

Mapping Rockfall Susceptibility in the Steep Rocky Slopes of Skagway, Alaska

by

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ABSTRACT

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Title: Mapping Rockfall Susceptibility in the Steep Rocky Slopes of Skagway, Alaska

Rockfall is a common occurrence in steep mountainous terrain which poses a hazard to nearby communities. It is useful to determine the likelihood of rockfall initiating from a given location, or rockfall susceptibility, which is largely controlled by discontinuities in the rock mass. Rockfall susceptibility can be evaluated by identifying unfavorably oriented discontinuities that intersect with the face of a rock slope, a technique called kinematic analysis. Modern kinematic analyses use Digital Elevation Models to identify common failure modes and rockfall susceptible slopes at the scale of entire valleys.

The area of interest for this study is the rugged topography surrounding Skagway, a small town in southeast Alaska that has been threatened by rockfalls that initiate from its steep valley walls. The aim of this study is to identify areas with high rockfall susceptibility, and compare the results to mapped talus deposits which are a proxy for past rockfall activity. In the granodiorite bedrock, two steeply dipping orthogonal joint sets, and a third set of sheeting joints were identified. The most prominent joint set dips steeply to the southeast, which predisposes northwest-facing rock slopes to block toppling failure. Kinematic tests show block toppling failure is more common than planar slide failure in the study area, particularly on the eastern sides of Skagway valley and Nahku Bay that generally face northwest. These findings are consistent with the more abundant talus deposits on the eastern sides Skagway valley Nahku Bay. Three distinct areas with particularly high rockfall susceptibility, and known rockfall source areas, were identified for further investigation and mitigation.

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INTRODUCTION

Rockfall are abrupt downward movements of discrete rock fragments which detach from steep slopes of rock. Rockfall is a common occurrence in steep rocky terrain that poses a hazard to nearby communities and their infrastructure. In the Port Hills near Christchurch, NZ, a Mw 6.2 earthquake in 2011 generated rockfall that killed five people and impacted over 200 houses (Macfarlane & Yetton, 2013). Rockfall activity is found in many settings, but is particularly commonplace in post-glacial landscapes. During deglaciation, as ice retreats from a valley, the steepened rock slopes are no longer supported by the weight of the glacier, which can result in periodic small scale rockfall events and talus deposits (Ballantyne, 2001). Rockfall occurs when the stresses acting on a steep slope of rock change, which can be triggered by a multitude of environmental factors. In Yosemite Valley, CA, rockfall triggers include rainfall events, snow melt, and freeze-thaw action (Wieczorek & Jäger, 1996) due to the increase in pressure along joints in the rock mass. In the same area, rockfall can also be triggered by cyclic solar heating of the granite cliffs, which propagates exfoliation fractures and leads to rock detachment (Collins & Stock, 2016). The timing of these environmental triggers can be elusive, and difficult to predict with enough accuracy to give actionable warning time to community members. Therefore, locating rock slopes with the propensity to generate rockfall, referred to here as rockfall susceptibility, is often the first step to managing these hazards.

Rockfall is aided by discontinuities, or preexisting planes of weakness (i.e. joints or fractures) that permeate the rock mass. Rock slopes are unstable where discontinuities intersect with the slope face at unfavorable orientations. Therefore, rockfall susceptibility can be evaluated by characterizing the discontinuities that are oriented unfavorably with respect to the rock slope face. This method of quantifying rockfall susceptibility is known as a kinematic analysis, an approach that identifies blocks of rocks that can move freely from the slope face (Hoek & Bray, 1981).

Kinematic analyses are readily applied over large areas to identify where the conditions for rockfall are met, and therefore can be used as a first order evaluation of rockfall hazard (Kundu et al., 2023). Kinematic analyses originally used stereonet to visualize the failure envelope for a given slope face, where discontinuities that meet the conditions for failure plot in a failure envelope. However, the stereographic-based technique of kinematic analyses is limited to evaluating individual slope faces of uniform orientation.

Traditionally, discontinuity measurements for kinematic analysis were collected in the field. More recent applications of kinematic analysis leverage Terrestrial Laser Scans (TLS) (Fanos & Pradhan, 2018) to extract discontinuity sets remotely from point cloud data, and test kinematic conditions on complex slope geometries like overhanging rock quarries (Gigli, 2022). These studies are limited by the availability of high-resolution point cloud data, typically acquired with TLS (Matasci et al., 2018) or UAV based structure from motion (Utlu et al., 2023), both of which are challenging to collect over large, forested areas where rock slopes may be obscured by vegetation. Due to its increasing availability, high resolution topographic data has been incorporated into rockfall susceptibility assessments at regional scales (Grant et al., 2016). To assess rockfall susceptibility across large areas that encompass many rock slopes of varying orientation, kinematic analysis has been adapted to accept Digital Elevation Models (DEM) as the topographic parameters, called GIS-based kinematic analysis (Kundu et al., 2023; Park et al., 2015).

Rockfall activity has plagued many areas of SE Alaska, particularly Skagway, a town with around 1,000 residents. It is situated in a narrow glacial valley, with steep rock slopes to the east and west. Descriptions of rockfall activity in Skagway date back to the early 20th century.

“The heavy rains yesterday afternoon and evening loosened another part of the hill side near Moore’s wharf and down it came completely covering the track near the south end of the approach to the wharf.” (The daily morning Alaskan, 1901)

The source area described in this historic rockfall event is located in the steep rocky slopes above Skagway’s harbor, which have generated numerous rockfalls in modern times. Rocks detached from the slope above the harbor on June 23, 2022, and impacted the cruise ship dock below where pedestrian traffic was common (Munson, 2022). Two more rockfall events originating in the rocky slopes above the harbor followed in rapid succession on August 3 and 5, 2022 (Wehmhoff, 2022). Motivated by this renewed activity, the purpose of this study is to identify rockfall-susceptible areas within the steep post glacial valleys in Skagway, Alaska. For validation, modeled rockfall susceptibility is compared to the location of rockfall events in Skagway, as well as mapped talus deposits which serve as a proxy for past rockfall activity.

BACKGROUND

As glaciers recede from a valley, rock slopes can undergo three types of deformation as described by Ballantyne 2001: (1) large-scale, catastrophic failure, (2) progressive rock mass deformation, which may result in catastrophic failure, and (3) rapid slope adjustment through periodic small-scale rockfall that result in talus deposits at the base of the slope. This study is focused on the last of these deformation types.

There are several approaches to evaluating rockfall susceptibility, or the likelihood of rockfall initiating from a specific location. Geomorphic mapping and rockfall inventories can be used to infer the frequency and size of future rockfall from past events (Loye et al., 2009). Other methods utilize the structure of the rock mass to identify rockfall susceptibility, which includes limit equilibrium approaches and kinematic analysis. Limit equilibrium approaches can be used to determine an instability's factor of safety, or the ratio of driving forces to resisting forces acting on a block of rock, however, they require extensive laboratory testing and cannot easily be applied over large areas (Wyllie & Mah, 2004). Therefore, to evaluate the rockfall susceptibility of the terrain in and around Skagway, GIS-based Kinematic analysis, which uses DEMs to compute slope orientation parameters, was the most fitting approach for this study.

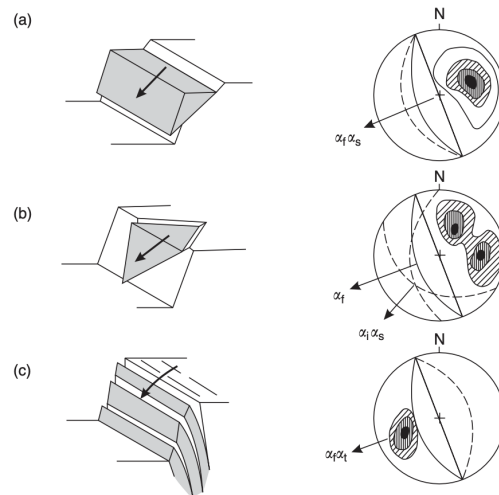


Figure 1: Diagrams representing common failure modes: (a) planar sliding, (b) wedge, and (c) toppling. On the right of each diagram are stereonet, where the rock slope face is represented by a solid black line, and poles to planar discontinuities that meet conditions for failure are contoured. Dashed lines represent general orientations of these discontinuities as planes. From Wyllie and Mah, 2004.

Common modes of rock slope failure (**Figure 1**) include planar sliding, wedge, and toppling are summarized below from Wyllie and Mah 2004. Planar slides occur when a block of rock slides on a single planar discontinuity from the slope face. Wedge failures occur when two or more planar discontinuities intersect, forming a wedge of rock, which then slides from the slope face. Toppling failures occur when discontinuities steeply dipping into the rock slope face form slabs or columns of rock that rotate forward along a fixed base. Two types of toppling failures can occur that are influenced by the strength of the rock mass and the nature of discontinuities. Flexural toppling, where slabs of rock bend forward until they break in flexure, is typical in shale and slate where orthogonal jointing is not well developed. Block toppling is common in hard rock with three well developed orthogonal joint sets, where two steeply dipping joint sets form the sides of blocks, and a third set of low angle, widely spaced joints form a basal failure plane.

In a public geotechnical site assessment, the active rockfall source area situated at the top of the slope above Skagway's cruise ship dock has been described as a progressive toppling failure with a stair-stepped basal feature (Brennan & Whistler, 2022). Topple failures observed in the field were consistent with this description, which closely aligns with block toppling failure. Since block toppling is the failure mode commonly observed in the study site (**Figure 2**), block toppling was chosen as one of the failure modes modeled with kinematic analysis in this study. Planar slide failures were observed in the field but were much less abundant, these were also included in the kinematic analysis. Wedge failures were not observed in the field and therefore were not included in the kinematic analysis.



