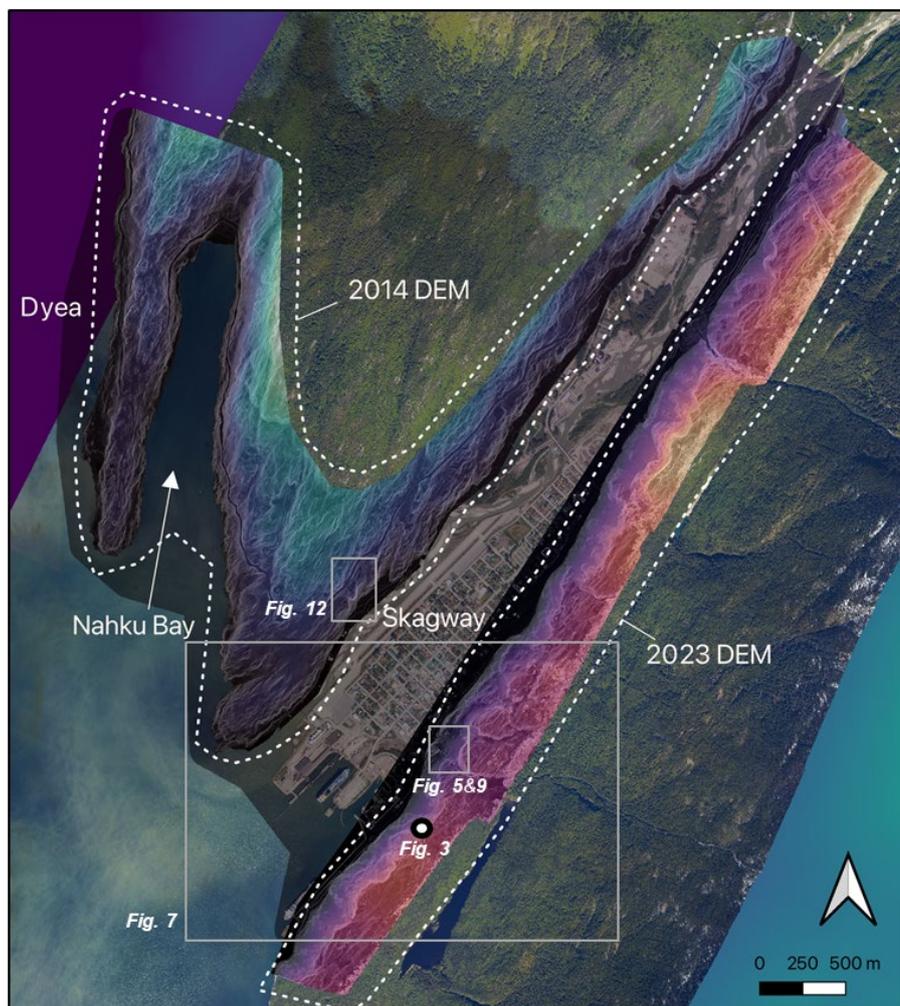


188 including the “Cemetery Slide”, a rockfall source area and runout zone stripped of vegetation by falling debris, which is
189 similar to the active source areas above the cruise ship dock. Although these zones of localized activity are well known, the
190 forest cover obscures the geologic and topographic signature of past rockfall activity along the remainder of the ridge such
191 that the pattern of relative susceptibility and runout remains ambiguous.

192 **3 Methods**

193 **3.1. Overview**

194 Motivated by renewed rockfall activity, this study seeks to identify areas susceptible to rockfall initiation and runout within
195 the steep, post-glacial valleys around Skagway. Our analysis extends to the west of Skagway along Dyea Road to the Tlingit
196 settlement of Dyea and the Chilkoot Trailhead, which is a well-travelled corridor that also provides the opportunity to test our
197 methodology across a wider range of topographic and structural configurations (Fig. 4). The components of our analysis
198 include a historical rockfall inventory, synthesis of new and existing lidar data, geomorphic and structural mapping, kinematic
199 analysis of rockfall susceptibility, and rockfall runout modelling.



200

201 Figure 4: Location map of Skagway River valley, Nahku Bay, and Dyea showing 2014 airborne survey and 2023 UAS lidar
202 DEM acquired for this study. The dashed lines demarcate the areas analyzed in this study. Gray boxes denote the extent of
203 other figures. Background image from USGS NAIP (National Agriculture Imagery Program).

204

205 3.2 Rockfall inventory

206 We searched newspaper articles (primarily the Skagway News) and public announcements that describe the location and
207 timing of rockfall events since August 26, 2017, which marks the beginning of rockfall mitigation efforts along the Skagway
208 Harbor. In addition, we accessed data generated for rockfall events between 2005 and 2022 from the GeoEvent Slope
209 Stability Database generated by the Alaska Department of Transportation & Public Facilities (AKDOT) Geotechnical Asset
210 Management Program (Thompson, 2017). This database features details from AKDOT maintenance and operations reports,



211 including the location, date, event type (e.g., debris flows, rockfalls, landslides, snow avalanches, flooding), relative
212 magnitude, and cost, of geologic events that impact the Alaska highway system.

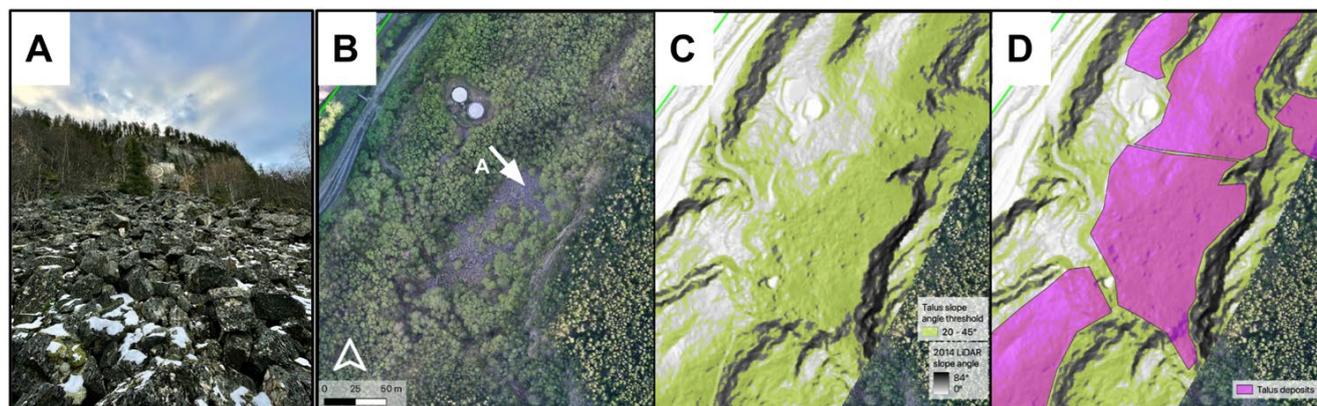
213 **3.3 High-resolution topography: Airborne and UAS lidar**

214 Our analysis used two sources of lidar data to inform geomorphic and bedrock mapping, kinematic analysis, and runoff
215 modelling. One lidar DEM acquired in 2014 with an average ground classified point density of 4.6 m^{-2} is available from the
216 Alaska Department of Geological and Geophysical Surveys (DGGs Staff, 2013) and includes low-elevation terrain in the
217 Skagway River valley, Nahku Bay, and part of Dyea valley (Macpherson et al., 2014). Because this lidar acquisition does not
218 span a significant portion of Skagway's rockfall-prone east ridge that abuts the township and harbour, we conducted a UAS
219 lidar survey in 2023 (Fig. 4). We acquired lidar data across the 2.3 km^2 area with peak elevations of 220 m near the cruise
220 ship docks and 320 m near the northern extent of the ridgeline (Roering et al., 2025). For the acquisition, the NSF RAPID
221 facility used a Trinity F90+ fixed wing drone with a Qube 240 lidar payload to fly $\sim 120\text{m}$ above ground with 90% coverage
222 overlap. The surveyed area was slightly abbreviated due to a patch of extremely steep terrain where the UAS could not be
223 flown safely at distances sufficiently close to the ground surface to acquire data. The UAS survey produced a point cloud
224 containing 650 million total points with 200 million ground classified points, giving an average ground point density of 43
225 m^{-2} . We used the ground points to create a 1 m DEM using CloudCompare (version 2.12.3) and combined it with the 2014
226 airborne lidar data to provide a seamless coverage for our analyses (Fig. 4).

