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ROCK GLACIERS IN THE EASTERN CASCADES, WASHINGTON

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ABSTRACT

ROCK GLACIERS IN THE EASTERN CASCADES, WASHINGTON

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The eastern portion of Washington State's Cascade Range is a place not previously examined for rock glaciers, due to proximity to the Pacific Ocean and its associated marine-influenced climate. The objectives of this study were to determine spatial, activity, and genesis patterns, and paleoclimatic implications of Eastern Cascade rock glaciers. Using Google Earth, I found 103 rock glaciers in the study area. Rock glaciers are more common further east of the Cascade crest and more north in latitude, with the largest concentrations occurring east of Lake Chelan (22) and in the Pasayten Wilderness (28) in the North Cascades. None were found south of the Goat Rocks. Rock glaciers generally face north to northeast. Genesis types include 72 debris, 23 gelifluction, and 8 glaciogenic types. Debris-type rock glaciers occur throughout the range and from 20-70km east of the crest. Gelifluction-types also generally occur north of 48°N, and range from 25-45km east of the crest. Glaciogenic-types occur north of 48°N and <40km east of the crest. Activity levels rise with elevation, with 31 active rock glaciers above 2000m, 55 inactive between 1600-2200m, and 18 relict below 1900m. These patterns suggest a strong past and present climatic role in determining Eastern Cascade rock glacier distribution. Out of the eight rock glaciers visited in the field, five are Little Ice Age features, while two are much older. These eight rock glaciers and data from other sources suggest a 250-300m rise in the 0°C isotherm over the last 100-150 years, with a 2°C general increase in temperature in the Eastern Cascades since the end of the Little Ice Age.

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SECTION 1

INTRODUCTION

1.1 Research Problem

Rock glaciers are lobate or tongue-shaped masses of rock and ice that form in vacated glacial cirques, or at the bases of steep cliffs in mountain settings. They are common landforms in continental, alpine environs, and have been the topic of study by numerous geomorphologists and glaciologists (Wahrhaftig and Cox, 1959; Thompson, 1962; Humlum, 1988; Krainer, 2006). They occur in many of the world's major mountain ranges, such as the Alps (Krainer, 2005), Rockies (Birkeland, 1973; Janke, 2007; Johnson, 2007), Andes (Brenning, 2005), Himalaya (Owens, 1998; Shroder, 2000) and the mountains of the Arctic and Antarctic (Capps, 1910; Ellis, 1979; Humlum, 1988; Serrano, 2000).

Rock glaciers are periglacial landforms that require rock weathering, rockfall, accumulation of debris, and the formation of interstitial or solid ice that lasts multiple years (Capps, 1910). The presence of an ice matrix or ice core inside rock glaciers functions as the mechanism of movement, producing a slow downhill creep (Degenhardt, 2009). Rock glaciers are often classified by their activity, with movement as the defining factor. Rock glaciers that currently move are considered active, while those that do not are inactive (Johnson, 2007). Rock glaciers have also been noted for their functionality as climatic and paleoclimatic indicators, and are indicative of periglacial climates with mean-annual temperatures (MAT) of less than -2°C that support extensive permafrost. Inactive rock glaciers have been used to indicate past periglacial climate zones (Barsch, 1977). Rock glaciers are also generally Holocene features and are valuable tools to understanding late Pleistocene and early Holocene landscapes (Nicholas and Butler, 1996).

Continental mountain ranges, such as North America's Rockies, contain many rock glaciers and have been extensively studied (Janke, 2007). However, few studies have been completed regarding rock glaciers in the Pacific Northwest. Rock glaciers have been noted in the more continental ranges of the northwest, such as the Wallowa Mountains of Oregon (Kiver, 1974) and the Lemhi Range of Idaho (Johnson, 2007). However, it is thought that heavily marine-influenced mountain ranges such as the Olympic and Cascade ranges lack the necessary conditions for rock glacier growth (Thompson, 1962). Welter (1987) identified rock glaciers in the Olympics, and in the Cascades, a few rock glaciers have been previously identified, mostly in the North Cascades of Washington (Thompson, 1962; Goshorn-Maroney, 2012).

1.2 Research Purpose

This study focused on rock glaciers in the Eastern Cascades of Washington State, stretching from the Washington/Oregon border to the U.S./Canada border. The Eastern Cascades of Washington have a more continental climate than the western half of the range, which creates better conditions for the formation of rock glaciers. The main objectives were to: 1) identify the spatial pattern of all rock glaciers; 2) determine their geneses; 3) record their activity levels; 4) determine their ages; and 5) use these data and other sources to make preliminary estimates of past climates in select parts of the Eastern Cascades.

1.3 Research Significance

Although rock glaciers have been mentioned in the literature for the Cascades, this study was the first of its kind to survey all rock glaciers in the Eastern Cascades of Washington. Studying rock glaciers in the Eastern Cascades and elsewhere can provide a more thorough geographical picture of a given area. Rock glaciers indicate a periglacial environment, and are influenced by climate and geological factors. Understanding rock glacier spatial distribution can help researchers to synthesize multiple factors, such as the climate and weathering characteristics of an area, and gives a better understanding of landscape development. Rock glacier genesis and activity levels are also key indicators regarding climate and lithology of an area. Rock glaciers may be used as calibration tools to better understand paleoclimates (Birkeland, 1973). Using these data, the effects of future climate change on rock glaciers can be better projected. The geology of an area also influences rock glacier development. Active rock glaciers signify an area of hard rock that is not easily weathered, yet is conducive to rockfall from a cliff or cirque. This, in turn, can be used to predict future weathering rates, rockfall and erosion rates for larger mountain systems. Rock glaciers also harbor various species of flora and fauna commonly found among talus fields, such as pika, marmots and various species of high-elevation trees and shrubs (Wahrhaftig and Cox, 1959). Areas that harbor rock glaciers are becoming increasingly important as habitat with a changing climate regime. Finally, rock glaciers containing an ice core or interstitial ice provide meltwater during the otherwise dry summer months, supplying human populations (Perrucca, 2011). Once rock glacier distribution is mapped, areas where rock glaciers are known to exist may be managed for their habitat and water-storage capacities.

SECTION 2

LITERATURE REVIEW

2.1 Rock Glacier Spatial Distribution

Rock glaciers are composed of rock and ice. As a result, their development and spatial distribution is constrained by underlying geology and surrounding climate.

2.1.1 Geologic Controls

Rock glaciers are controlled by the underlying geology. This includes rock type, rock weathering characteristics, and degree of jointing (Welter, 1987).

Rock type is influential in determining rock glacier distribution, because softer, sedimentary rocks generally fracture before rock glacier development can begin. Only harder igneous and metamorphic rocks seem to promote rock glacier development (Johnson, 2007). Bedrock with a tendency to fracture into large, blocky debris from weathering and jointing creates rock glaciers. Rocks of this type include granite, basalt, other intrusive and extrusive igneous rock, as well as metamorphic rocks (Barsch, 1977). Rocks that are not conducive to rock glacier development include platy schists, sandstone, and most sedimentary rocks, as a result of being easily weathered and susceptible to breaking down to small sizes >0.5m (Wahrhaftig and Cox, 1959).

Rock porosity has been observed to play a large role in areas with marginal climatic zones for rock glacier development. In Idaho's Lemhi Range, areas with metasedimentary rock were observed to hold water on the surface below rock masses, giving it a chance to re-freeze and form the interstitial ice necessary for rock glaciers, while places dominated by carbonate bedrock were typically dry as a result of drainage through this porous rock. As a result, rock glaciers there overwhelmingly occur in metasedimentary rather than carbonate rock (Johnson, 2007). Rock types in the Cascade Range are dominated by igneous and metamorphic rocks conducive to rock glacier development (Beckey, 2000).

Rock weathering characteristics determine where rock glaciers can form, because of the requirement of heavy rockfall to sustain development. Rocks such as sandstone are not conducive to rock glacier development because they weather too fast (Chinn, 1981). Rocks that are conducive to rock glacier development tend to weather slowly and are also prone to jointing (Bohlert, 2011). However, faster rock weathering rates also produce more rockfall, leading to increased rock glacier development (Wahrhaftig and Cox, 1959).

Densely jointed rock is also conducive to rock glacier development because it increases rockfall deposition. Headwalls measured above rock glaciers in the Sangre de Cristo Mountains of Colorado were found to have especially closely spaced joints that produced much rockfall (Morris, 1981). A study in the Swiss Alps also found that smaller joint spacing was found to be conducive to rock glacier development (Ikeda and Matsuoka, 2006). These same joints were heavily weathered and therefore were prone to producing rockfall. Densely jointed rock was found to produce larger and longer rock glaciers, compared to the less-jointed rock.

2.1.2 Climatic Controls

Rock glaciers form in intensely cold environments, which develop subsurface ice but lack sufficient precipitation for true glaciers to exist (Wahrhaftig and Cox, 1959). Climate influences rock glacier development on meso-scales and micro-scales.

Temperature and precipitation are the two most important factors for rock glacier development. Requisite factors for rock glacier formation include a mean-annual temperature (MAT) of -2°C or less, steep slopes supporting rockfall, and minimal precipitation and snow cover during the winter months (Brenning, 2005). Rock glaciers require intense cold during the winter months to stay active, while the thick debris cover insulates the ice core during the summer months (Degenhardt, 2009).