Figure 2: Rock slopes on the east side of Skagway valley with tension cracks and tall slabs of rock, consistent with the block toppling mode of failure.

Markland's test (Hoek & Bray, 1981) is a method of determining the possibility of planar slide, wedge, or toppling failure based on the orientation of discontinuities in the rock mass and how they intersect with the rock slope face. According to Markland, a rock slope is susceptible to planar sliding failure along a discontinuity if conditions in **Eq. 1** are met.

$$(1a) \quad |\alpha_A - \alpha_f| < 20^\circ$$

Eq. 1a: The dip direction of the discontinuity (α_A) is parallel or subparallel ($\pm 20^\circ$) to the dip direction of the slope face (α_f).

$$(1b) \quad \psi_A < \psi_f$$

Eq. 1b: The dip of the discontinuity (ψ_A) is shallower than the angle of the slope face (ψ_f), such that the discontinuity intersects, or 'daylights', in the slope face.

$$(1c) \quad \psi_A > \phi_j$$

Eq. 1c: The dip of the discontinuity (ψ_A) is steeper than the angle of friction (ϕ_j).

Also according to Markland, a rock slope is susceptible to block toppling failure if the conditions for dip direction of the discontinuity (**Eq. 2a**) and interlayer slip (**Eq. 2b**) are met.

$$(2a) \quad \alpha_f - 20^\circ < (\alpha_A \pm 180^\circ) < \alpha_f + 20^\circ$$

Eq. 2a: The discontinuity must dip into the slope face, and be parallel, or nearly parallel ($\pm 20^\circ$) from the dip direction of the slope face (α_f).

$$(2b) \quad (90^\circ - \psi_f) + \phi_j < \psi_A$$

Eq. 2b: The discontinuity dip must be steep enough to overcome friction and allow interlayer slip between blocks.

It should be noted that the original dip direction constraints for block toppling (**Eq. 2a**) proposed by Markland was $\pm 10^\circ$ (Hoek and Bray, 1981). It has been proposed that these constraints should be expanded to $\pm 20^\circ$ (Cruden, 1989), which is used in other modern applications of kinematic

analysis (Gigli et al., 2022), and therefore $\pm 20^\circ$ constraints were used in the kinematic analysis of this study.

Kinematic analysis requires a set of discontinuities that is representative of the rock structure.

Traditionally, discontinuity measurements are taken in the field, whereas some modern applications extract discontinuity orientations from high-resolution point clouds of the rock slope face (Utlu et al., 2023). Field measurements can still be relied on to capture a representative joint set (Kundu et al., 2023), especially where terrestrial laser scans are not feasible due to hazardous terrain or where slope faces are obscured by vegetation.

STUDY SITE

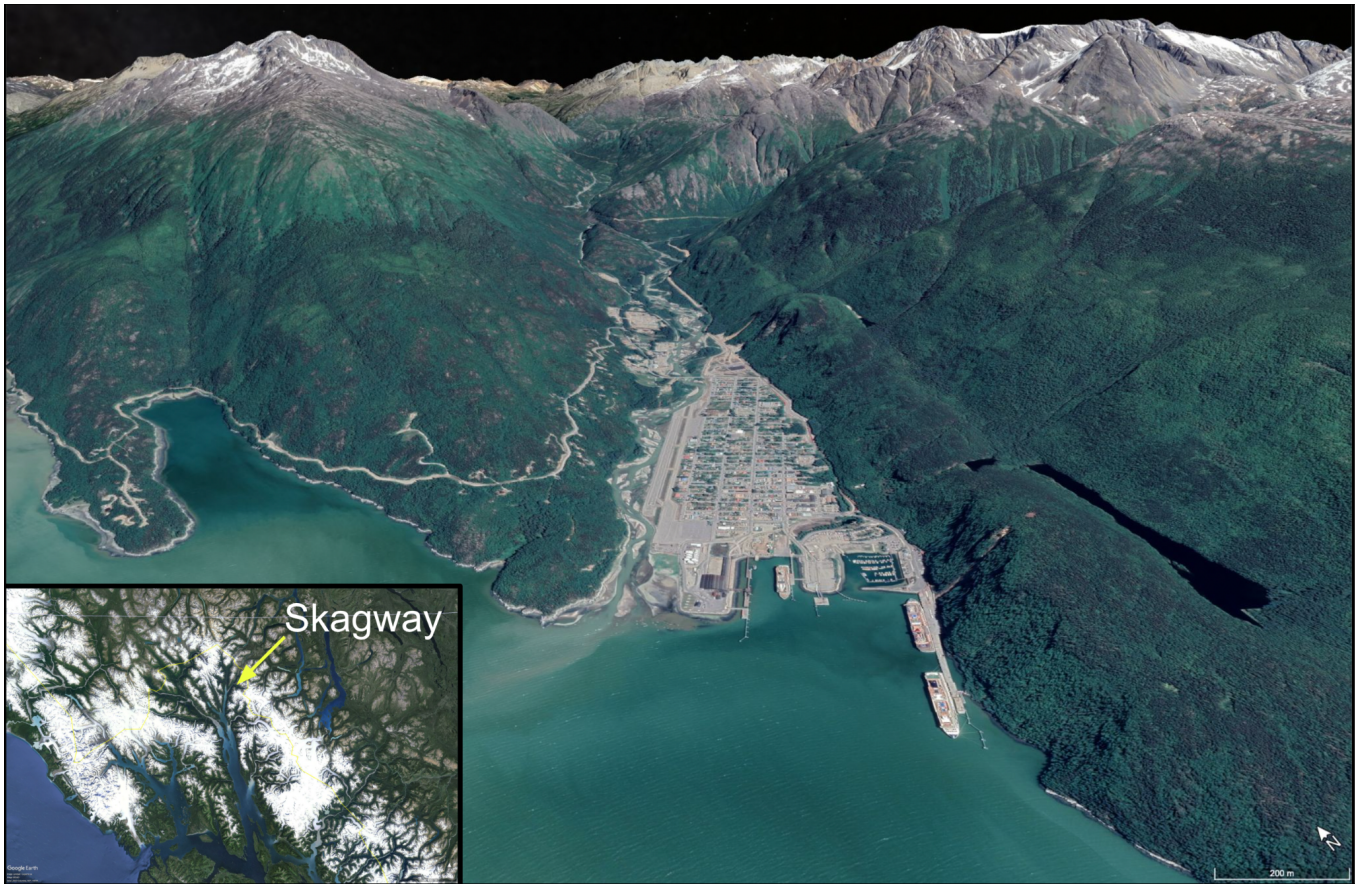


Figure 3: Oblique view of Skagway, Alaska and its steep valley walls.

At the head of the Taiya inlet, Skagway is situated in a U-shaped valley carved by glaciers (**Figure 3**) in the northern extent of the Alaskan panhandle. The surrounding terrain is steep and rugged, composed of Tertiary granodiorite bedrock of the Coast Range Batholith (Yehle and Lemke, 1972), a belt of plutonic and metamorphic rocks that extends to northern Washington. The Eastern Denali Fault and the Chatham strait fault lineaments meet just south of Skagway, which are both strike-slip fault systems (Choi et al., 2021).

A geologic study conducted in West Creek, a drainage just 9 km northwest of Skagway valley, identified three joint sets in the granodiorite bedrock (**Figure 4**), two northeast-striking sets with vertical or steep dips to the south, and one northwest-striking with a consistent vertical dip (Callahan & Wayland, 1965).

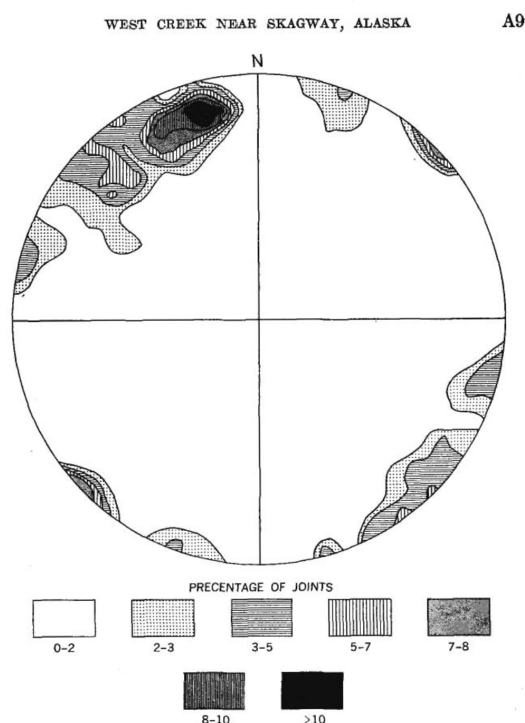


Figure 4. Equal-area, lower hemisphere stereonet with 1% area contours of 60 joints measured in West Creek, from Callahan and Wayland, 1965.

A study of geologic hazards in Skagway was conducted by Yehle and Lemke in 1972. A map of surface geology (**Figure 5**) from this study identified escarpments on the Skagway's eastern valley wall. Downslope of escarpments are Quaternary Colluvial deposits, consisting of landslide deposits, including talus from rockfall events. These quaternary colluvial deposits were further described as either active or inactive based on vegetation cover. It is of note that these talus deposits are much less prevalent on Skagway's western valley wall, and there are no escarpments mapped on the west side of the valley.

Rockfall hazard mitigation in Skagway is currently focused on the active rockfall source areas above the cruise ship dock. Engineering efforts have been underway, which include draping rock mesh over source areas, installing attenuator nets to block falling rocks, and scaling or knocking down loose rocks (Brennan 2022). Instrumentation has been installed to monitor the source area at the top of the slope, including extensometers installed at the top of the slope in 2017, which show that movement in the slide mass has increased from 1.5 inches per year to 2.5 inches per year as of 2022 (Brennan & Whistler, 2022). The 1 km length of rocky slopes above Skagway's cruise ship dock, where the engineered mitigation and monitoring efforts are focused, is only a fraction of the 5 km stretch of rock slopes that border Skagway to the east. Past geologic studies have mapped landslide escarpments in the remaining 4 km of rocky slopes to the north of the cruise ship dock (Yehle & Lemke, 1972), including the "Cemetery Slide", a rockfall source area and runout zone stripped of vegetation by falling debris, which is similar to the active source areas above the cruise ship dock.