227 **3.4 Geomorphic mapping**

228 We used field observations, historic photographs, and slope thresholds and surface texture from the combined lidar DEM to
229 identify and map talus deposits that reflect the accumulation of rockfall deposits. These talus deposits include both forested
230 and exposed occurrences. To define the characteristic slope angles associated with active talus slopes we measured slope
231 angles from 20° to 45° that coincide with mapped talus deposits along the eastern ridge. Slopes steeper than 45° tend to
232 correspond with bedrock cliffs and outcrops, whereas slopes gentler than 20° often reflect relatively uneroded bedrock
233 surfaces or deposits from fluvial or mass wasting processes. The relatively smooth texture of accumulated rockfall deposits
234 identified with hillshade and slopeshade layers (Burns and Madin, 2009) was also used to identify active talus slopes as well
235 as bedrock cliffs or outcrops that constitute a rockfall source area. Talus deposits occur on a wide range of scales and for this
236 analysis we focused on mapping patches of talus with area $>100\text{m}^2$ to ensure accuracy and highlight zones of significant
237 activity (Fig. 5).

238



239

240 Figure 5: Field images and lidar mapping of talus mantled slopes. See Fig. 4 for location. (a) View looking SE along an exposed
 241 talus deposit with boulder sized clasts at the base of a 40 m cliff known as Kirmse’s Cliff on far left of image, (b) Aerial
 242 imagery from 2023 UAS survey showing the talus deposit and cliff (center left), white arrow represents photograph location
 243 and view direction, (c) Terrain within the slope angle range of 20°-45° colored in yellow, and (d) map of talus polygons
 244 generated from lidar slope shade and slope angle maps and orthoimagery. Hillshades in c and d derived from DGGs lidar data.
 245 Background image from USGS NAIP (National Agriculture Imagery Program).

246

247 3.5 Bedrock structure and discontinuities

248 To quantify the geometry of joints and discontinuities that contribute to rockfall initiation, we collected structural
 249 measurements at a range of distinct locations within the study area and combined them to generate a comprehensive
 250 discontinuity dataset (Kundu et al., 2023). The steep, forested, and uneven terrain surrounding Skagway limits access to
 251 outcrops and the traditional ‘scanline’ method (Priest and Hudson, 1981) was untenable. Furthermore, the significant forest
 252 cover and expansiveness of the study area precluded the use of ground-based laser or SfM (structure from motion) methods
 253 for acquiring structural information. Instead, we traversed the base of outcrops as an approximation of scanlines and
 254 measured the orientation of planar surfaces expressed in the outcrop with FieldMoveClino, a digital compass-clinometer
 255 smartphone app (Oliinyk et al., 2020), which enabled rapid and accurate data acquisition. Our measurements were acquired
 256 across a wide range of locations in the study area in order to characterize spatial variations in discontinuity orientations. In
 257 particular, we visited outcrops along the eastern and western sides of the Skagway River valley as well as outcrops in
 258 secondary valleys perpendicular to these ridgelines to ensure that the full range of relevant joint orientations were
 259 represented (Terzaghi, 1965).

260 3.6 Kinematic analysis of rockfall susceptibility

261 To assess the spatial pattern of rockfall susceptibility across the study area, we adopted a kinematic analysis approach and
 262 applied criteria for planar sliding and toppling failure within our combined lidar DEM. This approach foregoes the



263 mechanical complexity and extensive parameterization of more sophisticated analyses (e.g., Matasci et al., 2018) in order to
264 generate results that span an extensive area. As described below, the remarkable consistency of discontinuity orientations
265 across the study area inspired this approach and therefore we invoked the entire distribution of measured joint orientations at
266 all locations to perform the kinematic analysis. Specifically, we applied the stability criteria for each failure mode at each
267 pixel in the combined lidar DEM by estimating the fraction of the 337 joint orientations that are predicted to be unstable
268 given the topographic aspect and slope angle of that pixel. The failure criteria for planar and toppling failure are defined
269 following Wyllie & Mah (2004) and described below. Essentially, this approach is equivalent to locally performing a
270 stereonet analysis of rock slope failure across our study area and aggregating the results to identify potential rockfall failure
271 modes as well as areas of high relative susceptibility. For the analysis, we used a friction angle of 40° , consistent with
272 measured values for jointed granodiorite similar to Skagway's lithology (Alejano et al., 2019). For validation of our
273 modelled rockfall susceptibility maps, we compared our predictions to the location of recent rockfall events in Skagway, as
274 well as mapped talus deposits which serve as a proxy for prior rockfall activity (Loye et al., 2009; Stock and Collins, 2014).

275
276 Planar slides occur when the inclination of a bedrock slab exceeds the friction angle and it slides along a planar
277 discontinuity. Toppling failures occur when discontinuities steeply dipping into the rock slope face form slabs or columns of
278 rock that rotate forward along a fixed base (Fig. 1). Two types of toppling failures can occur that are influenced by the
279 strength of the rock mass and the geometry of discontinuities. Flexural toppling, where slabs of rock bend forward until they
280 break in flexure, is typical in shale and slate where orthogonal jointing is not well developed. Block toppling is common in
281 bedrock with orthogonal joint sets, where two steeply dipping joint sets form the sides of blocks, and a third set of low angle,
282 widely spaced joints form a basal failure plane. The active rockfall source area situated above Skagway's cruise ship dock
283 has been described as a progressive toppling failure with a stair-stepped basal feature (Brennan and Whistler, 2022). Topple
284 failures observed in the field are consistent with this description, which is described by the block toppling failure
285 mechanism. As a result, our analysis focuses on block toppling although we also account for planar sliding given that
286 sporadic sliding was observed in the field. Field observations and geotechnical reports do not identify wedge failure as a
287 potential mechanism and we opted not to include it in our analyses.

288
289 The criteria for planar, wedge, or toppling failure is based on the orientation of discontinuities and their orientation relative
290 to the rock slope face (Wyllie and Mah, 2004). The dip direction of the discontinuity and rock slope is given by α_A and α_f ,
291 respectively, and the dip angle of the discontinuity and rock slope, both relative to horizontal, is given by ψ_A and ψ_f ,
292 respectively. The friction angle of the joint interfaces is given by ϕ .

293
294 Accordingly, a rock slope is susceptible to planar sliding failure along a discontinuity if the following three conditions are
295 simultaneously met:



296
$$|\alpha_A - \alpha_f| < 20^\circ; \psi_A < \psi_f; \psi_A > \phi \quad (1)$$

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

301

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

303
$$\alpha_f - 20^\circ < (\alpha_A \pm 180^\circ) < \alpha_f + 20^\circ; (90^\circ - \psi_f) + \phi < \psi_A \quad (2)$$

304 The first condition asserts that the discontinuity must dip into the rock slope face and be parallel, or nearly parallel (e.g., within
305 20°), to the dip direction of the slope face. The second condition indicates that the discontinuity dip must exceed the friction
306 angle allowing for interlayer slip between the blocks. In our model, the maximum allowable dip direction deviation is $\pm 20^\circ$
307 for both planar slide and block toppling failure. Although this value was often chosen to be $\pm 10^\circ$ for block toppling we
308 expanded the constraint to $\pm 20^\circ$, consistent with recent contributions (Cruden, 1989; Gigli et al., 2022).

309

310 Kinematic analysis requires discontinuity data that is locally representative. Traditionally, discontinuity measurements are
311 taken in the field, whereas many modern applications extract discontinuity orientations from high-resolution point clouds of
312 the rock slope face (Utlu et al., 2023). Field measurements remain a reliable and relevant means to capture joint orientations
313 (Kundu et al., 2023), especially in locales where terrestrial laser scans are not feasible due to hazardous terrain or where
314 slope faces are obscured by vegetation.

315

316 Using equations 1 and 2, we estimated the number of joints in our field-derived dataset ($n=337$) that are predicted to exhibit
317 planar and toppling failure, respectively, for each pixel in our combined lidar DEM. Our maps of planar and toppling failure
318 are then calculated as the percentage of joints that meet the conditions required for failure conditions. For example, a
319 toppling failure index value of 0.31 for a given pixel in our DEM indicates that 31% of the joints in our joint dataset satisfy
320 the two conditions in equation 2. This approach provides a description of relative rockfall initiation susceptibility across our
321 study area.

322 **3.7 Rockfall runout modelling with RAMMS**

323 To model potential runout paths associated with rock slopes that have high rockfall susceptibility, as determined by our
324 kinematic analyses, we used the 3D rockfall simulation software RAMMS:Rockfall (<https://ramms.ch/ramms-rockfall/>) to
325 represent the sliding, bouncing, and rolling motion of rock clasts. This model accounts for the energy balance of falling rocks



326 and has been used extensively at a range of scales for both applied and fundamental research studies (Leine et al., 2014; Lu
327 et al., 2019). The primary inputs required for the RAMMS model include digital elevation data (i.e., DEM), the location of
328 rockfall source areas, specification of ground cover, and the shape and size of the falling blocks.

