Reconstruction of rockfall events using dendrogeomorphological techniques in a highly visited climbing area

Reconstrucción de eventos de desprendimiento de rocas mediante técnicas dendrogeomorfológicas en un área de escalada de alta demanda

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ABSTRACT

Stawamus Chief Provincial Park, north of Vancouver, British Columbia, is a popular climbing and hiking destination affected by frequent, potentially hazardous rockfalls. This study documents the recent rockfall history below the North Wall of Stawamus Chief using dendrogeomorphological methods, providing a case study 'proof-of-concept' of the use of dendrogeomorphology for assessing rockfall hazards. We produced a geomorphic map of the North Wall based on an interpretation of lidar imagery and collected 245 samples from 74 rockfall-impacted trees (*Tsuga heterophylla*, *Pseudotsuga menziesii*, and *Thuja plicata*) at the base of the steep face at three sites. We generated a 167-year rockfall chronology and reconstructed the spatial and temporal pattern of tree damage using the Shroder index. A total of 911 growth anomalies relate to 51 rockfall events, 11 of which occurred between 1940 and 1959. In a search for possible causes and triggers, we compiled rainfall and temperature data from four meteorological stations and earthquake data from Earthquakes Canada. The average rockfall return period at site II (<14 years) is shorter than that at site I (>14 years); thus, the trees growing at site II appear to be exposed to more frequent rockfalls than those in site I. Twelve events occurred 3-5 days when at least 50 mm of accumulated rain, and seven occurred during years with strong earthquakes. We also consider other possible trigger phenomena, including freeze-thaw cycling and days with high temperatures and extreme diurnal temperature ranges. We demonstrate the potential of these methods for providing an improved understanding of rockfall and debris flow hazards in forested terrain and for guiding BC Parks on risks faced by hikers and rock climbers who visit Stawamus Chief Provincial Park.

Keywords: landslides, hazard evaluation, dendrochronology, Stawamus Chief Provincial Park, British Columbia.

RESUMEN

El Parque Provincial Stawamus Chief, al norte de la Ciudad de Vancouver, Columbia Británica, es un destino popular para escalar y hacer senderismo, el cual está afectado por frecuentes y potencialmente peligrosos desprendimientos de rocas. Este estudio documenta el historial reciente de desprendimientos de rocas debajo de la pared norte de Stawamus Chief utilizando métodos dendrogeomorfológicos, lo que proporciona un estudio de caso de "prueba de concepto" del uso de la dendrogeomorfología para evaluar los peligros de desprendimientos de rocas. Producimos un mapa geomorfológico de la pared norte basado en una interpretación de imágenes lidar y recolectamos 245 muestras de 74 árboles impactados por desprendimientos de rocas (Tsuga heterophylla, Pseudotsuga menziesii y Thuja plicata) en la base del escarpe en tres sitios. Generamos una cronología de desprendimientos de rocas de 167 años y reconstruimos el patrón espacial y temporal de daño a los árboles utilizando el índice de Shroder. Un total de 911 anomalías de crecimiento se relacionan con 51 eventos de desprendimientos de rocas, 11 de los cuales ocurrieron entre 1940 y 1959. En una búsqueda de posibles causas y desencadenantes, compilamos datos de precipitaciones y temperaturas de cuatro estaciones meteorológicas y datos de terremotos de Earthquakes Canada. Doce eventos ocurrieron entre 3 y 5 días, cuando se acumularon al menos 50 mm de lluvia, y siete ocurrieron durante años con fuertes terremotos. También consideramos otros posibles fenómenos desencadenantes, incluidos los ciclos de congelación y descongelación y los días con altas temperaturas y rangos térmicos diurnos extremos. Demostramos el potencial de estos métodos para proporcionar una mejor comprensión de los peligros geomorfológicos en terrenos boscosos para proporcionar orientación a BC Parks sobre los riesgos a los que se enfrentan los excursionistas y escaladores que visitan el Parque Provincial.

Palabras clave: deslizamientos de tierra, evaluación de peligros, dendrocronología, Parque Provincial Stawamus Chief, Columbia Británica.

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1. Introduction

Direct and indirect costs of landslides in Canada typically exceed CDN $200 million per year and include mitigation and prevention measures taken by the Canadian federal and provincial governments (Natural Resources Canada, 2008). This total includes rockfalls, which are defined as the free or bounding fall of rocks or debris down steep slopes under the influence of gravity (Luckman, 2013). Most rockfalls are relatively small, with volumes of less than 100 m^3 and comprise a small number of blocks, but some are much larger and border on small rockslides. Maximum velocities of individual blocks are commonly in the range of a few tens of metres per second (Evans and Hungr, 1993). Rockfalls in Canada pose a threat to people and property below steep rock slopes. They are particularly common in the mountainous western part of the country, where they can threaten people and transport along some road and rail lines in steep-sided valleys (Bunce *et al.*, 1997; Hungr *et al.*, 1999; Stoffel *et al.*, 2005; Macciotta *et al.*, 2015).

The causes of rockfall are fundamentally geologic (rock strength and structure) and topographic (slope and relief). Most rock masses have weak discontinuities, including joints, foliation, and, in the case of sedimentary rocks, stratification (Luckman, 2013). A steep slope (typically >45°) is required for rockfall, and relief affects the intensity and runout of the event. Triggering events, as opposed to causes, include extreme weather events and earthquakes (Luckman, 2013). Weather phenomena are important rockfall drivers and include diurnal freeze-thaw activity, spring thaw, extreme summer and winter temperatures, heavy or lengthy rainfall, and diurnal, seasonal, and annual temperature changes (Luckman, 2013; Šilhán *et al.*, 2011; Macciotta *et al.*, 2015, 2017; Collins and Stock, 2016; Dietze *et al.*, 2017; Matsuoka, 2019; Bozdağ, 2022; Graber and Santi, 2022). However, there may also be lags of days or months following extreme rainfall or temperature events (Strunden *et al.*, 2015).

Rockfall research, at least in Canada, has pivoted to document the spatial-temporal distribution of rockfalls and to model their potential runout (Evans and Hungr, 1993; Holm and Jakob, 2009). Such work is commonly done to design preventative and mitigation measures along road and rail lines (Bunce *et al.*, 1997; Hungr *et al.*, 1999; Macciotta *et al.*, 2015; Pratt *et al.*, 2018), and in settlements with infrastructure at risk in steep rock-walled valleys (Hungr *et al.*, 1999; Perret *et al.*, 2006; Trappmann *et al.*, 2013). There is now a general awareness of areas that are susceptible to rockfall in Canada, but managers in high-risk areas typically lack site-specific knowledge of the frequency, magnitude, velocity, and trajectory of rockfalls, all of which are required to assess the hazard and manage the risk (Stoffel *et al.*, 2005; Chiroiu *et al.*, 2022).

Over the past two decades, various methods have been developed to assess rockfall hazards. However, approaches based on prehistoric events often lack the temporal resolution necessary to establish reliable frequency–magnitude (F–M) relationships (Budetta, 2004). One tool, dendrochronology, may provide annual, even seasonal, resolution on rockfall activity in forested terrain extending back several hundred years (Stoffel and Bollschweiler, 2009; Stoffel *et al.*, 2010). Dendrochronology can also be applied over larger areas to better understand the site-related factors that control slope instability (Stoffel *et al.*, 2005; Chiroiu *et al.*, 2022), and can provide baseline data against which future changes in rockfall activity related to climate change can be evaluated (López-Saez *et al.*, 2016).

Dendrochronology is commonly combined with geomorphology to acquire data about past rockfall events and hazards (Stoffel and Bollschweiler, 2008, 2009; Butler, 2013; Butler and Stoffel, 2013). Nevertheless, the science of dendrogeomorphology must be applied with caution because disturbances of different origins may induce similar responses in trees. Therefore, it is necessary to carefully select trees for sampling based on supplementary spatial information. Such supplementary sources of information include geomorphological

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maps, aerial and lidar images, and archived historical information (Stoffel and Bollschweiler, 2008, 2009; Stoffel *et al.*, 2010). In many countries, the requisite supplementary data do not exist and must be generated as part of tree-ring studies. All such information can be examined and compared in Geographic Information Systems using high-speed computers with large data storage capacity. In applied studies, the goal is to evaluate rockfall hazard (magnitude, frequency, and surface) in areas undergoing, or slated for, growth and urbanization and to advance policies aimed at reducing risk in mountainous areas (Hooke, 2019).