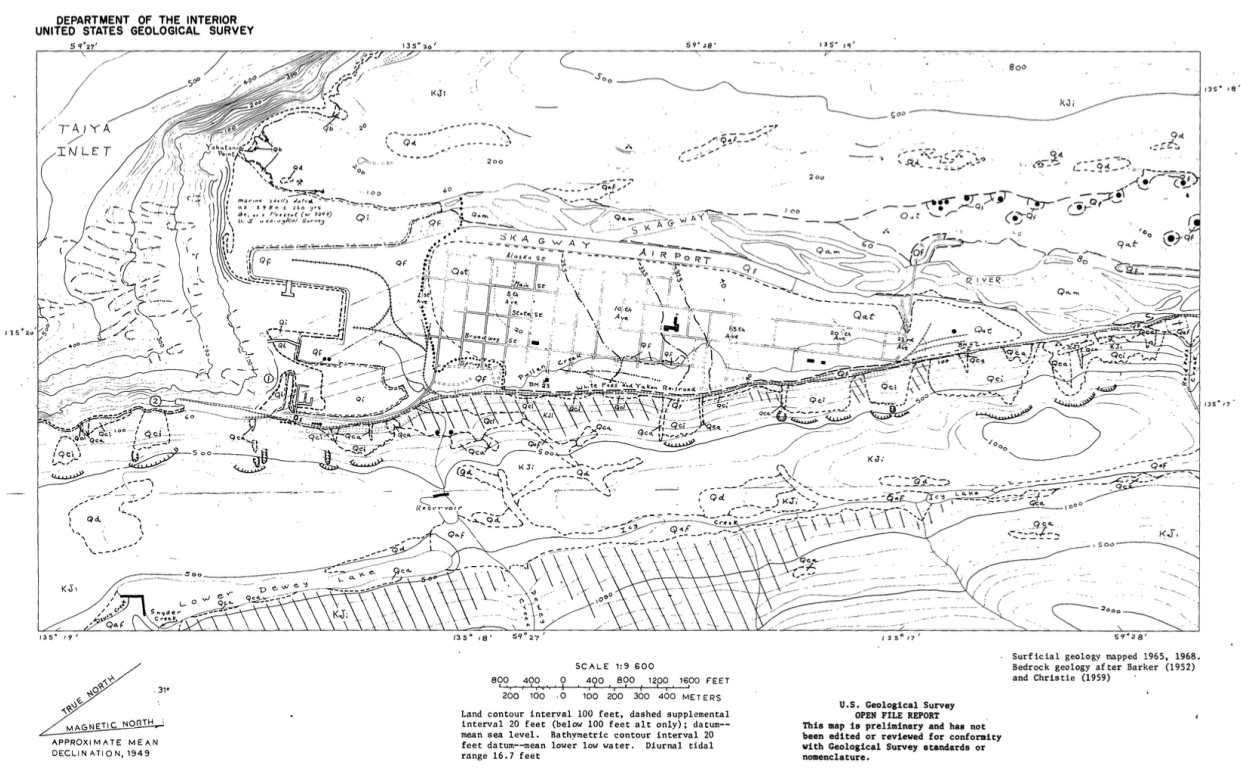


Figure 5: Surficial geology of Skagway valley. Escarpments are symbolized by solid lines with inward dashes. Mapped Quaternary colluvial deposits, both active (Qca) and inactive (Qci). Large inferred landslides are indicated with solid diagonal lines. From Yehle & Lemke 1972.

Skagway's climate is characterized by cold winters and cool, wet autumns (**Figure 6**). Peak precipitation generally occurs in the fall (Palecki et al., 2021), however it receives relatively low precipitation compared to other areas in southeast Alaska, due to the rain shadow effect of the coast range. Vegetation in Skagway is typically composed of spruce-birch forests, with a layer of spongy moss and spruce needles lining the forest floor.

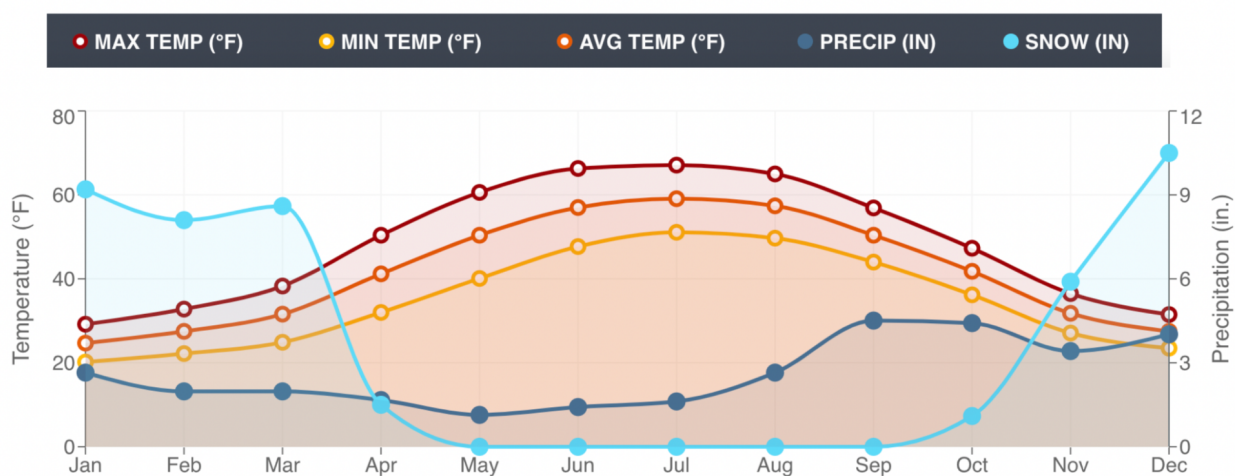


Figure 6: Climate normals in Skagway, Alaska from 1991-2020, from the NOAA climate normals database.

METHODS

Rockfall inventory

A rockfall event on August 26, 2017 marks the beginning of rockfall mitigation above Skagway's cruise ship dock (Files, 2017). A comprehensive search was conducted for news articles and public announcements that describe rockfall events from August 26, 2017 to present. Articles with timing and location of rockfall events were compiled. Precipitation data related to these events was gathered from a weather station located at Skagway's airport (NOAA, 2023)

Elevation data

Two Lidar DEMs were used in this study to map talus deposits and for the slope orientation inputs for GIS-based kinematic analysis. One Lidar DEM surveyed in 2014 (**Figure 7**) was available on the DGGs elevation portal, with 3x3 ft. cell size, which includes rock slopes in Skagway Valley, Nahku Bay and part of Dyea valley (Macpherson et al., 2014).

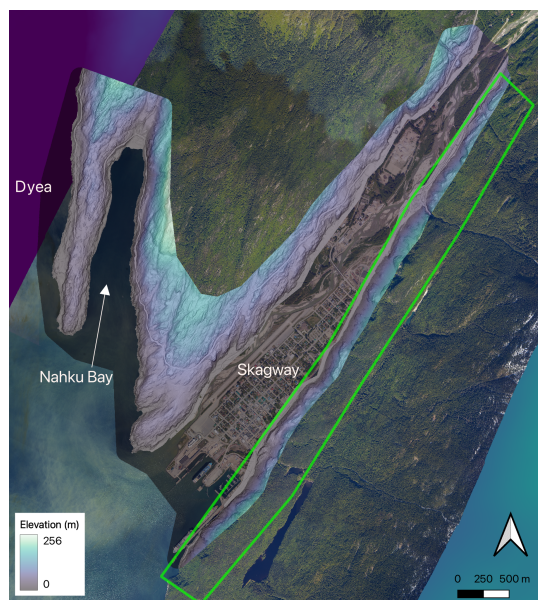


Figure 7: Coverage area a 2014 Lidar survey which includes Skagway valley, Nahku Bay, and one side of Dyea valley. The area of interest for the 2023 UAV Lidar survey is outlined in green.

A significant portion of Skagway's eastern valley wall is not covered in the 2014 survey, particularly the area above the cruise ship dock and township, so an additional UAV Lidar survey was planned and acquired in 2023. The area of interest for this survey was the 5 km stretch of rugged terrain on the eastern side of Skagway valley (**Figure 7**), a 2.5 km² area with elevations of 220 m above the cruise ship dock, and 320 m near Cemetery Slide. A Trinity F90+ fixed wing drone with a Qube 240 Lidar payload was flown 119 m above ground with 90% coverage overlap. The drone was equipped with a Real Time Kinematic positioning unit, which receives corrections from a base station for a more accurate position. Post processing was also used to increase the accuracy of the drone's position. The total surveyed area was 2.3 km², less than the planned area, due to a small gap in coverage over extremely steep terrain where the drone could not be flown safely. The resulting point cloud contained 650 million total points, with 200 million ground points. This yields an average ground point density of 43 ground points/m². The elevation of ground points in each 0.5 m cell was averaged to create a bare-earth DEM using Cloud Compare (version 2.12.3), a free and open-source point cloud processing software.

Geomorphic mapping

Slope angle thresholds have been used to identify rockfall source areas and talus deposits in mountainous terrain (Loye et al., 2009). Slope angle rasters were derived in QGIS from the 2014 and 2023 DEMs. A talus deposit at the base of a prominent vertical cliff, which includes both forested and exposed talus, (**Figure 8**) was used to define the threshold of slope angles that represent talus deposits in Skagway, which is typically 20°-45°. Talus deposits apparent at 1:1000 map scale, typically on the order of 1000's of m² but not smaller than 100's of m², were identified

based on the slope angle threshold of 20° - 45° as well as their proximity to steep rocky slopes, which are typically $>45^{\circ}$.

