Rock glacier activity and distribution in the southeastern British Columbia Coast Mountains

by

Ansley Adeline Charbonneau
B.Sc., University of Victoria, 2012

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Requirements for the Degree of

MASTER OF SCIENCE

in the Department of Geography

Supervisory Committee

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Abstract

Rock glaciers are common features in high alpine settings of the southeastern British Columbia Coast Mountains. The spatial distribution and characteristics of these periglacial features have not previously been documented. The goal of this research was to determine the distribution and activity of these rock glaciers in order to characterize their periglacial response to climatic variability.

A high-resolution aerial inventory documented the presence of 187 rock glaciers between Lat. 50° 10’ - 52° 08’ N. These rock glaciers occur at sites located between 1900 m and 2400 m above sea level, where rain shadow effects and continental air masses result in persistent dry cold conditions. Intact rock glaciers were the most prevalent form and accounted for almost 90% of the rock glaciers included in the inventory. Glacier-derived features outnumbered talus-derived features by a ratio of 4:1 and only 22 relict rock glaciers were identified. Rock glaciers in this region occupy predominately northwest- to northeast-facing slopes, with talus-derived rock glaciers largely restricted to north-facing slopes. All rock glaciers were found at locations above presumed Younger Dryas terminal moraines, suggesting that they began to form after 9390 BP.

Rock glacier activity during the Late Holocene was characterized using lichenometric methods to establish the relative surface age of three talus-derived features at Perkins Peak. Sustained periods of cool-wet climates activated pulses of rock glacier surface instability and movement, while a shift to warmer, drier conditions resulted in the loss of internal ice and increased surface stability. Varying degrees of present-day activity highlight a local topoclimatic control on talus-derived rock glacier behaviour. A dendrogeomorphological investigation at nearby Hellraving rock glacier indicated that it has been steadily advancing into surrounding forest since the beginning of the late Little Ice Age. Its continued advance in the face of warming temperatures suggests the internal thermodynamics of this rock glacier may be out of equilibrium with the contemporary climate. This research is the first to document and characterize rock glaciers in the Coast Mountains and challenges previous understandings of permafrost distribution in the southwestern Canadian Cordillera.

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Acknowledgements

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Dan 'DJ' Smith – you have been an excellent supervisor/alpine spirit guide. Thanks for tipping me off to the mysterious Coast Mountain rock glaciers and scrambling around on the surfaces of the ankle-hazards that they are. I have learned so much from hiking the backcountry with you and your team and it has been a remarkable experience. Working with you back in the lab has been equally rewarding and I want to thank you for all the support and guidance you provided (and continue to provide!).

Finally, thanks to my family and friends for listening to me talk about rock glaciers, over and over and over again. And a huge thank you to Shannon, for encouraging me to be my best self and not questioning my obsession with rocks and ice.

Chapter 1 – Introduction

1.1 Introduction

Rock glaciers are perennially frozen bodies of ice and debris that flow downslope under the weight of gravity (Haeberli 1985; Barsch 1996). Active rock glaciers require environments cold enough to support a year-round negative ground thermal, yet dry enough to prevent the development of valley glaciers and icefields (Haeberli 1985). Thus, the presence of active rock glaciers suggests the existence of permafrost conditions (Barsch 1996), while the occurrence of relict rock glaciers serves as an indicator of where permafrost previously occurred (Humlum 1998).

The widespread distribution of rock glaciers within the southeastern British Columbia Coast Mountains suggests permafrost may be extensive in this region. The purpose of this research is to document the abundance, distribution and activity of rock glaciers within this setting. Identification and morphological studies provide an opportunity to determine whether these features are intact, containing ice, or are relict forms without ice (Janke et al. 2013). Topoclimatic investigations offer the opportunity to situate the rock glaciers within the landscape and to describe the climatic conditions influencing their behaviour (Luckman and Crockett 1978; Humlum 1988). Finally, an evaluation of present-day surface activity and rates of frontal movement is used to establish morphoclimatic relationships that describe the long-term role Holocene climatic variability played in the development and persistence of permafrost and periglacial mass wasting processes in this setting (Refsnider and Brugger 2007). Collectively, an investigation on rock glaciers in this region serves to broaden understanding of the establishment and persistence of permafrost conditions in the southeastern British Columbia Coast Mountains.

1.2 Research Objectives

The objectives of this research were to:

1. Complete an inventory of the distribution and topographic controls of rock glacier landforms in the southeastern British Columbia Coast Mountains.
2. Document the present-day rate and paleo-history of rock glacier activity within the Pantheon Range.
3. Characterize the geomorphic response of rock glaciers in the Pantheon Range to changing climates.

1.3 Thesis Format

This thesis consists of four chapters. Chapter One provides an introduction to the research and outlines the objectives of the project. Chapter Two presents the findings of a high-resolution aerial inventory of rock glaciers identified within the southeastern Coast Mountain region. The chapter describes the location and topoclimatic controls of rock glaciers in this setting, and interprets these findings to present the first detailed description of permafrost in the southern Coast Mountains. Chapter Three presents the findings of lichenometric and dendrogeomorphological surveys at four rock glaciers in the Pantheon Range. The findings of these investigations are discussed in the context of climatic variability through the Little Ice Age to present-day. Chapters Two and Three were written as independent manuscripts for journal submission. Chapter Four summarizes the research and provides concluding remarks, followed by a presentation of the research limitations and suggestions for continued study.

Chapter 2 – Rock glaciers in the southern British Columbia Coast Mountains, Canada: Inventory, distribution and topoclimatic controls

2.1 Introduction

The British Columbia Coast Mountains flank the Pacific coast of Canada, rising from sea level to over 4000 m in the Mt. Waddington area (Figure 2.1). Along their windward maritime slopes deep winter snow packs persist into the summer months, allowing for the development of high elevation icefields and large valley glaciers. Eastwards, glaciers decrease in size and number, as strong rain shadow effects result in a relatively dry environment in the sub-continental front ranges abutting the Chilcotin Plateau. While icefields are absent in this region and glaciers are largely restricted to shaded northeast facing high elevation cirques (Falconer *et al.* 1965; Østrem 1966; Østrem and Arnold 1970), aerial imagery shows that rock glaciers of varying size and morphology are abundant.

Little is known about the age, activity or distribution of rock glaciers in the Coast Mountains (French and Slaymaker 1993). Reflecting debris accumulation and mass wasting under a periglacial climate (Humlum 2000; Haeberli *et al.* 2006), their occurrence describes a geomorphic response to permafrost thermal regimes that may or may not presently exist (Humlum 1998). Ground-based mapping of the contemporary limits of permafrost in the Canadian Cordillera is restricted to sites further to the east in the Canadian Rocky Mountains (Harris and Brown 1981; Harris 1986), as well to sites in northern British Columbia and the southern Yukon (Bonnaventure *et al.* 2012). Consequently, it remains to be determined whether these Coast Mountain landforms are the fossilized remains of rock glaciers active during an interval of Late Pleistocene

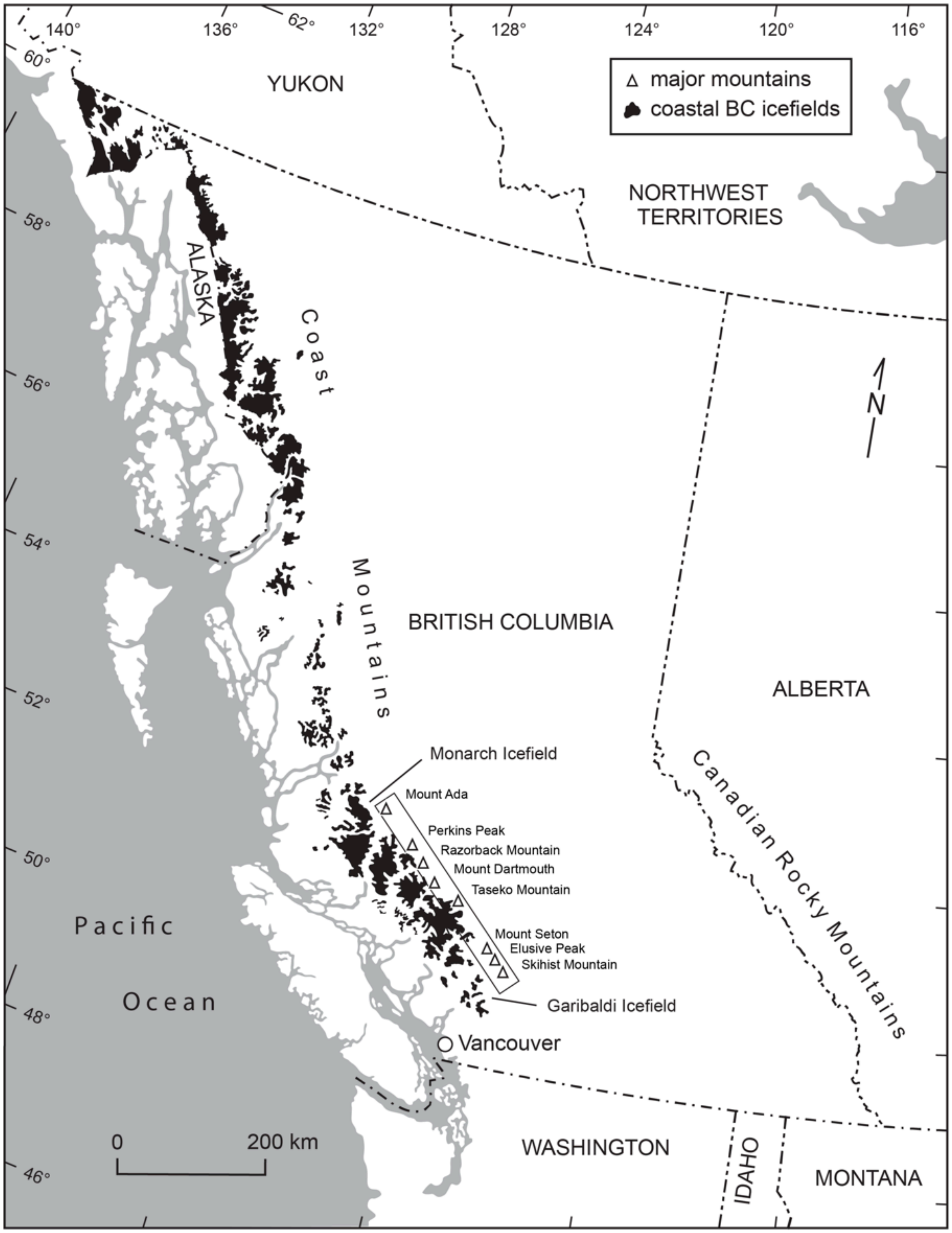

Figure 2.1: Location of the study area along the southeastern flank of the British Columbia Coast Mountains. The boundaries of the study area are shown by the rectangular box. Mountain peaks are provided for geographic reference.

climatic deterioration, or whether they illustrate a geomorphic response to the development and persistence of permafrost conditions during the Holocene to present-day.

The intent of this research was to document the distribution and general characteristics of rock glaciers in the eastern front ranges of the Coast Mountains. Following on this inventory, rock glacier activity is interpreted within the context of Holocene climatic variability and the findings are used to locate the lower limit of discontinuous permafrost in this region. To achieve these objectives, the characteristics of a large sample of rock glaciers from the region are compared to regional climatic gradients and topographic conditions.

2.2 Research Background

The term ‘rock glacier’ is associated with a range of landform-types found in arctic and alpine environments (Janke *et al.* 2013). By definition, rock glaciers consist of perennially frozen masses of ice and debris that creep downslope under the weight of gravity (Haeberli 1985; Barsch 1996; Haeberli *et al.* 2006). Transverse ridges and longitudinal furrows are the surface expression of this internal ice deformation (Barsch 1996; Frehner *et al.* 2014).

The surface of most rock glaciers consists of a seasonally-thawed active layer that acts as a barrier between external climatic conditions and the permanently frozen interior below the permafrost table (Wahrhaftig and Cox 1959; Humlum 1996; Haeberli *et al.* 2006). As a negative ground thermal regime is necessary to maintain a frozen state, active rock glaciers are seen as indicators of permafrost conditions (Lilleøren and Etzelmuller 2011; Boeckli *et al.* 2012; Lilleøren *et al.* 2013a; Scotti *et al.* 2013).

In high mountain regions, rock glaciers commonly form at sites characterized by cool air temperatures and moderate amounts of precipitation (Haeberli 1985; Humlum 1998). While rock glaciers are occasionally found in maritime climate regions (Humlum 1982; Martin and Whalley 1987; Lilleøren *et al.* 2013a), their distribution is largely restricted to continental climate zones. Rain shadow conditions are ideal for rock glacier formation, as the thin snow pack that characterizes many of these regions reduces insulation, allowing cold winter air temperatures to sustain negative ground temperatures (Humlum 1997; Haeberli *et al.* 2006). In mountainous settings rock glaciers are most commonly located where shading shields them from insolation and the local topography directs cold winds down into the debris layer (Humlum 1997; 1998).

Previous descriptions of rock glaciers in the Canadian Cordillera focus on those found in the southern Canadian Rocky Mountains in Alberta (Osborn 1975; Luckman and Crockett 1978; Gardner 1978; Koning and Smith 1999; Carter *et al.* 2000; Bachrach *et al.* 2004) and in the St. Elias and Selwyn Mountains in Yukon (Johnson 1978, 1980; Sloan and Dyke 1998). Most rock glaciers in the Canadian Cordillera are believed to have developed following retreat of the Cordilleran Ice Sheet at the end of the Pleistocene, although absolute origin ages have not been assigned (Johnson 1978; Luckman and Crockett 1978). The majority of rock glaciers in the southern Canadian Cordillera are located in high elevation, north-facing cirques where the local lithology exerts a strong control on their form and presence. In the southern Canadian Rocky Mountains rock glaciers are common in the shales and quartzites of the Main Ranges, but sparse in the shales and carbonates of the Front Ranges (Luckman and Crockett 1978).

2.3 Study Area

The study area includes the southeastern Coast Mountain front ranges, east of the Garibaldi Icefield (Lat 50°10’) to terrain northeast of the Monarch Icefield (Lat 52°08’ N) (Figure 2.1). The region is south of the continuous permafrost limit in western Canada, but is assumed to contain ‘isolated patches’ of permafrost (up to 10%) at high altitudes (Brown and Péwé 1973; Heginbottom *et al.* 1995; Rodenhuis *et al.* 2007; Gruber 2012). Mean annual air temperatures range between -5 and 0 °C at high elevation, with precipitation totals averaging 750 mm/year or greater (Dawson *et al.* 2008).

The region is located within the Coast Belt, a major tectonic feature located between the Insular and Intermontane superterranes of western British Columbia accreted along the continental margin from Middle Jurassic to Early Cretaceous time (Journeay and Friedman 1993). The study area contains younger intrusions of mid-Cretaceous to early Tertiary age bedrock within the Bridge River, Cadwallader, and Methow terranes (Journeay and Friedman 1993; Bovis and Evans 1996). Deformation and contraction associated with the bivergent Coast Belt Thrust System resulted in the deposition of pre-existing terranes into metamorphosed thrust sheets intruded with plutons (Journeay and Friedman 1993, Monger and Journeay 1994; Bustin *et al.* 2013). Pockets of volcanic and sedimentary rocks not consumed by the intrusion remain throughout the Coast Belt, particularly along the eastern border by the Yalakom fault, which separates the neighbouring Intermontane Belt (Massey *et al.* 2005).

Following degradation and downwasting of the Cordilleran Ice Sheet and a Late Pleistocene glacial advance in 10.7-10.5 ka (Grubb 2006; Margold *et al.* 2013), by 10.0 ka glaciers in the study area had retreated several kilometres upvalley to rarely expand beyond their mountain-front terminal positions through the Holocene (Menounos *et al.*

2009). Intervals of cooler/wetter and warmer/drier climates resulted in only minor ice front oscillations during the Holocene, at least until the last millennia when Little Ice Age (LIA) climate changes (Larocque and Smith 2005a; Steinman *et al.* 2014) initiated a period of sustained glacier expansion (Larocque and Smith 2005b; Wood *et al.* 2011). In the last century rising air temperatures and variable snow packs (Dawson *et al.* 2008) have resulted in negative mass balance conditions and significant volumetric losses of glacier ice (Schiefer *et al.* 2007; VanLooy and Forster 2008). Within the study area, many of the cirque glaciers active during the LIA have melted away entirely and a thick cover of rockfall debris mantles the surface of those that remain.