329
330 We used our combined lidar DEM, which has a 1x1 m pixels and spans the area shown in Fig. 4. To identify potential source
331 areas, we identified pixels in our maps of toppling susceptibility with values greater than 5%. Pixels with >5% toppling
332 susceptibility demarcate rocky cliffs situated above our mapped talus deposits as well as areas of recent rockfall activity in
333 the Skagway Harbor (Fig. 5). The pixels with a >5% high toppling susceptibility were converted to polygons and only
334 polygons with area greater than 25 m² were retained in order to eliminate local high-relief features like boulders and trees
335 that can perpetrate the signature of rockfall source zones. Rockfall source points for RAMMS modelling were randomly
336 distributed across the polygons with a density of 0.02 m⁻² and a minimum point spacing of 5 m. This methodology follows
337 convention used in other studies (Lu et al., 2021) and yielded nearly 5,000 rockfall initiation points for our RAMMS
338 simulations.

339
340 The slopes east of Skagway are heavily forested, except in locations where falling debris has stripped vegetation, such as the
341 cruise ship dock and at the northern extent of the eastern ridge bordering Skagway. In RAMMS, we represented forested
342 areas as spruce alpine forests and trees were simulated in these areas using the 'dense forest' category in RAMMS, which is
343 defined by a stem density of 600 trees per hectare with a mean diameter of 30 cm. These parameters were chosen based on
344 our field observations and the typical density of mixed red alder coniferous stands in Southeast Alaska (Poage et al., 2007).
345 The effect of trees in the RAMMS rockfall runout module is to attenuate energy and reduce velocity, thus constituting a
346 significant impact on hazard potential. The very small amount of terrain (less than 5% of the study area) that exists outside
347 these forested areas was set to the fine talus category in RAMMS, which reflects negligible ground cover atop relatively
348 fine-grained talus deposits. We performed simulations with and without forest cover in order to assess the potential role of
349 timber harvest and fire on rockfall runout and provide a conservative assessment of the hazard extent.

350
351 We estimated representative block size and shape by measuring blocks in exposed talus piles. To estimate block size, the
352 intermediate axis of 74 blocks was measured from high-resolution point clouds combined with orthoimagery. We determined
353 the mean intermediate axis size to be 1.08 m while the 50th percentile was 0.66 m and the 95th percentile was 3.56 m. Blocks
354 observed in the field are typically tabular and the shape of blocks was estimated by measuring the long, intermediate, and
355 short axes of 10 blocks with sufficient exposure to allow measurement using our UAS-derived point clouds. The block
356 dimensions were measured and we applied the resulting aspect ratio to the 50th percentile and 95th percentile intermediate
357 axis values from our block size measurements. The dimensions of the resulting rocks used in the simulation were 0.94 m x
358 0.66 m x 0.37 m (medium, 50th percentile), and 5.10 m x 3.56 m x 1.99 m (large, 95th percentile), which represent moderate



359 and large clast sizes, respectively. Given the tendency for large clasts to travel longer distances, our 95th percentile blocks are
360 intended to reflect the conservative (or long runout) scenario.

361
362 To simulate the range of potential rockfall impacts, we focused on four scenarios for RAMMS simulation with the following
363 parameterizations: 1) 50th percentile clasts with no forest cover, 2) 50th percentile clasts with dense forest, 3) 95th percentile
364 clasts with no forest over, and 4) 50th percentile clasts with dense forest. To account for the stochastic nature of rockfall
365 release, we used RAMMS to select 1 of 10 randomly chosen rock clast orientations to be released at each source point,
366 yielding nearly 50,000 individual rockfall runout paths in each of the four simulations.

367
368 For our runout analysis, we focused on the eastern NW-facing ridgeline of the Skagway River valley given the need to assess
369 impacts to the harbour and township. Because each simulated runout event results in an individual rockfall path, it can be
370 difficult to effectively visualize the cumulative pattern of predicted runout. To identify terrain with high likelihood of
371 rockfall runout we used RAMMS to count the number of rockfall events that traversed each pixel in our domain for each of
372 the four scenarios. As such, the cumulative number of rockfall passages at each pixel accounts for both the abundance of
373 upslope source areas as well as the tendency for topography to steer or direct rockfall into particular pathways. In addition,
374 we used RAMMS to create a “digital” boundary (or barrier) coincident with the railroad tracks along the base of the
375 ridgeline to record the number and kinetic energy of modelled rockfalls that bypass the boundary and impact the harbour and
376 township.

377 **4 Results**

378 **4.1 Rockfall inventory**

379 Descriptions of rockfall events before 2005 can be found in newspaper articles dating back over a century, although we focus
380 on recent events in this contribution. We identified 11 reported rockfall events reported in the Skagway News since 2017
381 (Table 1). These reports tended to reflect sporadic rockfalls along Dyea Road as well as activity in 2022 abutting Skagway
382 Harbor on the eastern ridgeline. Many reports are recorded in the police blotter section of the Skagway News, but the timing
383 and location of these events is sometimes unclear and those cases were not included in our rockfall inventory. The AKDOT
384 GeoEvent database includes 536 reports of rockfall-related maintenance and operation activities in our study area between
385 2005 and 2022. Notably, this database does not include events along the eastern ridgeline in Skagway because those events
386 do not impact the state highway system. Rather, the vast majority (>415) of the AKDOT reports originate from the NW-
387 facing sections of Dyea Road west of Skagway. Among those events, 7 resulted in road closures that lasted 3 days or longer
388 in March 2012, October 2012, January 2014, March 2015, February 2016, September 2016, and December 2020.

389
390 Table 1: Rockfall events reported in the Skagway News since 2017



Event date	Event time (local)	Pre-event 24-hr rainfall total (inches)	Location
9-Oct-2023	n/a	0.63	East Dyea Valley
7-Oct-2023	n/a	1.46	Eas Nahku Bay
18-May-2023	6:17pm	0	North Slide
29-Sept-2022	3:57pm	0.50	East Nahku Bay
5-Aug-2022	n/a	0.04	North Slide
3-Aug-2022	5:00pm	0.02	North Slide
23-Jun-2022	7:30am	Trace	South Slide
2-Dec-2020	12:23pm	3.24	East Nahku Bay
5-Sept-2017	5:30am	0.76	North Slide
5-Sept-2017	3:00am	1.05	North Slide
26-Aug-2017	6:30am	0.55	North Slide