British Columbia, an area of nearly 1,000,000 km^2, is the most mountainous province in Canada and has the highest frequency of landslides, including rockfalls, in the country (Clague and Bobrowsky, 2010). Rockfall events in the province are common on steep rock slopes, especially in areas where rainfall exceeds 2000 mm/yr (Blais-Stevens and Hungr, 2008) and in the western part of the province, which is subject to frequent earthquakes that occasionally exceed moment magnitude 8 (Rogers and Horner, 1991). Rockfall hazard assessment in British Columbia has typically been conducted along road and rail corridors because they are at greatest risk (Bunce *et al.*, 1997; Hungr *et al.*, 1999; Blais-Stevens and Hungr, 2008; Lan *et al.*, 2010; Blais-Stevens *et al.*, 2012; Macciotta *et al.*, 2017; Pratt *et al.*, 2018).

Stawamus Chief Provincial Park, north of Vancouver, British Columbia, is the most popular rock climbing site in Canada and is a known site of large historic rockfalls (Figure 1). The steep rock faces in the park are a source of rockfalls that pose a serious risk to hikers and climbers. Sampaleanu (2017) studied rockfalls on Stawamus Chief and concluded that the hazard is not well understood

Figure 1 Oblique photo, depicting the Grand Wall and the North Wall of the Stawamus Chief Provincial Park. On the lower left, there is a portion of Squamish, and at the bottom of the North Wall, there is Valleycliffe.

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by most of the large number of recreational users of the park. Understanding the potential magnitude, failure mechanisms, frequency, and distribution of rockfalls in the park is required by BC Parks to manage the hazard. To date, however, there has been no systematic study of rockfall frequency using dendrochronology or other means. The research summarized in this paper is intended to provide a case study 'proof-of-concept' of the use of dendrogeomorphology for assessing rockfall hazards. We aim to document the recent rockfall history on the precipitous north-facing wall of Stawamus Chief Provincial Park to aid authorities in managing rockfall risk in the park.

2. Study area

Stawamus Chief Provincial Park is a 530-ha protected area at the head of Howe Sound in the District Municipality of Squamish, just southeast of the town of Squamish, British Columbia (Figure 2). The Park was established in 1997 to preserve the spectacular, steep, glacially eroded, rock slopes developed in Middle Cretaceous granodiorite (Figures 1 and 3; Monger and Journeay, 1994; Cui *et al.*, 2017). The cliffs extend from about 10 to 695 m above sea level (asl).

The steep rock faces in the park have two aspects. The Grand Wall, a 3-km-long, 'Yosemite-like' rock face runs parallel to Howe Sound and is cut by a prominent set of northeast-striking, sub-vertical joints. Pleistocene glaciers flowing south down Howe Sound (Friele and Clague, 2002a, b) scoured this rock face and, more importantly, steepened it by plucking blocks of granodiorite along the steep joint set. Remnants of striated and polished granodiorite are preserved on parts of the Grand Wall. Scattered blocks and local blockfields exist along the base of the rock face (Evans and Hungr, 1993; their site 16). North of the Grand Wall are the northwest-facing North Walls (Figure 3). Here, the cliffs are cut by the northeast-striking, sub-vertical joints mentioned

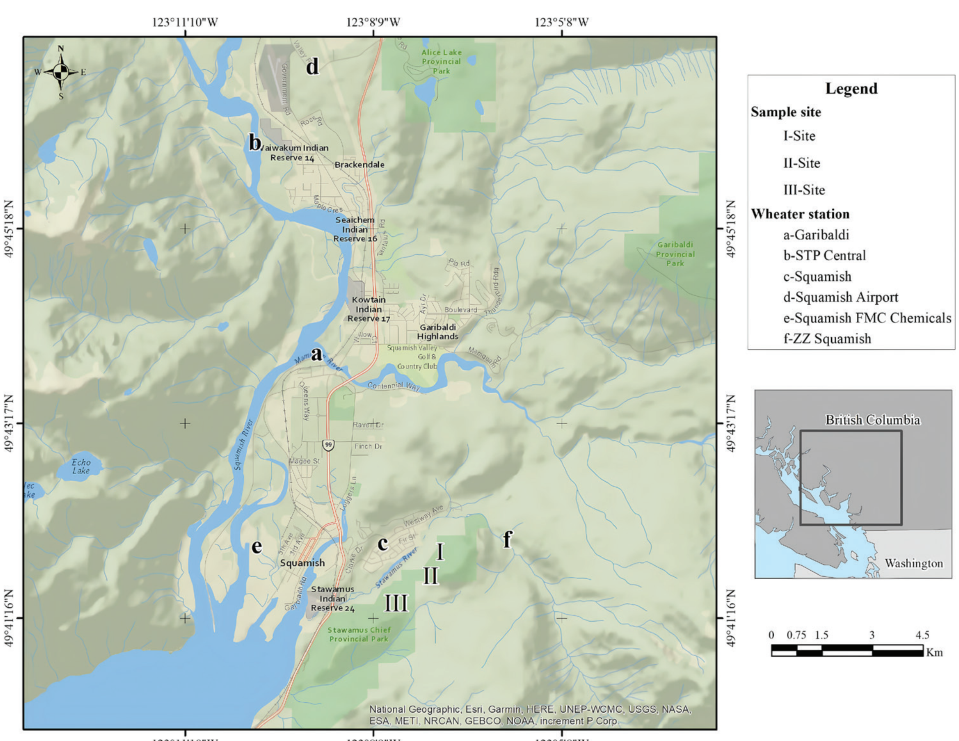

Figure 2 Study area and locations of the sampled trees and weather stations.

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above and by subhorizontal joints. Together, these joint sets have created rockfall-prone overhangs. A well-developed and extensive talus apron has formed from 40 to 350 m asl at the base of the North Walls (Sampaleanu, 2017). We focused our research and sampling on three areas below the North Walls where there have been recent rockfall events.

Squamish has a temperate coastal climate, with average annual precipitation of 2200 mm, much of which falls between October and March. The highest monthly precipitation is 175-400 mm, and the maximum daily precipitation is 100-130 mm. Snowfall occurs from November through March and is greatest at higher elevations. Summers are warm, with daily average temperatures of 18°C in July and August, and extremes of 36°-37°C during those months. Daily average temperatures in December and January are 2–3°C, with extremes of -10° to -15 °C (Squamish STP Central, Canadian Climate Normals 1981-2010). The largest daily temperature range (17.6°-25°C) occurs