Latitude and elevation combine to have large effects on temperature, hence rock glacier distribution. Rock glaciers generally decrease in elevation poleward, due to decreased amounts of solar radiation and lower annual temperatures (Thompson, 1962). Relict rock glacier deposits exist at the equator at 4,000m on Mount Kenya (Mahaney, 1980), while active rock glaciers occur at 4,000m in the Andes at 25°S (Perucca, 2011). Owen (1998) found that active rock glaciers in the Himalaya at 28°N descend to 3,800m. Active rock glaciers in the Swiss Alps occur at 2400m at 40°N, and at around 3300m in the Colorado Rockies (Bodin, 2009; Janke, 2007). Further poleward, active rock glaciers occur at 1070m in the Alaska Range and at 990m in the Brooks Range (Wahrhaftig and Cox, 1959; Luckman and Crocket, 1978). In the mountains of the Arctic and Antarctic, active rock glaciers can reach to sea level (Humlum, 1988; Serrano, 2000).

Rock glaciers preferentially occupy continental areas, as opposed to maritime-influenced areas. This can be largely attributed to temperature and precipitation differences between the different mountain systems. Continental areas experience larger annual temperature variations, and less precipitation than their coastal counterparts, conditions that are conducive to rock glacier development. Large winter snowpacks characteristic of more marine mountains insulate rock glaciers and prevent cold air drainage from occurring, therefore inhibiting rock glacier development (Thompson, 1962). As a result, rock glaciers exist in large numbers in the Rocky Mountains of the interior west, but are not as numerous in the Sierra Nevada, Cascades, and Olympic Mountains of the west coast of North America (Konrad, 1998; Thompson, 1962; Welter, 1987). Another effect of topography is the ability of mountains to create precipitation shadows on their leeward slopes (Welter, 1987). This is evident in the Rocky Mountains, where the majority of rock glaciers occur on the eastern, leeward slopes (Janke, 2007). In the more marine Olympic Mountains of Washington State, Welter (1987) found nine rock glaciers, all of which were on the leeward (i.e., more continental) side of the range and only one of which was active. Further inland, Kiver (1974) noted several rock glaciers in the Wallowa Mountains of northeastern Oregon.

In the Cascades, rock glaciers have been mentioned only on the leeward, more continental slopes. In the Cascades of Oregon, Carver (1972) found several rock glaciers on the eastern side of the range. Crandell and Miller (1974) focused on the glaciation of Mt. Rainier, and found nearly 20 rock glaciers on the eastern side of the mountain, while Beckey (2000) also found one northeast of Mt. Rainier. Although Mt. Rainier lies west of the Cascade crest, its rainshadow is sufficiently strong for rock glacier development on its leeward side. Hopkins (1966) noted a few rock glaciers in the southern North Cascades of Washington, while Beckey described rock glaciers existing on a number of eastern North Cascade peaks, such as on Silver Star Mountain and Oval Peak (Beckey, 2000). Thompson (1962) located several on Silver Star Mountain on the east side of the North Cascades of Washington, but thought that the range was not conducive to any more than a small number of rock glaciers. Goshorn-Maroney (2012) also accomplished limited identification of rock glaciers in the North Cascades of Washington, documenting a total of 17 rock glaciers.

Rock glaciers almost exclusively occupy north-facing cirques in the northern hemisphere, and otherwise occur in well-shaded areas with steep slopes blocking incoming solar radiation (Janke, 2007). Cirques are similarly oriented in the Rockies and the Cascades. Cascade cirque orientations exist most commonly between 0° and 90° (Mitchell, 2006). The few rock glaciers observed previously in the Cascades are generally north-facing as well (Thompson, 1962; Goshorn-Maroney, 2012).

2.2 Rock Glacier Genesis

2.2.1 Glacial Origins

Early studies of rock glaciers produced more questions than answers regarding their genesis and mechanisms of movement. The earliest study to specifically focus on rock glaciers was completed by Capps (1910). He documented numerous rock glaciers in the Wrangell Mountains of Alaska, theorizing that rock glaciers develop from blocky debris in the terminal moraines left by melting glaciers. This debris becomes saturated with meltwater, which then freezes in the interstices of the debris. Capps excavated several rock glaciers, in which he discovered interstitial ice “forming, with the rock, a breccia with the ice as a matrix.” Later, Brown (1925) described a rock glacier in the San Juan Mountains of Colorado that had a mining tunnel dug by a private company, in which the first 300 feet contained an ice matrix. Past this ice matrix, a central core of solid, massive ice was encountered, which extended 100 feet to the rock wall. He interpreted this as a once heavily debris-covered glacier, forming into an active rock glacier via a large landslide.

In the Absaroka Mountains of Wyoming, Potter (1972) introduced the concept of a glaciogenic origin for rock glaciers, using the Galena Creek rock glacier as an example. In essence, glaciogenic rock glaciers originate from ice glaciers, with yearly deposition of snowfall in layers. Once enough layers of snow have been deposited over multiple seasons, glacial ice forms and it begins to flow. However, it becomes exceedingly covered with rock falling from the cirque headwall. That forms a glaciogenic rock glacier that exhibits different flow dynamics than a debris-covered ice glacier. Rock glacier flow is not well understood; however, it is believed that deformation of the ice core, rather than basal sliding, causes forward movement. These rock glaciers are similar to true glaciers, with accumulation and ablation zones (Wagner, 1992).

2.2.2 Periglacial Origins

In contrast to the previous theories of a glacial origin for rock glaciers, Wahrhaftig and Cox (1959) proposed an exclusively “periglacial” origin for rock glaciers based on their studies in the Alaska Range. Periglacial environments are influenced by intense freeze-thaw cycles, which in turn create rockfall through frost wedging. Although they acknowledged that, theoretically, a continuum of ice glaciers to periglacial rock glaciers exists, they pointed to the unique periglacial climatic conditions required for rock glacier formation, therefore precluding transitional forms. The mechanism of ice formation in the periglacial model is called Balch Ventilation, after Balch (1897), which stipulates that interstitial ice is maintained by cold air drainage during the winter months. Interstitial ice forms when rain or snowmelt flows into interstices of a talus body or rock glacier, freezing at the permafrost margin and producing a rock glacier's unique form (Wahrhaftig and Cox, 1959). Barsch (1987) and Haeberli (1985) indicated that rock glaciers are all manifestations of mountain permafrost, and that the glaciogenic model of rock glacier formation points to nothing more than heavily debris-covered glaciers. The assumption of Barsch (1996) shows rock glaciers exclusively existing in the mountain permafrost belt, rather than areas of higher precipitation that produce ice glaciers.

2.2.3 Modern Genesis Classification Schemes

Because most investigations of rock glaciers now acknowledge the possibility of more than one origin, numerous classification schemes based on the periglacial-glacial continuum have been developed, with three major types recognized: 1) glacier-derived rock glaciers, 2) talus-derived rock glaciers, and 3) landslide-derived rock glaciers (Humlum, 1988). Glacier-derived rock glaciers belong to the glaciogenic model, while talus and landslide-derived rock glaciers are periglacial in origin. Talus-derived rock glaciers originate from accumulations of talus, and are primarily climatically controlled (Humulum, 1988). Landslide-derived rock glaciers are short-lived, due to their mass-wasting origin, and are not as constrained by climate.

Brazier et al (1998) formulated a three-pronged classification scheme based on field research in New Zealand. Her classifications were primarily morphological, with glacier-derived landforms, talus-derived landforms, and undifferentiated landforms with possible combinations of the previous genetic forms. These classifications were further subdivided into categories based on activity.

This study uses a three-pronged classification, developed by Corte (1987) and followed by Whalley and Martin (1992), Barsch (1996), and Janke (2007), which includes: 1) glaciogenic-type, 2) debris-type, and 3) gelifluction-type rock glaciers. Glaciogenic-type rock glaciers exist at higher elevations and with an almost exclusive northerly aspect compared to debris and gelifluction-type rock glaciers (Humlum, 1988). Glaciogenic rock glaciers also occur closer to mountain crests, presumably because they require additional precipitation when compared to the other two types of rock glaciers (Janke, 2007). Debris-type rock glaciers include talus and landslide derived rock glaciers, and have the widest climatic range. Gelifluction-type rock glaciers are entirely climatically controlled, and originate below gelifluction slopes or large accumulations of rock supplied by gelifluction (Humlum, 1988).

2.3 Rock Glacier Activity

Rock glacier activity has been extensively studied in rock glacier surveys in Greenland (Humlum, 1988), the Rocky Mountains (Janke, 2007; Johnson, 2007), and in New Zealand (Brazier et al, 1998). Each of these studies found that the main controlling factor for rock glacier activity is climate. Rock type also plays a role.

Although many rock glacier studies use genesis as their main method of classification, classifying by activity has also been found to be useful. Johnson (2007) produced a classification scheme for Idaho's Lemhi Range, describing rock glaciers in terms of activity rather than genesis, possibly due to the lack of Holocene glaciation in the area. Class 1 rock glaciers contain smooth upper surfaces and are not vegetation covered, with over-steepened front slopes. Class 2 rock glaciers have deep furrows, and ridges are partially covered by lichen or other vegetation. Class 3 rock glaciers are heavily pitted, mostly covered in vegetation, and have stable, shallow front slopes.