2.4 Methods and Data

2.4.1 Rock glacier classification

The rock glacier inventory was completed through an aerial classification using high-resolution satellite imagery (2004/2005) available through Google Earth. Google Earth was previously used for rock glacier identification in the Bolivian Andes (Rangecroft *et al.* 2014) and Kush–Himalayan region (Schmid *et al*. 2014). In the Coast Mountains it represents the best available imagery for detecting rock glaciers across large spatial areas. Aerial identification was supplemented with field validation where access permitted.

Rock glaciers were categorized based on genesis and activity. It is widely accepted that rock glaciers are transitional features, oftentimes marking the interaction between ice of mixed glacial and periglacial origin (Haeberli *et al.* 2006). For this reason, the classification scheme distinguishes between rock glaciers predominately influenced by slope dynamics (talus-derived; Figure 2.2a) and those related to glacial dynamics (glacier-derived; Figure 2.2b). Talus-derived rock glaciers originate from talus slopes directly attached to headwalls (Humlum 1984; Haeberli 1985; Barsch 1996; Haeberli *et al.* 2006); these are often referred to as 'true rock glaciers' in the literature (e.g. Clark *et al.* 1998). Within the glacier-derived category, several forms are present: a) rock glaciers originating from glacial debris such as lateral and terminal moraine deposits. These features satisfy Barsch's (1996) classification of 'debris rock glaciers' and are identical to those detailed in previous moraine-derived classification schemes (Lilleøren and Etzelmuller 2011; Lilleøren *et al.* 2013a); and, b) rock glaciers that are visually connected to glaciers but lack a defined boundary between the glacier ice and the rock glacier below. The upper sections of these rock glaciers frequently contain thermokarst thaw pits or are characterized by a depression between the mountain side and the rock glacier deposit. Humlum (1996; 1997) describes similar features in western Greenland, arguing that despite the similarity to glaciers these features display active-layer dynamics and should be termed permafrost landforms. Similar features have been documented in Wyoming (Clark *et al.* 1998), the Andes of central Chile (Brenning 2005) and in the French Alps (Monnier *et al.* 2013). The glacier-derived category of rock glaciers includes landforms influenced by glacial activity more broadly, but does not make the claim that these features are of a glacigenic origin (e.g. Clark *et al.* 1998).

Two activity classes were identified: intact (active/inactive) rock glaciers and relict (fossilized) rock glaciers. In this research, the 'intact' classification was used to group active and inactive features, as no distinction can be made between the two types from satellite imagery (Haeberli 1985; Janke *et al.* 2013). Active rock glaciers gradually translate ice and frozen debris downslope through the process of creep, whereas

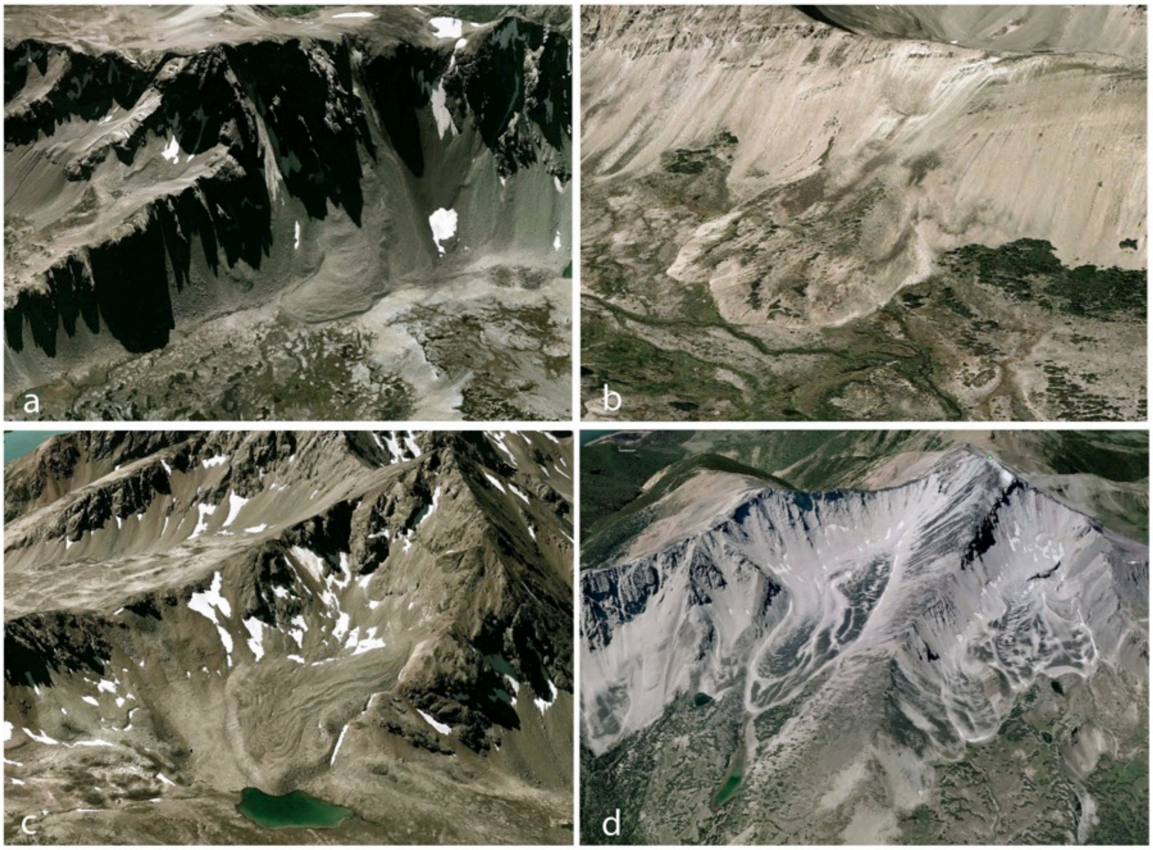

Figure 2.2: Rock glacier classification: (a) intact talus-derived; (b) relict talus-derived; (c) intact glacier-derived; and (d) relict glacier-derived (see text for details).

deformation has ceased within inactive features (Haeberli 1985; Barsch 1996). Intact rock glaciers, therefore, were used to denote the lower limit of present-day permafrost distribution (Haeberli 1985; Barsch 1996) and fossilized features were seen as indicators of palaeoclimatic conditions (Humlum 1998).

An intact rock glacier was identified as a feature with a steep front at or near the angle of repose, with a collection of spilled boulders commonly found in the foreground indicating surface transport (Haeberli 1985; Barsch 1996). Internal deformation was apparent from ridge/furrow morphology along the surface and material sorting was visible at the front and sides (Figure 2.2a and b). Intact features lacked vegetation as unstable surfaces, seasonal snowpack, and frequent avalanche activity limited growth (Haeberli 1985).

‘Relict’ rock glaciers were identified as landforms that no longer contain permafrost, either due to changes in the climate following their development, or because the supply of ice and/or debris was insufficient to maintain them in an intact state (Haeberli 1985). These fossilized features were flatter and thinner owing to ice loss, with many having frontal ramps that gradually sloped down to the valley floor (Ikeda and Matsuoka 2002). Forests growing on relict rock glaciers were used as an indicator of prolonged surface stability (Figure 2.2c and d).

2.4.2 Inventory analysis

The topographic and climatic characteristics of the rock glaciers identified in the inventory were recorded in a Geographical Information System (GIS) environment (ArcMap 10.0). The toe coordinate of each rock glacier was joined with elevation and aspect layers derived from a 50 x 50 m digital elevation model (DEM) (Geogratis 2013).

A geologic layer from the B.C. Ministry of Energy and Mines (1:250,000)(Massey *et al.* 2005) was added to the rock glacier location data to include rock class within the spatial database. Mean annual air temperature (MAAT) and mean annual precipitation (MAP) interpolated weather station data (800 m x 800 m grid) were obtained from ClimateBC version 5.04 for each site (Wang *et al.* 2012; Spittlehouse and Wang 2014).

Environmental conditions were summarized for the two rock glacier categories: intact/relict rock glaciers and glacier-/talus-derived rock glaciers. Average and standard deviation values were calculated to characterize the categories, followed by pairwise comparisons using the Kruskal-Wallis one-way analysis of variance by ranks for non-parametric data. This tested the null hypothesis, that rock glacier categories were taken from the same population, and the alternative hypothesis, that categories reflected genuine population differences. All statistical calculations were completed using the software environment R (version 3.1.2). Circular plots were used to determine the relative spread or concentration of slope aspect across rock glacier categories.

2.4.3 Permafrost distribution

In the absence of ground temperature data from the study area, the spatial distribution of rock glaciers was compared to the location of glaciers and the position of the upper treeline to estimate the position of the periglacial climate belt (e.g. Harris and Brown 1981; French and Slaymaker 1993). An inverse relationship was assumed to exist between the lower limit of permafrost and the altitude of glaciers (French and Slaymaker 1993). Where heavy snowfall results in low-lying glaciers near treeline, the ground is insulated from perennial freezing and permafrost is restricted to the highest elevations. Conversely, in regions with less precipitation, glaciers form at higher elevations.

Discontinuous permafrost generally occurs between the lower limits of glaciation and the contemporary treeline, where forest cover shelters snow accumulation from wind distribution and insulates the ground (French and Slaymaker 1993).

To facilitate comparison between glaciers, treeline and rock glaciers at the valley scale, a spatial query selected the closest glacier or treeline position to each rock glacier within a 10-kilometre search distance. The geographic location of glaciers within each search area was derived from the centre point of Global Land Ice Measurements from Space (GLIMS) polygons (Racoviteanu *et al.* 2009) and the upper treeline limit was digitized as a polyline in Google Earth. Mean elevation values for each GLIMS polygon were derived from the 50m x 50m DEM and treeline elevation was determined using the polyline vertices. MAAT and MAP were also gathered for proximal glaciers and treeline using ClimateBC scale-free interpolated weather station data (Wang *et al.* 2012; Spittlehouse and Wang 2014) to discuss the climatic constrictions associated with discontinuous permafrost distribution. The dependence of MAAT on elevation was tested using the Pearson product-moment correlation coefficient, after which a trend line was used to determine the elevation of the -3 and 0° C isotherms across the range.

2.5 Results

A total of 187 rock glaciers were identified in the study area (Figure 2.3). An indeterminate number were possibly overlooked due to topographic shading or poor image quality. Massive ice was confirmed at Razorback rock glacier (Figure 2.4a), supporting the glacier-derived classification scheme. The activity status of intact rock glaciers was confirmed at Hell Raving Creek, where a rock glacier was observed advancing into standing forests (Figure 2.4b).

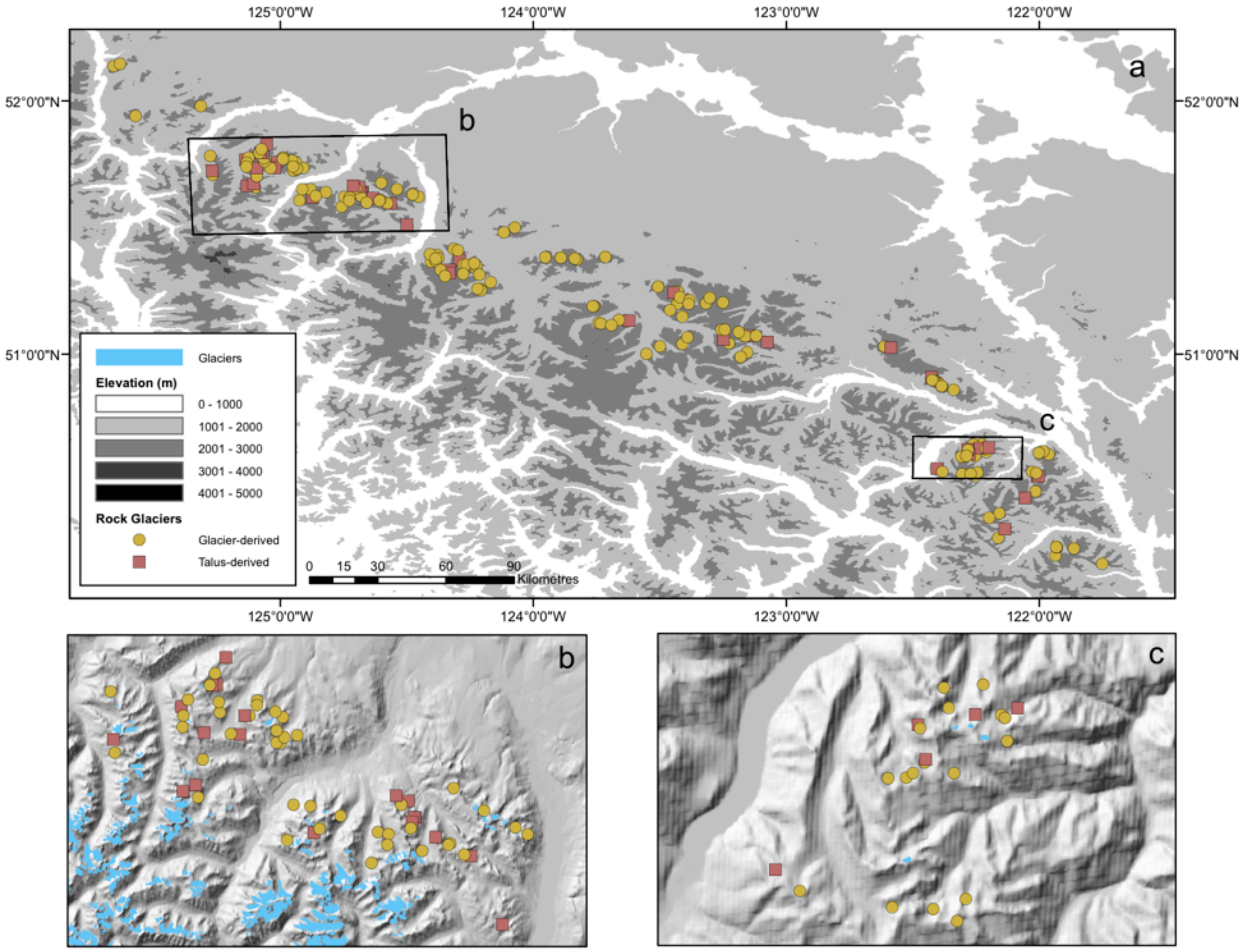

Figure 2.3: Spatial distribution of rock glaciers a) in the front ranges; b) in the Perkins Peak/Razorback Mountain area; and c) in the Mount Seton area.

Figure 2.4: a) Arrow points to massive ice exposure at Razorback rock glacier (hikers in the upper right corner for scale); and b) rock glacier front advancing into standing forest at Hell Raving Creek.

Rock glaciers appeared evenly distributed within the intrusive, metamorphic, sedimentary and volcanic rocks that characterize the eastern front ranges of the Coast Mountains. Rock glacier distribution was bounded by the Yalakom and Fraser faults to the east and plutons to the west. Rock glaciers have formed within the volcanic, marine, and sedimentary rocks of the Bridge River, Cadwallader, Methow and Overlap terranes. Rock glaciers also appeared to form within sporadic granitodioritic intrusives associated with the Post Accretionary terrane, along the border between the southeast and southwest Coast Mountains.

In the study area, rock glaciers occupied predominately northern-facing (NW, N, NE) slopes (Figure 2.5a). Intact glacier-derived rock glaciers displayed the broadest range of slope aspects, while intact talus-derived rock glaciers were strongly restricted to north-facing slopes (Figure 2.5b and c). Relict rock glaciers for both categories occupied more westward slopes than intact features of the same origin.