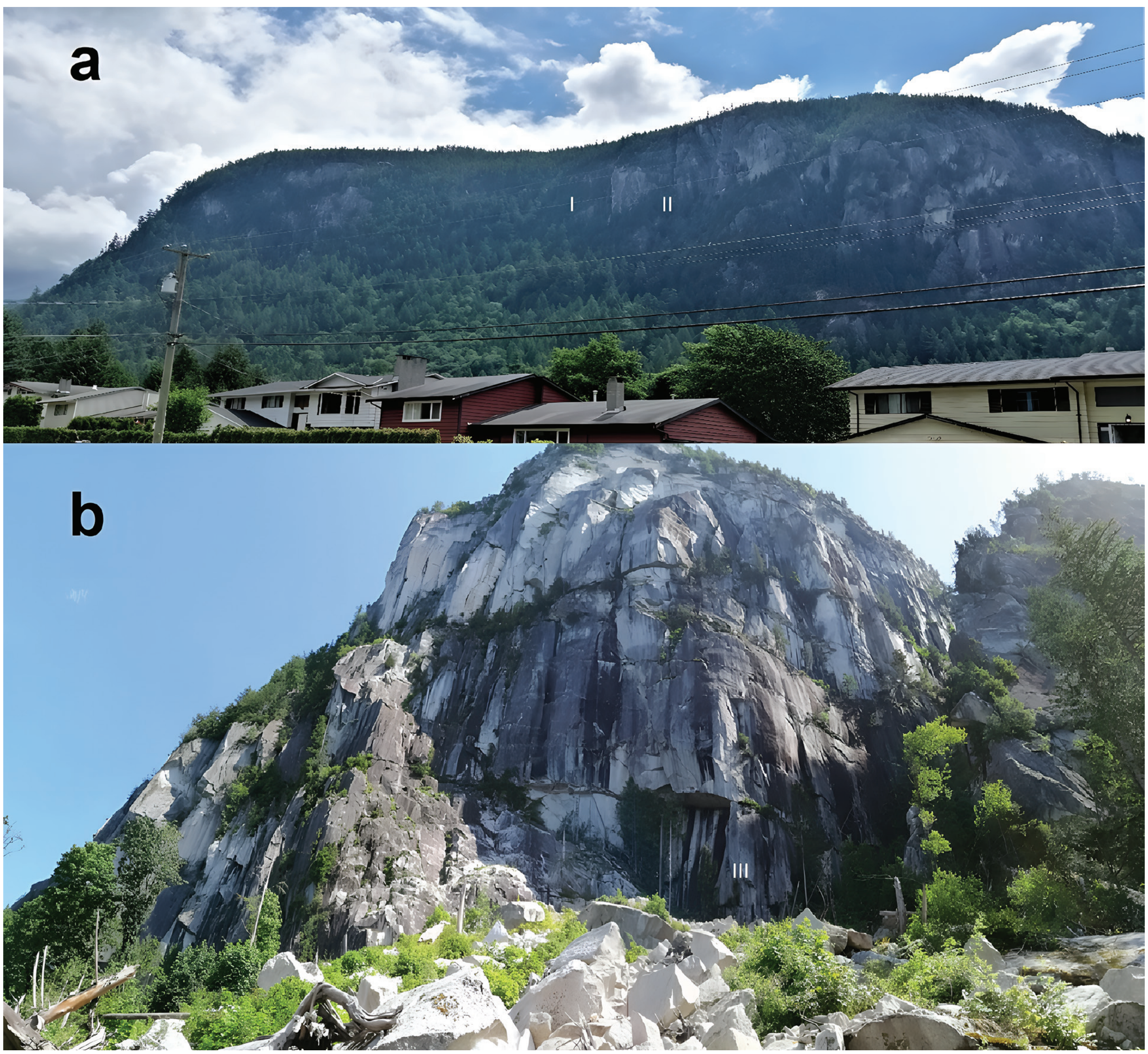

Figure 3 Views of the steep, glacially eroded rock slopes developed in the Middle Cretaceous granodiorite of Stawamus Chief. a) Valleycliffe, where sites I and II are located. B) North end of Grand Wall, site III. See Figure 1 for locations.

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Table 1. Data summary for meteorological stations near the study area that were used in this study (locations shown in Figure 1).

Station name	Distance to sampling zone (km)	Initial date	Final date	Missing precipitation data (%)	Maximum missing temperature data (%)	Minimum missing temperature data (%)
Squamish	1.5	01/01/1959	31/08/1996	1.00	5.10	4.76
ZZ Squamish	2.8	25/05/1970	03/05/1988	0.00	none	none
Squamish FMC Chemicals	2.5	01/11/1968	28/02/1983	0.16	none	none
STP Central	9.2	01/08/1986	31/10/2005	0.07	0.03	0.07
Garibaldi	4.9	01/09/1975	31/12/2000	1.12	10.39	11.23
Squamish Airport	10.5	17/05/1985	31/12/2017	1.00	0.13	0.15

during late winter and early fall, and freeze-thaw conditions can occur from October through April.

Mote (2003) provides a detailed analysis of 20th-century climate trends for the Georgia Basin—Puget Sound region. Average annual temperature increased 1.5 °C during the 20th century, with most of this warming occurring in winter months. Precipitation increased until 1950, then became more variable. With increased temperatures and warmer winters, snowpacks have declined by about 30% in areas surrounding the Strait of Georgia and Puget Sound.

The rockfall aprons at the base of the steep rock slopes of the Grand and North Walls support forest consisting mainly of *Pseudotsuga menziesii*, *Thuja plicata*, Picea sitchensis, *Tsuga heterophylla*, and Tsuga mertensiana. Early seral species following disturbance include *Alnus rubra* Bong, *Acer macrophylla* Pursh, *Acer circinatum* Pursh, and *Betula papyrifera* Marsh (Lemus Rodríguez, 2020).

3. Methods

3.1. GEOMORPHIC MAP

To characterize our study site, we produced a geomorphic of the North Walls and environs in ArcGIS 10.6.1 using lidar imagery with a resolution of 1 m per pixel. The lidar dataset generated contour lines, topographic profiles, shaded relief, slope, and aspect maps. Data inputs and fieldwork survey landform units were interpreted according to Zinck's classification system (2013).

3.2. DENDROCHRONOLOGICAL SAMPLING AND SAMPLE PROCESSING

We sampled living trees with evidence of past injury from rock impacts (impacted trees with recent and old scars), collecting cores from 74 trees at three sites that we chose based on the most recent events on the wall (sites I, II, and III; Figure 2). Two or three cores were extracted using a Pressler increment borer (10 mm diameter) from each tree (Stoffel and Bollschweiler, 2008, 2009). Sampled trees include *Tsuga heterophylla*, *Pseudotsuga menziesii*, and *Thuja plicata*. Samples were taken from both sides of wounds or scars, or callus tissue. For each damaged tree, we recorded the species, diameter at breast height (DBH), height to the center of the scar and its orientation, the ground slope, and substrate characteristics.

Samples were preprocessed using the standard methodology of Schweingruber *et al.* (1990). Increment cores were polished using sandpaper with progressive grain sizes (80 to 1200 grains cm^{-2}) to allow dating, measurement of individual rings, and identification of growth disturbances. We dated the increment cores by matching the

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narrow rings of the dendrochronological series, allowing us to assign an exact year of formation to every ring in every sample (Stoffel *et al.* 2005, 2010). Identifications and measurements were made under a stereoscopic microscope.

3.3. GENERATION OF ROCKFALL EVENT CHRONOLOGY AND STATISTICAL ANALYSIS

We generated a chronology of rockfall events using FHAES (Fire History Analysis and Exploration System) software, a tool used to evaluate fire regimes, insect attack, volcanic eruptions, and geomorphic processes (Sutherland *et al.*, 2017). FHAES helps researchers to illustrate the frequency, geographic extent, timing, and relationships between natural events and tree growth (Speer *et al.*, 2019).

The ring data were statistically analyzed using the "event-response index", which for a given year, t, is the number of trees injured in that year divided by the total number of trees living in year t, expressed as a percentage (Shroder, 1978):

$$I_t = \sum R_t \Big/ \sum N_t \, x100\% \qquad (1)$$

where It = event-response index for year t; Rt = number of trees injured in year t, and Nt = total number of trees living in year t.

We used a threshold index value of 10% to define a damaging rockfall event, which is considered appropriate for the process involved (Corona *et al.*, 2014; Tichavský and Fabiánová, 2022). Some falling rock fragments strike just one tree on