Rock glacier activity is closely linked to the state of the interstitial ice or ice core within, allowing three levels of characterization (Martin and Whalley, 1987). Active rock glaciers exhibit movement and contain an active ice layer. Inactive rock glaciers do not move, but still contain an ice layer that is no longer active. Relict rock glaciers have lost their ice and no longer exhibit movement. They often have a deflated appearance when viewed from above.

2.3.1 Active Rock Glaciers

Active rock glaciers contain interstitial ice or an ice core, exhibit current downslope flow, have dramatic pressure ridges and furrows, and generally lack vegetation on the surface (Martin and Whalley, 1987). Active rock glaciers may indicate a true periglacial climate; however, they can also indicate a recently altered climate where the rock glacier is not in equilibrium with its surroundings. An active rock glacier can persist for many years after the climate has risen above a MAT of -2°C because of heavy insulation of internal ice by overlying debris (Bodin, 2009). Active rock glaciers are generally found 200-300 meters lower than present-day ice glaciers in the Rockies and the Alaska Range (Janke, 2007; Wahrhaftig and Cox, 1959). Reasons for this discrepancy involve temperature and precipitation. The ice glacier zone receives too much precipitation for sustained rock glacier development, and as glaciers retreat upslope with warmer conditions, rock glaciers tend to fill in the vacated cirques and valleys left behind. In addition to higher snowfall rates in the ice glacier zone, snowfall occurs year-round, preventing rock glacier formation. Both ice glaciers and rock glaciers generally face northward in the northern hemisphere (Mitchell, 2006). Because active rock glaciers function as indicators of permafrost, they give researchers an accurate indication of the -2°C isotherm in high mountain environments where climate data is scarce.

2.3.2 Inactive Rock Glaciers

Inactive rock glaciers can also contain ice, but have stopped moving and tend to have gentler, more rounded frontal slopes than active rock glaciers (Birkeland, 1973). Inactive rock glaciers can also be distinguished from active rock glaciers by their vegetation cover that typically ranges from minimal to 50 percent cover (Janke, 2007). They are generally found below present-day active rock glaciers. Inactive rock glaciers can also be oriented to a wide range of aspects, because they may have formed under a much colder climate regime (Janke, 2007). They are valuable to researchers as paleoclimatic indicators because they indicate a previously more rigorous climatic regime. Only inactive and relict rock glaciers can be used as paleoclimatic indicators, because active rock glaciers cannot sustain tree or lichen growth (see below).

2.3.3 Relict Rock Glaciers

Relict (or fossil) rock glaciers contain no ice and have been inactive for long periods of time (Wahrhaftig and Cox, 1959). Relict rock glaciers often exhibit substantial vegetation cover (>50%) and a subdued, deflated appearance when viewed from above (Janke, 2007). Relict rock glaciers become deflated through the loss of their internal ice core or interstitial ice. As a result, the center of the rock glacier caves in, and the front stabilizes. Relict rock glaciers are found at the lowest elevations, and exhibit a wide range of aspects (Janke, 2007).

2.4 Rock Glacier Age

Relative and absolute ages of rock glaciers provides insight into their formation and past activity levels, and can be used to determine past climate and confirm existing climate data sets (Brazier et al, 1998). Inactive and relict rock glaciers are especially useful in this regard.

2.4.1 Late Pleistocene

Climate in the Pleistocene was highly variable, and driven by the changing orbital relationship between the earth and sun. Glacial cycles occurred regularly every 100,000 years, when the orbital parameters described by Milankovitch took full effect. The end of the last large-scale glaciation was approximately 18 ka, leading towards better conditions for rock glaciers. The late Pleistocene had three main events significant to rock glaciers; the last glacial maximum (25-18 ka), the Bølling-Allerød interstadial (14.7-12.7 ka), and the Older (13.7-13.4 ka) and Younger Dryas (12.8-11.5 ka). Rock glaciers have generally been observed to be Late Pleistocene or Holocene features, rarely being older than 15,000 years in the Northern Hemisphere (Thompson, 1966; Konrad and Clark, 1998). This is a result of glaciation; during glacial epochs, rock glacier deposits are often overridden by ice and erased from the landscape. For example, Kerschner (1978) found that large rock glacier advances occurred in the Alps during the cold Younger Dryas period. This supports the hypothesis that rock glaciers generally expand with lower temperatures, leading to increased ice formation and further expansion of freeze/thaw cycles.

Rock glaciers have been found to advance during glacial periods across different mountain ranges (Konrad and Clark, 1998; Ribolini et al, 2007). It can be hypothesized that rock glacier advances in the Cascades also correlate to glacier advances. In the Cascades, Porter (1975) indicated glacial advances at 14,000 and 11,000 yr BP, while Heine (1998) indicated glacial advances at 13,200, and between 10,800 and 9,950 yr BP at Mt. Rainier. The Younger Dryas period saw glacial retreat at Mt. Rainier, most likely due to a steep drop in precipitation, but the onset of warmer temperatures and higher precipitation caused glaciers to advance at 10,800 yr BP. It is unlikely that rock glaciers advanced during this time, as a result of detrimental high temperatures and precipitation.

2.4.2 Holocene

Little evidence is available for early Holocene rock glaciers; however, it can be assumed that rock glacier advances generally correlate to glacial advances in many areas. Rock glaciers advanced in the Rockies during the Neoglacial (5 to 2 ka) and also in the Sierra Nevada (Nicholas and Butler, 1996; Konrad and Clark, 1998). Refsnider (2007) found strong correlations between rock glacier activity and glacial advances in the central Colorado Rockies, at 3080, 2070 and 1150 yr BP. Cooler temperatures and increased precipitation resulted in glacier and rock glacier advances during these times. Glacial advances in the Cascades occurred at 8,750, 4,900 and most recently between 1500 and 1800 (Porter, 1975; Kaufman et al., 2003). I assume that rock glacier advances correlated with glacial advances here as well.

The Little Ice Age (LIA, 16th-19th centuries) was a period of increased cold and precipitation in the northern hemisphere, that especially affected Europe and North America. LIA advances of rock glaciers have been recorded in the Colorado Front Range (Birkeland, 1973), the La Sal Mountains of Utah (Nicholas and Butler, 1996), and the Alps (Ribolini et al, 2007). Evidence for increased rock glacier activity during cold periods is found in many settings (Birkeland, 1973; Kerschner, 1978; Refsnider, 2007). In the Cascades, O'Neal (2005) found that glacial advances occurred throughout the Cascades, at Mt. Adams, Mt. Rainier, and the North Cascades from 1700 onward to the turn of the 20th century. Although glacial advances benefit from increased precipitation coupled with decreased temperatures, LIA precipitation data indicates only a decrease in temperature with no net increase in precipitation during this time in the Cascades (Steinman, 2012). Rock glaciers in the Cascades would have benefited from the cold conditions during this time.

SECTION 3

STUDY AREA

3.1 General Description

The study area resides entirely in the Eastern Cascades in Washington State, comprising an area of about 14,500 km^2 (Figure 3-1). The Eastern Cascades are defined as the area east of the Cascade crest, and west of the Columbia and Okanogan rivers. The North Cascades are generally defined as everything north of Snoqualmie Pass, while the South Cascades extend down to northern California. For this study, the South Cascades stop at the Oregon-Washington border. The study area includes all of the eastern side of the North and South Cascades. The Cascade crest between Snoqualmie Pass and the Canadian border lies about 200km east of the Pacific Ocean, and between 80-100km east of the Puget Sound.

The northern and southern boundaries are the Oregon-Washington and U.S.-Canada borders, respectively, while the western boundary is the Cascade Crest. This area spans >4 degrees of latitude (45°40'N to 49°N). The eastern boundary is approximately 121°W longitude from the Oregon-Washington border to Ellensburg, then follows the Columbia River and the Okanogan River to the U.S.-Canada border. The study area is accessible by numerous highways and roads. These include (from south to north) U.S. Route 12, Interstate 90, U.S. Route 97, and State Highway 20. Major forest roads include (from south to north) the Bumping Lake Road, Teanaway River Road, and the Twisp River Road. The vast majority of the study area is located on U.S. Forest Service lands, much of which is designated as federal wilderness. Small portions are also located on Bureau of Land Management, Washington State Department of Natural Resources, and private lands; however, no rock glaciers were found outside of National Forest lands.