391

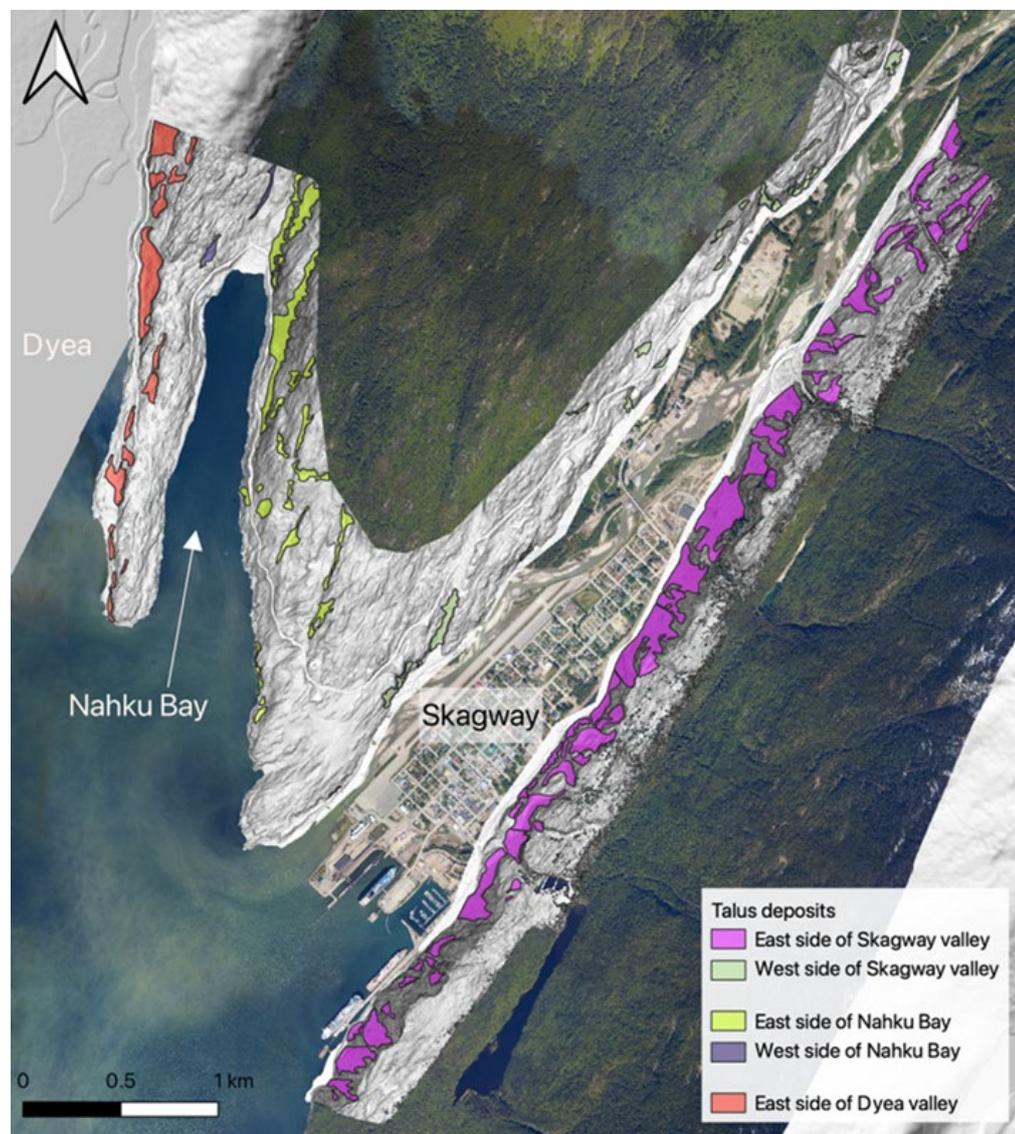
392 Rockfall events reported in the newspaper and AKDOT database occur sporadically throughout the year with most activity
 393 in the summer and fall months. Some high impact events correspond with intense rainfall events although most events do not
 394 coincide with an obvious climatic trigger. Rockfall activity on December 2, 2020, was preceded by over 3 inches of rainfall
 395 in the previous 24 hours. By contrast, a May 2023 event, which we observed in the field, initiated on a clear, sunny day with
 396 no precipitation in the 24 hours leading up to the event. In addition, the August 2022 events that impacted Skagway Harbor
 397 were not preceded by notable rainfall. Thus, while precipitation plays a role in initiating some rockfall events in Skagway
 398 other triggers maybe relevant making prediction difficult.

399 **4.2 Geomorphic mapping**

400 The morphology of glaciated valleys around Skagway is variable owing to bedrock structure, differential glacial erosion, and
 401 post-glacial landscape evolution. These factors generate systematic variations in the abundance of bedrock cliffs that serve as
 402 rockfall source areas as well as long, steep slopes that facilitate long rockfall runout. On the east side of the lower Skagway
 403 River valley, our lidar DEM and field observations reveal a distinct northwest-facing bedrock escarpment that runs parallel
 404 just below the crest of the ridgeline (Fig. 1, 6). This feature is particularly distinct above the cruise ship dock, where the
 405 ridgeline has high relief compared with sections to the north that abut the township. A similar high-relief escarpment also
 406 emerges on the same ridgeline near the northern extent of the township. Below these bedrock escarpments, we observe
 407 abundant talus deposits that extend continuously downslope to the base of the ridgeline and the valley floor (Fig. 6). An
 408 undated historic photograph which postdates the 1899 construction of the current Museum and City Hall depicts the eastern
 409 ridgeline in a state of minimal forest cover such that the escarpment and talus slopes above the harbour are clearly visible
 410 (Fig. 2b). These observations imply substantial post-glacial erosion through lateral (southeastward) retreat of the ridgeline as
 411 talus slopes convey bedrock downslope creating long and relatively smooth pathways for rockfall runout. On that image, the
 412 ridgeline slopes just north (on the left side of the image) exhibit gentler slope angles and a benchy morphology which
 413 implies less extensive post-glacial erosion and slope modification via rockfalls (Fig. 2b). Atop the ridgeline and east of the
 414 escarpment, the ridgeline contains abundant evidence of unmodified glacial erosion features. The west side of the lower



415 Skagway River valley has a very different morphology, in that it lacks a distinct escarpment and instead exhibits consistent
416 and gradual slopes that imply minimal post-glacial modification. Locally, we observe vertical cliffs along the Skagway
417 River. Otherwise, the topography on the west side of the lower Skagway River valley primarily consists of rock slopes that
418 form prominent ridges that parallel the strike of the valley. We observe a similar pattern of bedrock escarpments and talus
419 deposits along northwest-facing slopes of two parallel ridgelines between Skagway and Dyea (Fig. 6).
420



421
422

423 Figure 6: Distribution of talus deposits in study area. Polygons identified by their location: Skagway River valley, Nahku Bay,
424 and Dyea valley. Note the abundance of talus deposits on the NW-facing ridgeline in Skagway and on NW-facing slopes in



425 Nahku Bay and near Dyea. Hillshade derived from DGGS lidar data. Background image from USGS NAIP (National
426 Agriculture Imagery Program).

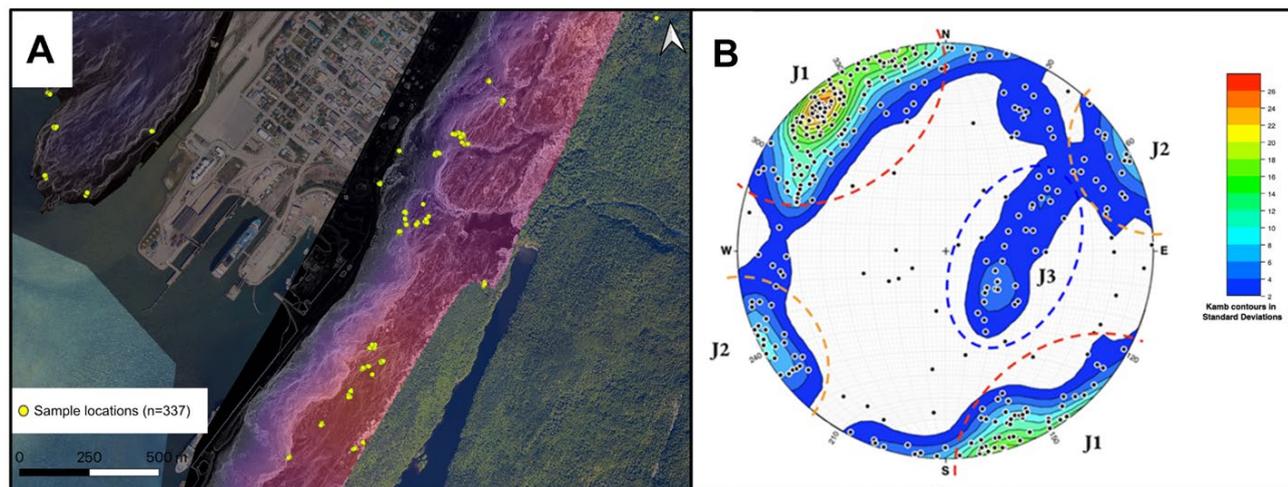
427

428 Our lidar- and field-derived mapping revealed abundant talus slopes on northwest-facing ridgelines across our study area.
429 More generally, talus deposits compose 12% of the 7.2 km² total mapped area. Along the eastern ridgeline, we identified 56
430 talus slopes with an average area of 9,290 m², which collectively make up 20% of that ridgeline area. On the west side of the
431 lower Skagway River valley, the southeast-facing ridgeline hosts 20 talus deposits, and these talus slopes constitute only 3%
432 of the 1.67 km² mapped area on that side of the valley. Similarly, talus deposits on the southeast-facing ridgelines bordering
433 Nahku Bay are much less abundant (1%) and smaller in area than on the northwest-facing ridgeline that abuts the bay (11%).

434 **4.3 Bedrock structure and discontinuities**

435 To characterize the geometry of discontinuities with the potential to generate rockfalls, we collected 337 joint orientations
436 from 36 granodiorite outcrops across the study area (Supplemental material) and plotted the data as poles to planes on an
437 equal area stereonet to identify dense clusters of poles which were then grouped into joint sets (Fig. 7). Three joint sets were
438 identified in this survey, two steeply dipping orthogonal sets (*J1* & *J2*), and one set that dips gently to the west (*J3*). The
439 steeply dipping joints are of relevance, as they tend to be conducive to toppling, which is the most observed failure mode in
440 Skagway. The most densely defined joint set is *J1*, which parallels the strike of the lower Skagway River valley and the
441 eastern ridgeline and predominantly dips to the southeast. The less densely defined joint set (*J2*), is approximately
442 orthogonal to *J1*, has near vertical dips, and strikes northwest. The third, gently dipping joint set (*J3*), are interpreted as
443 sheeting joints, typical in plutonic rocks, which have significantly higher curvature at the outcrop scale than the steeply
444 dipping orthogonal joints resulting in an elongate field of poles on the stereonet.