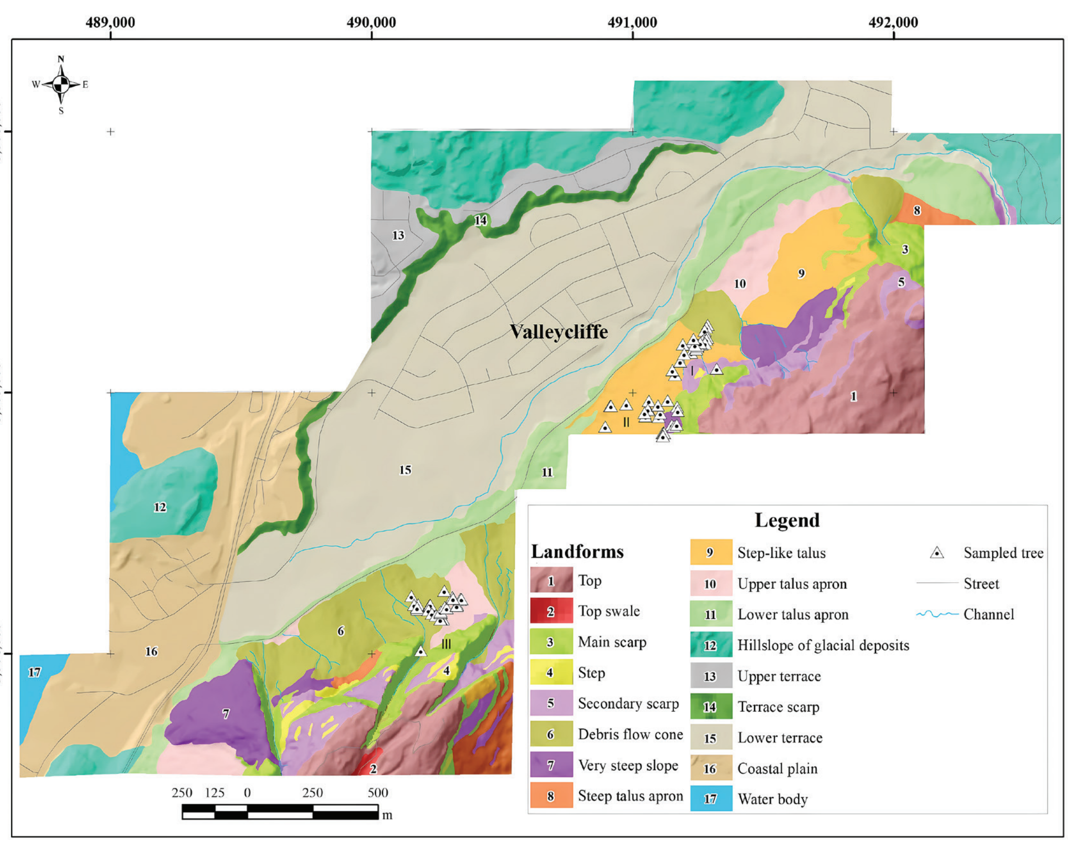

Figure 4 Geomorphic map of the northwest face of Stawamus Chief and the adjacent community of Valleycliffe. The three sample sites are labeled I, II, and III.

Table 2. Average age of the three species of sampled trees.

Species	Site I	Site II	Site III	Average
Pseudotsuga menziesii	164	115	47	108
Tsuga heterophylla	109	87	62	86
Thuja plicata	64	101	48	71

their way down the slope, whereas others might impact several trees or no trees at all (Perret *et al.*, 2006). Return periods of rockfalls were assessed by dividing the number of impacts by the age of the impacted tree. Maps of tree age and rockfall events were created using double inverse distance weighted interpolation in ArcGIS 10.6.4 (Favillier *et al.*, 2018).

3.4. TRIGGER ANALYSIS

We obtained climate data for the period 1959-2017 at six sites in the vicinity of the study area from the Pacific Climate Data portal (https://data.pacificclimate.org/portal/pcds/map/) (Table 1). The data include daily precipitation, snowfall, maximum and minimum temperatures, and wind speed.

Once the rockfall years were determined, maximum daily precipitation was entered into our database, and 3 and 5 days of accumulated precipitation were calculated. We also identified days with air temperatures fluctuating above and below 0 °C (*i.e.*, when freeze-thaw might have happened).

Earthquake Canada provided dates and locations of moderate to large (M 4.5-8) earthquakes

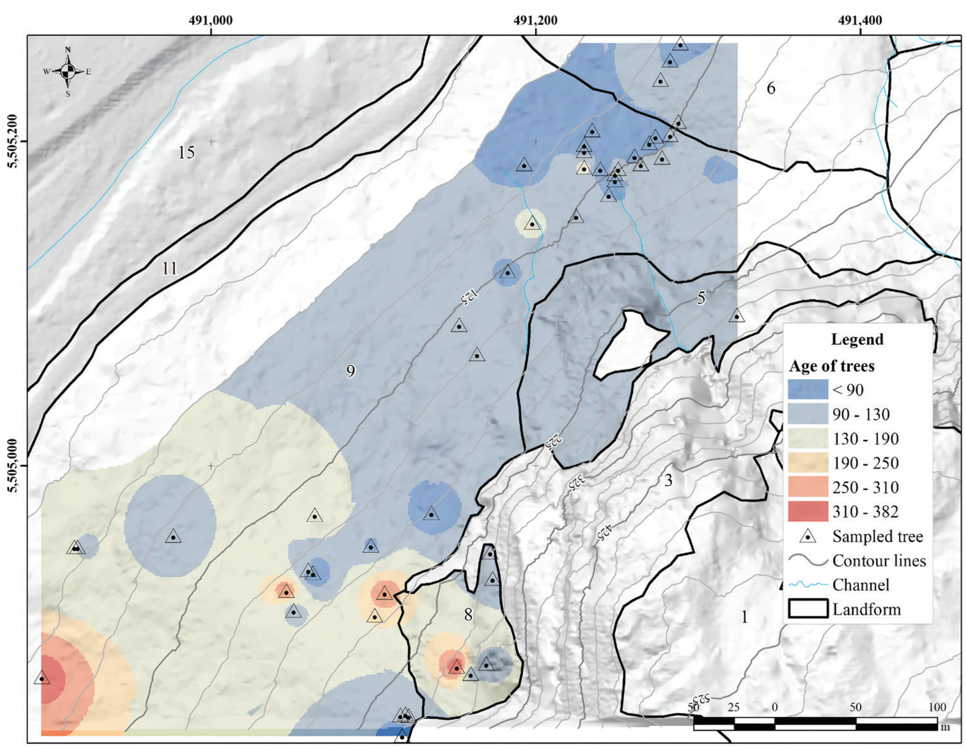

Figure 5 Distribution of tree ages at sample sites I and II. Landform symbols: 1. top of Stawamus Chief, 3. main scarp, 5. secondary scarp, 6. debris flow and rockfall cone, 8. steep talus apron, 9. step-like talus, 11. lower talus apron, 15. terrace.

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Table 3. Summary of tree ages at the three sample sites.

		Ages			
Sample site	No. of trees	Average	Standard deviation	Maximum	Minimum
I	22	137	100.05	384	18
II	25	91	27.31	161	32
III	27	63	18.39	99	13

that happened in British Columbia and at the Pacific margin (https://earthquakescanada.nrcan.gc.ca/historic-historique/map-carte-en.php). This dataset comprises 161 earthquakes within 500 km of the study area.

4. Results

4.1. GEOMORPHOLOGY

The Stawamus Chief massif was created by uplift and exhumation of a Cretaceous pluton during the Cenozoic Era. Based on the lidar image and field observations, we identified 16 morphogenetically distinct landforms, including different slopes, scarps, aprons, talus, and debris flow cones (Figure 4). Two levels of terraces border Stawamus River north of Stawamus Chief. The community of Valleycliffe is located on these terraces outside the North Walls and associated talus.

4.2. DENDROCHRONOLOGY

We collected 245 samples from 74 rockfall-impacted trees. Some of the samples were discarded because they were rotten or because we were unable to reliably see all their rings. The average age of impacted trees is 107 years (Table 2); the minimum and maximum ages are, respectively, 13 and 384 years (Table 3). Because we did not reach the pith in some samples, their ages are minimal.

The oldest trees are *P. menziesii*, followed by *T. heterophylla* (Table 3). The average ages of sampled trees differ at the three sample sites, perhaps due to differences in the history of logging, fires, and rockfall disturbance.

Sites I and II are located, respectively, on a step-like talus slope and a very steep slope (Figure 5). Sample site III is located higher (125-225 m asl) on a colluvial apron formed primarily by rockfalls and debris flows.