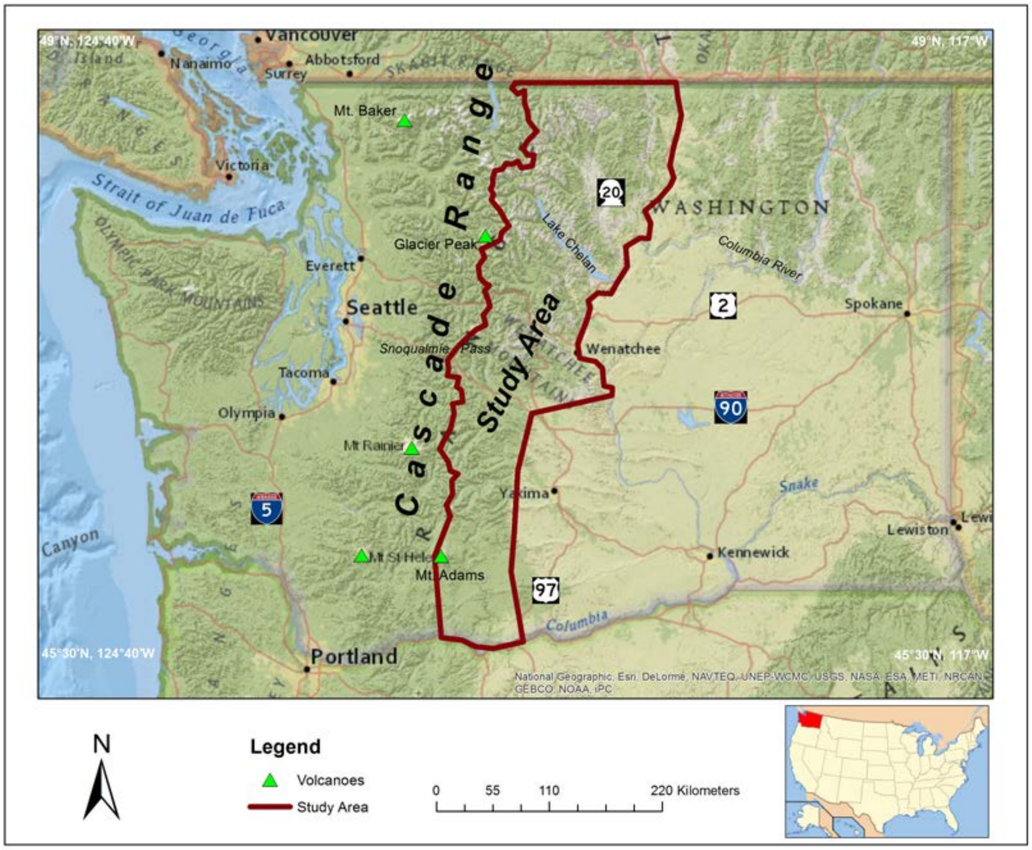

Figure **3-1:** Rock glacier study area in the Eastern Cascades, WA

3.2 Eastern Cascade Geology

The Cascade Range has a north-south orientation, and it widens northward, from ~110km near the Oregon-Washington border to over 160km at the U.S.-Canada border. Additionally, average elevations of the high peaks increase northward from 1800 to nearly 2400m (Beckey, 2000). The highest peaks, excluding the large volcanoes, rise to over 2750m. Washington is home to five major volcanoes on the western side of the range: from south to north, Mt. St. Helens (2550m), Mt. Adams (3743m), Mt. Rainier (4392m), Glacier Peak (3213m), and Mt. Baker (3286m) tower over the rest of the range.

The Washington Cascades can be divided nearly in half by their rock type at Snoqualmie Pass. The area south (i.e., South Cascades) is mostly composed of Cenozoic volcanic rocks, with andesite, basalt and dacite common, and with more volcanoes than the north. The terrain is more subdued because of less resistant, older rock than its northern counterpart. The area north (i.e., North Cascades) consists of late Paleozoic-Mesozoic metamorphic and plutonic rocks, with large Quaternary composite cone volcanoes composed of extrusive igenous rock. Rock types include granite, serpentine, schist and gabbro (Schuster, 2005). The terrain is far more rugged because of its relatively young age, resistant rock, and because much of the high Cascades are currently glacierized.

3.3 Climate

The Cascades are a maritime-influenced mountain range located near the Pacific Ocean. The South Cascades of Washington are ~200km east of the Pacific Ocean, while the North Cascades are adjacent to the Puget Sound. The eastern side of the crest lies in the rainshadow of the peaks to the west, resulting in a much drier, more continental climate in Eastern Washington as compared to the west. Below 1,800 meters, mean annual temperatures (MATs) for the Eastern Cascades vary from 3-8°C, depending on elevation (Beckey, 2000). Precipitation also varies, depending on distance east from the crest. Sites <20 km east of the crest receive 100-150cm of precipitation, however, sites >20km east receive <100cm of precipitation (Beckey, 2000). The majority of this precipitation on the eastern side of the crest, in contrast to the western slopes, falls as snow. Temperature also decreases further north. At Satus Pass (947m) in the South Cascades, MAT is 7.4°C. At Blewett Pass (1292m) in the central eastern Cascades, MAT is 5.9°C, while at Salmon Meadows (1360m) in the North Cascades, MAT is 3.2°C (PRISM Climate Group, 2012).

3.4 Cascade Geomorphology

The Cascades are extremely varied in their geomorphology, and much is dependent on what part of the range is specified. Many different geomorphic processes combine to produce unique landscapes.

3.4.1 Glacial History

The last major glaciation to affect large portions of the Cascades was the Fraser Glaciation, which ended approximately 20 ka. The Cordilleran Icesheet covered much of the Cascades north of Glacier Peak at 48°N. South of the icesheet, ice caps mantled high points along the crest of the range, with Mt. Rainier and Mt. Adams having much larger ice caps than they do today. Outlet glaciers from these ice caps reached to 130m and 500m elevation on the western and eastern sides, respectively, and extended between 35 and 70km from their sources. At the Cascade crest, evidence of glaciation includes aretes, horns, cirques and moraines (Hammond, 1989). Glaciers continue to exist, with the present glaciation threshold above 2200m for much of the North Cascades. This threshold rises to 2800m at Mt. Shasta in the California Cascades (Porter, 1976). Cirques were formed in the higher parts of the range, some of which still hold glaciers today. Large U-shaped valleys were carved on both sides of the range, and they have not been eroded significantly since.

3.4.2 Fluvial, Mass Wasting, and Weathering Processes

The Cascades receive over 250cm of precipitation annually near the crest. Fluvial processes are, for the most part more active today than glacial processes, and this is evident in the lower river valleys. Fast flowing rivers incise deep V-shaped valleys on both sides of the range. On the eastern side of the range, the Naches, Yakima, Wenatchee and Methow rivers form the main channels for runoff. Because of high precipitation, landslides are an integral part of the erosional process in the range. In the higher elevations, large talus aprons are formed by frost action and subsequent rockfall. Freeze/thaw cycles dominate for nearly 9 months of the year at high elevations (Hammond, 1989). Weathering rates are accelerated by the high precipitation amounts in the Cascades, but are somewhat slower on the eastern side of the range.

3.5 Eastern Cascade Flora

Vegetation consists of numerous large tree species such as Douglas fir, ponderosa pine, lodgepole pine, and western white pine at the lower elevations, and western larch, subalpine larch, Engelmann spruce, whitebark pine, lodgepole pine and subalpine fir at higher elevations. Treeline varies depending on precipitation and elevation. In Washington's South Cascades, treeline extends up to 2500m. In the North Cascades, treeline gradually drops reaching 2200m at the Canadian border (Arno, 1984). High-elevation understory is composed of forbs, herbs, and shrubs, with many species of flowers such as lupine, glacier lily, and Indian paintbrush. At the highest elevations above treeline, lichen is the primary form of plant growth, occurring on exposed rock. The most common form of lichen in the Cascades is *Rhizocarpon Geographicum*, which is the main species used for lichenometry in this study.

SECTION 4

METHODS

4.1 Rock Glacier Identification and Spatial Distribution

Before this study, 19 rock glaciers were known to exist in Washington's Eastern Cascades (Thompson, 1962; Hopkins, 1966; Goshorn-Maroney, 2012). Google Earth was chosen as the medium for imagery in this study. This program has been considered an important geomorphic tool since its introduction in 2005, especially for teaching situations (Dunegan, 2007). However, Google Earth has not been used before to identify rock glaciers, except in limited identification in the North Cascades by Goshorn-Maroney (2012).

In Google Earth, paths were first drawn using the Path Tool to delineate specific search areas within the Eastern Cascades. These areas were kept small (no more than 10 km in width) to ensure thoroughness in identification. In total, 35 search areas forming a grid were used for the Eastern Cascades. In each of these search areas, main ridges and peaks were searched first, then spur ridges and peaks, then lowland areas. As a general rule, areas below 1200m were not examined due to poor climate conditions for rock glaciers, which was also verified in the field. The present average glaciation threshold for the Cascades is 2250m at the crest, and approximately 2590m at 30km east of the Cascade Crest, as identified by Porter (1977). Glaciation threshold is determined by taking the mean altitude between the lowest glaciated mountain, and the highest mountain devoid of glaciers in a given area. Rock glaciers generally occur between 200-

300m below glaciers (Janke, 2007), giving a rock glacier appearance level (RAL) of 1950-2290m. RAL is identified by Humlum (1988) as a counterpart to the concept of glaciation thresholds. In short, it is the mean elevation between the highest peak devoid of a rock glacier, compared to the lowest peak harboring one. To account for inactive and relict rock glaciers, maximum Fraser glaciation thresholds (i.e., late Pleistocene) were taken into consideration. The glaciation threshold at the crest of the Cascades during this time was 1500m, and 30km east of the crest it was 1850m (Porter, 1977). A value of 1200-1550m was thus obtained as a minimum elevation for RAL in the Cascades. Identification on Google Earth proceeded using four main criteria, each being established morphological characateristics for rock glaciers. These included: 1) a lobate or tongue-shaped mass of rock (Ellis, 1979); 2) evidence of past or present movement based on steep side and front slopes, and movement away from its source area (Capps, 1910); 3) a visible source of past or present rockfall from a cirque cliff or headwall (Corte, 1987); and 4) transverse or longitudinal ridges and furrows, as well as surface pits in the rock mass, giving further evidence of movement (Janke, 2007).