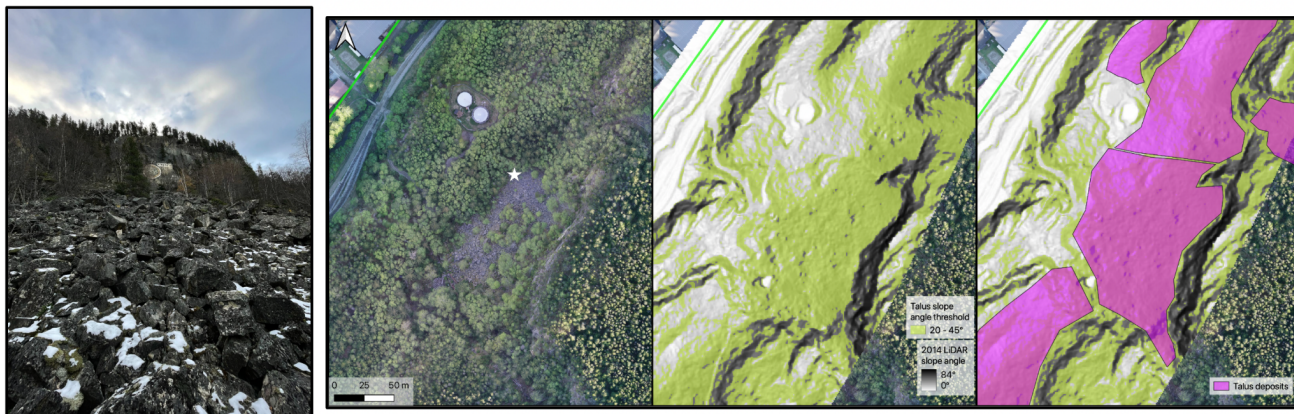


Figure 8: Photo taken from an exposed talus deposit with boulder sized clasts at the base of a 40 m cliff known as Kirmse’s Cliff (far left). Aerial imagery from 2023 of the talus deposit and cliff (center left), white star represents photograph location. Terrain within the slope angle threshold of 20° - 45° colored in yellow (center right), which are used to identify talus deposits (far right).

Structural Survey

To capture the variability of discontinuities, structural measurements from several localities within a study area have been combined into a comprehensive discontinuity set composed of hundreds of discontinuity measurements (Kundu et al., 2023), which was the approach taken in this study. The steep and uneven terrain surrounding Skagway limits access to outcrops, and the traditional ‘scanline’ method of laying out a tape across an outcrop and measuring discontinuities that intersect it (Priest & Hudson, 1981), was not practical. Instead, while walking along the base of the outcrop, which represents an approximate scanline, the orientation of planar surfaces expressed in the outcrop were measured with FieldMoveClino, a digital compass-clinometer smartphone app (Oliinyk et al., 2020). Measurements can be collected rather quickly with FieldMoveClino compared to a traditional Brunton compass. This was leveraged to take hundreds of discontinuity measurements ($n=337$) with the aim of capturing the variability of discontinuity orientations

across the study site. Outcrops from both sides of the Skagway valley, and outcrops in secondary valleys perpendicular to them, were included in the survey to ensure slope faces of varying orientations were sampled, since joints that strike parallel to outcrops are not well represented (Terzaghi, 1965).

GIS-based Kinematic Analysis

The method used to quantify rockfall susceptibility in this study closely resembles traditional kinematic analysis, which carry out Markland's test for a number of discontinuities on a rock slope face of uniform orientation (Wyllie & Mah, 2004). Instead of approximating the orientation of an area of rock slope and visualizing the failure envelope on a stereonet, the slope orientation of each cell in a DEM is computed, and Markland's test is carried out in each cell with a set of discontinuities that is assumed to be representative of the rock mass structure in the study area.

The metric for rockfall susceptibility in this study is the number of measured discontinuities (n=337) that meet conditions for planar sliding or block toppling failure, called potential failure planes, based on their orientation relative to the steepness and aspect of a given cell in a DEM. It should be noted that this metric is relative to the number of total discontinuities measured (n=337), but should provide a relative sense for which of these failure modes are most common, and the relative rockfall susceptibility within the study area.

For the rock slope orientation parameters, slope angle and aspect were computed on the 2014 and 2023 Lidar DEMs in QGIS. A friction angle of 40° was chosen for the kinematic analysis based on tilt measurements in a jointed granodiorite rock quarry (Alejano et al., 2019), which is consistent with Skagway's lithology. Azimuth constraints of $\pm 20^\circ$ were used for both planar slide and block toppling failure. To calculate the number of potential failure planes in each cell, a Python program

tested the conditions for both planar sliding and block toppling failure modes (**Eq. 1 & 2**) on each of the 337 discontinuities measured in the study area. Discontinuities that met conditions for each failure mode were added to a counter in each cell. The resulting rockfall susceptibility maps are colored based on the number of discontinuities that meet conditions for block toppling or planar sliding.

RESULTS

Rockfall inventory

The search for rockfall records identified 11 rockfall events since 2017 (**Table 1**). Descriptions of rockfall events before this date can be found in newspaper articles dating back over a century, (The daily morning Alaskan, 1901), but the timing and environmental conditions of these events is uncertain and were not included in this inventory. During the search for rockfall events, it became evident that local law enforcement, and sometimes the Department of Transportation, are often contacted to remove debris from minor rockfall events along Dyea road. These are recorded in the police blotter section of the Skagway News, but timing and location of these events is uncertain and were not included in this rockfall inventory. This rockfall inventory is therefore not an exhaustive list, but still provides useful context for the antecedent conditions and locations of rockfall in the study area.

| Event date | Event time (local) | Precip. total 24 hours before event (inches) | Start of highest 24 hr. precip. in month of event (inches) | Location | Source |
|------------|--------------------|--|--|--------------------------|---------------------------|
| 9-Oct-23 | ? | 0.63 | 12-Oct | East side of Dyea valley | d'Eprenesnil 2023 |
| 7-Oct-23 | ? | 1.46 | 12-Oct | East side of Nahku Bay | d'Eprenesnil 2023 |
| 18-May-23 | 6:17 PM | 0.00 | 25-May | North Slide | Field observation |
| 29-Sep-22 | 3:57 PM | 0.50 | 25-Sep | East side of Nahku Bay | Skagway Police Dept. 2022 |
| 5-Aug-22 | ? | 0.04 | 16-Aug | North Slide | Munson 2022 |
| 3-Aug-22 | 5:00 PM | 0.02 | 16-Aug | North Slide | Munson 2022 |
| 23-Jun-22 | 7:30 AM | Trace | 12-Jun | South Slide | Munson 2022 |
| 2-Dec-20 | 12:23 PM | 3.24 | 1-Dec | East side of Nahku Bay | Wehmhoff 2020 |
| 5-Sep-17 | 5:30 AM | 0.76 | 4-Sep | North Slide | Files 2017 |
| 5-Sep-17 | 3:00 AM | 1.05 | 4-Sep | North Slide | Files 2017 |
| 26-Aug-17 | 6:30 AM | 0.55 | 25-Aug | North Slide | Files 2017 |

Table 1: Inventory of rockfall events in Skagway, their location, and the precipitation totals in the preceding 24 hours. The North slide and South slide refer to areas above the cruise ship dock.

Rockfall in Skagway typically during the Summer and Fall months during a variety of different atmospheric conditions. Some rockfall events in Skagway are preceded by heavy precipitation. The

rockfall on December 2, 2020 was preceded by over 3 inches of rainfall in the 24 hours prior. On the same day, 25 km south of Skagway, a fatal landslide was triggered in Haines, Alaska by an atmospheric river (Darrow et al., 2022). The May 2023 event, which was observed in the field, initiated on a clear sunny day with no precipitation in the 24 hours leading up to the event. The August 2022 events were similarly not preceded by heavy rainfall. Based on these observations, it appears precipitation plays a role in initiating some rockfall in Skagway, but other triggers may be relevant.

Geomorphic mapping

On the east side of Skagway valley, there is a sharp inflection point at the top of the slope, which is particularly distinct above the cruise ship dock, where a flat topographic bench abruptly contacts steep, rugged terrain that continues downslope (**Figure 9**). Below this inflection point, talus deposits are located at the base of steep slopes. The bench has retained much of its glacially smoothed texture, therefore the sharp inflection point marks the extent of post-glacial rock slope failure. The west side of Skagway valley has considerably different morphology, in that it lacks a distinct topographic bench and is overall more consistent and gradual than the east side. Some vertical cliffs are present along the Skagway River, otherwise, the topography on the west side of Skagway valley mainly consists of rock slopes that form prominent ridges that parallel the strike of the valley.