Intact rock glaciers were considered to be indicators of discontinuous permafrost under contemporary climatic conditions (Lilleøren and Etzelmuller 2011; Boeckli *et al.* 2012; Lilleøren *et al.* 2013a; Scotti *et al.* 2013). The majority of intact rock glaciers were found at sites located from 1900 ± 50 m to 2300 ± 50 m above sea level (Figure 2.6). The mean elevation for intact glacier-derived features was 2100 ± 50 m, while intact talus-derived features were located slightly lower at 2090 ± 50 m (Table 2.1). This distribution placed rock glaciers near the lower altitudinal boundary of glaciers (Figure 2.7a) and the upper elevational extent of treeline (Figure 2.7b), delineating a 500 m wide altitudinal belt conducive to discontinuous permafrost (Figure 2.8).

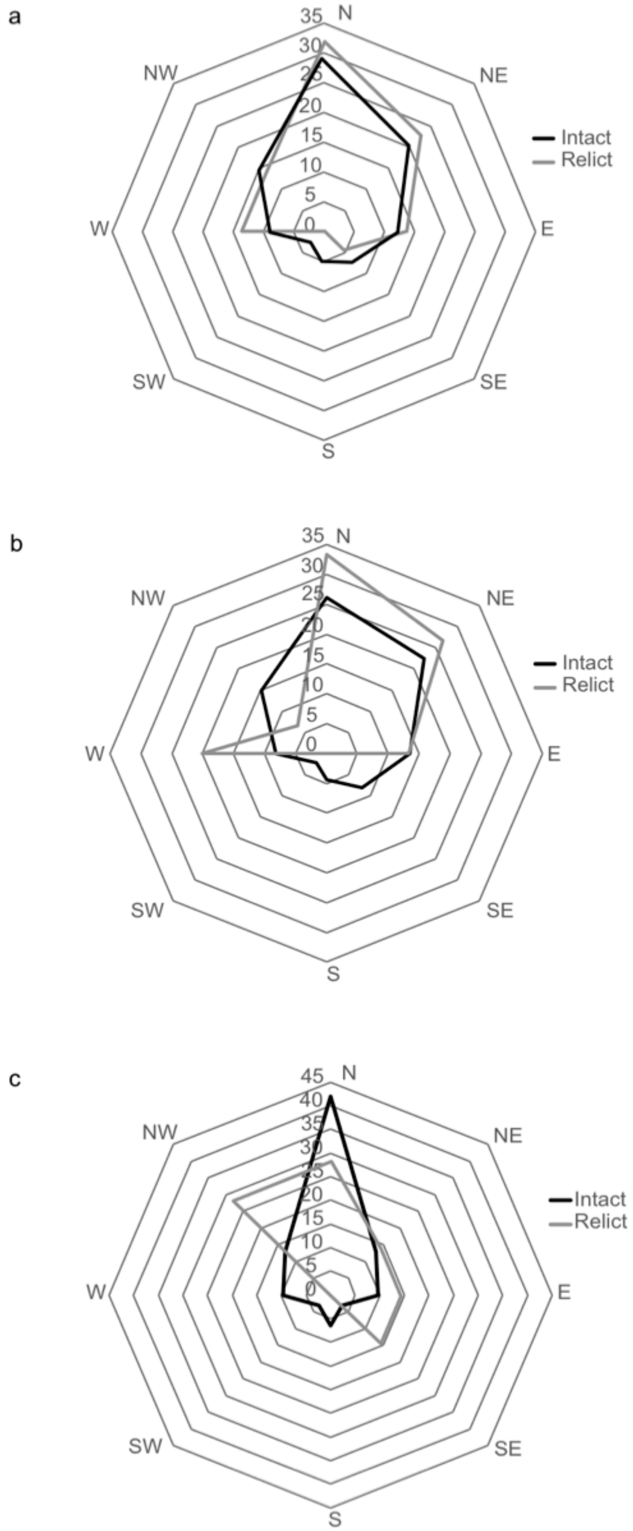

Figure 2.5: Relative abundance of slope aspects for (a) all rock glaciers, (b) glacier-derived rock glaciers, and (c) talus-derived rock glaciers.

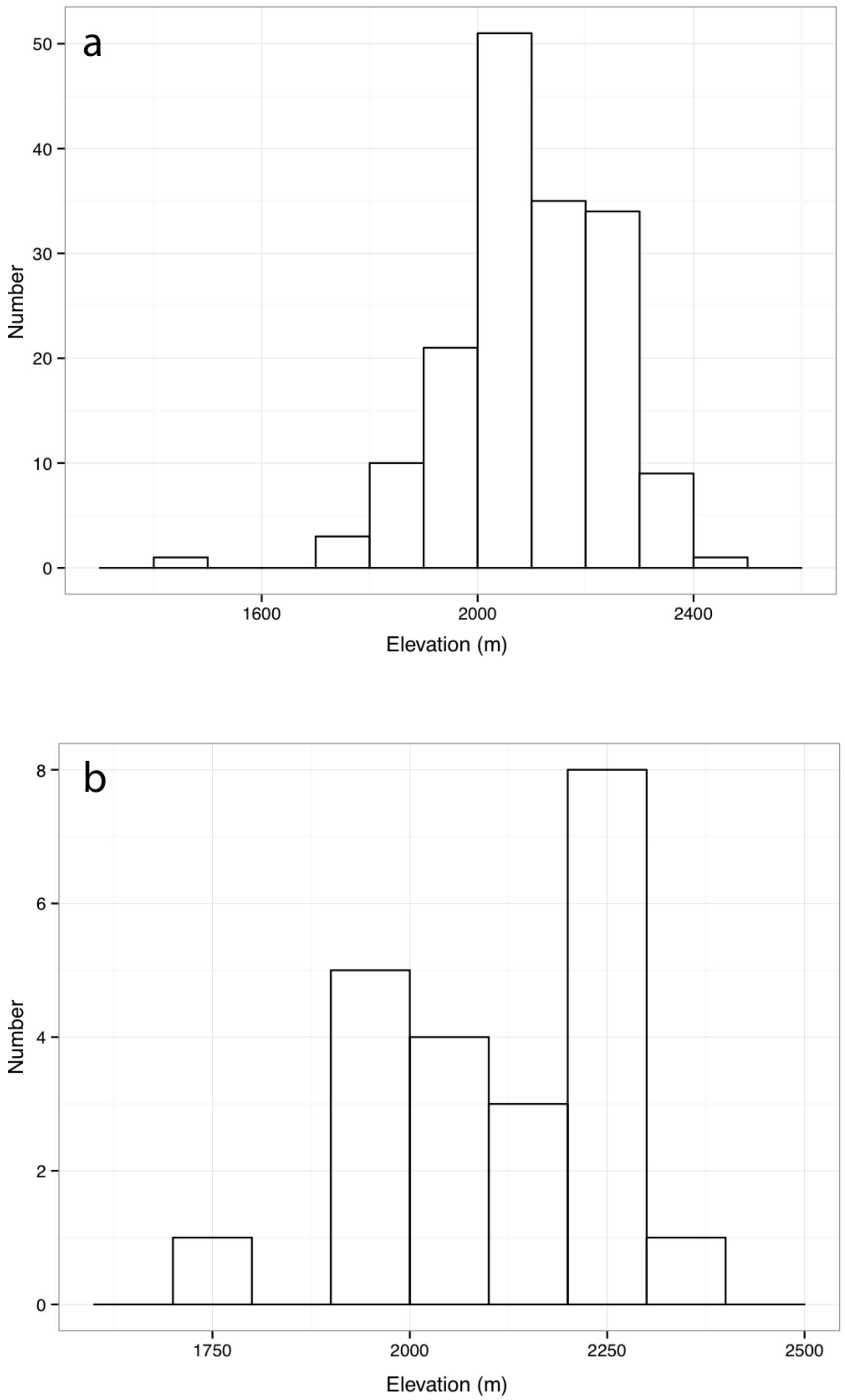

Figure 2.6: Regional elevation histograms for (a) intact and (b) relict rock glaciers. Each column represents 100 m in elevation.

Table 2.1: Summary of the environmental variables collected within the rock glacier inventory.

Landform Category		Number of Landforms	Elevation (m)	MAAT °C (1971-2000)	MAP mm/yr (1971-2000)
Intact	All intact rock glaciers	165	2102 (152)	-1.2 (0.8)	1258 (245)
	Glacier-derived	134	2104 (153)	-1.2 (0.8)	1264 (249)
	Talus-derived	31	2090 (147)	-1.1 (0.8)	1236 (229)
Relict	All relict rock glaciers	22	2134 (151)	-1.1 (0.6)	1251 (140)
	Glacier-derived	15	2149 (161)	-1.1 (0.7)	1232 (145)
	Talus-derived	7	2101 (130)	-1.2 (0.6)	1293 (128)
Glacier-derived		149	2109 (154)	-1.2 (0.8)	1260 (240)
Talus-derived		38	2092 (143)	-1.1 (0.8)	1246 (213)
All rock glaciers		187	2105 (152)	-1.2 (0.8)	1258 (234)

MAAT, mean annual air temperature; MAP, mean annual precipitation; standard deviation in brackets.

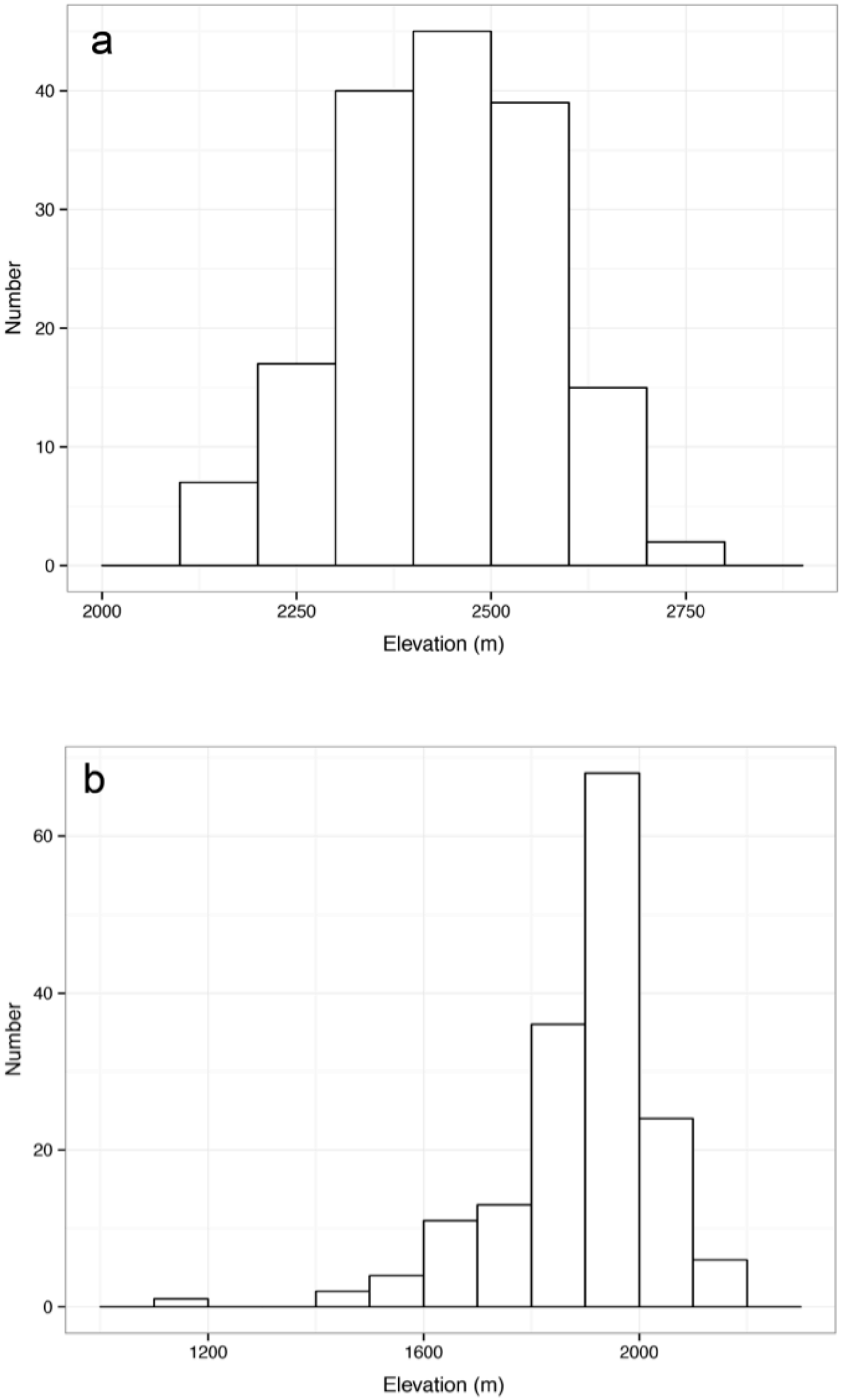

Figure 2.7: Regional elevation histograms for (a) glaciers and (b) treeline. Each column represents 100 m in elevation.

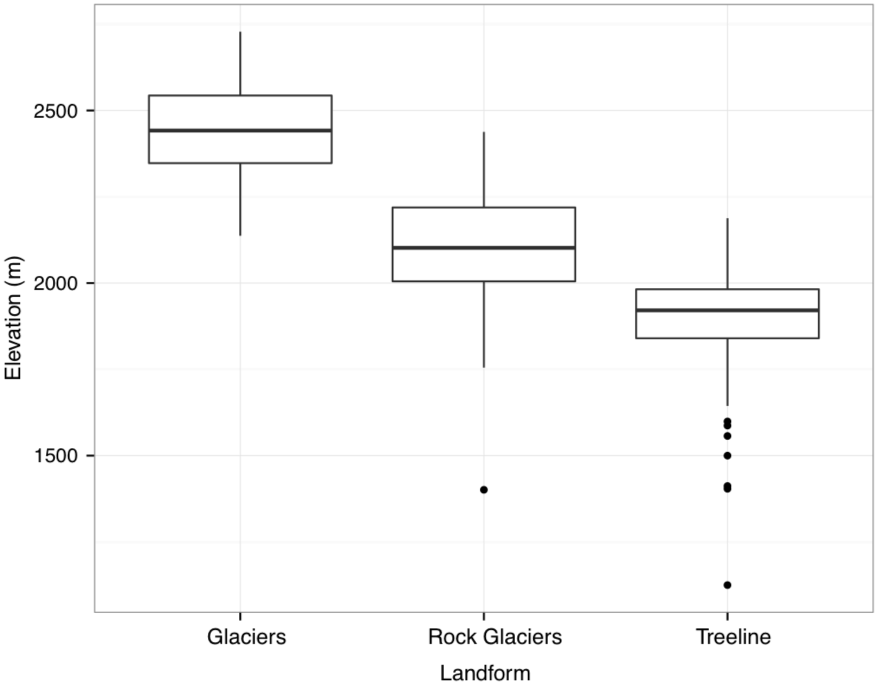

Figure 2.8: Boxplots indicate the elevation of inventoried rock glaciers as compared to glaciers and treeline. Outliers are shown as dots.

Relict rock glaciers plotted higher in elevation than intact features (Figure 2.9), with relict glacier-derived rock glaciers located at sites 45 m higher than intact features (Table 2.1). These locations also received 30 mm less precipitation per year than locations occupied by intact glacier-derived rock glaciers (1260 mm/year). In comparison, relict talus-derived features received more precipitation per year (> 60 mm/year) than their intact counterparts (1235 mm/year) (Table 2.1) yet existed at similar elevations. The average MAAT for all rock glacier categories ranged from -1.2 to -1.1 °C. Despite these variations, statistical analyses indicated that rock glacier categories were reflective of the same population with respect to origin and activity status (Table 2.2).

The relationship between MAAT and elevation for glaciers and treeline was used to estimate the -3 and 0 °C isotherms, respectively ($r = -0.87$ for both; Figure 2.10). The distribution of rock glaciers with respect to MAAT revealed that most rock glaciers exist below the -3 °C isotherm (2400 m) with only one crossing the 0 °C isotherm (1800 m) (Figure 2.11).