Each rock glacier's latitude and longitude, aspect, length, and width were recorded. The elevation of the toe (lowest elevation of rock movement) and head (highest source of rockfall) of each rock glacier was also recorded. Latitude and longitude were easily recorded by moving the cursor over the center of a rock glacier. Aspect was recorded as cardinal directions split into quarters (N, NNE, NE, ENE, E, etc.), and as degrees. Degrees were obtained using a compass overlay in Google Earth. Aspect was recorded by orienting the screen to face due north, then drawing a line facing north and south. Another line was oriented east to west to complete the aspect measurement. Width and length were recorded using the Google Earth ruler. Width was measured as the widest point just above the toe, and length was measured from the highest indication of pressure ridges to the toe. Length and width were later used to estimate vegetation cover to determine activity, and give a rough relative estimate of age, as longer rock glaciers are generally older than their shorter counterparts (Johnson, 2007).

Once all rock glaciers were found, select rock glaciers were chosen for further field investigation. Eight rock glaciers were subsequently visited in the field. Rock glaciers were subsequently mapped using ArcGIS, and split up into five sections for greater detail.

4.2 Rock Glacier Genesis Classification

Google Earth also provided insight regarding the genesis of rock glaciers. Multiple 1:100,000 United States Geological Survey (USGS) geologic maps of portions of Washington State was used to determine the original parent material of all rock glaciers in the study area. Rock type was verified in the field for eight select rock glaciers, and rock types were compared to determine if they played a role in rock glacier distribution. I followed Corte's (1987) classification scheme of glaciogenic, debris, and gelifluction-type rock glaciers. Using Google Earth and select field observations, glaciogenic-type rock glaciers were identified by their proximity to current glacial ice, locations near cirques, and the existence of fine morainal debris. Glaciogenic rock glaciers were limited to being classified as active, because it is difficult to differentiate between inactive or relict glaciogenic rock glaciers in relation to the other two types. Debris-type rock glaciers were identified by their location next to avalanche chutes and couloirs (a narrow gully with a steep gradient in mountainous terrain). Gelifluction-type rock glaciers were identified by their lack of avalanche chutes and couloirs and their association with boulder and talus fields.

4.3 Rock Glacier Activity Levels

Activity levels were assessed for all rock glaciers using Google Earth. Additionally, activity levels of eight rock glaciers were assessed in the field. Google Earth and field methods followed the classification scheme of Whalley and Martin (1992), Barsch (1996), and Janke (2007). Active rock glaciers were distinguished from inactive and relict rock glaciers by their vegetation cover and front slope angles. Vegetation cover included any shrubs, trees, or other woody plants existing on top or in rock glacier furrows. Lichen was excluded from the analysis, because it was generally not visible from airphotos. Rock glaciers existing above treeline were differentiated by the prominence of their furrows and ridges, front slope angle and the likelihood of continued rockfall from their source areas (Table 4-1).

Table **4-1:** Characteristics of Rock Glacier Activity Types.

Rock Glacier Activity Type	**Percentage Vegetation Cover**	**Front Slope Angle (°)**
Active	Little to nonexistent	>35°
Inactive	<50%	20-35°
Relict	>50%	<20°

The percentage of vegetation cover was determined by multiplying length and width to determine approximate rock glacier area. A polygon was drawn around the areas of vegetation cover to determine the vegetated area, which was then divided by total rock glacier area. This was only necessary to differentiate between inactive and relict rock glaciers. Front slope angle was only determined on the eight rock glaciers visited in the field by using a protractor. The protractor was placed on the ground, and leveled with a bubble level at the base of the toe of each rock glacier, and the front slope angle was approximated to the nearest degree.

4.4 Rock Glacier Ages

Rock glaciers visited in the field were dated using dendrochronology, lichenometry, and weathering rind development. Multiple dating techniques were used to account for inherent inaccuracies in each particular dating technique; cross-referencing dating techniques has been shown to provide a more thorough picture of rock glacier ages (Birkeland, 1973; Bohlert, 2011).

Dendrochronology involves extracting tree cores using a borer, then counting individual rings to determine the specific age of the tree, documenting the cessation of rock glacier movement (Stokes and Smiley, 1968). It was assumed that only inactive and relict rock glaciers without movement could support tree growth (Nicholas and Butler, 1996). Rock glaciers with tree cover were sampled in the area close to the toe; trees did not grow near the head on any of the visited rock glaciers. Cores from seven trees on seven rock glaciers, taken with a 400mm long by 5mm diameter Haglöf borer, were extracted from approximately 30cm above the surface of each rock glacier. All cores were obtained from high-elevation conifer tree species. Sampled tree cores were dated by counting rings in the Central Washington University Geomorphology and Soils lab, using a binocular microscope, following Stokes and Smiley (1968). The relative location of each tree, species, and approximate height were also noted. Tree height was estimated from the ground level to the top. Rock glaciers often experience a substantial lag time behind the climate regime they operate under. Rock glaciers have been found to experience a lag time of >150 years in some cases, such as in the Alps. However, most rock glaciers have lag times between 100-150 years (Roer et al, 2005).

Lichenometry requires the measurement of the diameter of lichen thalli, then a comparison of the data to other measurements as a relative measure, and to lichen growth curves developed for the specific area to obtain a more absolute age (Birkeland, 1973). It was assumed that lichen formation began after the cessation of rock glacier movement (Nicholas and Butler, 1996). Samples of *Rhizocarpon geographicum* were obtained from eight rock glaciers, following Birkeland (1973),. Twenty lichen samples were obtained from each rock glacier - ten were taken from the toe area, and ten were taken from the area closer to the head. Rock type was noted for each rock glacier as well, to account for different lichen growth rates on different lithologies. Lichen with the largest area were measured on different boulders with Neiko 150mm digital calipers to the nearest millimeter. Lichen diameters on different rock glaciers were compared, producing relative ages. These data were averaged and compared to Cascade Range lichen growth curves produced by Porter (1981) and O'Neal (2003) to obtain more absolute ages. These curves were developed on the western side of the Cascade range. Because lichen is known to grow slower in the colder and drier climates indicative of the Eastern Cascades, the ages obtained can be considered minimums. In addition, lichen colonization rates average about 10 years after surface stabilization (O’Neal, 2003). These ages were used to assign dates to the cessation of recent activity on each of the measured rock glaciers, then compared to the tree ring data.

A weathering rind is the outer, oxidized layer on a rock that begins forming as soon as it falls from its source area (cliff or headwall). The thickness of the rind tells one how long it has been since the rockfall (Chinn, 1981). Weathering rind dates for rock glaciers indicate total rock glacier age, from the deposition of rockfall to present (Nicholas and Butler, 1996). In addition to time, lithology and climate also affect weathering rind thickness. Certain lithologies have faster weathering rates than others, and warmer and wetter climates have faster weathering rates than cold, dry climates (Chinn, 1981). Weathering rinds were obtained from seven rock glaciers. Samples from the same areas sampled for lichen growth were obtained, following Chinn (1981). Ten rocks from the frontal slope, and ten from the head areas were gathered and broken to reveal the rinds. Special note was taken for rock type, due to differing speeds of rind development in differing lithologies (Chinn, 1981). Rinds were measured with Neiko 150mm stainless steel digital calipers to the nearest millimeter and recorded. Rind thicknesses were averaged for each rock glacier, and compared to tree rings and lichen, producing a relative age for each. These thicknesses were also plotted against a curve developed by Porter (2008) for granitic rocks in the Stuart Range of the Eastern Cascades, and one developed by Colman and Pierce (1981) for the Yakima Valley and Mount Rainier, giving absolute ages.

4.5 Paleoclimate and Climate Implications

Rock glaciers are useful paleoclimatic indicators for several reasons. First, while a rock glacier is active and moving, the climate in the surrounding area must have a MAT below 0°C. Also, in areas of high weathering and rockfall such as the Cascades, climate tends to be the most limiting factor.

Rock glaciers visited and dated in the field were used as relative age indicators of times where the climate of a particular area was at or below a MAT of 0°C. Mean annual temperatures at the heads of current inactive and relict rock glaciers were assumed to be above the active threshold of -2°C (Barsch, 1996; Janke, 2007). Head elevation was chosen to represent rock glacier elevation, because the upper portion of a rock glacier is where the interstitial ice (or glacial ice) is formed. Inactive and relict rock glaciers were used to define the lowest possible elevational boundary of the -2°C isotherm. Current climatic data for the Eastern Cascades were obtained from PRISM (1981-2010 climate normals) and SNOTEL, giving this study a reference point for present data. SNOTEL sites used included Pope Ridge, Salmon Meadows, Upper Wheeler, Bumping Ridge and Blewett Pass, all of which were either within or in close proximity to the study area. Rock glaciers visited in field were analyzed for their ages and the location of the -2°C isotherm in the past.