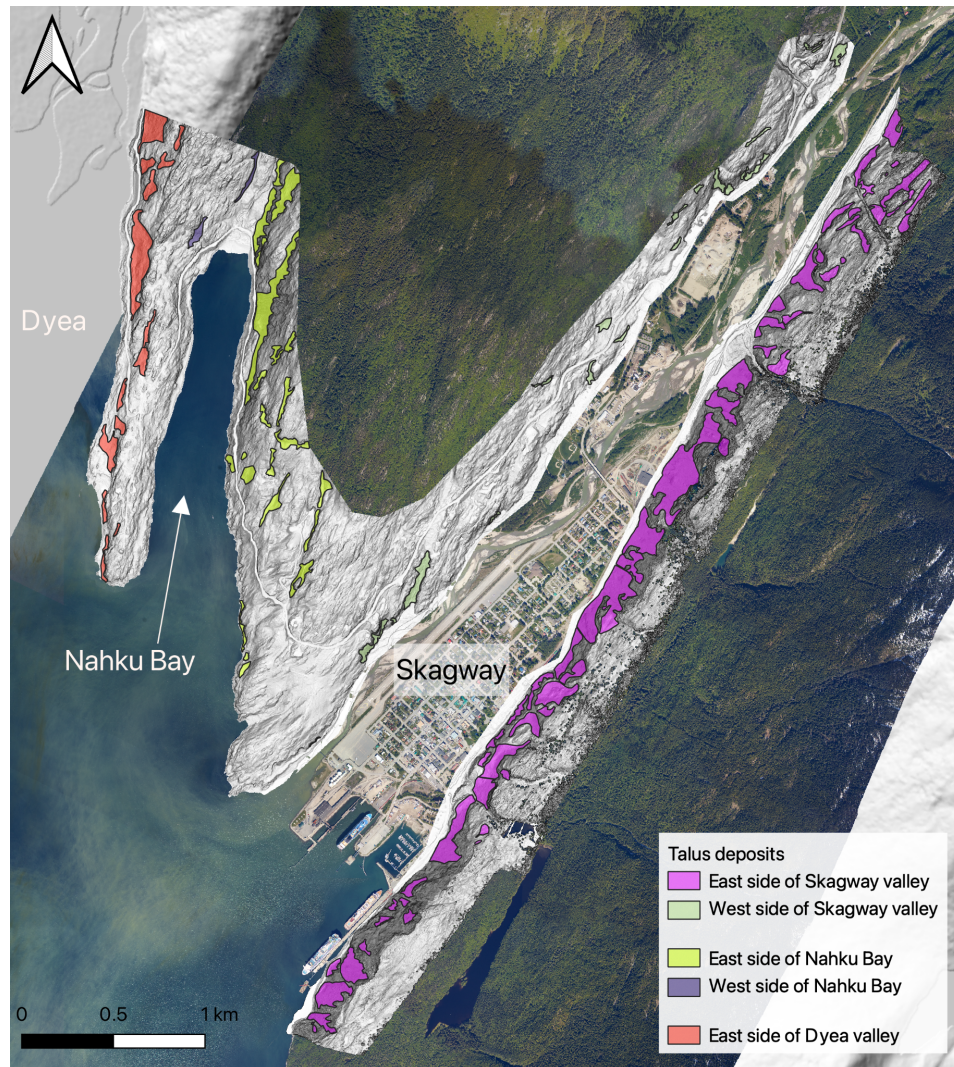


Figure 9: Manually mapped talus deposits colored by their location within Skagway valley, Nahku Bay, and Dyea valley. Slope angle base maps from 2014 and 2023 lidar datasets.

Talus deposits compose 12% of the 7.2 km² total mapped area (**Figure 9**). On the east side of Skagway valley, 56 talus piles were mapped, with an average area of 9,288 m², which make up 20% of the 2.62 km² mapped area. On the west side of Skagway valley the 20 talus deposits were on average smaller in area than those on the east side of the valley (**Table 1**), and only constituted 3% of the 1.67 km² mapped area.

| Area | mapped area (m ²) | total talus area (m ²) | # of talus deposits | average deposit area (m ²) | % area of talus deposits |
|-----------------------------|-------------------------------|------------------------------------|---------------------|--|--------------------------|
| East side of Skagway valley | 2,613,092 | 520,135 | 56 | 9,288 | 20% |
| West side of Skagway valley | 1,688,738 | 55,847 | 20 | 2,792 | 3% |
| East side of Nahku Bay | 1,260,682 | 144,271 | 22 | 6,558 | 11% |
| West side of Nahku Bay | 1,116,437 | 9,575 | 2 | 4,788 | 1% |
| East side of Dyea valley | 575,177 | 114,217 | 14 | 14,278 | 20% |
| Total | 7,254,126 | 844,045 | 114 | | |

Table 2: Talus deposits manually mapped in the study site.

Similarly, talus deposits on the west side of Nahku Bay are less abundant, smaller in area, and cover less of the landscape than the eastern side of the bay (**Table 2**). The east sides of Skagway Valley and Nahku Bay, with rock slopes that generally face northwest, are characterized by expansive talus deposits at the base of steep slopes. The west side of Dyea valley is outside the 2014 Lidar coverage area and was not mapped, but based on the abundance of talus deposits of the east side of Dyea valley, it likely follows a similar pattern of talus deposited preferentially on northwest facing slopes.

Structural Survey

A discontinuity set composed of 337 joint orientations was collected from 36 granodiorite outcrops across the study area, and plotted as poles to planes on an equal area stereonet to identify dense clusters of poles which were grouped into joint sets (**Figure 10**). Three sets were identified in this survey, two steeply dipping orthogonal sets (*J1* & *J2*), and one set that dips gently to the west (*J3*). The steeply dipping joints are of particular relevance, as their steep or vertical joints are conducive to toppling, which is the most commonly observed failure mode in Skagway. The most densely populated joint set is *J1*, which roughly parallels the strike of the Skagway valley and predominantly dips to the southeast. The less densely populated joint set (*J2*), is orthogonal to *J1*, has vertical dips, and strikes northwest. The third, gently dipping joint set (*J3*), are interpreted as

sheeting joints, typical in plutonic rocks, which have more curvature than the steeply dipping orthogonal joints.

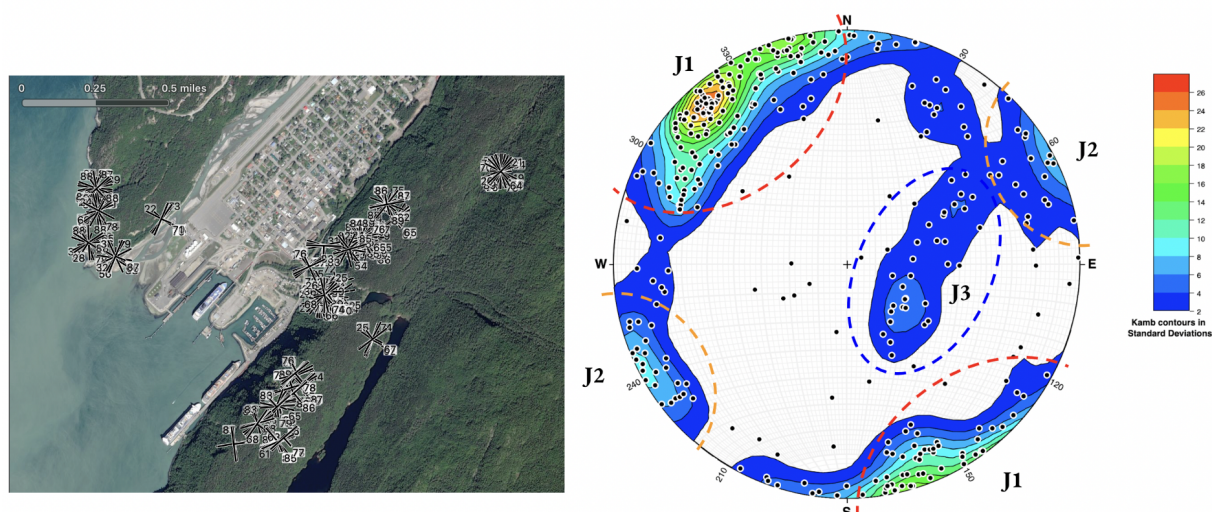


Figure 10: Locations of the 337 structural measurements as strike and dip symbols, from 36 outcrop locations (left). Lower hemisphere equal area stereonet of joint measurements visualized as planes to poles ($n=337$) with Kamb contours to highlight dense clusters of poles, which were grouped into three joint sets (right).

Kinematic Analysis

On the east side of Skagway valley, the glacially flattened bench at the top of the slope is generally not steep enough to meet topographic conditions for either failure mode (**Figure 11**). Where the bench terminates abruptly, steep, vertical, or overhanging rock slopes are formed. In these slopes, it is not uncommon for a substantial portion (> 90) of the 337 total discontinuities, to be potential failure planes for block topple failure. Other rock slopes of varying susceptibility are present below this inflection point, some of which are in close proximity to Skagway. The maximum number of potential failure planes for block toppling failure in a cell was 103. In slopes on the west side of Skagway valley, it is rare for more than 50 of the discontinuities in the set to be potential failure planes for block toppling failure. This reflects relatively low susceptibility to block toppling failure when compared to slopes on the east side of the valley, which commonly exceed 80 potential failure

planes. Cells with at least one potential failure plane for block toppling failure composed 17% of the 2014 survey area, and 39% of the 2023 survey area (**Table 3**).

| Area | Failure mode | Cells area (m ²) | Cells that met conditions for failure | Area that met conditions for failure (m ²) | Total cells with data | Total area (m ²) | % area that met conditions for failure |
|-------------------|----------------|------------------------------|---------------------------------------|--|-----------------------|------------------------------|--|
| 2014 lidar | block toppling | 0.84 | 1,052,034 | 883,709 | 808,063.12 | 5,320,275 | 17% |
| 2023 lidar | block toppling | 0.25 | 3,594,949 | 898,737 | 9376279 | 2,344,070 | 39 % |
| 2014 lidar | planar slide | 0.84 | 486,948 | 409,036 | 6,333,661 | 5,320,275 | 8% |
| 2023 lidar | planar slide | 0.25 | 2,256,809 | 564,202 | 9,376,279 | 2,344,070 | 24% |

Table 3: Results of the GIS-based kinematic analysis for block toppling and planar sliding failure within 2014 and 2023 DEMs.

For planar slide failure, cells with at least one potential failure plane composed 8% of the 2014 survey area, and 24% of the 2023 study area (**Table 3**), and the maximum number of potential failure planes in a cell was 87. For planar slide failure, it is rare for potential failure planes to exceed 20 on either side of Skagway valley.