445



446

447

448 Figure 7: Structural data (a) Location of 337 structural measurements from 36 outcrop locations distributed across Skagway
 449 Valley and the AB ridgeline separating Skagway from Nahku Bay. See Fig. 4 for location. (b) Lower hemisphere equal area
 450 stereonet of joint measurements visualized as poles to planes (n=337) with Kamb contours to highlight dense clusters of poles,
 451 which were grouped into three joint sets (J1, J2, and J3). Background image in (a) from USGS NAIP (National Agriculture
 452 Imagery Program).

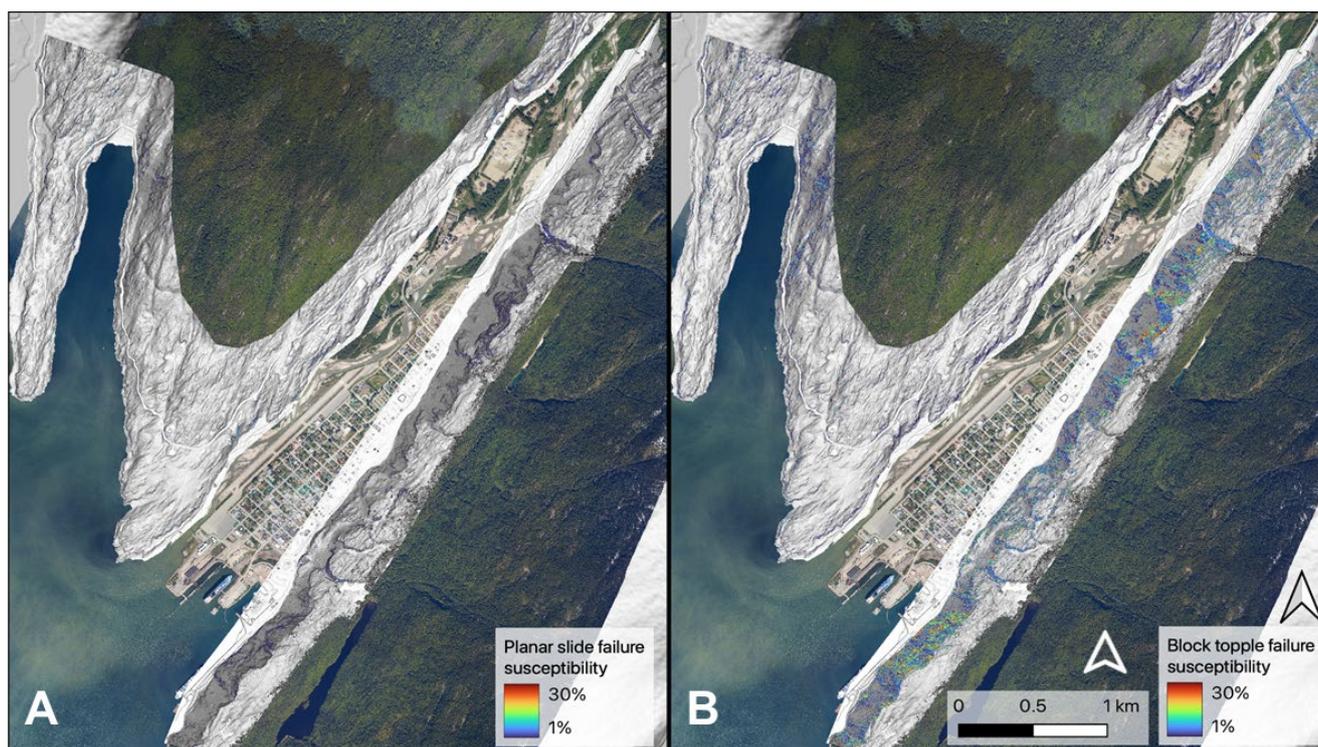
453

454 4.4 Kinematic analysis of rockfall susceptibility

455 The abundance of consistently oriented joints with vertical or sub-vertical dips suggests that rock toppling is the dominant
 456 rockfall mechanism in Skagway, which is supported by field observations. Furthermore, given the consistent orientation of
 457 sub-vertical joints, the primary control on susceptibility to toppling is the orientation and inclination of rock faces (equation
 458 2). On the crest of the eastern ridgeline in the lower Skagway River valley, for example, the glacially flattened bench at the
 459 top of the slope is not steep enough to meet topographic conditions for either failure mode (Fig. 5). As one moves to the west
 460 side of the crest, however, the gentle ridgetop abruptly transitions to the steep escarpment where overhanging, cliffy bedrock
 461 slopes are observed. At this position on the ridgeline, our analyses show that large patches of terrain have a substantial
 462 portion (> 25%) of discontinuities that promote toppling failure according to equation 2 (Fig. 8). At downslope locations
 463 (i.e., between the ridgeline and valley floor), rock slopes continue to exhibit patchy zones of toppling susceptibility, many of
 464 which are in close proximity to Skagway township and harbour. Along the rock slopes on the west side of Skagway, our
 465 analyses reveal fewer and smaller patches of terrain susceptible to toppling with less than 10% of the discontinuities
 466 predicted to be unstable. We observe a similar pattern along the sub-parallel ridges west of Skagway along Dyea Road with
 467 northwest-facing ridgelines exhibiting abundant patches of terrain with high propensity for toppling failure (Fig. 8). Finally,
 468 we observe small areas of terrain with planar failure susceptibility according to equation 1 and in these patches, less than 5%



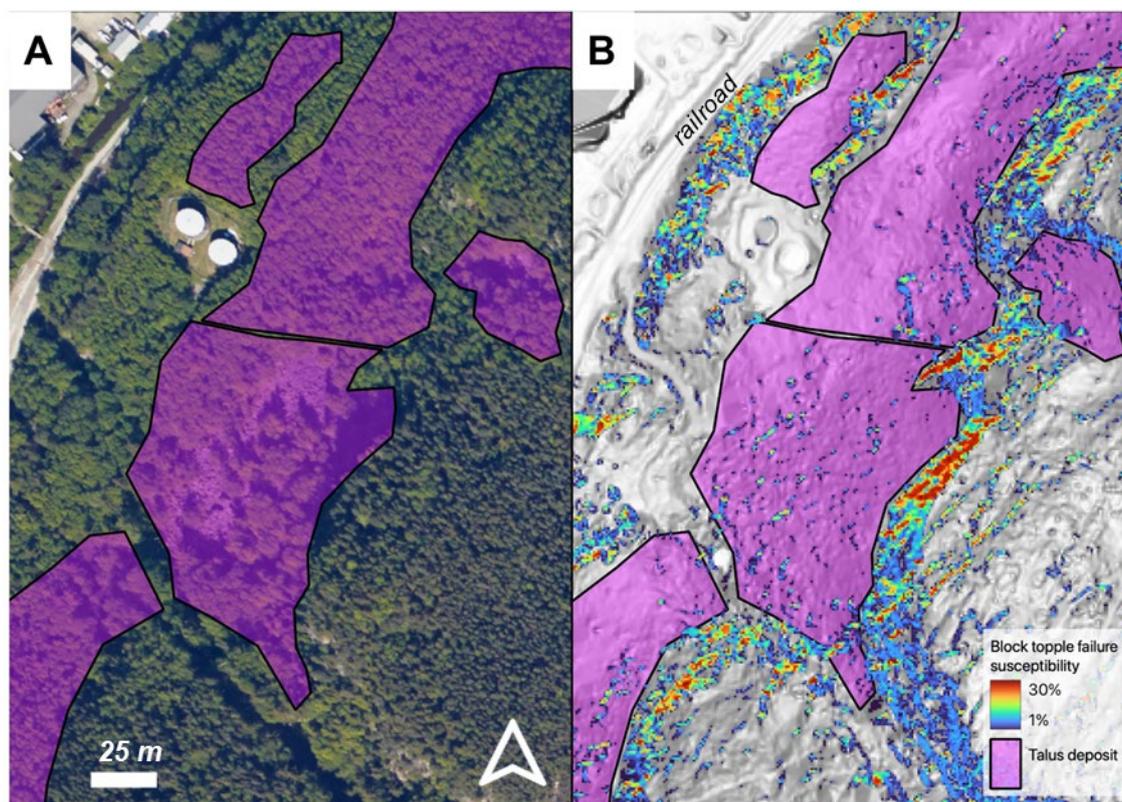
469 of the joints are predicted to promote planar sliding. More generally, by combining our talus slope maps with toppling failure
470 susceptible zones, we note a strong correspondence such that zones with >5% toppling failure commonly occur just upslope
471 of talus-mantled slopes (Fig. 9).