SECTION 5

RESULTS AND DISCUSSION

5.1 Spatial Distribution

A total of 103 rock glaciers were found in Washington's Eastern Cascades. Rock glaciers are unevenly distributed across the study area because of the effects of latitude, elevation, aspect, and distance from the Cascade crest. Rock glaciers vary from being widely distributed in the south, to occurring in large clusters further north. In the South Cascades, nine rock glaciers are found surrounding Darland Mountain and Bear Creek Mountain (Figure 5-2). A rock glacier gap occurs between Bumping Lake and Blewett Pass, a distance of 75 km. Between Blewett Pass and Stevens Pass, seven rock glaciers occur (Figure 5-3). Further north, rock glaciers are nonexistent between the crest 10km south of Stevens Pass and Saska Mountain, a distance of nearly 50km. Seventeen rock glaciers occur just northeast of Lake Chelan in a 60km^2 area (Figure 5-4), and another fifteen occur in the 75km^2 area centered around Abernathy Peak (Figure 5-5). Clusters are not as prominent in the far North Cascades; however, there are numerous high quality examples of rock glaciers in the area (Figure 5-6).

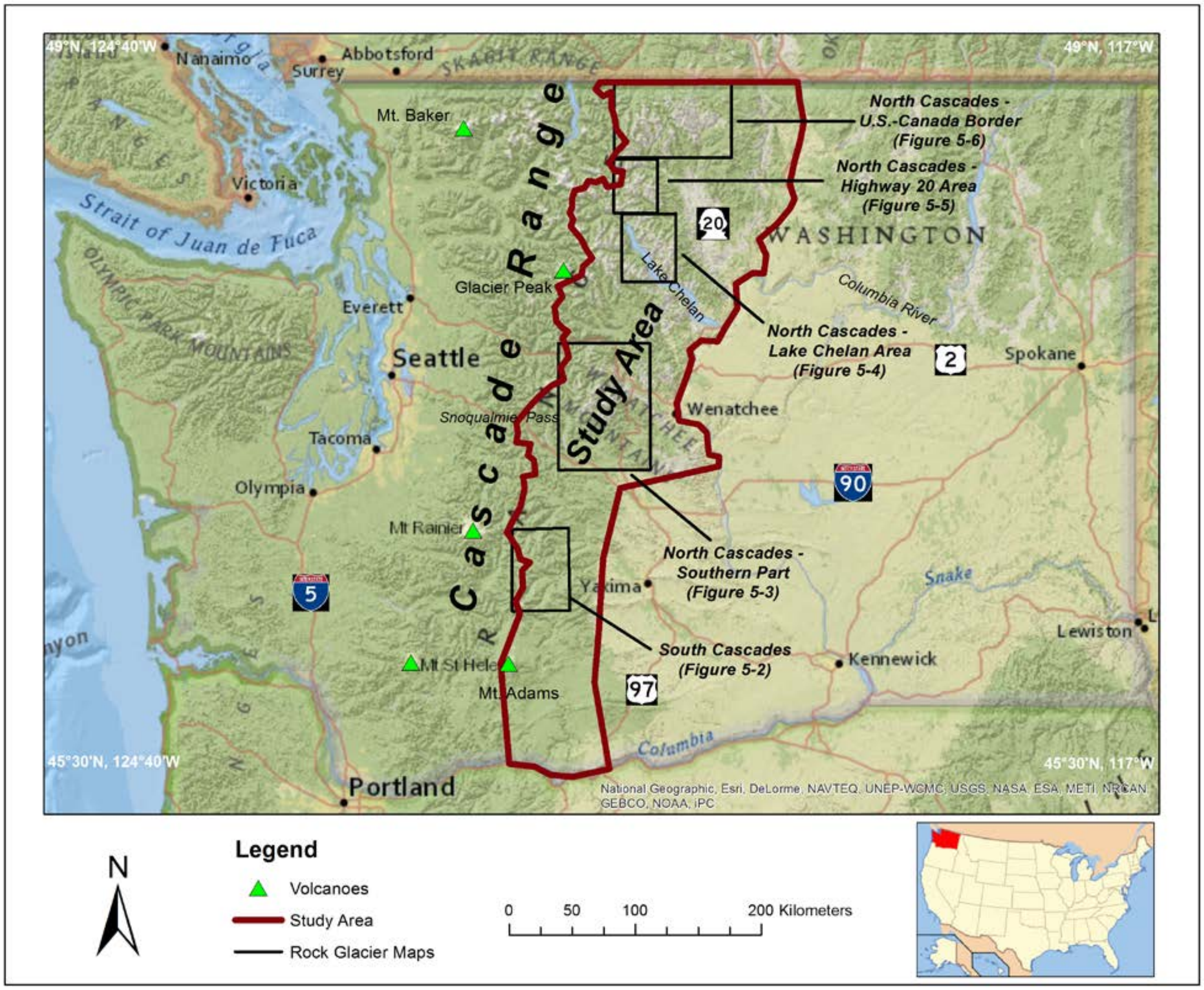

Figure **5-1:** Eastern Cascade study area. Rectangles within correspond to areas with rock glaciers.

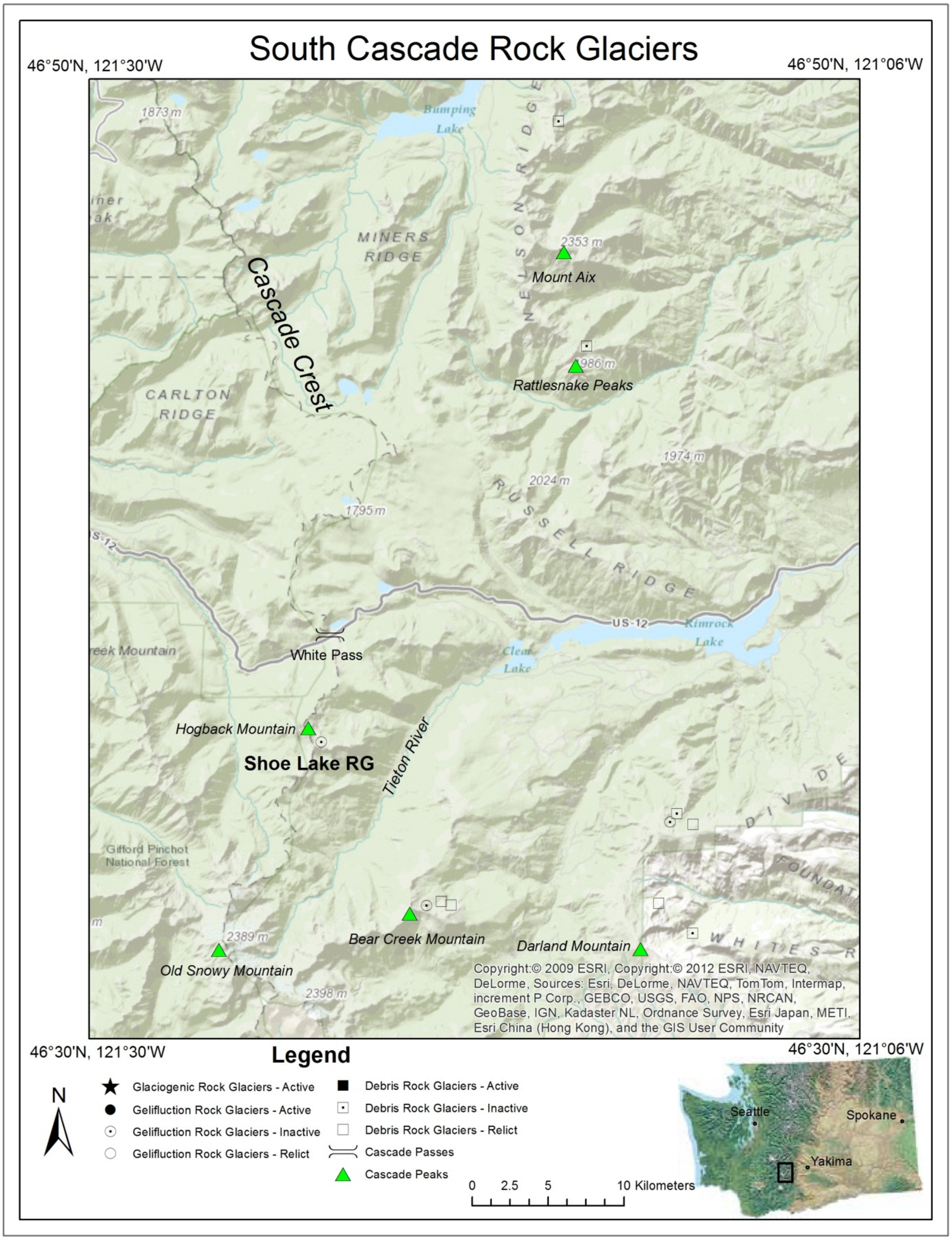

Figure **5-2:** South Cascade rock glaciers. (Names refer to rock glaciers visited in field.)