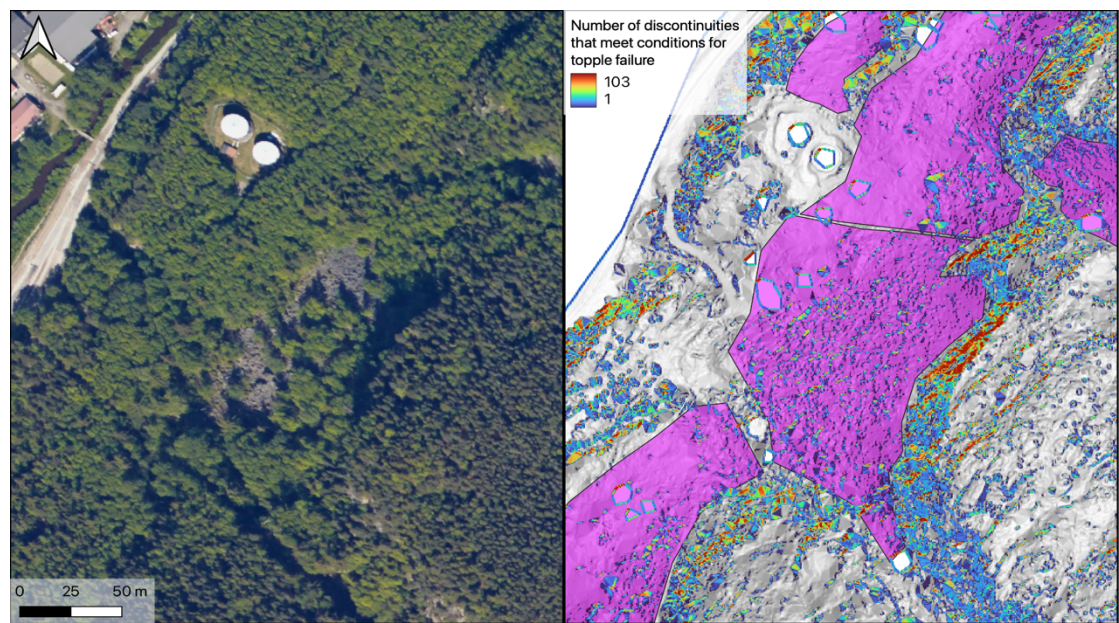


Figure 11: Kirmse's cliff and the partially forested talus deposit at the base of the slope (left), and rockfall susceptibility to block topple failure with mapped talus piles in purple (right)

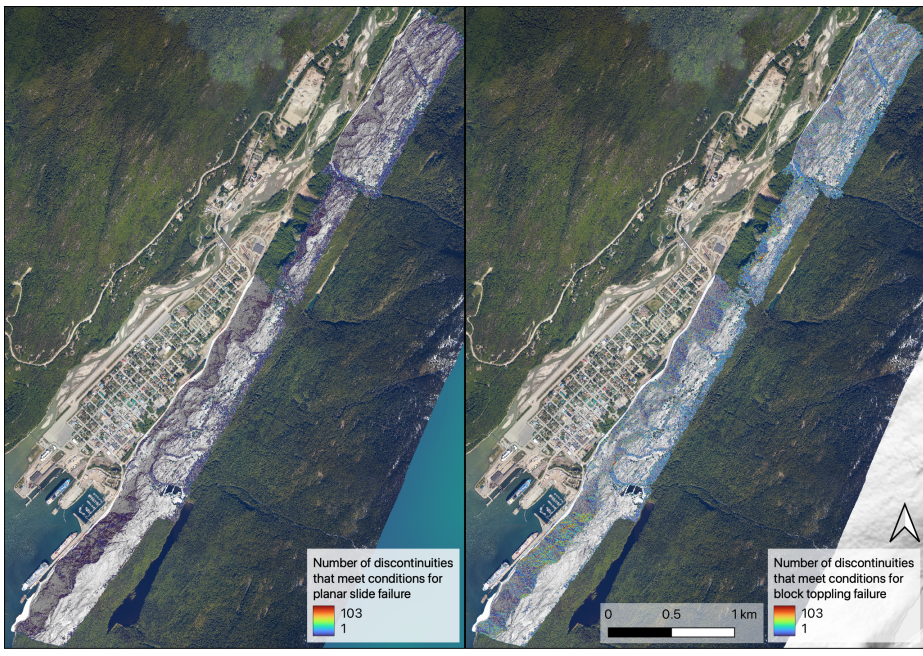


Figure 12: Susceptibility of rock slopes to planar slide failure (left), and block topple failure (right) within the 2023 lidar coverage area. Areas with no potential failure planes are not colored.

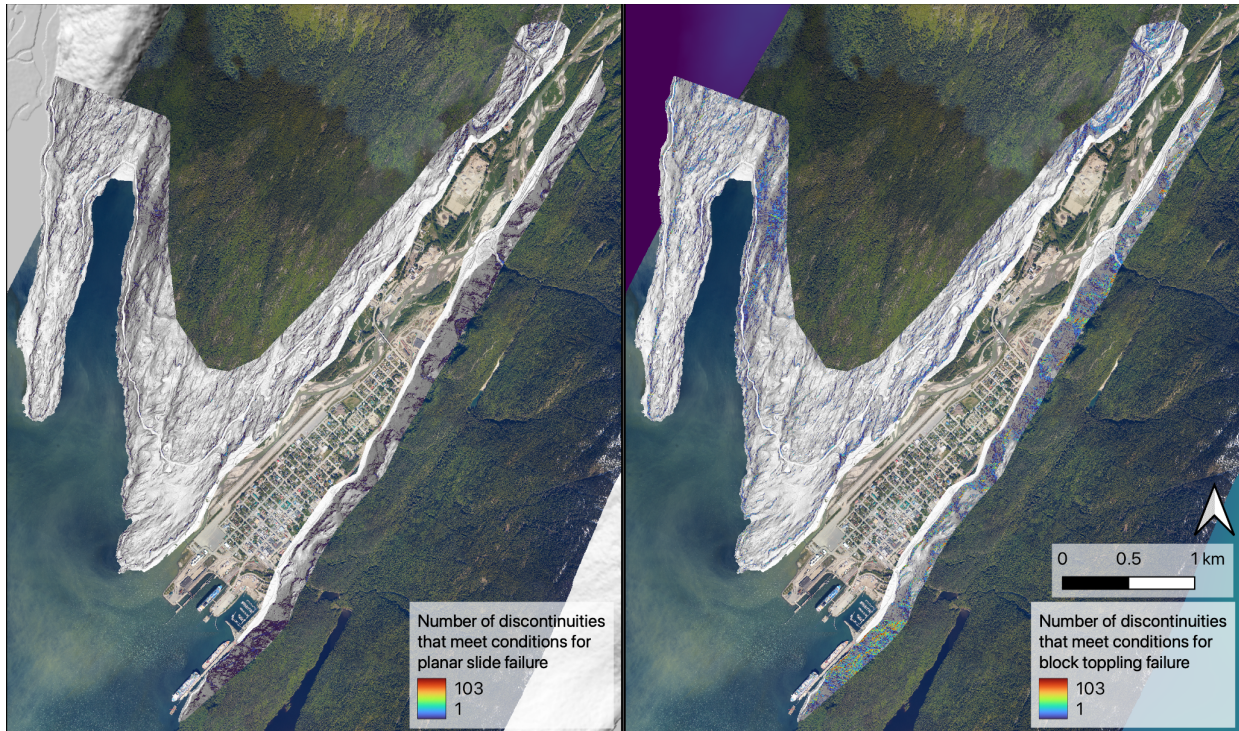


Figure 13: Susceptibility of rock slopes to planar slide failure (left) and topple failure (right) within the 2014 lidar coverage area. Areas with no potential failure planes are not colored.

DISCUSSION

Precipitation likely plays some role in initiating rockfall in Skagway, but not all rockfall events are preceded by heavy precipitation. Therefore, accurately predicting the timing of rockfall events based on precipitation metrics, like rainfall initiation thresholds used to estimate the likelihood of landslide initiation in Sitka, AK (Patton et al., 2023), is not likely. Therefore, estimating the likelihood that a rockfall will initiate at a given location is a useful approach to mitigating rockfall hazard. Known rockfall source areas are located on the eastern sides of Skagway valley, Nahku Bay, and Dyea valley, which generally consist of northeast facing rock slopes, indicating a topographic control on rockfall activity.

The joints measured in this study (**Figure 14**) are consistent with the steeply dipping, orthogonal joint sets measured in a nearby structural survey in West Creek (Callahan & Wayland, 1965), and described in a geotechnical assessment of the rock slopes above Skagway's cruise ship dock (Brennan & Whistler, 2022). High angle joints are likely formed by the tensile component of shear stress from the nearby Chatham Strait fault and Eastern Denali fault systems, while sheeting joints are formed by releasing overburden pressure.