2.6 Discussion

Rock glaciers are abundant in the eastern front ranges of the Coast Mountains, with several forms present within a limited spatial area. Rock glaciers can be observed originating from talus accumulated below steep headwalls, as well as in connection with retreating glaciers. Rock glaciers are often seen extending from large hummocky moraines or directly from the debris-covered snouts of glaciers. Most rock glaciers appear to originate from fresh debris and are, therefore, identified as intact features. Relict rock glaciers occur rarely and are assumed to signify isolated instances of permafrost degradation.

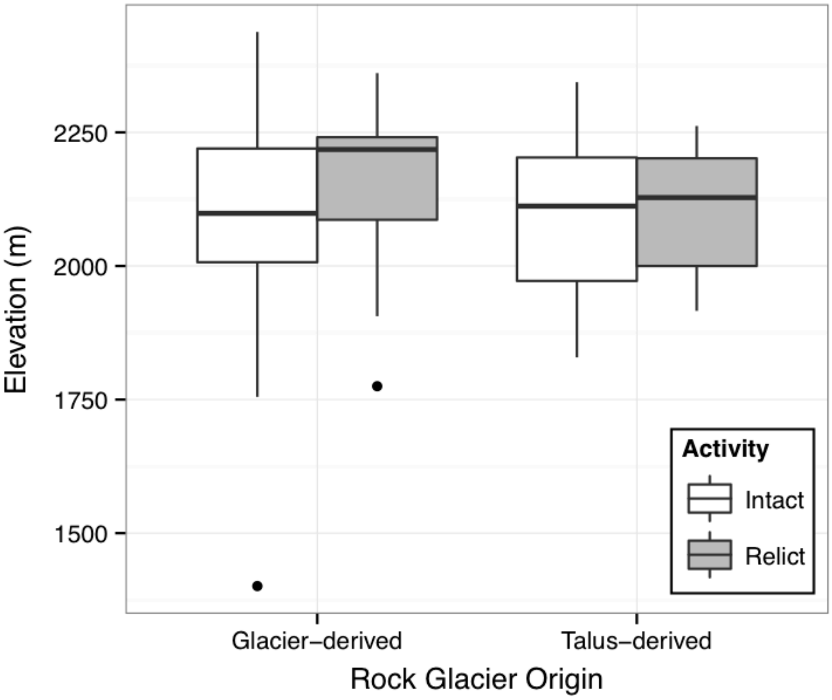

Figure 2.9: Boxplots indicate the elevation of each rock glacier category in the inventory. Rock glacier origin is further separated by activity, with outliers shown as dots.

Table 2.2: Results of the pairwise comparisons of environmental variables by rock glacier category.

Variable	Intact	Relict	Glacier-derived	Talus-derived	All rock glaciers	All rock glaciers
	Glacier-derived vs. talus-derived	Glacier-derived vs. talus-derived	Intact vs. Relict	Intact vs. Relict	Glacier-derived vs. talus-derived	Intact vs. Relict
Elevation (m)						
Chi-square	0.172	1.045	1.823	0.070	0.392	1.249
Significance	0.678	0.307	0.177	0.792	0.531	0.264
MAAT (°C)						
Chi-square	0.013	0.045	0.017	0.116	0.009	0.007
Significance	0.909	0.832	0.897	0.734	0.926	0.931
MAP (mm/yr)						
Chi-square	0.831	0.548	0.236	1.319	0.351	0.003
Significance	0.362	0.459	0.627	0.251	0.553	0.940

MAAT, mean annual air temperature; MAP, mean annual precipitation.

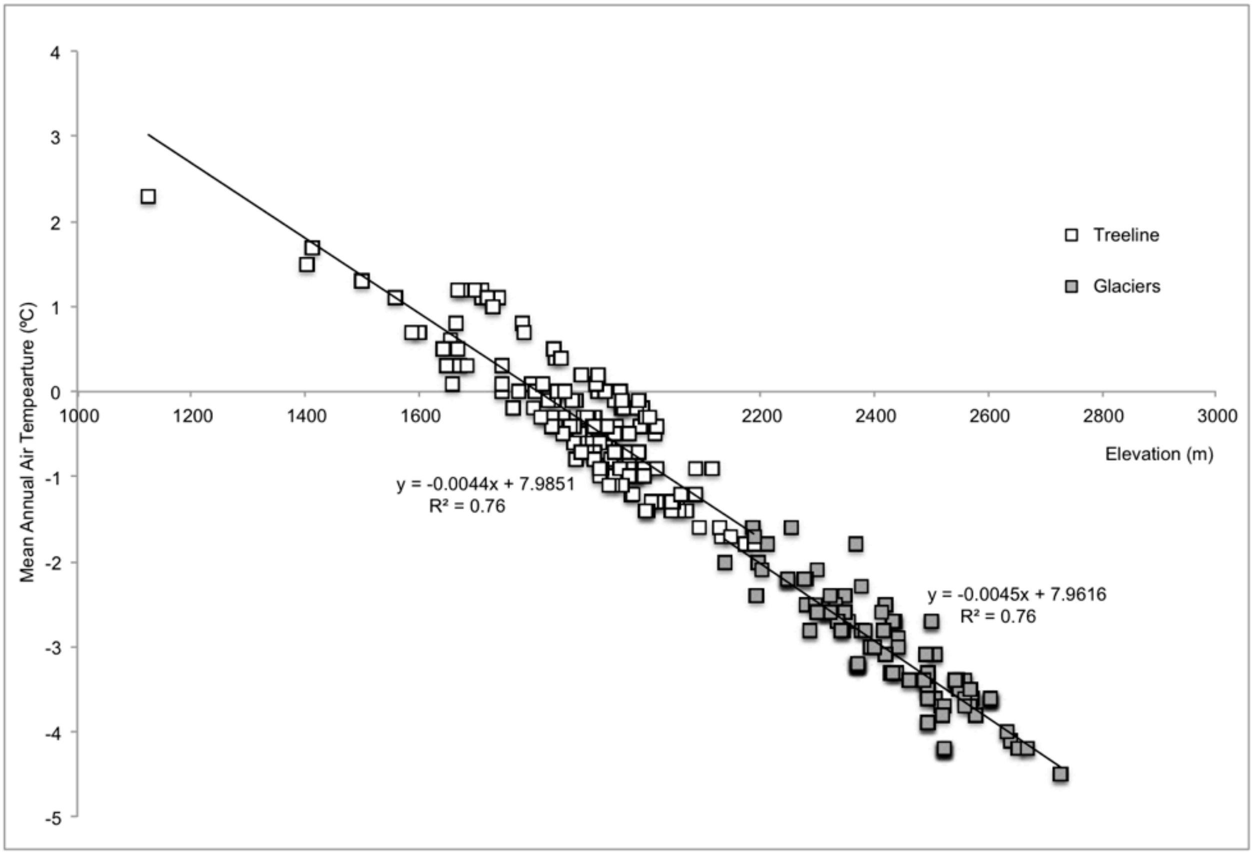

Figure 2.10: The relationship between mean annual air temperature and elevation used to estimate the 0 °C and -3 °C isotherms.

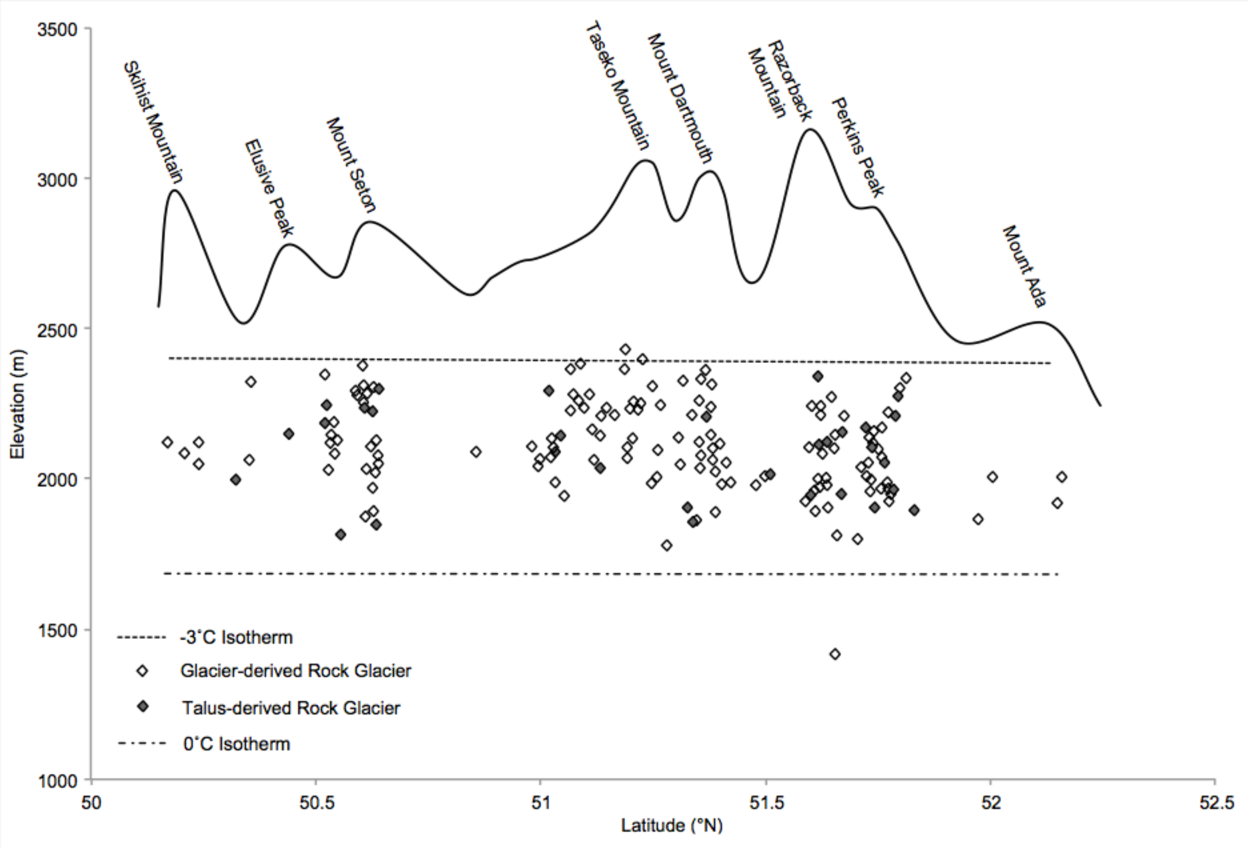

Figure 2.11: Latitudinal profile of the southeastern Coast Mountains indicating the spatial and altitudinal distribution of intact rock glaciers. Mountain peaks provided for geographic reference.

The results indicate that discontinuous permafrost is likely widespread along the eastern extent of the Coast Mountains. Rock glaciers are prominent features on the landscape east of high elevation peaks from 50°10’ to 52°08’ N Lat, where the occurrence of intact rock glaciers from 2400 ± 50 to 1900 ± 50 m delimits an altitudinal belt containing discontinuous permafrost (Figure 2.8). The lower limit of discontinuous permafrost undulates roughly 200 ± 50 m above treeline (Figure 2.11), with active rock glaciers occasionally advancing into subalpine forests below 1900 ± 50 m (Figure 2.4b).

An average MAAT of -1.2 °C for all rock glaciers (Table 2.1) agrees with regional estimates of the lower limit of permafrost distribution along MAAT isotherms of -1 °C (Brown and Péwé 1973; French and Slaymaker 1993) and colder than 0 °C (Harris 1981; Rodenhuis *et al.* 2007)(Table 2.3). Only a single rock glacier was located at a presumed ‘warmer’ location below treeline (Figure 2.11). The moderate precipitation totals and cool temperatures that characterize the rock glacier sites included in the inventory agree with established climatic boundaries for rock glacier development (Harberli and Burn 2002). The distribution of rock glaciers is, therefore, a realistic representation of discontinuous permafrost in the southern Coast Mountains.

This inventory complements prior regional studies describing rock glacier distribution. Rock glaciers exist at high elevations with below 0 °C MAAT and moderate precipitation (>2500 mm/year; Table 2.1), conditions often displayed in rock glacier inventories (Haeberli 1985; Brazier *et al.* 1998; Johnson *et al*. 2007; Scotti *et al*. 2013). Glacial history and rock supply (cf. Johnson *et al*. 2007) also control rock glacier distribution in the front ranges. The dominance of glacier-derived rock glaciers is consistent with other coastal-proximate studies, where frequent interaction between

Table 2.3: Previous estimates of permafrost in the front ranges.

Author	Scope of Research	Permafrost attributes in the Southern Coast Mountains	Methodology
Distribution of permafrost in North America (Brown and Péwé 1973)	North America	Map: Large extent of eastern portion indicated as "permafrost areas at high altitude in cordillera south of [discontinuous] permafrost limit"	Review of permafrost research in North America; adapted "Permafrost in Canada" map (Brown 1967)
National Atlas of Canada 5th edition: Permafrost (Heginbottom *et al.* 1995)	Canada	Map: Eastern extent contains 'isolated patches' (0-10% permafrost)	Contoured ground temperature measurements (Heginbottom 2002)
Climate Overview (Rodenhuis *et al.* 2007)	British Columbia	Map: Large extent of eastern portion with MAAT below 0 °C isotherm, indicative of frozen terrain	Annual mean temperature (Canadian Climate Normals 1961-1990) interpolated using PRISM (4km) (Wang *et al.* 2006)
Canada's Cold Environments (French and Slaymaker 1993)	"Canada's Cold Land Mass"	Secton of alpine permafrost exists in the southern Coast Mountains; southern limit of discontinuous permafrost coincides with MAAT of -1 °C	Map adapted from Associate Committee on Geotechnical Research (1988)
	"Cold Mountains of Western Canada"	Permafrost restricted to high mountain altitudes > 2300 m; periglacial activity occurs below treeline (~ 1650 m) west of the continental divide	Lowest visible indicator of permafrost/periglacial activity in Garibaldi National Park

surface ice and permafrost conditions results in composite ice-debris features of both periglacial and glacial material (Ribolini and Fabre 2006; Berthling 2011; Lilleøren *et al*. 2013a). Within the Canadian Rocky Mountains, rock glaciers in Jasper National Park are almost equally of talus and glacier origin (Luckman and Crockett 1978).

Rock glacier distribution in the Coast Mountains appears to be consistent across bedrock lithologies. A close spatial association with the Yalakom fault system of the southern Chilcotin Ranges (Umhoefer and Schiarizza 1996), however, suggests tectonic activity may influence headwall weathering rates and the production of talus. Where the large size of rock glaciers is unexplained by local weathering rates and lithology, proximity to major faults known to trigger rock avalanches may account for high talus production (Bolch and Gorbunov 2014). Steep east-dipping faults, metamorphism, and volcanic arcs on the retro-wedge side of the bivergent Coast Mountain range (Mustard and van der Heyden 1997; Bustin *et al.* 2013) warrant more investigation yet are outside the scope of this research.

The pronounced spread within relict rock glacier aspects indicates that a relict feature could be related to topographic shading from insolation. This finding is emphasized in the talus-derived category, as intact rock glaciers occupy a more niche topography on shaded north-facing slopes than relict talus-derived rock glaciers, which occur over a broader range of orientations (Figure 2.5c). This observation suggests that locations with greater insolation are not favourable for the persistence or development of permafrost conditions under the contemporary climate (Lilleøren and Etzelmuller 2011; Lilleøren *et al.* 2013a; Scotti *et al.* 2013; Rangecroft *et al.* 2014). The relative absence of talus-derived rock glaciers further suggests that talus accumulation under permafrost conditions has been scarce.

Glacier-derived rock glaciers display a broader distribution in aspect orientation. While the majority face to the north-northeast, between 10 to 15% of the rock glaciers occupy east and west-facing slopes (Figure 2.5b). A similar distribution exists for both activity classes, yet almost 10% of intact features are found on south-facing slopes. This finding suggests that topographic shading is not the dominant control of intact glacier-derived forms and that local conditions are important. Retreating glaciers lose energy through meltwater escape, resulting in cold ablation areas with permafrost below the equilibrium line (Etzelmuller and Hagen 2005; Kneisel and Kaab 2007; Lilleøren *et al.* 2013b). This outcome, in combination with the high sediment supply of debris-covered glaciers (Kirkbride 2011), may result in a proglacial environment that is highly conducive to permafrost in the front ranges. In high elevation cirques with small firn patches and less annual precipitation, the presence of relict glacier-derived rock glaciers further implies the important role of glaciers in the persistence of permafrost.