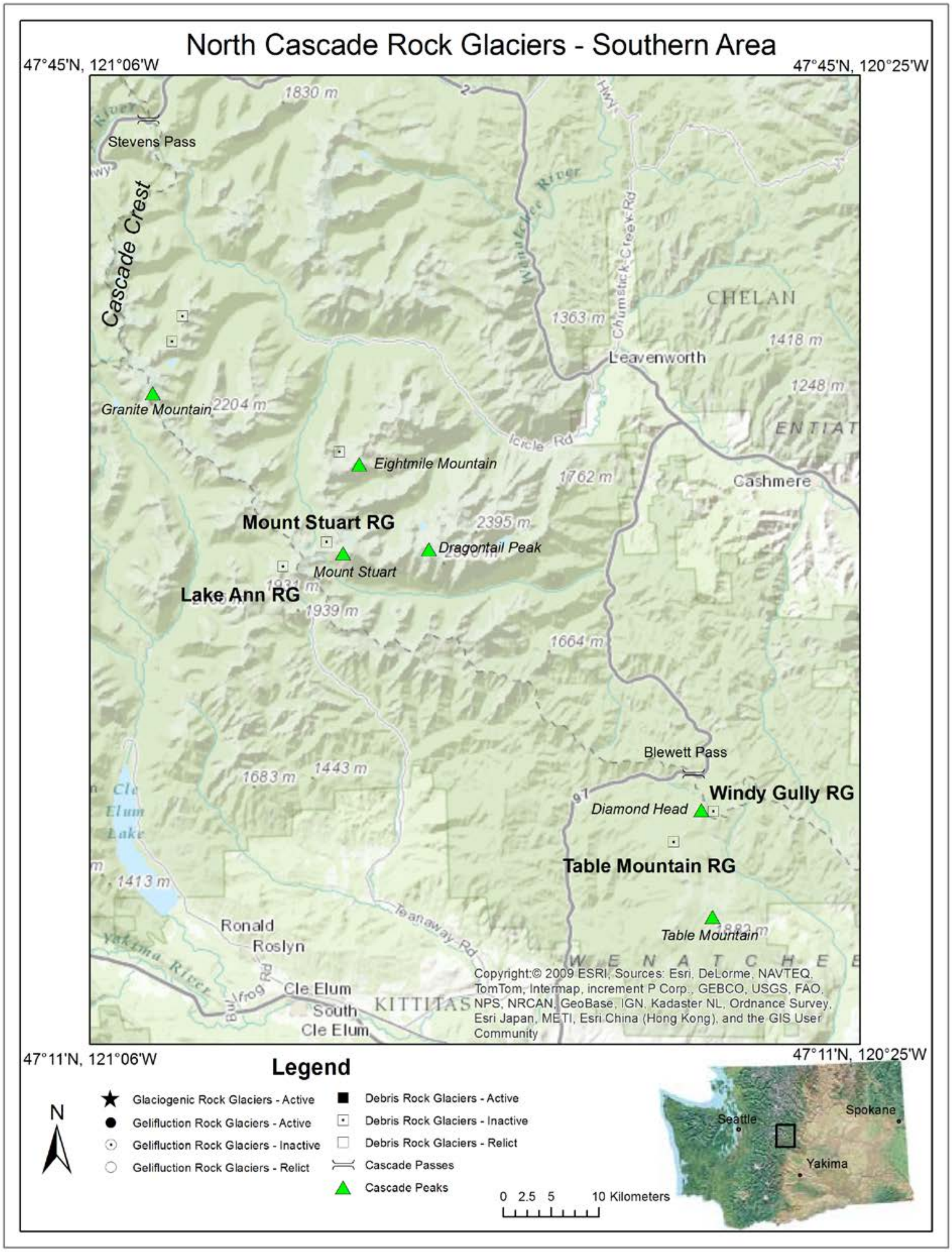

Figure **5-3:** North Cascade rock glaciers between Stevens and Snoqualmie Pass. (Names refer to rock glaciers visited in field.)

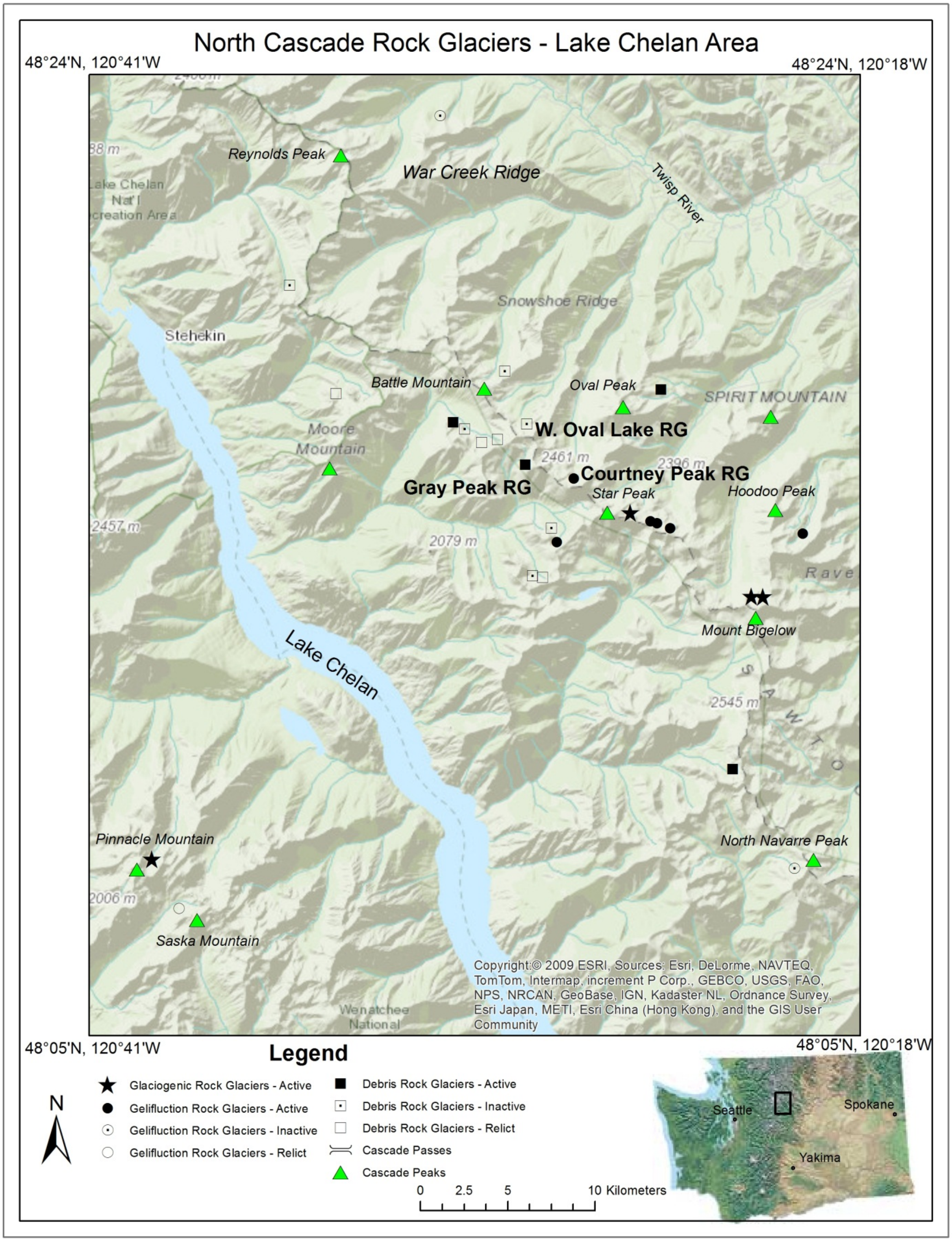

Figure **5-4:** North Cascade rock glaciers in the vicinity of Lake Chelan. (Names refer to rock glaciers visited in field.)