4.3. ROCKFALL CHRONOLOGY

We assign 911 growth disturbances (GD) at the three sites to rockfalls. About 82% of the disturbances are represented by sudden growth suppression, and 14% involve the creation of tangential resin ducts (Table 4). Based on event-response index values, we identified 74 rockfall events over the entire dendrochronological period (1635-2017). However, the number of samples dating to the period 1635-1850 is small (10), which likely would contribute to temporal bias, thus, we limited subsequent analyses to the period 1850-2017 (Figure 6). There were 51 rockfall events between 1850 and 2017 (Figures 7 and 8). The highest event-response index values correspond to the periods 1860-1879 (50%), 1940-1959 (23%), 1980-1999 (60%), and 2000-2017 (47%). The rockfall event in 1991 is recorded in 135 samples, with high event-response index values (60% at site I, 48% at site II, and 49% at site III). Rockfalls on the North Walls of Stawamus Chief were most frequent during the first half of the 20th century and have decreased considerably since 1960. Eleven events, with an average event-response index value of 53%, occurred during the period 1940-1959,

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Table 4. Grorth anomalies identified in the tree ring series at the three sample sites.

Response	Site I	Site II	Site III	Total	Percent GD
Growth suppression	249	346	160	755	82.9%
Tangential resin ducts	39	68	24	131	14.4%
Callus tissue	4	12	5	21	2.3%
Compression wood	1	2	1	4	0.4%
				911	100.0%

whereas between 1980 and 1999, we found only two rockfall events, with event-response index values of 49 and 60%.

4.4. ROCKFALL RETURN PERIODS

The average rockfall return period at site II (<14 years) is shorter than that at site I (>14 years), thus, the trees growing at site II appear to be exposed to more frequent rockfalls than those in site I (Figure 9). However, samples collected on a step-like talus apron near the base of a very steep slope at site I have an average return period of <8 years, whereas those in a similar position at site II have return periods of >18 years (Figure 8).

Sampled trees on the northern part of site I are less than 120 years old, whereas those on the southern part of the site are >200 years old. Trees

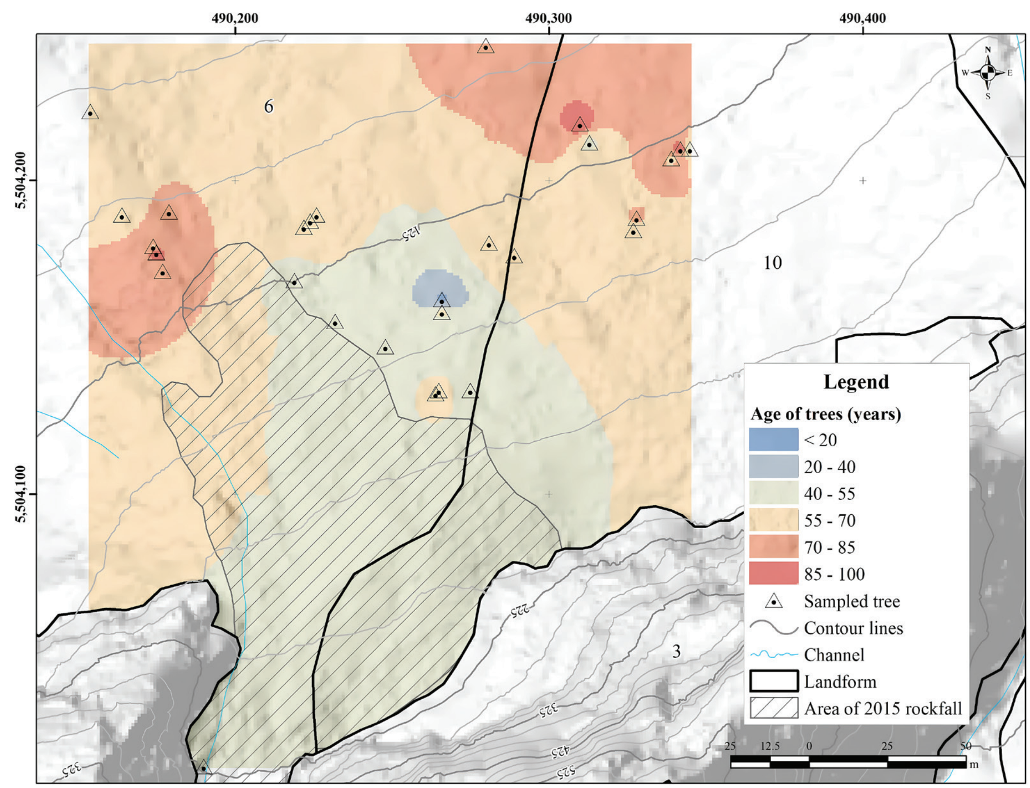

Figure 6 Distribution of tree ages at sample site III. Landform symbols: 3. main scarp, 6. debris flow cone, 10. upper talus apron.

growing on talus more distant from the steep rock face are older (>140 years) than those close to the face and have average rockfall return periods >14 years. Trees growing close to the steep rock face at site II have average return periods of 10-12 years. All trees at this site are <80 years old, suggesting they began to grow after one or more large rockfalls between 1925 and 1930.

Sampled trees at site III are located on the upper talus and debris flow deposits. They indicate an average rockfall return period of <25 years (Figure 10). Samples close to the steep rock face have return periods of 10-20 years. Sampled trees at 100-150 m asl at site III are 40-80 years old and have return periods of 10-15 years. In contrast, trees at higher elevations are 40-60 years old and have return periods >15 years. Only two trees located near the escarpment, which were not affected by the 2015 event, are young (<20 years). The only surviving tree at the base of the escarpment is 40-60 years old.

4.5. POTENTIAL TRIGGERING FACTORS

Meteorological data from the Squamish area show that high precipitation events in the study area typically occur in October and November. Our climatic dataset includes 12 rockfall events during the period for which precipitation data are available (1959-2017). Maximum rainfall values of >50 mm over a 3–5-day period are limited to fall and winter months (November-February). Five-day cumulative precipitation values that are at least 10% of the total annual precipitation are limited to four years: 1989, 1991, 2009, and 2015. The highest Shroder index value (60%) we calculated is for the year 1991; this year had 275 mm of precipitation over five days (Table 5). Of these four years, 2009 registered the highest number of days (97) with a range of temperatures that enabled freeze-thaw processes; the other three registered between 53 and 68 days with a range of temperatures above and below 0°C. In 1991, 2003, 2007, and 2015, the maximum five-day precipitation was twice the total November precipitation. These years also correspond to rockfall events with event-response index values of 60.0, 18.8, 17.0, and 49.1, respectively. Those years had between 64 and 82 days with a range of temperatures above and below freezing. Between 1909 and 2005, there were 61 moderate to large earthquakes (Mw 4.5–8.1), earthquakes in British Columbia.

Ten of the largest earthquakes (Mw 6–8.1) occurred in years during which seven (14%) of the rockfall events happened.

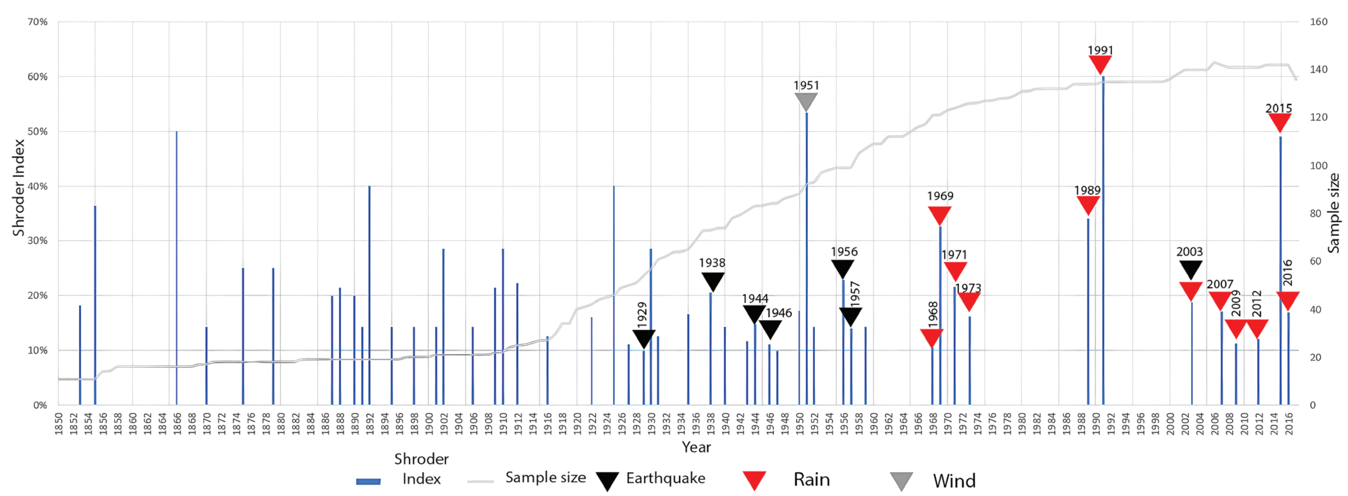

Figure 7 Rockfall events and possible triggers. Black triangles represent earthquakes; red triangles are three-day precipitation values exceeding 10% of the annual precipitation; grey triangles indicate strong winds.