473 Figure 8: Maps of rockfall susceptibility indices using combined 2014 airborne and 2023 UAS lidar datasets. (a) Susceptibility
474 to planar slide failure according to equation 1, and (b) susceptibility to block toppling according to equation 2. Both indices
475 are estimated as the percentage of joints deemed unstable at each pixel. Note the abundance of toppling failure zones on NW-
476 facing rock slopes that border Skagway and Nahku Bay. Hillshades in a and b derived from DGGS lidar data. Background
477 image from USGS NAIP (National Agriculture Imagery Program).

478

479



480

481 Figure 9: Map of talus deposits and block toppling susceptibility index (percentage of joints deemed unstable in each pixel
482 according to equation 2). See Fig. 4 for location. (a) Orthoimage of Kirmse's cliff and the partially forested talus deposit at the
483 base of the slope, (b) Block toppling susceptibility index. Note the abundance of susceptible toppling areas perched above the
484 talus deposits. Background image in (a) from USGS NAIP (National Agriculture Imagery Program). Hillshade in (b) derived
485 from DGGs lidar data.

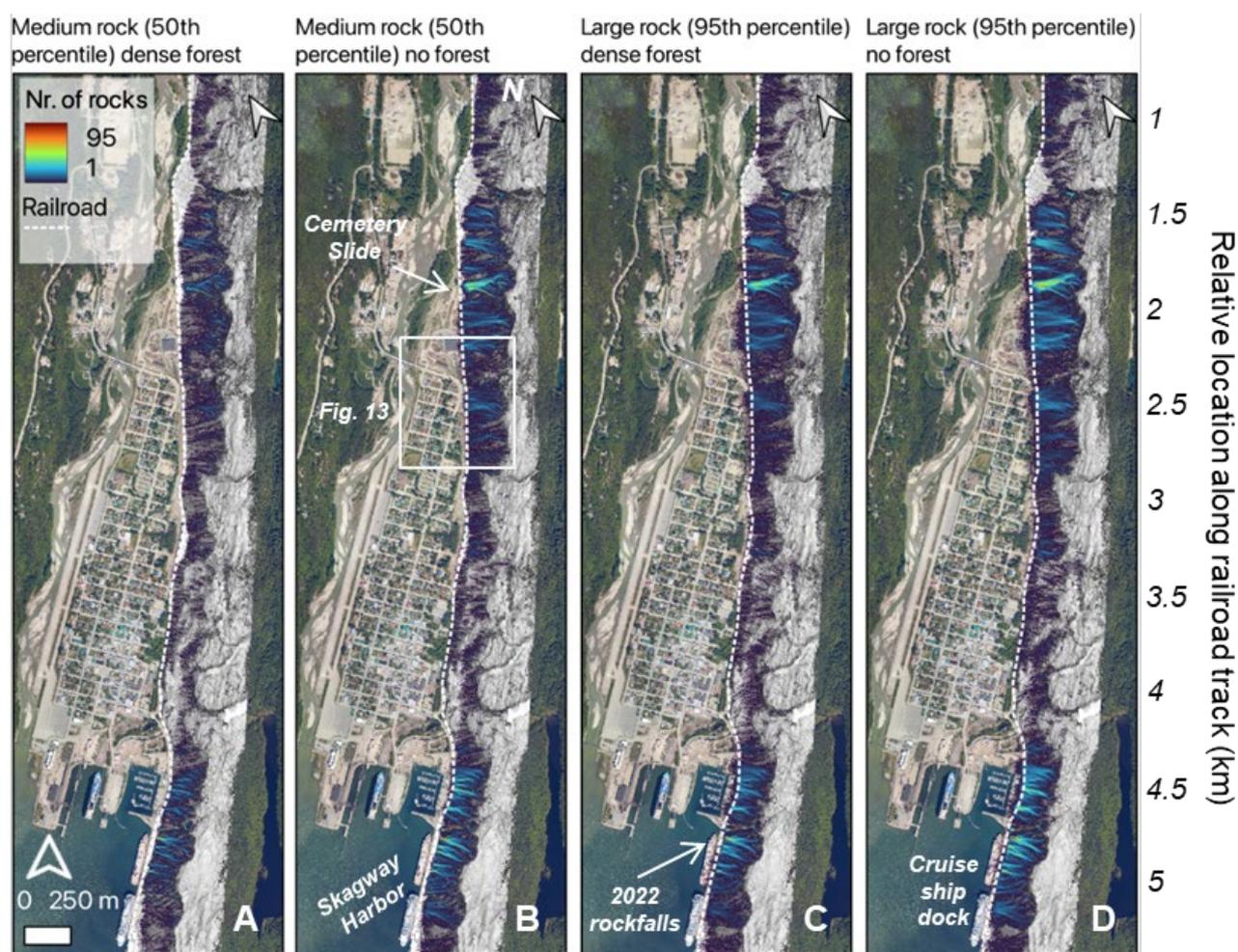
486

487 4.5 Rockfall runout modelling using RAMMS

488 By using zones of high toppling susceptibility ($>5\%$) as source areas for rockfall initiation we used RAMMS to model the
489 runout of nearly 50,000 rockfall events for each of the four scenarios that account for differences in clast size and ground
490 cover. Our simulations showing the total number of rockfall events traversing each pixel reveal distinct zones subject to high
491 rockfall susceptibility as well as extensive downslope transport (Fig. 10). In each of the four scenarios, the southern end of
492 the ridgeline above the harbour (between 4 and 5km on our railroad-based transect) exhibits ~ 10 specific chutes or paths of
493 likely rockfall runout whereby initiation near the escarpment results in the concentration of rockfall runout along these paths
494 and conveyance to the cruise ship docks and/or harbour (Fig. 10). This zone coincides with the area of high-relief terrain and
495 extensive escarpment development. In contrast, the central portion of the ridgeline (between 2.8 and 4km) immediately



496 adjacent to much of the township exhibits patchy and less frequent rockfall activity along gentle and irregularly oriented
 497 bedrock steps and benches. Further north, our simulations again reveal abundant long rockfall runout paths at the northern
 498 extent of the township with a concentration near the Cemetery Slide area (between 1 and 2km). Finally, at the northernmost
 499 extent of our simulation domain (near 1km), the results show patchy and short rockfall transport paths coincident with
 500 gentle, benchy topography. Although the relative pattern of predicted runout described here is consistent across the four
 501 scenarios, our simulations of 95th percentile size clasts and no forest cover result in the most abundant passage of rockfall
 502 events to the valley floor with high potential for impacting infrastructure and imperilling public safety (Fig. 10d).
 503



504

505 Figure 10: Map of modeled rockfall runout along eastern ridgeline in Skagway Valley conducted for 4 scenarios with variable
 506 clast size and land cover (panels a-d). The number of rockfall events that traverse each cell is indicated by the color ramp with
 507 warm colors reflecting frequent rockfall passage. Note the abundance of long runout events in the SW section bordering the
 508 harbour and near the northern extent of the township. The dashed white line denotes the railroad track used to document
 509 rockfall runout and kinetic energy in Fig. 11 for relative position along the tracks. The white box in (c) denotes the area shown