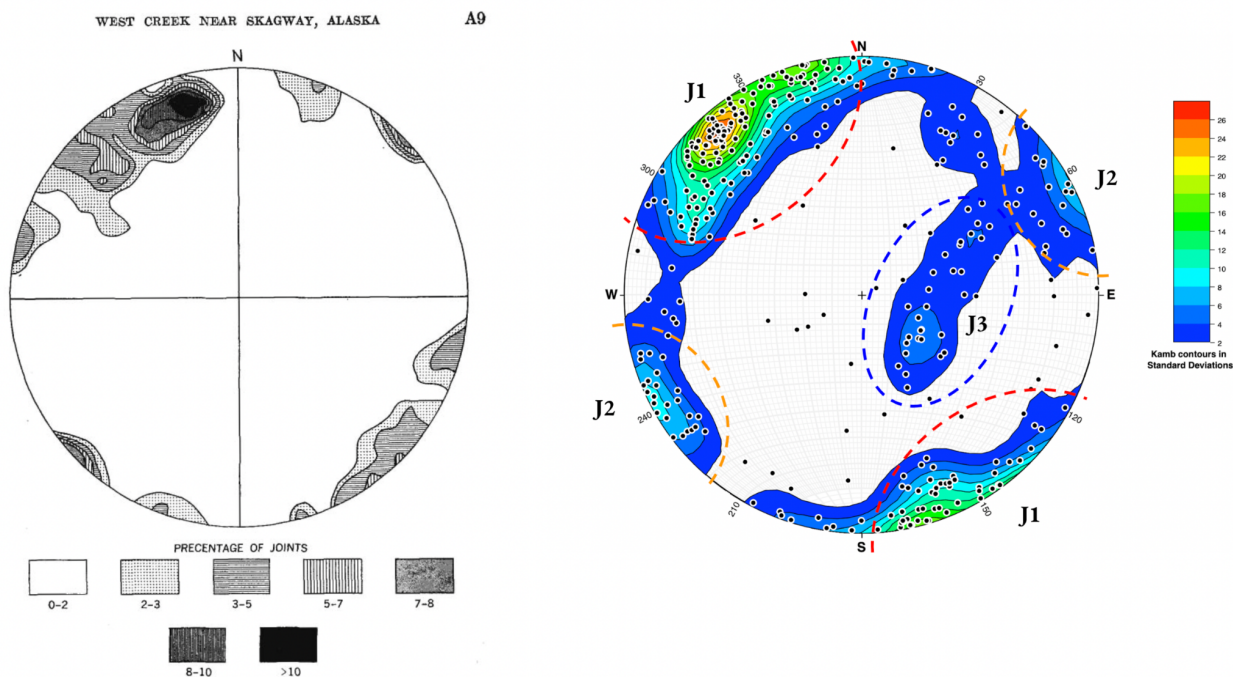


Figure 14: Lower hemisphere equal area stereonet where joints are plotted as poles, from joints measured in West Creek (n=60) (left), and in Skagway (n=337) (right), which are grouped into two orthogonal joint sets (J1 & J2) and one set of low angle sheeting joints (J3).

Rock slopes with orthogonal jointing are predisposed to block toppling failure, where steep orthogonal joints form the sides of toppling blocks and low angle joints, like the sheeting joints observed in this study, act as the basal failure plane (Wyllie & Mah 2004). Given the densest cluster of joints (**Figure 14**) dips steeply to the southeast, rock slopes facing northwest would generally form anti-dip slopes which are conducive to toppling failure. This is supported by larger and more abundant talus deposits on the east sides of Skagway valley and Nahku bay, indicating the rockfall occurs preferentially on northwest facing slopes.

Rockfall susceptibility maps are consistent with the failure mode and location of rock slope failures observed in the field. At the edge of the glacially flattened bench above the cruise ship dock, parallel slabs of rock are formed by tension cracks, which are likely to experience toppling failure as

vegetation and other processes widen these cracks (**Figure 15**). This is consistent with the results of the kinematic analysis for block toppling; cells proximal to this feature contain >70 potential failure planes for block toppling failure, which is a relatively high susceptibility. The same cells are also susceptible to planar sliding failure to a much lesser degree, which contain <10 potential failure planes.

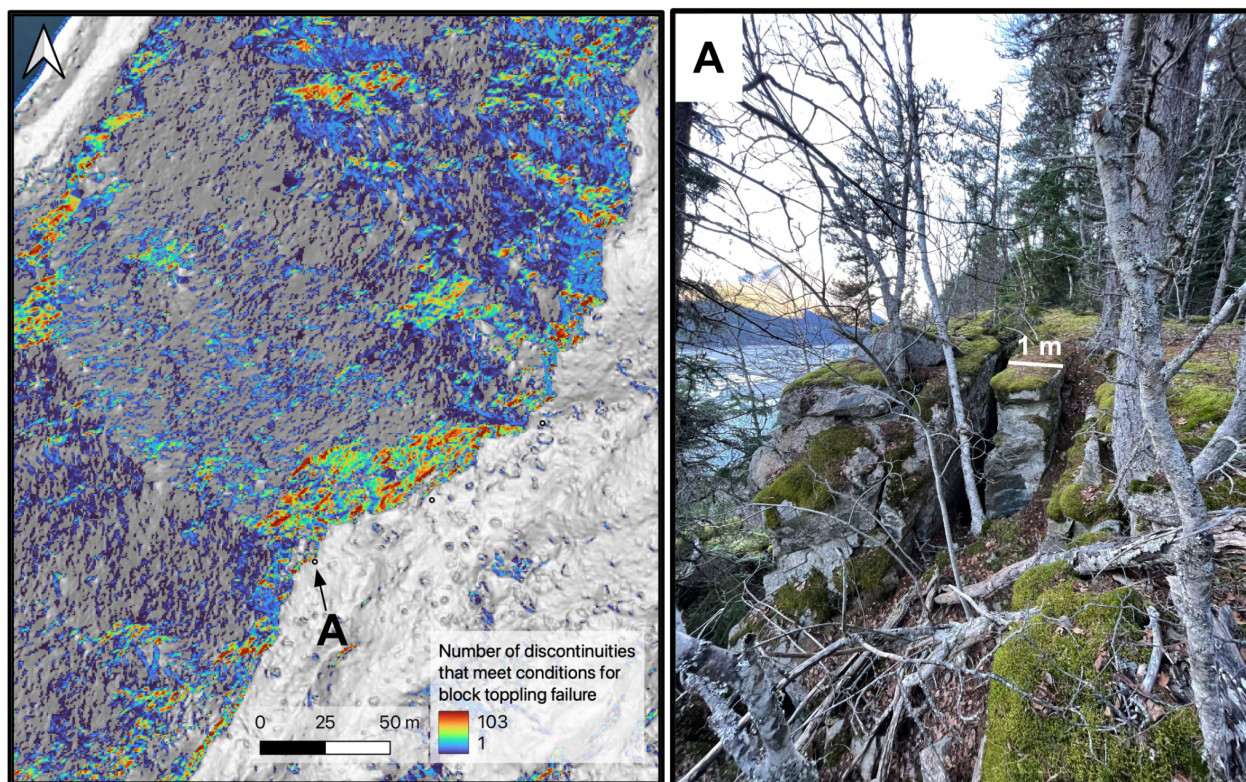


Figure 15: Tension cracks developing in a rock slope that will likely topple in the future (right), which is consistent with the high rockfall susceptibility in the same area for block topple failure.

The results of the kinematic analysis in this study show rock slopes in the steep rugged terrain surrounding Skagway are generally more susceptible to block toppling failure than planar slide failure, which is consistent with block toppling failures observed in the field. The preference for toppling failure is potentially due to the inclination of joints, which are generally steep and conducive to toppling failure, but their steepness may preclude them from daylighting in rock slope

faces, a necessary condition for planar slide failure. On the west side of Skagway valley, some steep vertical cliffs are susceptible to planar slide failure (>70 potential failure planes in some cells). In the same area, past planar slide failures are evident, which release from sheeting joints and slide on joints steeply dipping southeast (J1).

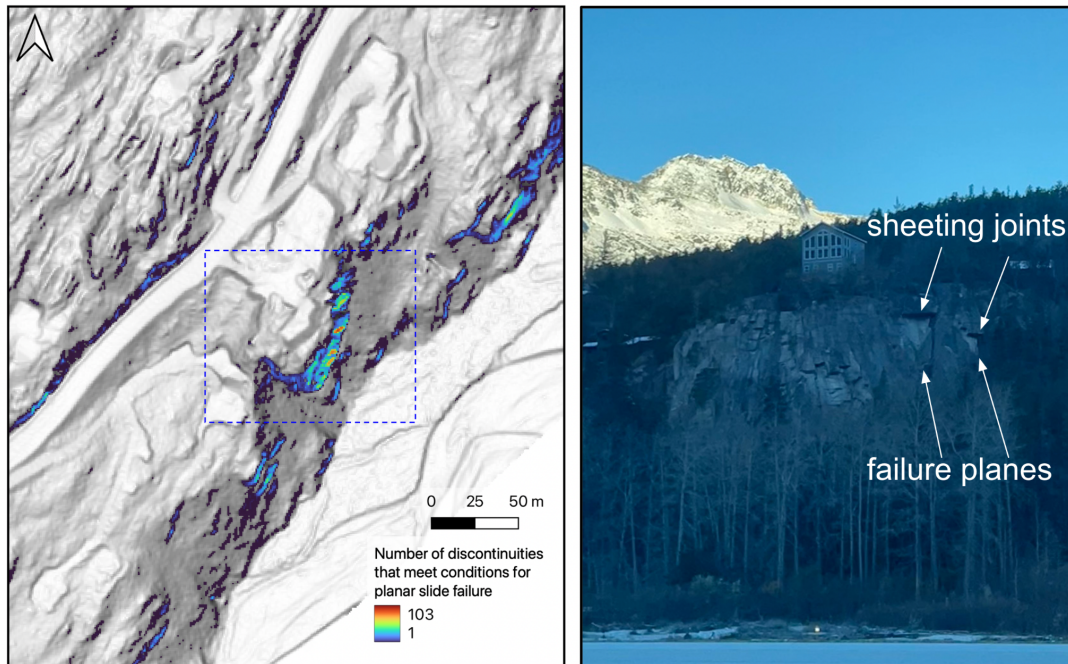


Figure 16: A rock slope with relatively high susceptibility to planar slide failure (left), and a photograph of the rock slope and scars from past rockfall events. Rocks detach along sheeting joints and slide along steep failure planes.