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5. Discussion

5.1. POTENTIAL TRIGGERING FACTORS

Historical rockfall events at Stawamus Chief have not been systematically recorded, thus, no compiled archive of historical data exists. However, a few significant events have been reported. On June 23, 1946, a magnitude 7.3 earthquake with an epicentre on central Vancouver Island about 160 km from Squamish triggered several small rockfalls on Stawamus Chief (Hungr and Skermer, 1992). On January 14, 1999, heavy rain (77 mm in 24 hours) triggered a large (~103 m^3) rockfall and two smaller ones (Shoults, 1999). On April 19, 2015, a large (~2500 m^3) rockfall produced a large damage track in the forest at the base of Stawamus Chief and a visible dust cloud (Golder Associates, 2015 in Sampaleanu, 2017). This event was not triggered by an earthquake or extreme weather event (*i.e.*, no large daily range in temperature, freeze-thaw activity, extreme heat, or precipitation). However, it may have been a delayed response to an earlier above-normal 5-day rain event. A moderate-sized rockfall occurred on the North Wall on June 27, 2021 (Chua, 2021) during an unprecedented heat wave, when the temperature in Squamish exceeded 40°C for the first time in recorded history. The daily temperature range from July 26 to 28 was also extensive (22°C). Another significant rockfall happened one month later, on July 26, 2021, this time from the west-facing Grand Wall (Gripped, 2021). Although there was no obvious trigger, this event and a series of intervening smaller undocumented events were likely related to the June heat wave (Friele 2022; Figure 11). Extreme temperature has been recently evaluated as an environmental factor affecting mountain geohazards, such as debris flow and rockfall (Xu *et al.*, 2024); they explored the responses of mountain geohazards to climate change, including the rising temperature and precipitation, identifying their close relation to a warming climate. Personal observations by the authors, the climbing community, and social media indicate that an unknown number of small rockfall events go unrecorded.

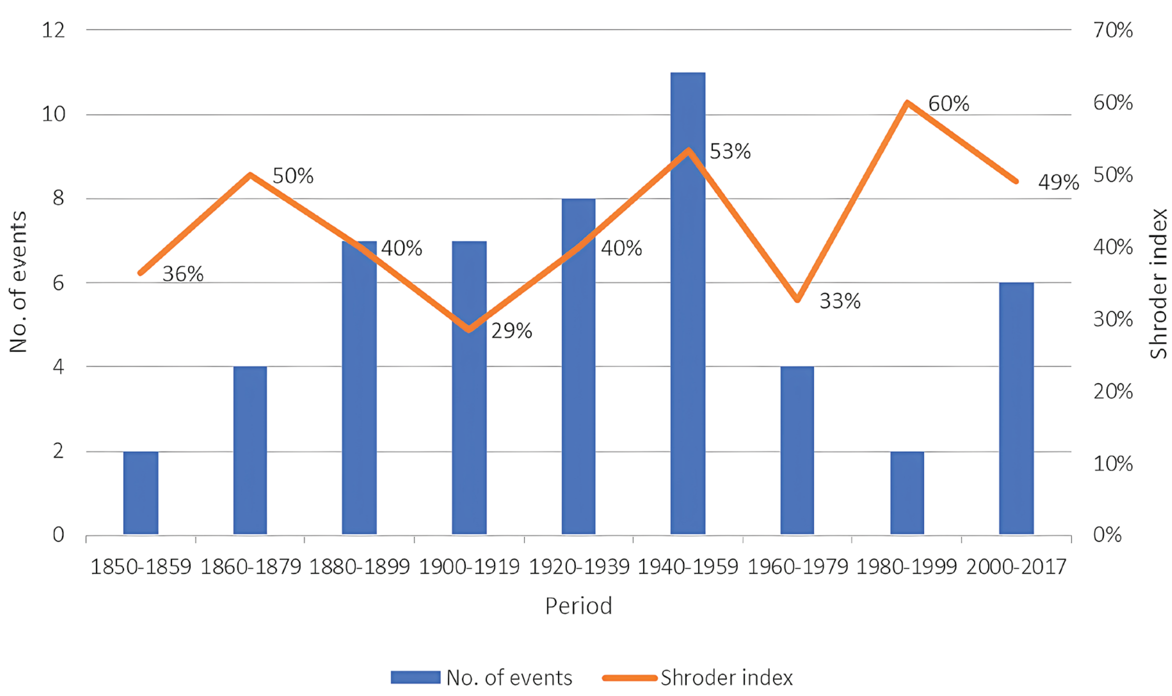

Figure 8 Number of inferred rockfall events and maximum event-response percentage index values binned in 20-year intervals.

For example, shortly after noon on November 24, 2015, Lars Unilla notified Pierre Friele of a loud rockfall and associated dust cloud, "very likely caused by a combination of freezing temperatures following yesterday's rain and very strong winds (70 km/hr gusts) loading the trees". Similar small rockfalls (100-102 m^3) are likely common on Stawamus Chief, and scouring social media might reveal a record of such rockfall activity; similar conditions have been registered in Spain (Leyva *et al.*, 2022).

Based on the magnitude-frequency model of Hungr *et al.* (1999), a 1 m^3 rockfall should occur at Stawamus Chief, on average, once or twice annually; a 10 m^3 rockfall every two years; and a 100 m^3 rockfall roughly every five years.

Our analysis of daily precipitation over the 1959-2019 period shows that rockfall events occurred in years with at least one day of >50 mm precipitation, which Macciotta *et al.* (2017) suggest is a threshold value for rockfall triggering in southwest British Columbia near our study area. In 1991, the year with the highest Shroder index value, a well-known flood event occurred locally, with a debris flow on Cheekye River (Friele and Clague, 2005; Jakob and Friele, 2010). Rainfall decreases in March, but melting spring snow can trigger rockfall events (Macciotta et al, 2017). Three-day cumulative precipitation at Squamish (up to 238 mm) is within the range that Delonca *et al.* (2014) and Macciotta *et al.* (2017) argue is capable of triggering rockfall.

The large rockfall in 1999 did not happen during or after an extreme precipitation event, but it occurred during a lengthy period with days during which temperatures cycled above and below freezing (102 days). Nevertheless, no rockfalls are known in 1985 during a similar long period of temperature cycling above and below zero (93 days). These results indicate the need to