Insignificant pairwise comparisons (cf. Lilleøren and Etzelmuller 2011; Lilleøren *et al.* 2013a) indicate that intact and relict rock glaciers co-occur within the environmental parameters evaluated (Table 2.2). Where terminal moraines associated with the Younger Dryas advance at 9390 ± 40 BP (Grubb 2006) were identified, all of the intact and relict rock glaciers surveyed were located several kilometres up valley (Figure 2.9). This finding provides a maximum age for the rock glaciers surveyed that agrees with that established by Luckman and Crockett (1978) for rock glaciers in the Canadian Rocky Mountains (9000 ± 500 BP).

Despite reports of up to seven Holocene glacier advances in the region (Menounos *et al.* 2009), pre-LIA moraines are largely absent in the study area. Instead, rock glaciers, ice-cored moraines, and push moraines exist proximal to inferred LIA terminus positions. These permafrost landforms are large, well developed and unlikely to have been produced by LIA climates alone. Many permafrost landforms in the front ranges are, therefore, assumed to pre-date the LIA and signify the presence of a periglacial belt influenced by glacial climates during the Holocene.

Active debris-ice features proximal to retreating glaciers indicate that a transition is occurring from glacial to periglacial processes under the contemporary climate (Seppi *et al.* 2015). These features respond slower than glaciers to climatic variability due to the cooling and insulating effects of a thick debris cover (Kirkbride 2011; Janke *et al.* 2013). Environmental conditions in the front ranges are, therefore, presently conducive to periglacial activity yet are unable to support glacial dynamics. This finding further suggests that a periglacial belt persisted throughout interstadial periods of glacial retreat during the Holocene.

2.7 Conclusion

This study is the first to report on the presence of intact and relict rock glaciers within the eastern front ranges of the B.C. Coast Mountains. The survey shows that their distribution can be partly explained by topography and Holocene climates, although the presence of relict features indicates permafrost occurrence and distribution is more complex than revealed by this study. Statistical rock glacier distribution models, with variables related to surface characteristics, snow accumulation, and topography (i.e. Brenning and Trombotto 2006; Brenning *et al.* 2007; Johnson *et al.* 2007; Esper

Angillieri 2010) as well as ground temperature data, will be necessary to provide a detailed distribution of permafrost conditions (cf. Bonnaventure *et al.* 2012) in the Coast Mountains.

The presence of rock glaciers in the Coast Mountains challenges previous understandings of the distribution of permafrost in the southwestern Canadian Cordillera. French and Slaymaker (1993) extrapolate findings in heavily glaciated Garibaldi Provincial Park to suggest the lower limit of periglacial activity is below treeline (< 1650 m), while permafrost occurs only at the highest elevations (> 2300 m). The inventory results indicate that most rock glaciers in the region are intact features originating from the moraines and heavily debris-laden tongues of small alpine glaciers located between 2400 and 1800 m above sea level.

The abundance of glacier-derived rock glaciers suggests that glacial and periglacial systems are highly interrelated in the Coast Mountains. As air temperatures are predicted to continue rising in the study area (Dawson *et al.* 2008), the influence of disappearing glaciers on permafrost landforms downslope should be monitored. Rock glaciers can store significant amounts of fresh water in arid settings, and an understanding of their behaviour is important to future water security in this region (Rangecroft *et al.* 2014). The inventory presented here is the first step towards monitoring rock glacier dynamics under changing climate regimes in the mountain landscapes of southwestern British Columbia.

Chapter 3 - An evaluation of rock glacier activity in the southeastern British Columbia Coast Mountains

3.1 Introduction

Rock glaciers are a common landform in the eastern front ranges of the British Columbia Coast Mountains. The high-resolution aerial inventory in Chapter Two documented the presence of almost 200 rock glaciers within a 15,000 km^2 area south of the Monarch Icefield. Found adjacent to the Chilcotin Plateau, where rain shadow effects and continental air masses result in persistent dry-cold conditions, the majority of these rock glaciers appear to have originated from moraines or the debris-covered termini of glaciers. It remains to be determined whether these landforms are currently active, or whether they represent the fossilized remains of inactive rock glaciers.

Previous descriptions of rock glacier activity in the southern Canadian Cordillera are restricted to investigations completed in the southern Canadian Rocky Mountains in Alberta, where movement rates are reported to range from as much as 80-30 cm/yr (Osborn 1975) to less than 2 cm/yr (Koning and Smith 1999; Carter *et al.* 2000; Bachrach *et al.* 2004). By comparison there have been no reports of the rates of either Holocene or present-day rock glacier activity from the British Columbia Coast Mountains (French and Slaymaker 1993).

The aim of this research was to document of the activity of four rock glaciers located within the Pantheon Range (Figure 3.1). Lichenometric surveys were completed to describe the relative surface age and activity of three rock glaciers and dendrochronology was used to describe the rate at which an additional rock glacier was advancing into a standing forest. These findings were then compared to regional climatic

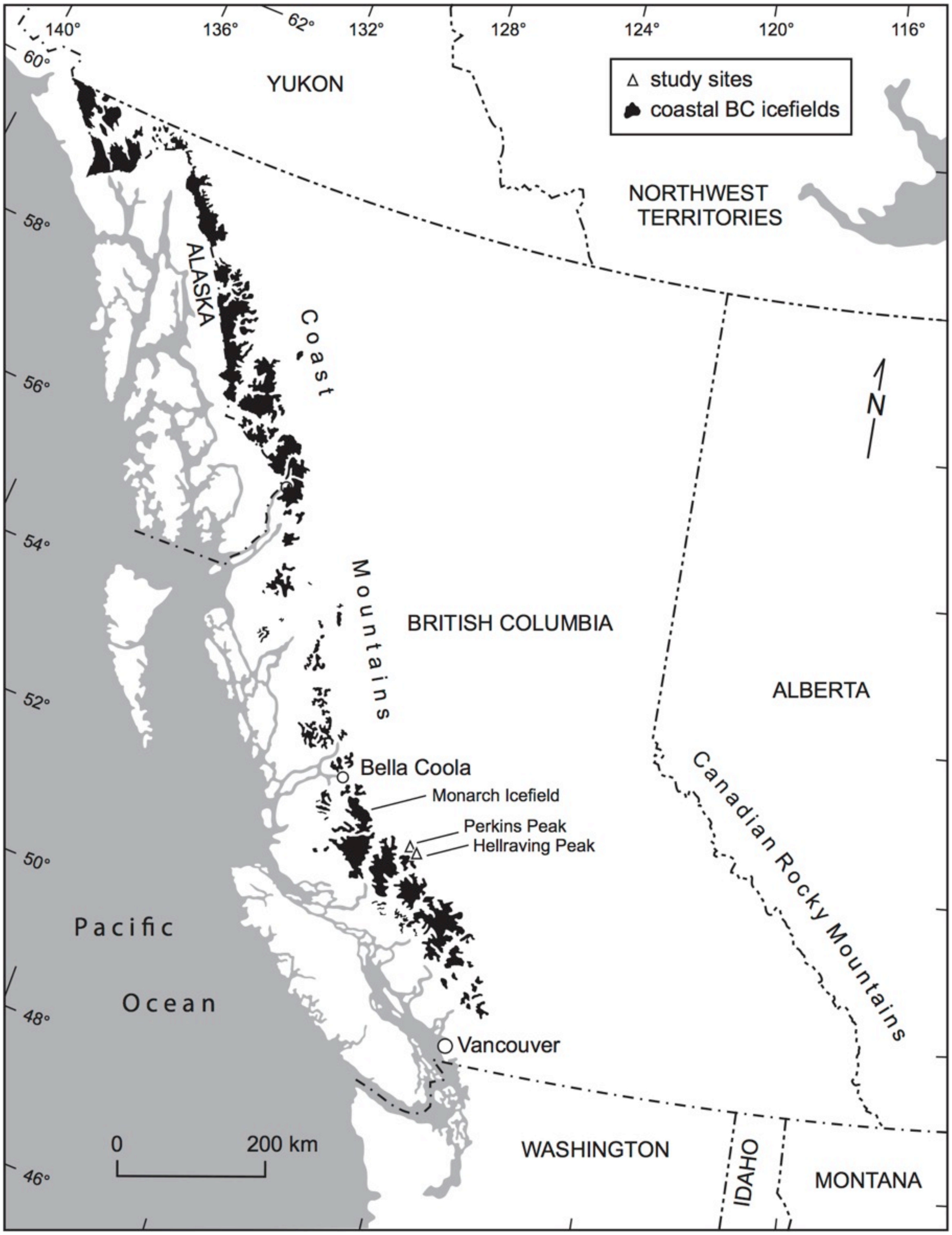

Figure 3.1: Location of the Perkins Peak and Hellraving Peak study sites in southwestern British Columbia.

events to elucidate the relationship between rock glacier movement and climatic variability.

3.2 Research Background

Rock glaciers move downslope under the weight gravity through the deformation of internal ice (Haeberli 1985; Barsch 1996). Steady state, or secondary, creep dominates rock glacier movement (Haeberli *et al.* 2006), the rate of which is highly influenced by the temperature and character of deforming layers (Haeberli *et al.* 2006; Moore 2014). Borehole studies in active rock glaciers indicate that the highest rates of movement generally occur within a low viscosity shear zone commonly found 6-30 m below the surface (Bucki and Echelmeyer 2004; Haeberli *et al.* 2006). Additionally, water has been recognized as instrumental to flow acceleration (Haeberli *et al.* 2006; Ikeda *et al.* 2008), with the deformation rate dependent upon the temperature and relative concentration of ice and debris (e.g. Moore 2014).

Inter-annual to decadal changes in rock glacier activity have been linked to variability in air temperature and winter precipitation. Higher creep rates have been observed following a shift towards warmer higher mean annual air temperatures, with a delay of several months registering in shallow permafrost layers (Delaloye *et al.* 2000; Wirz et al. 2015). Thick winter snow cover can also increase inter-annual rock glacier movement rates by providing additional early season meltwater that serves to enhance the deformation rate in warming rock glacier systems (Delaloye *et al.* 2000). Increased rock glacier movement at decadal-scales has also been related to warmer summer air temperatures and negative glacier mass-balance over the 20th century (Sorg *et al.* 2015). A link to winter precipitation at this temporal scale has not been discussed, however, the importance of meltwater in coupling atmospheric and internal conditions has been suggested (Sorg *et al.* 2015).

The insulating effects of the debris cover, the rheology of ice-debris mixtures, and the lag between air and ground temperatures all determine the complex response of rock glacier movement to climatic variability (Janke et al. 2013). The abovementioned studies focus on recent changes to rock glacier movement and are concerned with monitoring permafrost behaviour in response present-day climates (Haeberli *et al.* 2006). Longer-term studies of the geomorphic response of rock glaciers to climate changes are less common given the challenge of dating unstable rock glacier surfaces and interpreting their internal structures (Monnier *et al.* 2011). An understanding of rock glacier response to centennial or millennial scales of climatic variability is necessary, however, to elucidate the initiation and characteristics of rock glacier activity over the Holocene (Haeberli 1985; Barsch 1996; Humlum 1998).

3.3 Study Sites

Field investigations of rock glacier activity were undertaken in the vicinity of Perkins and Hellraving peaks (Figure 3.1). Both sites are located along the eastern flank of the Pantheon Range, where rainshadow effects sustain small cirque glaciers and result in only thin winter snowpacks (Falconer *et al.* 1965; Østrem 1966; French and Slaymaker 1993). While permafrost in this region is estimated to be associated with only 0-10% of the landscape (Brown and Péwé 1973; Heginbottom *et al.* 1995; Rodenhuis *et al.* 2007; Gruber 2012), the existence rock glaciers delineates a 500 m altitudinal band from 2400 m to 1900 m above sea level (asl) where alpine permafrost is likely commonplace.

3.3.1 Perkins Peak rock glaciers

The Perkins Peak rock glaciers are found within an eastward-facing high elevation valley located below Perkins Peak (2842 m asl)(51º49’30” N; 125 º4’50” W; Figure 3.1). Located above the local treeline, the valley bedrock is comprised of Upper Triassic Mosley formation red and grey volcaniclastic sandstones, red siltstones, and limestones and early Cretaceous Cloud Drifter formation sandstones, siltstones, and conglomerate clasts of volcanic and quartzose granitoid rocks (Mustard and van der Heyden 1997).

At the valley headwall, immediately below the east face of Perkins Peak, Perkins Glacier (*unofficial name*) descends from a high elevation col to terminate at 2445 m asl. A hummocky and degrading Little Ice Age (LIA) moraine complex 50 m down valley hints at the persistence of buried ice-rich sediments. Further down valley the snouts of several unvegetated north-facing rock glaciers descend to the valley floor at 2230-2195 m asl (Figure 3.2a).

Three rock glaciers were selected for study. The lowest in elevation is RGA, a small rock glacier tongue about 250 m long and 100 m wide (Figure 3.2b). RGA originates immediately below the mountain freeface where unweathered talus feeds directly into the rock glacier. Downslope the surface morphology of RGA is generally smooth, with subtle ridges and rock debris sorting visible at the front and sides of this feature. Weathered and partially lichen-covered (*Rhizocarpon* spp.) angular boulders mantle the rock glacier surface to depths exceeding 1-2 m. The rock glacier snout features a large break in slope from the upper surface, dipping steeply (>30°) to the valley floor where numerous isolated boulders have spilled down the snout. Boulders and

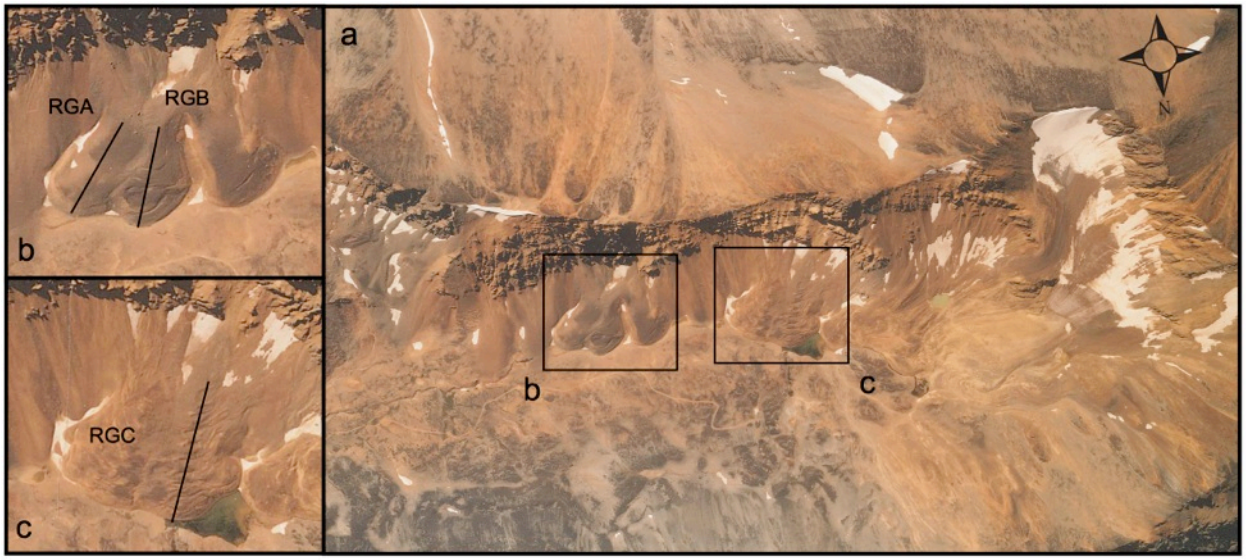

Figure 3.2: Perkins Peak study site. (a) Several rock glacier complexes descend from the north-facing valley wall with Perkins Glacier to the west; (b) RGA and RGB with lichen transects; and (c) RGC with lichen transect.

debris found on the front and flanks of the rock glacier are fresh-appearing and free of lichen.