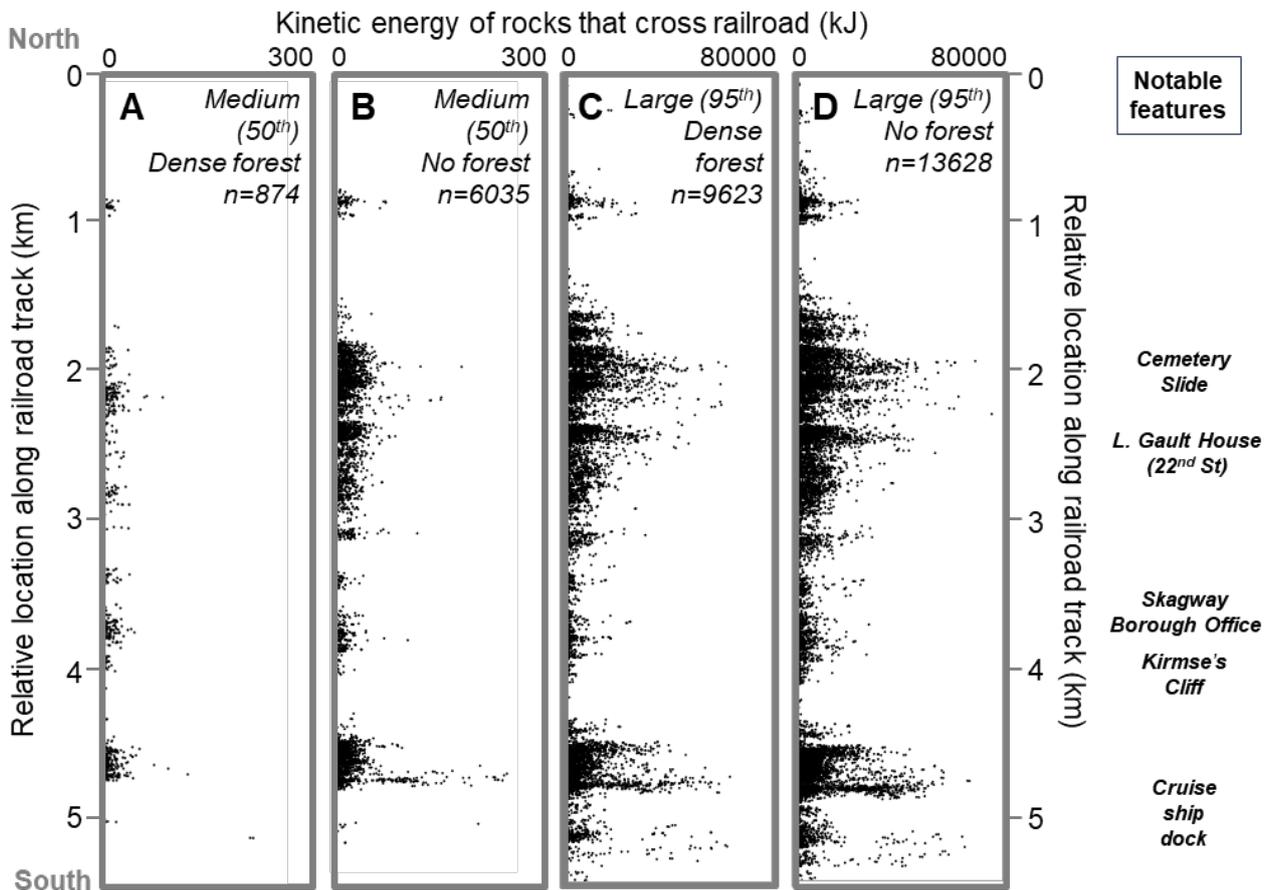


510 in Fig. 13, site of an historic rockfall event that impacted the township. Hillshade derived from DGGs lidar data. Background
511 image from USGS NAIP (National Agriculture Imagery Program).

512

513 To characterize the location and potential impact of simulated rockfall events that reach the valley floor, we tallied the
514 number and kinetic energy of simulated rockfall events that traverse the railroad track (Fig. 11). In each of these scenarios,
515 the north-to-south alternating pattern of high-low rockfall runout hazard is reflected in the number and kinetic energy of
516 clasts that travel to the base of the ridgeline. Given the 49,450 simulated rockfall events in each of the four scenarios, <2%
517 and 12% rocks crossed the railroad for the dense forest and no forest scenarios with the 50th percentile clast size,
518 respectively. By contrast, using the 95th percentile clast size resulted in nearly 20% and 28% rockfall passage of the railroad
519 in the dense forest and no forest scenarios, respectively. These results highlight the importance of dense forest and clast size
520 in determining risk of rockfall runout.

521



522



523 Figure 11: Kinetic energy of simulated rocks that pass the railroad tracks (see Fig. 10 for location) for 4 scenarios with variable
524 clast size and land cover (panels a-d). Note the difference in scale of kinetic energy between panels (a,b) and (c,d). The number
525 of rocks that pass across the track is highest for the scenario with the largest clast size and no forest cover. Notable locations
526 are annotated along the right margin of the plots.

527

528 **5 Discussion**

529 Rainfall appears to be responsible for triggering some rockfall events in Skagway, but the majority of rockfall events are not
530 preceded by heavy precipitation. Therefore, accurately predicting the timing of rockfall events based on precipitation
531 metrics, like rainfall initiation thresholds used to estimate the likelihood of landslide initiation in Sitka, AK (Patton et al.,
532 2023), is not likely to be successful. Instead, estimating the spatial pattern of rockfall susceptibility is a useful approach to
533 mitigating rockfall hazard. Taken together, our analyses of rockfall susceptibility and talus deposition maps demonstrate that
534 rockfall source areas and runout paths tend to be located on northwest-facing rock slopes in the lower Skagway River valley,
535 Nahku Bay, and the lower Taiya River valley, indicating a strong topographic control on rockfall activity owing to the
536 regularity of glacial valleys and joint orientations in the area.

537

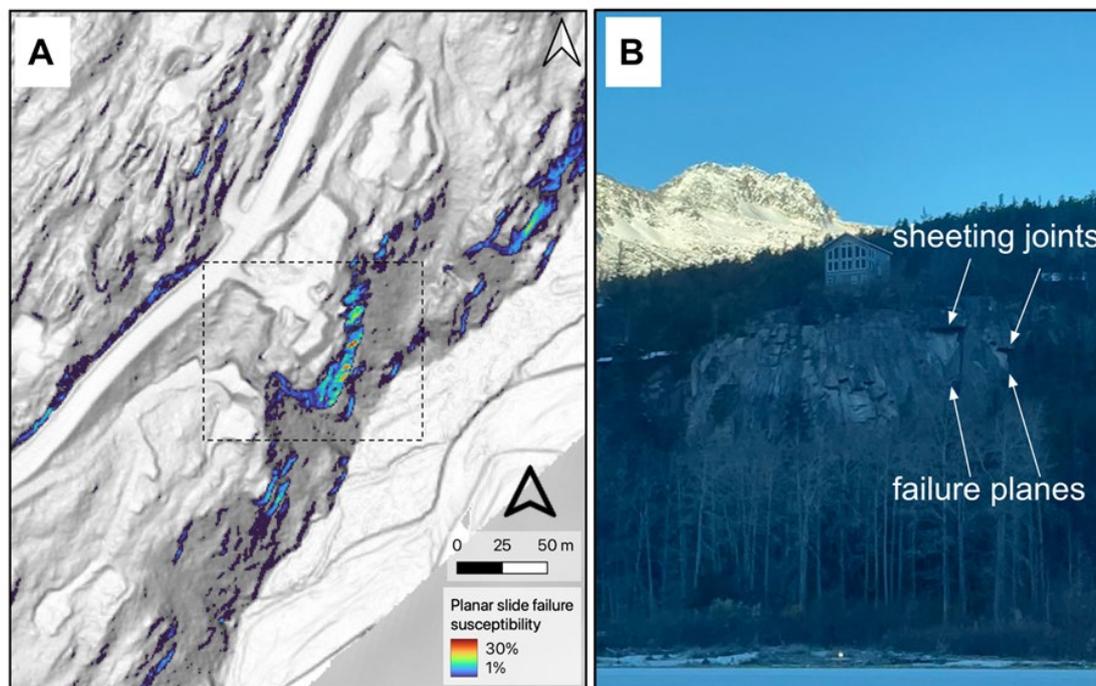
538 The joints measured in this study are consistent with the steeply dipping, orthogonal joint sets measured in a nearby
539 structural survey in West Creek (Callahan and Wayland, 1965) and described in a geotechnical assessment of the rock slopes
540 above Skagway's cruise ship dock (Brennan and Whistler, 2022). High angle joints are likely formed by the tensile
541 component of shearing from the nearby Chatham Strait fault and Eastern Denali fault systems, while sheeting joints reflect
542 the combined influence of far field tectonic stresses and topographic stress that arise from landscape curvature (Martel, 2006,
543 2017). Rock slopes with orthogonal jointing are often predisposed to block toppling failure particularly where steep
544 orthogonal joints form the sides of toppling blocks and low angle joints, like the sheeting joints observed in this study, act as
545 the basal failure plane (Wyllie and Mah, 2004). Because the densest cluster of joints we observed dips steeply to the
546 southeast, rock slopes facing northwest tend to form anti-dip slopes which are conducive to toppling failure. This is
547 supported by larger and more abundant talus deposits on the east sides of the lower Skagway River valley and Nahku bay,
548 confirming that rockfall occurs preferentially on northwest-facing slopes (Fig. 6).