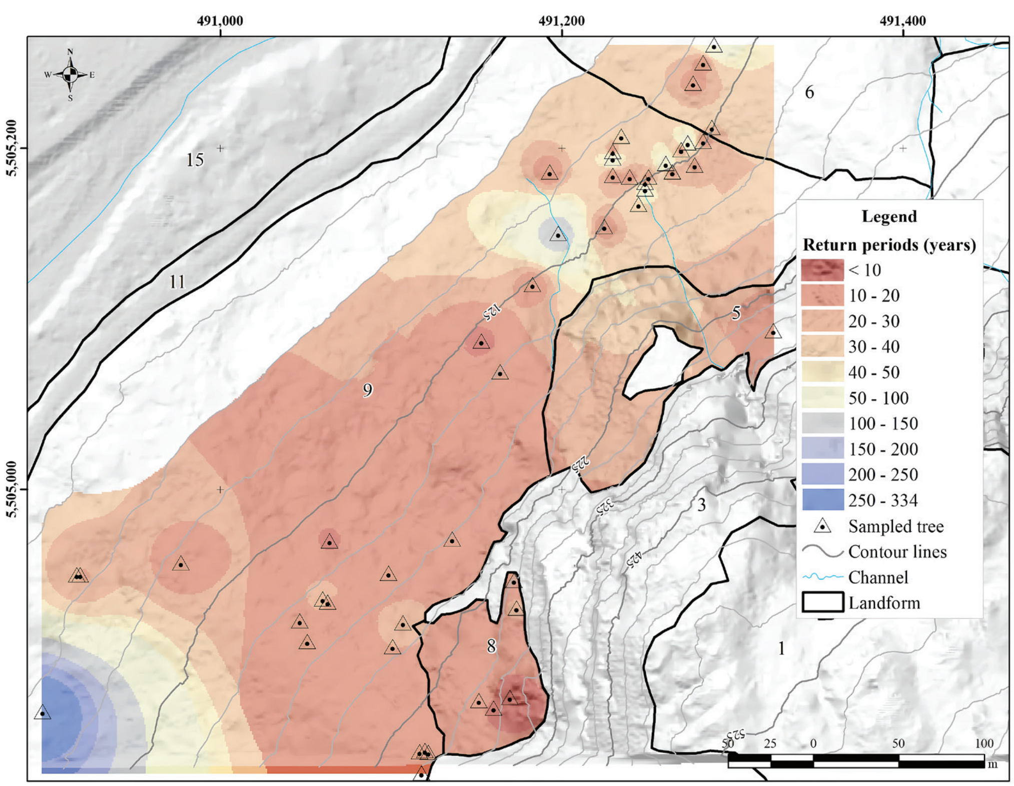

Figure 9 Return periods of rockfalls in sites I and II. Landform symbols: 1. top of Stawamus Chief, 3. main scarp, 5. secondary scarp, 6. debris flow and rockfall cone, 8. steep talus apron, 9. step-like talus, 11. lower talus apron, 15. terrace.

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Table 5. Three- and five-day cumulative precipitation during the period 1960-2017 (years in which percentages exceed 10% of the total are bolded).

	Event response index		Precipitation (mm)			Percent of annual precipitation	
Year	**Maximum value**	**Total value for the study area**	**3 days**	**5 days**	**Annual**	**3 days**	**5 days**
1968	10.5%	0.0%	206.7	228.3	2739.9	7.5	8.3
1969	32.6%	26.4%	71.4	124	2051.1	3.5	6
1971	21.6%	14.5%	134.1	173.5	2148.3	6.2	8.1
1973	16.2%	11.1%	187.2	205.2	2146.1	8.7	9.6
1989	34.0%	27.6%	183.4	**214.8**	2118.1	8.7	**10.1**
1991	60.0%	51.9%	194.8	**273.8**	2259.8	8.6	**12.1**
2003	18.8%	10.7%	167.8	248.4	2702.4	6.2	9.2
2007	17.0%	14.1%	238.3	251.6	2905.8	8.2	8.7
2009	11.3%	0.0%	189.4	**289.4**	2097.2	9.0	**13.8**
2012	12.2%	0.0%	155	173.5	2271.4	6.8	7.6
2015	49.1%	36.6%	215.2	**246.2**	2393.3	9.0	**10.3**
2016	17.0%	0.0%	50.8	172.5	2403.7	2.1	7.2

monitor temperatures near the escarpment, as well as to continue sampling damaged trees along other sections of the cliff.

5.2. THE USE OF TREE RINGS IN HAZARDS

Tree rings are an important proxy source of information on the frequency and spatial distribution of geomorphic processes in mountains, and dendrogeomorphological studies can improve analyses of hazard and risk in these settings (*e.g.*, Friele and Clague, 2005; Jakob and Friele, 2010). In the case of our study, we systematically sampled trees displaying visible wounds and stem responses to rockfalls in Stawamus Chief Provincial Park. We used a threshold event-response index value of 10% to assess rockfall events based on our tree ring dataset. Based on the rockfall dendrogeomorphic literature, this value is adequate for samples of about 60 trees (Morel *et al.*, 2015). If, for example, the index is 50%, half of the sampled trees record a disturbance in ring growth in that specific year. High index values indicate more important events than those with low values. All years with a value of 10% or more were considered in this study as years with rockfalls.

Rockfall is the principal natural hazard in Stawamus Chief Provincial Park. With the increased popularity in climbing and the growth of Squamish, exposure to the hazard and hence risk has increased. We have identified 33 rockfall events on the Squamish Chief North Walls between 1850 and 1949, and Blais-Stevens and Hungr (2008) found that the largest number of landslides (43) in the Sea-to-Sky corridor occurred in the decade between 1990 and 2000. We identified only one rockfall during that period, despite it having the highest event-response index value (60%) in our dataset. We could not find evidence of the large rockfall event of January 1999 at Site III, possibly because of tree loss caused by the subsequent 2015 rockfall. In general, temporal biasing due to tree loss is a limitation of dendrochronology in hazard evaluation studies (Ballesteros-Cánovas *et al.*, 2015). Stand destruction by rockfalls, rockslides, and debris flows creates a mosaic of stand ages. Future research needs to emphasize, on one hand, mapping of forest stand ages and, on the other, interviews with local inhabitants to document and understand more deeply the events that have left records in the local landscape.

In this study, we found that extremely long and short-period precipitation could be an important cause of rockfall at Stawamus Chief. That finding does not discount the fact that other triggers and the underlying geology and topography contribute to the hazard. Earthquake, seasonal freeze-thaw, extreme temperatures, and large diurnal temperature ranges can also be important. Also, a particular triggering factor, such as an earthquake or extreme rainfall event, will not necessarily trigger rockfall (Delonca *et al.*, 2014), indicating a degree of stochastic behavior, which is a research problem in any mass movement study.

Frost and snowmelt in fractures can independently trigger a rockfall, and slow fatigue of an intact, but fractured, metastable rock mass can cause rockfalls and rockslides without an obvious trigger. At Squamish, minimum daily temperatures below -8°C and maximum daily temperatures of about 7.5°C, which are common during March, induce a cycle of freeze-thaw activity that presumably favors rockfalls (Macciotta *et al.*, 2017; Pratt *et al.*, 2018). Additional research on freeze-thaw processes in fractured rock masses is required to better understand the effect of these processes on rock stability (Arosio *et al.*, 2013).

Strong earthquakes are a common trigger of rockslides and rockfalls in areas of steep terrain within several hundred kilometres of epicenters, especially in highly fractured rocks or sedimentary rocks with favorably oriented bedding planes. Bartle (2016) concluded that earthquakes in the zone of high seismicity along the British Columbia coast are an important trigger of rockfalls on Stawamus Chief. Earthquakes can also be a secondary cause of rockslides. A strong earthquake might create or enlarge fractures in the steep rock faces at Stawamus Park, destabilizing a metastable rock mass that fails much later, possibly in a rainstorm or freeze-thaw cycle.

Land-use changes are also an important cause of landslides (Reichenbach *et al.*, 2014; Persichillo *et al.*, 2017). While there has been no significant land-use change in Stawamus Chief Park, there has been a rapid increase in local climbing, begin-