Immediately up valley from RGA, a second rock glacier (RGB) of similar size descends from talus below the bedrock freeface (Figure 3.2b). The undulating surface of RGB is distinguished by numerous ridges that cross the centre axis. A large transverse furrow separates the gently sloping snout of RGB from the main body of the rock glacier. All exposed rock surfaces are weathered, with many densely covered by *Rhizocarpon* spp. and black crustose lichens.

Rock glacier C (RGC) is located 500 m up valley from RGA and RGB, adjacent to the LIA terminal moraine constructed by Perkins Glacier (Figure 3.2c). RGC is about 350 m long and 320 m wide, and distinguished by a deep centre furrow with near-symmetrical transverse ridges on both its flanks. A small stream exits the snout of the RGC along its central axis, about 13 m below the rock glacier surface. *Rhizocarpon* spp. thalli were variable in distribution on the surface of RGC, with individuals present on boulders found on the tops of ridges but absent on rocks located within both the longitudinal and transverse furrows. Debris sorting was present near the front and sides of the feature, illustrating that a boulder mantle 1-2 m thick overlies finer sediments. Except for sites close to the centre furrow, sediment within the steeply sloping (>30°) 20 m high frontal apron is unstable and fresh appearing.

3.3.2 Hellraving rock glacier

Hellraving rock glacier is located 10 km south of Perkins Peak (51°42'10" N, 125° 5'23" W; Figure 3.1), at the foot of a steep north-facing bedrock wall 5 km south of Hellraving Peak (2905 m asl) in the headwaters of Hellraving Creek. Local geologic descriptions are sparse indicating only that the surficial bedrock is comprised of mid-Cretaceous granitic and gneissic rocks associated with an unnamed pluton (Roddick 1983; van der Heyden *et al.* 1994).

The gently sloping surface (15°) of Hellraving rock glacier is mantled by large angular boulders and covers approximately 0.5 km^2 (Figure 3.3a). The eastern extent of Hellraving rock glacier is distinguished by several older nested moraines with convoluted flow patterns and is bounded by a prominent fresh-appearing moraine beyond which a large depression is evident on the rock glacier surface. Downslope of the depression, a series of transverse ridges are indicative of compressional flows within the rock glacier that are directed towards the toe area (i.e. Whalley and Martin 1992; Barsch 1996). Vegetation and lichen were absent on the rock glacier surface.

At the rock glacier snout and flanks, sediment sorting is evident. Larger angular boulders form a 1-2 m thick layer on the top of the rock glacier, while smaller cobbles and sands extend down the steeply sloping snout (>30°) to the valley floor at 1800 m asl. Boulders spilled beyond the rock glacier snout form a characteristic ring of boulders or ‘boulder collar’ (Haeberli 1985). Where the snout has extended into a mixed stand of whitebark pine (*Pinus albicaulis*) and subalpine fir *(Abies lasiocarpa*) trees, dead and partially buried tree trunks as well as sheared stumps emerge from the toe debris and boulder collar (Figure 3.3b).

3.4 Research Methods

To evaluate the long- and short-term activity of rock glaciers in this setting, two approaches were taken. Lichenometric surveys were undertaken to provide a relative measure of surface displacement at Perkins Peak where numerous *Rhizocarpon* spp. thalli

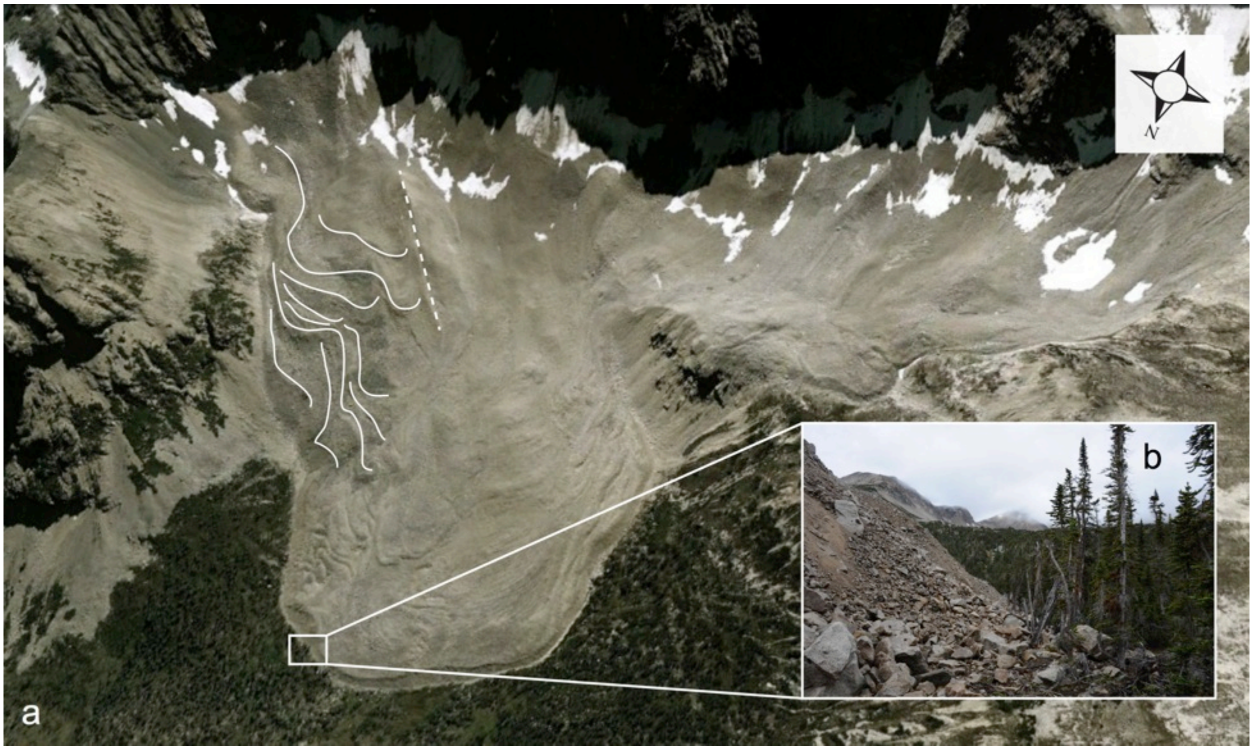

Figure 3.3: Hellraving rock glacier. (a) Older nested moraines are highlighted on the east side of the rock glacier (solid white lines) with the prominent moraine in the centre of the feature (dotted white line); and (b) Trees partially buried in the rock glacier toe debris.

cover many rock surfaces. Lichenometry uses the growth rate of lichen thalli to estimate the minimum age of a surface by comparing the largest lichen diameter to established age-growth curves (Innes 1985). While there are issues and concerns with some lichenometric methodologies (Osborn *et al.* 2015), researchers have employed lichenometry to describe relative rates of surface movement and spatial stability associated with rock glaciers (Sloan and Dyke 1998; Koning and Smith 1999). In this setting a locally calibrated *Rhizocarpon* spp. growth curve was previously developed by Larocque and Smith (2004) to assign surface ages to LIA moraines. Subsequent applications of the curve confirm it can be judiciously employed in the southern Coast Mountains to provide relative surface ages over the last few centuries (Allen and Smith 2007; Koch *et al.* 2007; Koehler and Smith 2011; Harvey and Smith 2013).

Dendrogeomorphological methods were employed to date the historical rate of rock glacier advance into a standing forest (Shroder 1978; Carter *et al.* 2000). Where trees have been killed by an advancing rock glacier, their death date can be obtained by cross-dating their annual growth rings to living tree-ring chronologies (Giardino *et al.* 1984). An annual rate of movement activity is then assigned by dividing the number of years since the time of death by the horizontal distance to the leading edge of the toe debris (Carter *et al.* 1999; Bachrach *et al.* 2004).

3.4.1 Lichenometry at Perkins Peak

Lichenometric surveys were completed along linear transects positioned on the surface of the Perkins Peak rock glaciers (Figures 3.2b and 3.2c). Where the transects bisected transverse ridges and the toe area, the 30 largest *Rhizocarpon* spp were located and their A and B axis lengths measured with digital calipers (precision of 0.1 mm). Only circular or near-circular thalli were selected to prevent the sampling of anomalously large or coalesced lichens (McCarthy and Smith 1995; Osborn *et al.* 2015). After averaging the two axes measurements, the mean of the five largest lichens was selected to reflect the earliest colonizers at each location (Innes 1984; Refsnidder and Brugger 2007). Given recent criticism on the validity of lichenometry (Osborn *et al.* 2015) and the unstable nature of rock glacier surfaces, a conservative estimate was decided upon and the ages rounded to the nearest decade.

The Bella Coola-Mt. Waddington *Rhizocarpon* spp curve was used to estimate the minimum surface age. The curve consists of 25 independently-dated central control points (Smith and Desloges 2000; Larocque and Smith 2004; Koehler and Smith 2011; Harvey and Smith 2013) and is distinguished by a logarithmic trend over the first 100 years of growth, followed by linear growth rates for several centuries (Koehler and Smith 2011). In this instance, surface ages were estimated from lichen diameters using only the linear portion of growth curve (Figure 3.4).

A laser range finder was used to estimate rock glacier length to the nearest metre, as well as to survey the longitudinal profile of each rock glacier. Points of inflection on the rock glacier profiles were used to position the rooting zone, or the zone of talus input (Sloan and Dyke 1998). Using the horizontal distance from the rooting zone to the dated surface, relative rates of movement downslope were calculated for each lichen measurement point. These values were then averaged to provide long-term rates of movement. This method of calculating rock glacier movement assumes that the dated surfaces originate at the rooting zone to eventually stabilize further downslope. Any

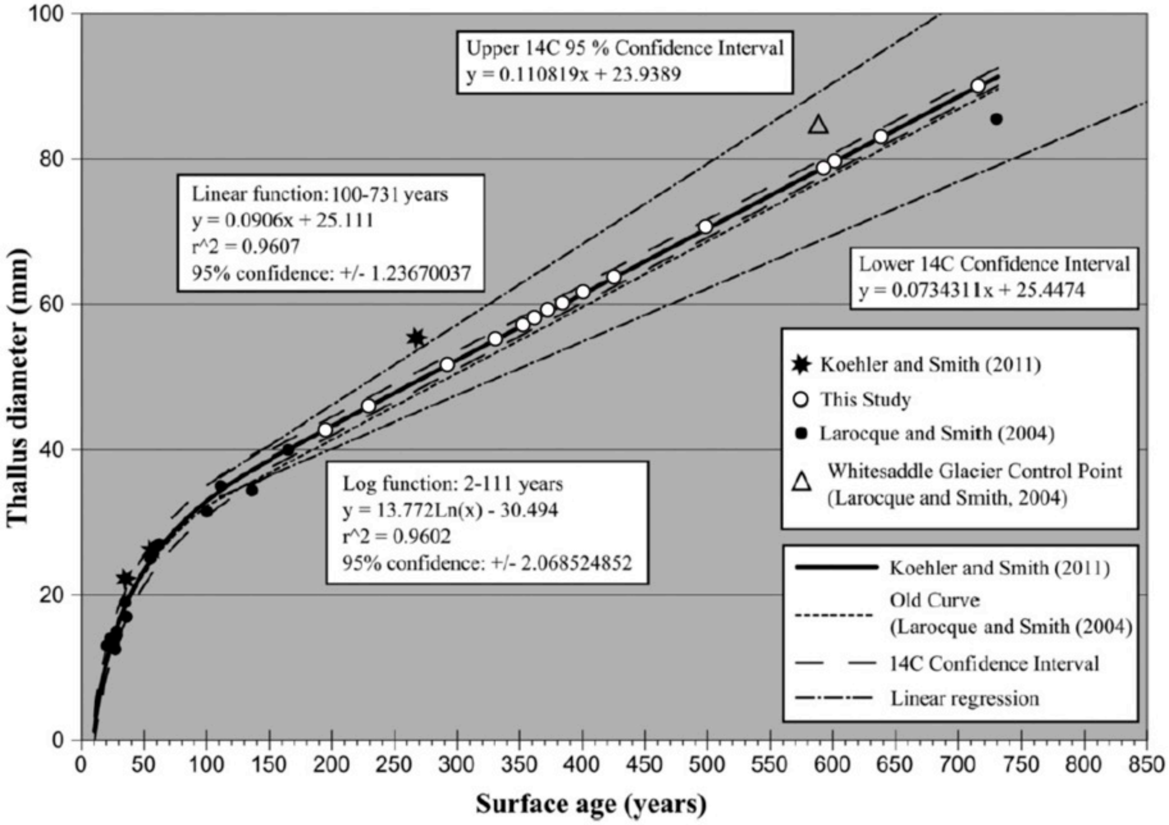

Figure 3.4: The Bella Coola-Mt. Waddington lichen curve (modified from Harvey and Smith 2013) with calculated relative surface ages for the Perkins Peak rock glaciers shown by open circles (RGA-RGC).

subsequent surface movement results in relatively undisturbed transport over time (Sloan and Dyke 1998).

3.4.2 Dendrogeomorphology at Hellraving rock glacier

At Hellraving rock glacier the partially-buried rooted stumps and trunks were excavated and cross-sections of the stems cut with a chainsaw (Figure 3.3b). These samples were returned to the University of Victoria Tree-Ring Laboratory where they were allowed to air-dry, and the tree species was identified using bark and anatomical characteristics (Hoadley 1990). Following this the samples were sanded to a fine polish to highlight the annual ring boundaries. The samples were then scanned with a high-resolution scanner to obtain digital images and the annual ring widths were measured along the longest pathway with a WinDendro (v. 2012c) image processing measurement system (Guay *et al.* 1992).

Minimum kill dates were assigned by cross-dating the samples to existent master chronologies. Subalpine fir samples were cross-dated to a chronology collected at Jacobsen Glacier in the Monarch Icefield area (AD 1533- to 2009; Starheim *et al.* 2013) and whitebark pine samples were cross-dated to a chronology from nearby Siva Glacier (AD 1189-2000; Larocque and Smith 2005a)(Table 3.1). The cross-dating was verified using COFECHA and the age of the outermost ring assigned using the COFECHA master chronology (Holmes 1983; Grissino-Mayer 2001).

3.5 Results

3.5.1 Perkins Peak rock glaciers

The Perkins Peak rock glaciers have a dense covering of *Rhizocarpon* spp. on the crests of most asymmetrical ridges characterizing their surfaces. Surface ages for areas

Table 3.1: Characteristics of master tree-ring chronologies

Statistic	Subalpine fir[a]	Whitebark pine[b]
No. of trees	9	27
No. of cores	19	48
Chronology interval	1533-2009	1189-2000
Mean series correlation[c]	0.571	0.493
Mean sensitivity	0.192	0.214
Autocorrelation	0.768	0.856

a. Jacobsen Glacier, Starheim *et al.* (2013)
b. Siva Glacier, Larocque and Smith (2005a)
c. Correlation coefficients are significant at the 99% confidence interval for $r > 0.328$

proximal to the headwall range from AD 1640 to 1810 AD (Table 3.2), with the rock glacier surfaces generally increasing in age with distance from the headwall (Figure 3.5). Minimum lichen ages within the toe areas of all three rock glaciers indicate that those areas stabilized before AD 1400. Two rock glaciers with collapsed toes, RGB and RGC, disrupted this trend, as the surface above the collapse was older by 130 and 20 years, respectively. The middle section of RGB also contained ages inconsistent with the abovementioned trend, although the ridge-to-ridge differences in this area fall within the computed 95% confidence interval for calculated surface ages (Table 3.2).

The rock glaciers ranged in length from 420 to 330 m from the headwall to the break in surface slope at the toe (Figure 3.5). The rates of surface displacement at RGA and RGB average 30 to 40 cm/yr, respectively (Table 3.2). The rate of surface transport at RGC averages 70 cm/yr, but ranges from 100 cm/yr near the zone of talus input to 50 cm/yr near the toe (Table 3.2).