549

550 The results of our kinematic analysis demonstrate that rock slopes in the steep rugged terrain surrounding Skagway are more
551 susceptible to block toppling failure than planar slide failure. The preference for toppling failure is due to the inclination of
552 joints, which are generally steep and conducive to toppling failure as their near verticality may preclude them from
553 daylighting in rock slope faces, a necessary condition for planar slide failure. On the west side of the lower Skagway River
554 valley, an isolated zone of steep vertical cliffs is susceptible to planar slide failure as recent planar failures are evident, which
555 release from sheeting joints and slide on joints steeply dipping southeast (Fig. 12).



556



557

558 Figure 12: Planar sliding susceptibility along the western ridgeline in Skagway River Valley. Location depicted in Fig. 4. (a)
559 Map of planar failure susceptibility index using equation 1. (b) Image of SE-facing ridgeline in lower Skagway River valley.
560 Note high values on SE-facing steep bedrock cliffs that coincide with field evidence for sheeting joints and planar failures.
561 Hillshades derived from DGGs lidar data.

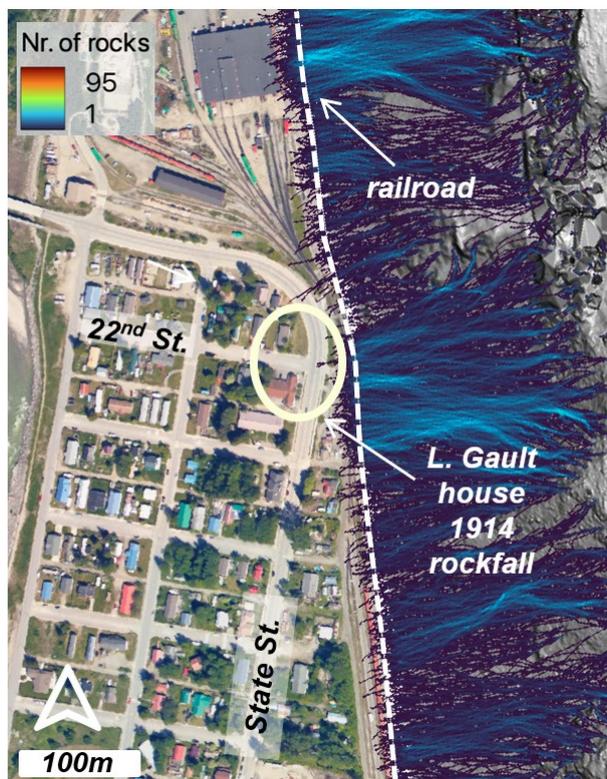
562

563 Rockfall susceptibility maps are consistent with the failure mode and location of rock slope deformation observed in the
564 field. Just uphill of the prominent escarpment along the eastern ridgeline in the lower Skagway River valley, we observed
565 numerous instances of detached parallel slabs of rock separated by tension cracks (Fig. 3). These blocks appear to be
566 experiencing early phases of toppling failure as vegetation and other processes contribute to crack widening. These
567 observations indicate that our predicted zones of toppling failure along active bedrock escarpments are likely to continue
568 propagating to the southeast providing additional blocks available to initiate rockfall. More generally, these observations
569 suggest that erosion and SE-oriented lateral migration of the eastern ridgeline has been substantial since the glacial retreat 10
570 to 12 kya. Reconstruction of the ridgeline to its immediate post-glacial geometry implies that 10 to 100 meters of lateral
571 erosion has occurred during the Holocene. On-going rockfall activity along this ridgeline suggests that this unravelling and
572 retreat of the escarpment will continue.

573



574 Importantly, extensive rockfall activity and lateral divide migration does not occur along the entire ridgeline. Rather, our
575 results show large sections of the 5-km long ridgeline with patchy and localized talus deposits and benchy bedrock
576 landforms. On Kirmse's Cliff (at 4 km on the railroad transect), for example, talus deposits extend upslope from the valley
577 floor to vertical cliff faces that terminate at the ridgeline (Fig. 5). In this area, rockfall susceptibility is relatively high, but
578 concentrated in a relatively small area of vertical rock slope, and a forested talus deposit and benchy zone sits between the
579 cliff and infrastructure in Skagway (Fig. 9). By contrast, several areas along the escarpment exhibit high potential for
580 rockfall runout to reach the valley. At the cruise ship dock (4.5 to 5 km), continuous, rockfall-prone slopes above the cruise
581 ship dock span from the escarpment to the base of the slope, resulting in a large area with high rockfall susceptibility in close
582 proximity to harbour infrastructure. Similarly, from 1.5 to 2.5 km on our railroad transect, a high-relief escarpment with
583 steep vertical bedrock outcrops near the crest exhibits a continuous steep slope to the valley floor (Fig. 10). In this area,
584 which is the source area for the Cemetery Slide, rockfall susceptibility and long runout potential are high and we observed
585 frequent spalling rocks during our field work (Fig. 10b). In addition, The Daily Alaskan reported a 1914 rockfall event just
586 south of the Cemetery Slide at 2.5km along the transect which coincides with our simulations of high rockfall runout
587 potential (Figs. 10 & 13). During that event, L. Gault noted “an avalanche of earth and stone” that “leaped the railroad
588 track...pounding against the fence.” Gault noted that the railroad track served as a “safety barrier” because “the force of the
589 descent had been so much lessened.” Further afield in the NE section of Nahku Bay, another zone of high rockfall
590 susceptibility is revealed by our analysis. Steep rocky slopes rise to an elevation of 250 m with close proximity to Dyea
591 Road. This area lacks a well-developed runout path, but it does coincide with source areas for two events in the AKDOT
592 rockfall inventory that impacted Dyea Road. Most generally, a rigorous characterization of rockfall risk in Skagway requires
593 estimation of occupation and usage of structures and transportation corridors coupled with our results (e.g., Michoud et al.,
594 2012).
595



596

597 Figure 13: Detailed map of modeled rockfall runout (Medium rock (50th percentile), no forest) with location depicted shown
598 by white box on Fig. 10b. Note the location of rockfall near the intersection of 22nd and State Street described by L. Gault in
599 the March 26, 1914, edition of The Daily Alaskan. That location corresponds with a region of likely rockfall runout identified
600 by our coupled initiation-runout simulations. Hillshade derived from DGGS lidar data. Background image from USGS NAIP
601 (National Agriculture Imagery Program).

602

603 Our analyses reveal distinctive zones of high rockfall runout hazard in the Skagway region that result from the combination
604 of glacial erosion that sets the morphology of bedrock slopes and the orientation of joint sets that determine the geometry of
605 potential bedrock failures. Most likely, the orientation and extent of glacial erosion is not independent of the joints. Rather,
606 we suspect that the nearly parallel orientation of joints and the N-NE trending ridgeline along the eastern margin of the lower
607 Skagway River valley arise due to glacial erosion tracking discontinuities that facilitate erosion more readily than
608 undeformed bedrock. Localized zones of the prominent ridgeline that abuts Skagway River valley exhibit abundant historic
609 rockfall activity and over long timescales this activity is likely to continue. As such, our findings provide key constraints for
610 identifying areas at risk to inform mitigation efforts.



611 **6 Conclusions**

612 Rock slope failure is a major driver of landscape evolution in Skagway since glacial retreat. The steeply dipping orthogonal
613 joints in Skagway's rock slopes are conducive to block toppling failure. Our results highlight a distinct contrast in the
614 morphology of Skagway River valley's eastern and western ridgelines, which is primarily determined by the predisposition
615 of northwest-facing slopes to block toppling failure along a densely fractured joint set that dips steeply to the southeast. This
616 is consistent with geomorphic evidence of extensive rockfall activity, where talus deposits are more abundant and larger on
617 the eastern side of the lower Skagway River valley than the west. This structural control on rockfall activity is also reflected
618 in the east and west sides of Nahku Bay, situated to the west of Skagway. Historic rockfall records indicate a similar
619 preference for initiating on northwest-facing slopes. Our simulations show areas with high rockfall susceptibility that may
620 merit further investigation and mitigation: 1) the ridgeline and slopes above the cruise ship dock, 2) the high-relief
621 topography at the north end of Skagway (which includes the Cemetery Slide), and 3) the eastern ridgeline bordering Nahku
622 Bay. Recent rockfall source areas located in these regions are characterized by steep northwest facing slopes that are highly
623 susceptible to block toppling failure and reach >200 m in elevation which facilitates long runout paths.

624 **7 Data availability**

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

626 **8 Author contribution**

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

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638



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