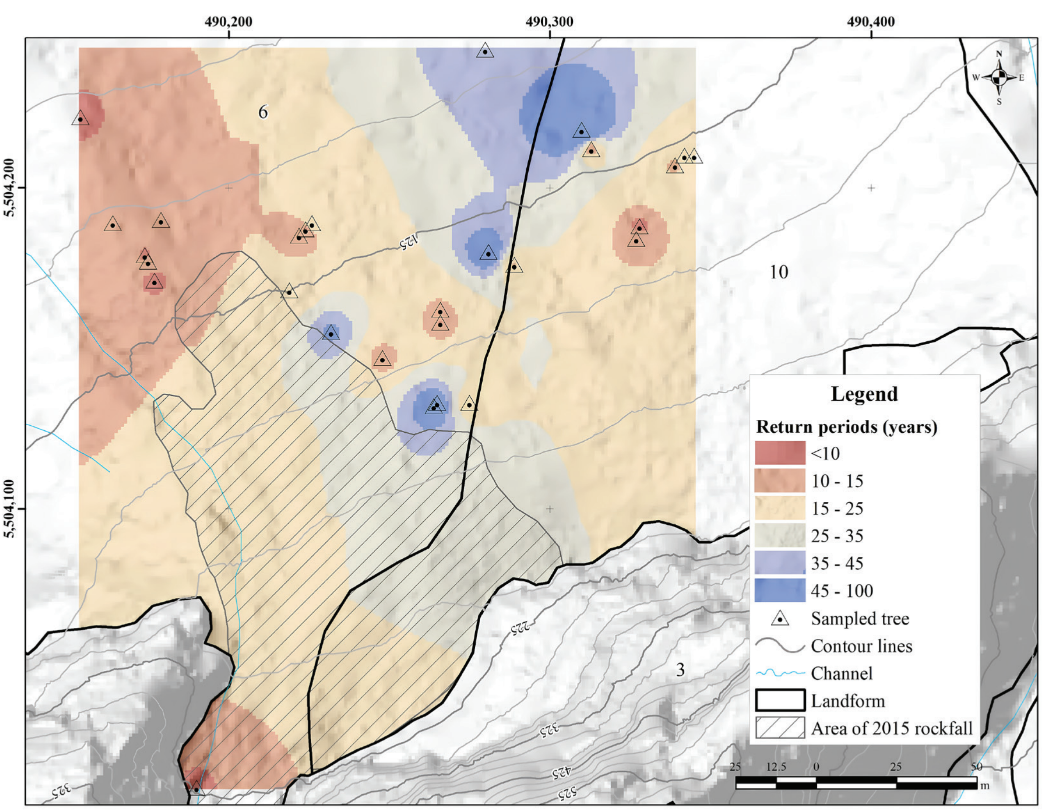

Figure 10 Return periods of rockfalls at site III. Landform symbols: 3. main scarp, 6. debris flow cone, 10. upper talus apron.

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ning in 1968 and notably increasing after about 1980. Climbers have established and cleaned routes, felling trees, cutting roots, cleaning accumulated organics from cracks and fissures, and dislodging loose rock fragments.

Splodge (2013) has written about this, and social media have reported incidents where a climber has been struck by rock fragments during dangerous trundling. A notable example is a very recent, 10 m^3 rockfall from a new climbing route that reached the base of the steep face, as observed by P. Friele, one of the authors.

Measures can be taken to mitigate rockfall hazards. In the case of Stawamus Chief Provincial Park, the apron of forest at the base of the steep rock slopes effectively mitigates all but the largest rockfalls from reaching the highway because trees decelerate falling and bouncing blocks (Moos *et al.* 2018). Even so, the forestry road along Mamquam River near the base of the North Walls was affected by rockfalls in 2015 and 2023.

The greatest rockfall risk in Stawamus Chief Provincial Park is faced by people bouldering among talus at the base of the Grand Wall, traversing hiking and climbing trails, and climbing the rock walls themselves. In comparison, the risk to drivers on the forestry road is low, as few rockfalls reach the road, and the exposure time of drivers is low. When discussing risk, one also needs to differentiate voluntary (climbers) and involuntary (road users) risk, because of the different risk tolerances associated with the two.

Our results demonstrate the usefulness of dendrochronological techniques for identifying and assessing rockfall hazards. However, application of these methods is constrained by the possible losses of temporal and spatial information due to large magnitude rockfalls that reset the forest (Ballesteros-Cánovas *et al.*, 2015).

Finally, we emphasize that such work should be integrated with terrain analysis and vegetation mapping, numerical modelling of trajectories of falling and bouncing rock blocks, and assessments of the value of forests for protecting at-risk infrastructure and people from rockfalls. For example, an approach recently proposed by Farvacque *et al.*

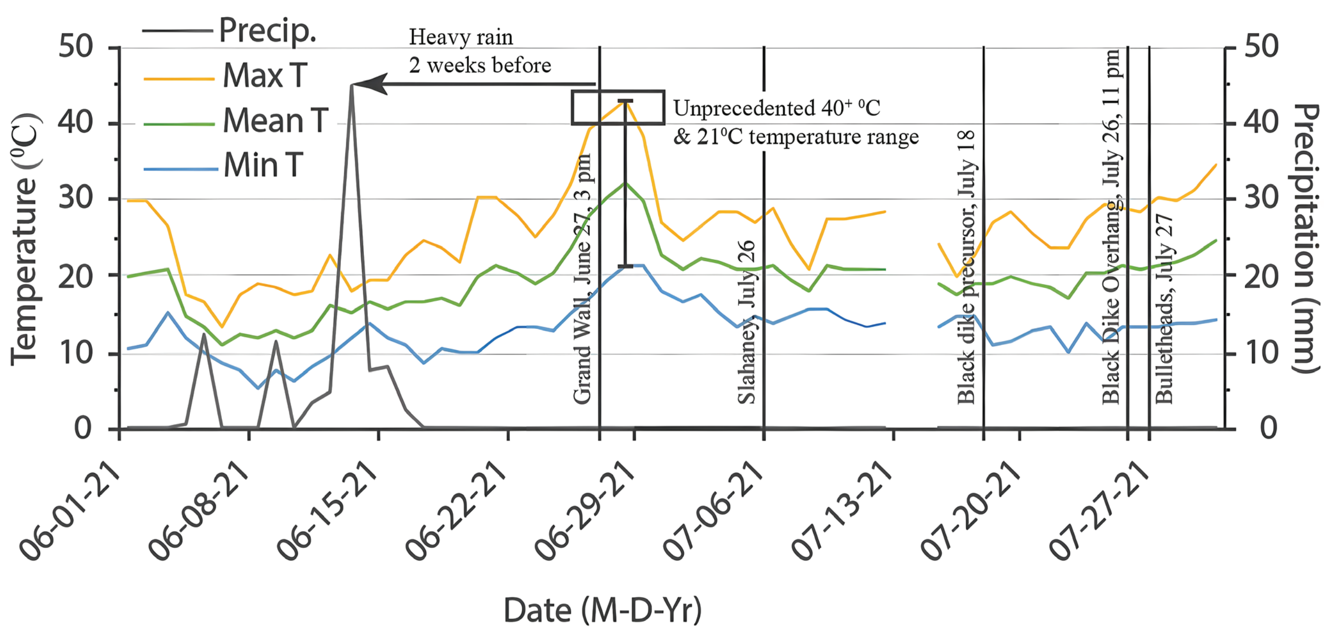

Figure 11 Daily weather values associated with the 2021 rockfall events.

(2022) to quantify rockfall frequencies at the cliff level based on records of impacts and accumulations at protection barriers, coupled with tree ring analysis, and rockfall modeling. It could become a standard procedure for future critical rockfall management strategies.

6. Conclusions

We have documented the frequency and spatial distribution of rockfalls on the steep northwest rock faces in Stawamus Chief Provincial Park using dendrogeomorphological methods. Of the trees sampled in this study, *Tsuga plicata* and *Pseudotsuga menziesii* best display and preserve growth anomalies (growth suppression and tangential resin ducts). *Tsuga heterophylla* proved to be less useful for recording damage from rockfalls in our study area. We identified 51 rockfalls over the period 1850-2017. As many as seven of these events may have been triggered by earthquakes, and up to 12 could have happened in connection with storms during which more than 50 mm of rain fell over a 3-5 day period. Our tree ring dataset allowed us to generate the first rockfall chronology in the park, producing return period maps that highlight hazardous areas. Other natural processes that contribute to instability include freeze-thaw cycling within the ubiquitous joints of the granodiorite monolith, extreme temperatures and extreme diurnal temperature range, root growth within joints, snow melt, and slow rock fatigue.

Our pilot project demonstrates the potential of these methods for providing an improved understanding of rockfall and debris flow hazards in forested terrain, and in this specific case, for guiding BC Parks on risks faced by hikers and rock climbers who visit Stawamus Chief Provincial Park.

Contributions of authors

1) Conceptualization: MEM; OL: (2) Analysis or data acquisition: OL MEM; (3) Methodologic/technical development: OL, MEM; (4) Writing of the original manuscript: OL, MEM; (5) Writing of the corrected and edited manuscript: MEM; (6) Graphic design: OL; (7) Interpretation: DBR, MEM, JVD; (8) Financing: MEM

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Data availability statement

The data that support the findings of this study are available from the corresponding author, M.E.M., upon reasonable request.

Handling editor

Avto Gogichaishvili.

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