3.5.2 Hellraving rock glacier

The remains of erect and partially-buried tree trunks found along the leading edge of Hellraving rock glacier were excavated in 2014. The majority of trunks were traced to rooted stumps and, where the boles were tipped over, were broken in the direction of assumed rock glacier movement (Figure 3.6). Eleven cross-sections were collected: 10 were identified as subalpine fir trees and were cross-dated to the Jacobsen Glacier chronology (Figure 3.7); and, one was identified as a whitebark pine tree and cross-dated to the Siva Glacier chronology (Figure 3.8). Most samples had significant correlations with their respective master chronology ($r > 0.328$) (Table 3.3), and all samples were

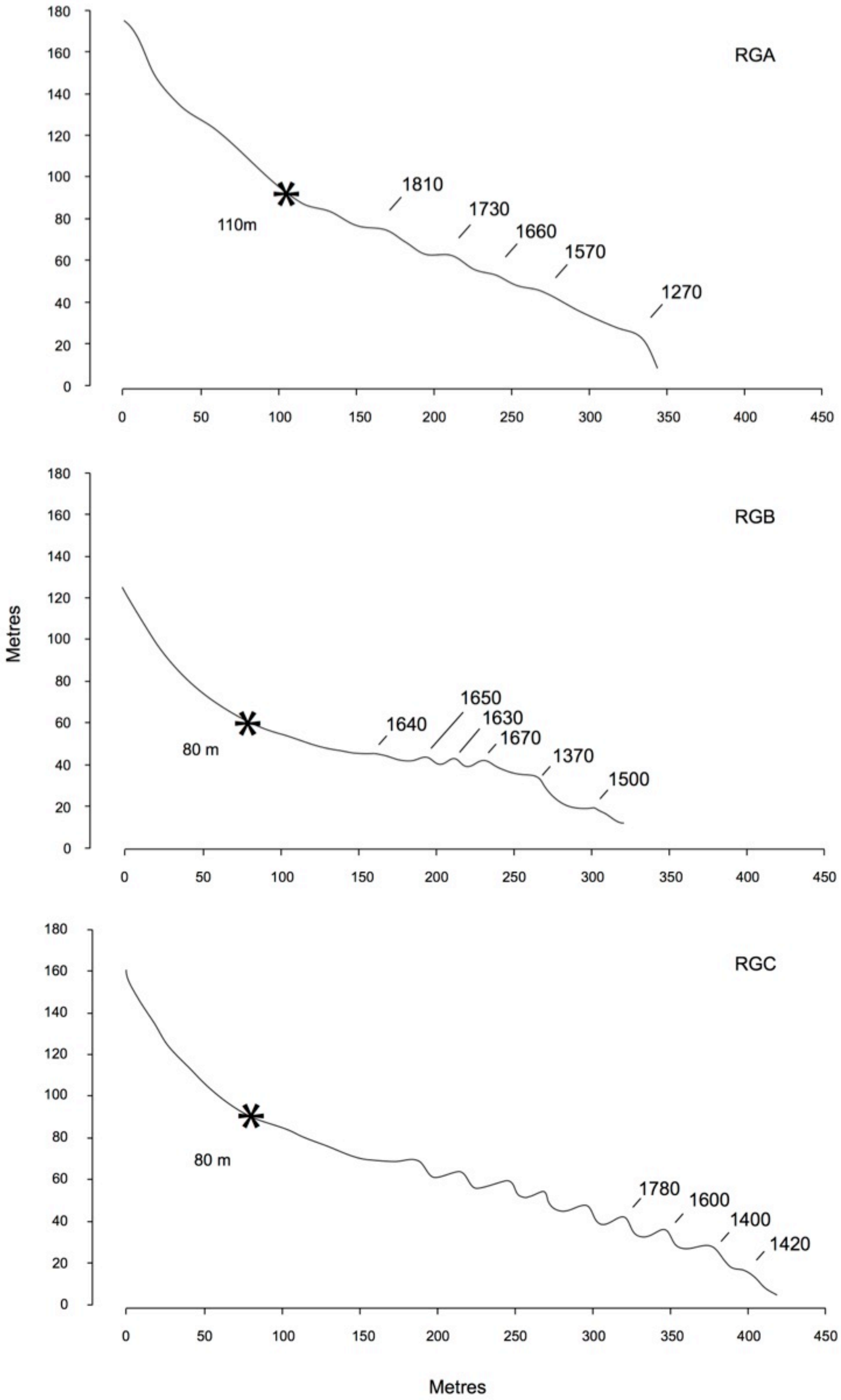

Figure 3.5: Perkins Peak rock glacier profiles with relative surface ages (years AD). The asterisk indicates the point of inflection, or rooting zone, for each rock glacier with the distance from the headwall below.

Table 3.2: Surface stabilization dates and estimates of rock glacier movement rates at Perkins Peak

Sample Number	Thallus Diameter[a] (mm)	Surface Age[b] (yr)	95 % CI (yr AD)	Minimum Stabilization Date (yr AD)	Distance from talus input (m)	Rate of movement (cm/yr)
RGA_01	43.13	199	1770-1840	1810	57	29
RGA_02	50.52	280	1670-1770	1730	92	33
RGA_03	57.42	357	1580-1710	1660	122	34
RGA_04	65.07	441	1470-1640	1570	152	34
RGA_05	91.88	737	1110-1400	1270	211	29
				Average rate of movement		32
RGB_01	59.23	377	1550-1690	1640	86	23
RGB_02	57.96	363	1570-1700	1650	118	33
RGB_03	59.98	385	1540-1690	1630	138	36
RGB_04	56.05	342	1600-1720	1670	156	46
RGB_05	83.33	643	1220-1480	1370	189	30
RGB_06	72.12	519	1380-1580	1500	226	43
				Average rate of movement		35
RGC_02	46.387	235	1730-1810	1780	238	102
RGC_03	61.813	405	1520-1670	1600	264	65
RGC_04	80.57	612	1260-1500	1400	293	48
RGC_05	79.27	598	1280-1510	1420	314	52
				Average rate of movement		67

a. The average of the 5 largest lichens at each sample location
b. Surface age calculated using the Bella Coola Mt. Waddington lichen growth curve (Koehler and Smith 2011)

Figure 3.6: Partially buried trunks and sheared stumps in the frontal debris of Hellraving rock glacier.

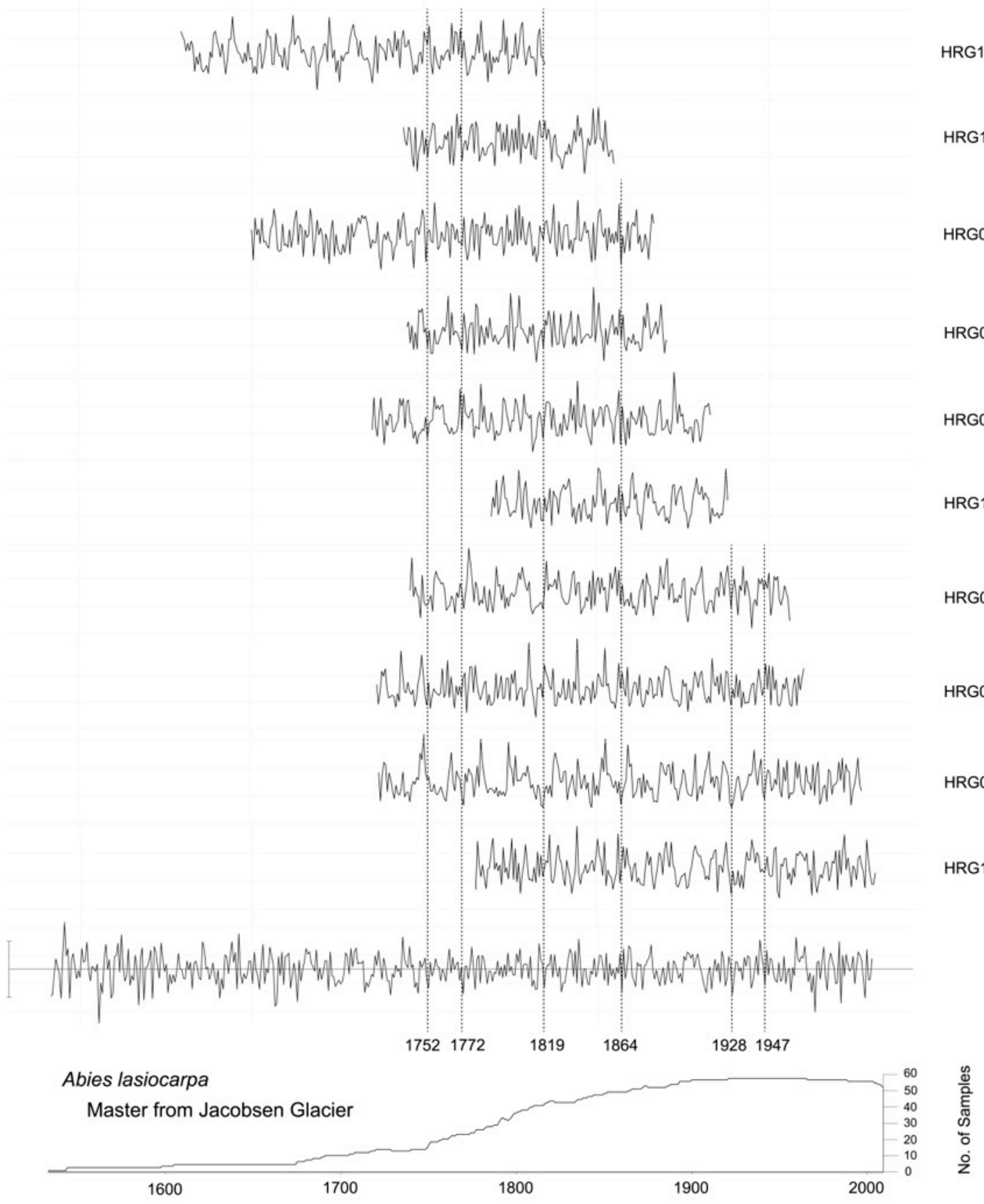

Figure 3.7: Subalpine fir samples from Hellraving rock glacier visually cross-dated into living subalpine fir master chronology from Jacobsen Glacier (Starheim *et al.* 2013).

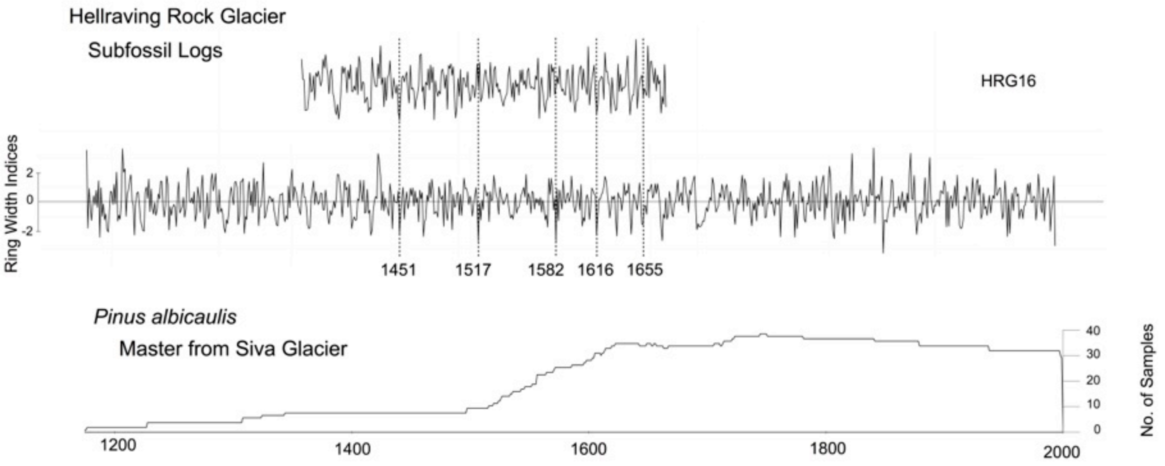

Figure 3.8: Whitebark pine sample from Hellraving rock glacier visually cross-dated to living whitebark pine master chronology from Siva Glacier (Larocque and Smith 2005a).

Table 3.3: Kill dates and estimates of Hellraving rock glacier movement rate

Sample Number	Species	Mean correlation to master [c]	Death date (yr AD)	Distance buried (cm)	Rate of movement (cm/yr)
HRG_01a	SAF	0.204[a]	1883	0	--
HRG_02b	SAF	0.371[a]	1916	0	--
HRG_04b	SAF	0.375[a]	2003	0	--
HRG_06b	SAF	0.546[a]	1890	100	0.81
HRG_08a	SAF	0.359[a]	1962	0	--
HRG_09a	SAF	0.446[a]	1970	0	--
HRG_12a	SAF	0.432[a]	2013	0	--
HRG_13a	SAF	0.377[a]	1926	150	1.72
HRG_14a	SAF	0.205[a]	1820	175	0.91
HRG_15a	SAF	0.547[a]	1860	200	1.31
HRG_16a	WBP	0.307[b]	1674	500	1.47
HRG_16b	WBP	0.312[b]	1659	500	1.41
			Average Rate of Movement		1.27

a. Jacobsen Glacier, Starheim *et al.* (2013)
b. Siva Glacier, Larocque and Smith (2005a)
c. Correlation coefficients are significant at the 99% confidence interval for r > 0.328

strongly correlated to the master chronology for the last 100 years of growth (Figure 3.7 and 3.8).

The kill dates of ten samples ranged from AD 1674 to 2003, with one tree at the outermost margin of the debris apron alive when sampled (Table 3.3; Figure 3.9a). While most samples were located within 1-2 m of the talus edge (Figure 3.3b), the oldest kill date was associated with a trunk (HRG16) found pressed against the proximal face of a large boulder 5 m from the debris edge (Figure 3.9b). Assuming that all the trees died shortly after burial was initiated, Hellraving rock glacier has been advancing over the last 400 years at rates ranging from 1.7 to 0.8 cm/yr (average 1.3 cm/yr; Table 3.3). An estimate of the accumulated sediment volume along a linear transect in the vicinity of HRG16 indicates that approximately 2.6 cm^3/yr of debris has spilled down the rock glacier front over the same interval.

3.6 Discussion

The discovery that Hellraving rock glacier has been advancing down valley since AD 1674 suggests that rock glaciers in this setting remained active through the LIA. The observed rates of displacement are comparable to those described at sites in the Canadian Rocky Mountains where geodetic surveys at King's Throne rock glacier describe present-day frontal advances rates averaging 1.6 cm/yr (Koning and Smith 1999). Similarly, dendrogeomorphological investigations in Banff National Park describe rates of frontal advance at two rock glaciers ranging from 1.6-1.2 cm/yr over the last several centuries (Carter *et al.* 2000; Bachrach *et al.* 2004).

The variable rates of surface movement described at the Perkins Peak rock glaciers (30-60 cm/yr) are consistent with those documented elsewhere in North America.