On the east side of Skagway valley, rockfall susceptibility is not distributed homogeneously across the landscape. On Kirmse's Cliff, talus deposits extend from the valley bottom to the base of a uniform vertical cliff face that terminates at the bench at the top of the slope (**Figure 8**). In this area, rockfall susceptibility is high, but concentrated to a relatively small area of vertical rock slope, and a partially forested talus deposit sits between the cliff and structures in Skagway. Above the cruise ship dock, rockfall susceptible slopes are not concentrated to a single area (**Figure 11**). Instead, rock slopes susceptible to block toppling failure are continuous from the topographic

bench down to the base of the slope, resulting in a large area of high rockfall susceptibility in very close proximity to Skagway's infrastructure.

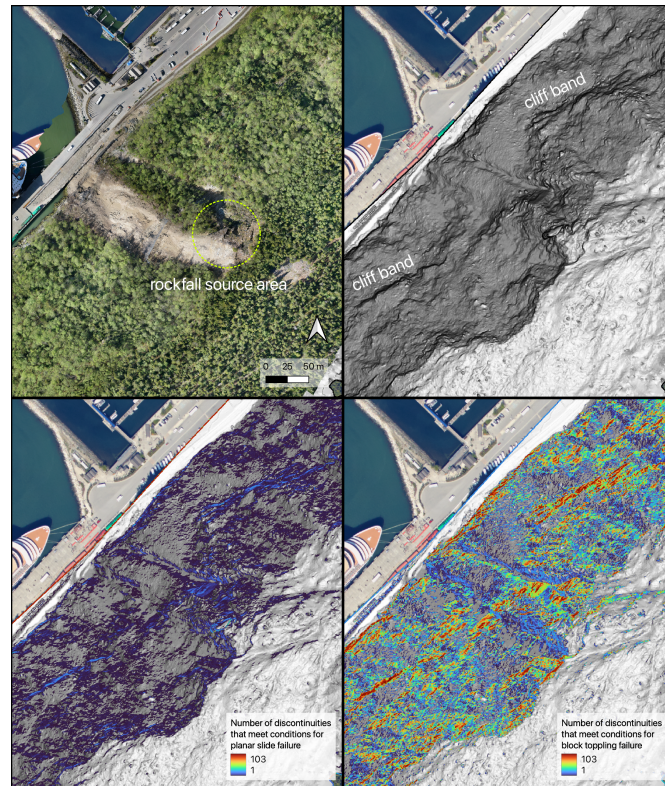


Figure 17: The steep slopes above the cruise ship dock. Aerial imagery taken in 2023, which shows the rockfall source area of the North Slide. Attenuator nets are located midslope and at the base of the slope (top left). Slope angle map with labeled cliff bands (top right). Rockfall susceptibility for planar slide (bottom left) and block topple failure (bottom right).

An area with similar slope characteristics can be found 3 km north of the harbor, where the slopes reach 320 m above the valley floor. A prominent rock slope is continuous from the topographic bench down to the valley floor; vertical cliffs are also present at the top of the slope (**Figure 18**). The source area for the Cemetery Slide, which is comparable to the active rockfall area above the cruise ship dock, is located at the inflection point at the top of the slope along this prominent topographic rise. No rockfall records from this area were examined in this study, but the runout

zone of the Cemetery Slide is consistent with other active rockfall source areas in Skagway. A lineament runs along the back of this topographic rise, which is potentially formed by a tension crack extending to the north. The lineament strikes parallel to the valley, consistent with other tension cracks observed in the field, but this location was not visited in the field, and thus the presence of a tension crack could not be verified.

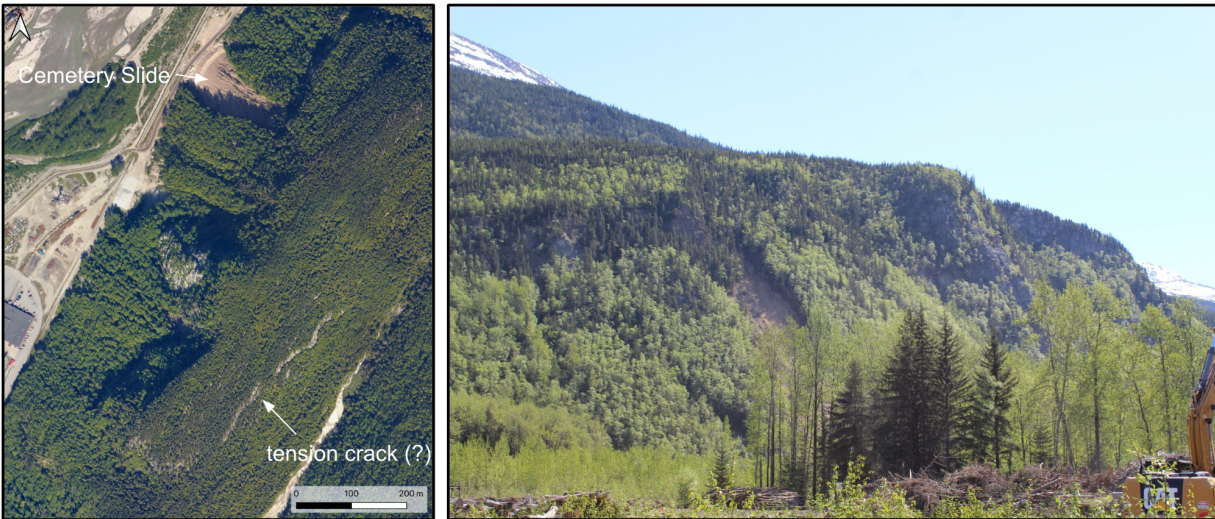


Figure 18: The Cemetery Slide area at the north end of Skagway valley, with a runout path stripped of vegetation. Lineament striking NE/SW, potentially a tension crack opening to the north (left). Photo of the slope face taken from Skagway valley (right).

In the northeast part of Nahku Bay, another zone of high rockfall susceptibility is also present (**Figure 19**). Steep rocky slopes rise to an elevation of 250 m within 200 m horizontal distance from Dyea road. This area lacks a distinct runout path like those apparent at the Cemetery Slide and above the cruise ship dock, but does encompass source areas for two events in the rockfall inventory that impacted Dyea road.

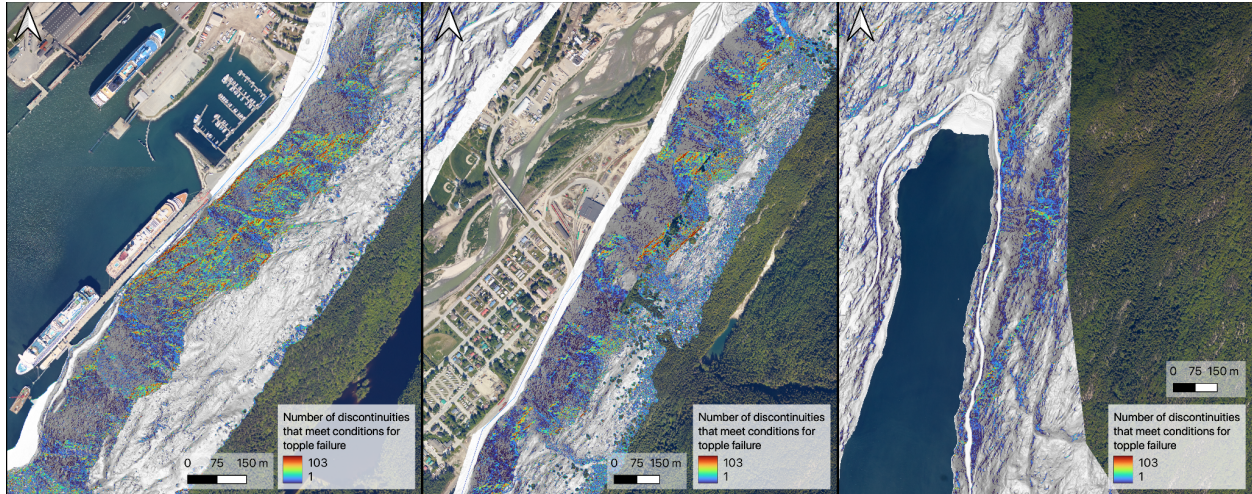


Figure 19: Three areas that are characterized by large continuous areas of rockfall susceptible slopes that are present continuously from the base of slopes to high elevations (>200m), which are found above the cruise ship dock (left), along the topographic rise near the Cemetery Slide (center), and on the east side of Nahku Bay (right).

CONCLUSION

Rock slope failure is a major driver of landscape evolution in Skagway since glaciers left the valley. The steeply dipping orthogonal joints present in Skagway's rock slopes are conducive to block toppling failure. More topography around Skagway is susceptible to block toppling failure than planar sliding failure. There is a stark contrast in the morphology of Skagway's east and west valley walls, which is primarily shaped by the predisposition of northwest facing slopes to block toppling failure along a densely fractured joint set that dips steeply to the southeast. This is consistent with geomorphic evidence of rockfall activity, where talus deposits are more abundant and larger on the east side of Skagway valley than the west. The same structural control on rockfall activity is reflected in the east and west sides of Nahku Bay. Rockfall records indicate a similar preference for initiating on northwest facing slopes.

Rock slopes, with varying degrees of rockfall susceptibility, are pervasive in the steep terrain surrounding Skagway, particularly the east side of Skagway valley. Three regions with particularly high rockfall susceptibility have been identified and should be considered for further investigation and mitigation: 1) the slopes above the cruise ship dock, 2) the topographic high point at the north end of Skagway valley (which includes the Cemetery Slide), and 3) the east side of Nahku Bay. Known rockfall source areas located in these regions are characterized by steep northwest facing slopes that are highly susceptible to block toppling failure and reach >200 m in elevation.

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