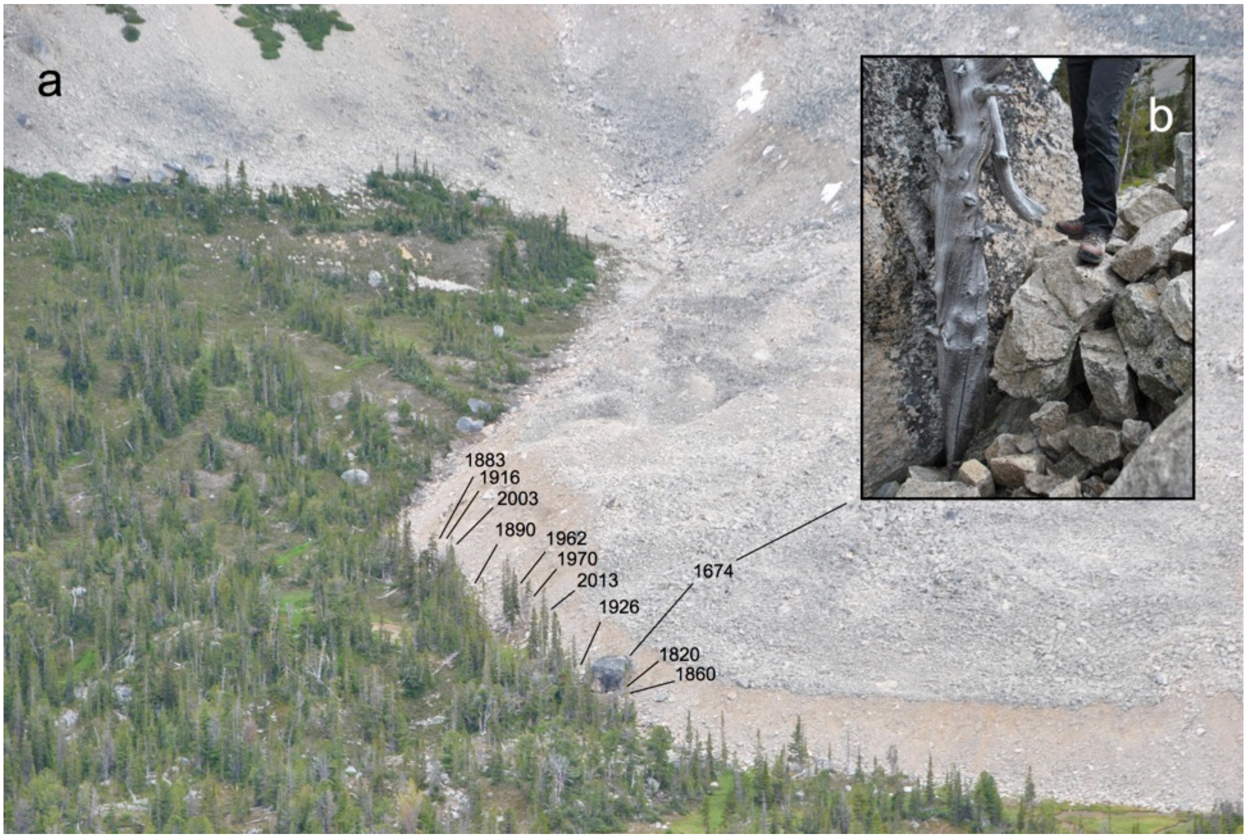

Figure 3.9: Hellraving rock glacier. (a) Kill dates for trees overrun by the advancing rock glacier; and (b) Oldest sample (HRG16; kill date AD 1674) shown pressed up against the proximal face of the glacial erratic (person for scale).

In Yukon Sloan and Dyke (1988) report mean surface velocities of 20 cm/yr and in the Canadian Rocky Mountains Osborn (1975) describes rock glacier surface movements ranging from 80-30 cm/yr. To the south, in the continental U.S.A, horizontal movement rates at rock glacier sites in Colorado range from 20-5 cm/yr (White 1971; Benedict *et al.* 1986; Janke *et al.* 2005) and in Wyoming from 80-6 cm/yr (Potter 1972; Potter *et al.* 1998).

The surface ages assigned to the Perkins Peak rock glacier surfaces indicate that all three experienced punctuated intervals of stability and instability. These intervals broadly coincide with the climate changes responsible for the mass balance fluctuations that led to LIA glacier expansion and retreat. Glacier advances in this region coincide with periods of lower than average summer temperatures (Pitman and Smith 2013) and increased amounts of winter precipitation (Steinman *et al.* 2012). As Figure 3.10 shows, a comparison to these proxy climate records suggests that the Perkins Peak rock glacier surfaces stabilized as the regional climate shifted to warmer, drier conditions (Figure 3.10). This finding is consistent with what is known about the kinematics of rock glacier movement in response to climatic variability. Sustained intervals of cooler air temperature and high winter precipitation result in enhanced intervals of ice segregation and snow accumulation from avalanches (Barsch 1977). These mass balance additions increase local shear stresses to result in ice deformation and mobility of the ice-debris mixture in the downslope direction (Giardino *et al.* 1984; Haeberli 1985). As the climate shifts towards warmer and drier conditions, ice accumulation slows and the advancing surface material stabilizes (Kirkbride and Brazier 1995). Talus continues to accumulate

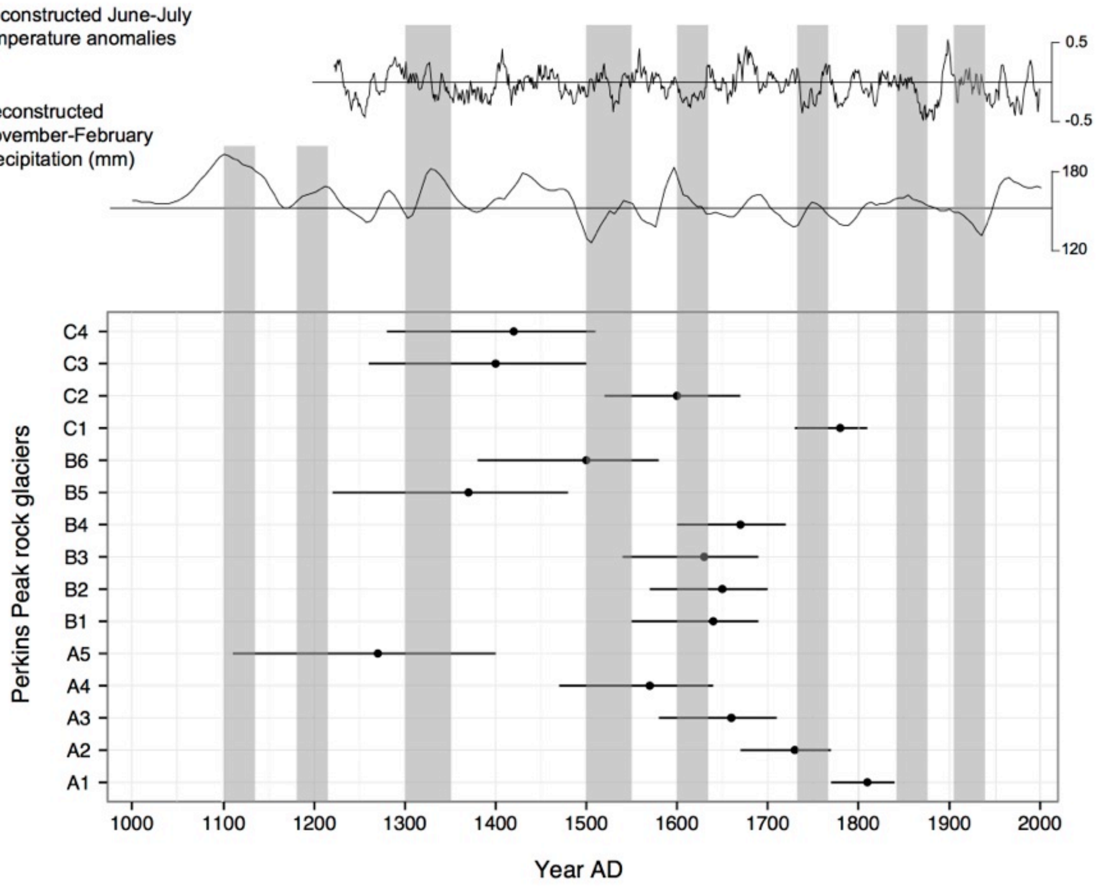

Figure 3.10: Visualization of lichen stabilization dates (with 95% confidence intervals) and periods of glacial advance from Larocque and Smith (2003). Reconstructed summer temperature (Pitman and Smith 2012) and winter precipitation (Steinman *et al.* 2012) are included for further visual reference.

near the headwall throughout this period of rock glacier stability, at least until a subsequent interval of cooler temperatures provides the internal ice content necessary to remobilize the debris-ice mixture (Shakesby *et al*. 1987; Refsnider and Brugger 2007).

The number of climatic reversals registered on the rock glacier surface will be determined by the rate of rock supply (Kirkbride and Brazier 1995). Cold conditions will only result in surface mobilization when the debris load exceeds the critical shear stress of accumulated ice (Barsch 1977; 1996). At Perkins Peak, each rock glacier records climatic variability differently, indicating the unique dynamics of each feature. This is apparent on RGB, with only three distinct pulses of rock glacier activity yet four ridges dated to one pulse between AD 1600 and 1700 (Figure 3.10). The amount of debris transported on RGB during this time was sufficient to mobilize four deposits and marked the final pulse of surface mobility on the feature (Figure 3.5). Insufficient talus production leading up to the subsequent periods of cooler climate would explain why the debris-ice mixture near the headwall remained immobile (Kirkbride and Brazier 1995). Talus production rates appear to be faster on the other rock glaciers given the consistent pattern of rock glacier movement throughout the LIA (Figure 3.10).

Surface ages near the toe of RGB provide some insight into rock glacier activity during warmer, drier periods of the LIA. The lower-most surface is younger than the surface above, indicating that movement occurred following the stabilization of the toe in AD 1370. The younger surface dates to AD 1500 and stabilized at the end of a warmer period, rather than immediately following a glacial advance. Warmer permafrost will deform at higher strain rates as the viscosity decreases (Haeberli *et al.* 2006; Kääb *et al.* 2007; Sorg *et al.* 2015) and rock glacier mobility will occasionally increase during warm periods before the active layer thickens and mechanical stability is lost (Haeberli 2000; Kneisel *et al.* 2007). It is possible that the toe of RGB mobilized downslope before collapsing into the subsided deposit that currently exists (Figure 3.5).

Surface movement at RGA remained relatively consistent throughout the LIA (Table 3.2) and the unstable snout and flanks indicate the feature remains active. Complete lichen cover and the gently sloping snout of RGB, however, suggest inactivity. On the upper surface of RGC, fresh-appearing talus, lichen-free ridges, and the highest rate of surface movement (> 1 m/year) observed for all features suggests that this rock glacier has remained unstable since the end of the LIA. Lichen are also absent between surface ridges on RGC, indicating continued deformation within the shear zone (Potter 1972). The 20 m ridge wavelengths observed on the surface of RGC are consistent with stresses caused by convex curvature from the headwall to the valley floor (Frehner *et al.* 2014). Compression or shortening within the shear zone suggests that RGC has not reached equilibrium between gravitational stresses, the confining topography and the resistance of internal ice (Barsch 1996; Frehner *et al.* 2014). An outlet stream in the snout of RGC indicates an active layer 18 m thick, uncharacteristic of active rock glaciers (Barsch 1996), therefore this feature may be experiencing ice loss resulting in the observed mechanical failure near the snout.

3.7 Conclusion

This research shows that rock glaciers located within the eastern front ranges of the southern B.C. Coast Mountains are actively advancing downslope under present-day climates, and that they have remained active for the past 400 years. Lichenometric studies on the surfaces of three rock glaciers suggest that rock glacier movement rates over this interval likely varied in response to distinct periods of cool-wet and warm-dry conditions. The discovery that Hellraving rock glacier continues to advance downslope, despite rising temperatures and widespread glacial downwasting and retreat (Schiefer *et al.* 2007; Bolch *et al.* 2010), suggests that its internal thermodynamics have not reached equilibrium with present-day climates. Given that rock glaciers in the European Alps have already started to show signs of decreased mobility and mechanical stability under similar degrees of climate change (Kääb *et al.* 2007; Kneisel *et al.* 2007), the distribution and geomorphic activity of rock glaciers in the B.C. Coast Mountains may soon fundamentally change.

Chapter 4 – Conclusion

4.1 Thesis Summary

The goal of this thesis was to describe and map the previously undocumented presence of rock glaciers in the southern Coast Mountains. A primary objective was to complete a systematic inventory of the characteristics, distribution and morphoclimatic position of the rock glaciers found along the eastern margin of the range. A secondary objective of the thesis research was to document the late Holocene and present-day activity of these rock glaciers, and to relate that behaviour to recent and paleo-climatic variability.

A high-resolution aerial inventory along the southeastern margin of the Coast Mountains provided the characteristics and distribution of almost 200 rock glaciers. Rock glaciers in the southeastern Coast Mountains are mostly intact, glacier-derived forms that extend from the moraines or debris-covered termini of glaciers. These rock glaciers are restricted to locations on the landscape where the mean annual air temperature is below 0 °C and where annual precipitation amounts are low to moderate. The upper boundary of rock glacier distribution is approximated by the -3 °C isotherm, where rain shadow effects and minimal seasonal snowpacks result in the persistence of only small alpine glaciers at high elevations. Within this air temperature range, rock glaciers are limited to shaded, north-facing slopes or the cold ablation areas of retreating glaciers. The distribution of rock glaciers is a first estimate of the spatial distribution of sporadic permafrost in this setting at locations between 2400 to 1900 m above sea level.

The altitudinal position of these rock glaciers places them several hundred metres above the elevation of presumed Younger Dryas moraines, indicating these features developed as a periglacial response to climatic conditions during the Holocene. Intact rock glaciers with frozen internal cores of ice and debris are widespread, whereas fossilized forms are relatively uncommon and reflect localized instances of permafrost degradation. The presence of other permafrost landforms such as push moraines suggests that periglacial activity persisted through interstadial periods of the Holocene.

Lichenometrically-dated surfaces of three talus-derived rock glaciers at Perkins Peak indicate that surface activity was influenced by climatic variability during the LIA. The sustained periods of cool-wet climates that resulted in glacial expansion similarly activated pulses of rock glacier surface instability and movement. Climate shifts that resulted in succeeding intervals of reduced winter precipitation and warm summer air temperatures resulted in the loss of internal ice and increased surface stability. The latter process may be occurring in one feature at Perkins Peak, evidenced by frontal collapse near a deep central furrow, with a meltwater channel exiting the feature 18 m below the surface. The importance of local topography on talus-derived rock glaciers is highlighted by individual responses to historical and contemporary climate.

The dendrogeomorphological investigation at Hellraving rock glacier indicates that the glacier-derived feature has been steadily advancing into surrounding forest since the late LIA. Continued movement despite rising air temperatures suggests that internal thermodynamics may be out of equilibrium with contemporary climate.

4.2 Research Limitations

a. Aerial inventory: Ground-truthing was only possible at a limited number of rock glacier sites and no fossilized glacier-derived features were visited. Further on-the-ground observation would be useful to constrain identification methods and increase accuracy when inventorying rock glaciers.

b. Data resolution and accuracy: The Digital Elevation Model (DEM) used to determine the elevation and aspect of rock glaciers had a 50 m spatial resolution. A higher resolution DEM paired with in-situ climate data would provide a more accurate representation of rock glacier distribution.

c. Lichenometric dating: Limited ground control points in the linear portion of the Bella Coola-Mt. Waddington lichen growth curve results in a wide 95% confidence interval for surface dates at Perkins Peak. Smaller error bars would constrain surface ages and strengthen the interpretation of rock glacier morphodynamic response to climatic variability.

d. Dendrogeomorphology: The time elapsed between tree burial and death is unknown. This, combined with limited sample depth, prevented a discussion of rock glacier advance in response to climatic variability. Although rock glaciers are rarely observed at treeline in the Coast Mountains, the method could potentially determine contemporary rock glacier response to climate changes in the 20th and 21st centuries, important information for predicting rock glacier behaviour in the future.

4.3 Future Research

While this research documented the presence and spatial distribution of rock glaciers within the southeastern Coast Mountains, the area covered by these permafrost features and the volume of ice stored inside remains to be determined:

a) Additional field reconnaissance is required to determine the relative percentages of internal ice and debris within rock glaciers of varying morphology. This research could be accomplished by extrapolating borehole measurements or by interpreting geophysical soundings on the surfaces of features.

b) Further research on the behaviour of rock glaciers under projected climate scenarios is needed to understand future water security in the arid Chilcotin Plateau. A subsequent aerial inventory that would more precisely delineate the areal extent of individual rock glacier boundaries would enable estimation of the total volume of water presently stored within them.

c) High-resolution monitoring is required to elucidate the complex relationships between glaciers, debris-covered glaciers, and rock glaciers, and the external climatic variables that influence the behaviour of these systems. While these rock glaciers are seemingly unresponsive to the recent rise in air temperature, the longevity of this trend is currently unknown.

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