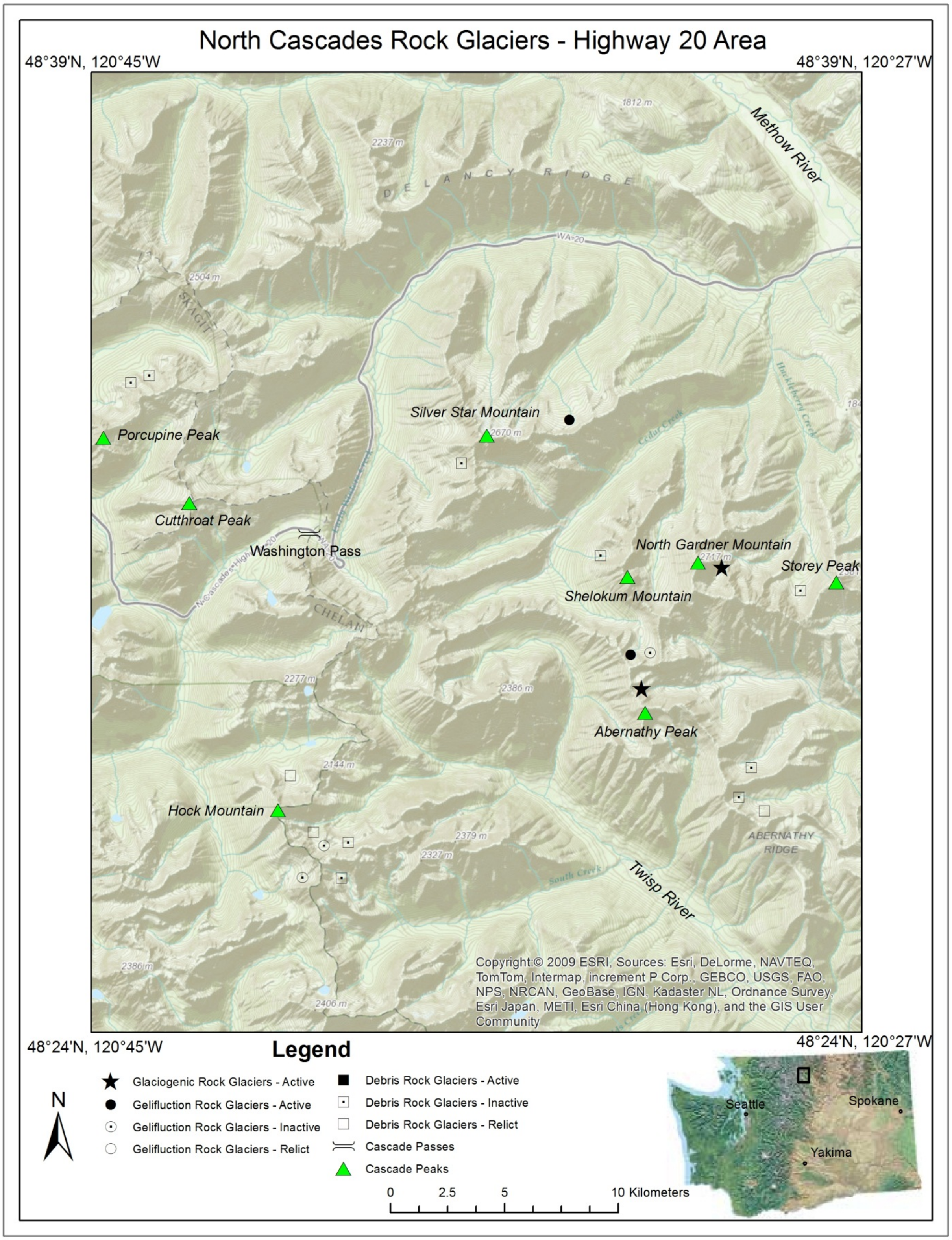

Figure **5-5:** North Cascade rock glaciers in the vicinity of Washington state highway 20.

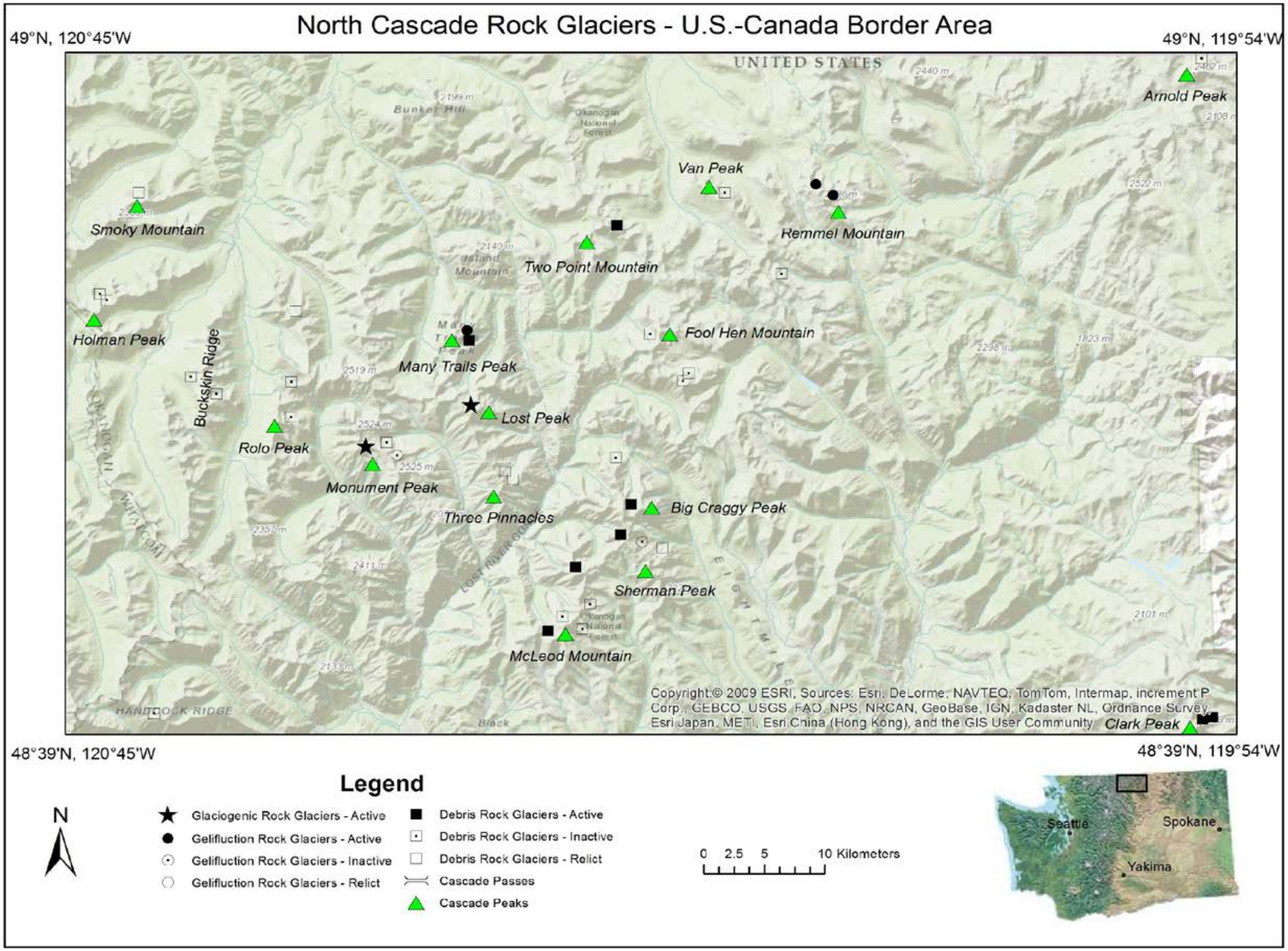

Figure **5-6:** North Cascade rock glaciers in the vicinity of the U.S.-Canada border area.

5.1.1 Latitude

Rock glaciers occur between 46°30’’N and 49°N in latitude, and between 119°34’’W and 121°20’’W in longitude (Figure 5-7). No rock glaciers were found between approximately 45°45’’N (Washington-Oregon border) and 46°30’’N (Goat Rocks). Rock glaciers are overwhelmingly concentrated in the northern latitudes of Washington, with 85 occurring in the North Cascades, versus only 18 in the South Cascades (Figures 5-2, 5-3, 5-4, 5-5, 5-6). Over half of the rock glaciers occur in the northern ¼ of Washington State (57), north of 48°25’’N (Figures 5-5, 5-6).

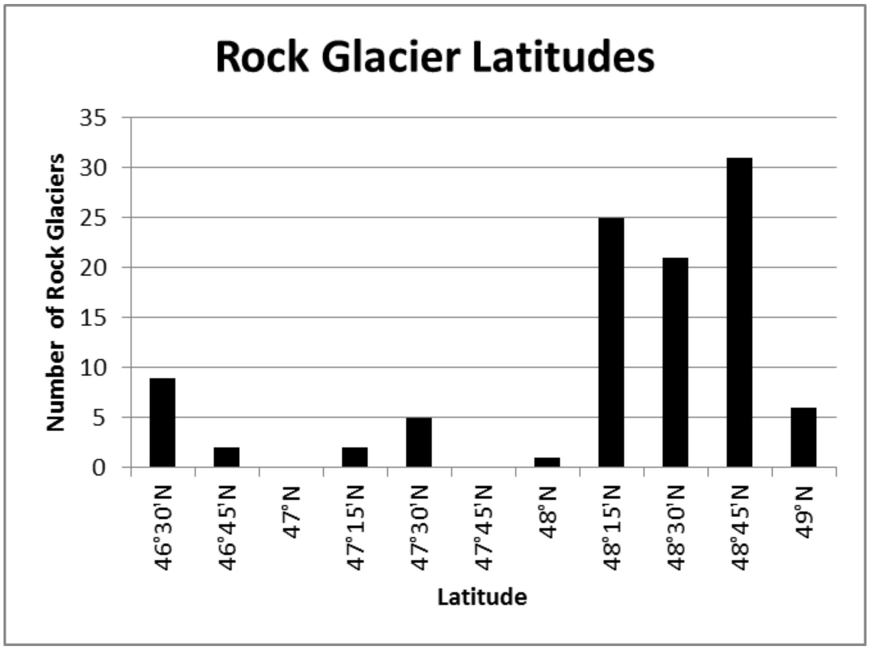

Figure **5-7**: Rock glacier latitude in the Eastern Cascades.

The spatial pattern of Eastern Cascade rock glaciers can be attributed to the climate of the Cascade Range. Climate gradually becomes colder further north, providing a more conducive climate for rock glacier growth. The mean elevation of the -2°C isotherm lowers because of the increase in latitude, creating a larger elevational range for rock glacier formation. Researchers elsewhere have found similar results.

In the Andes of South America, rock glaciers are numerous at 28°S; however, they become even more numerous at 35°S (Perrucca, 2011; Brenning, 2006). Likewise, in the Colorado Front Range, the northernmost and easternmost subrange of the Rockies in Colorado, rock glaciers occur in larger numbers than in the more southerly sub-ranges of the state (Janke, 2007). Although the Cascades in Washington only extend 4° of latitude, the principle is the same.

5.1.2 Elevation

Eastern Cascade rock glacier head elevations range from 1630m to 2574m (Figure 5-8). Head elevations for rock glaciers are observed to be concentrated between 2200-2350m, tapering off above 2400m. Only 31 rock glaciers have head elevations below 2200m, while 51 rock glaciers exist between 2200-2400m.

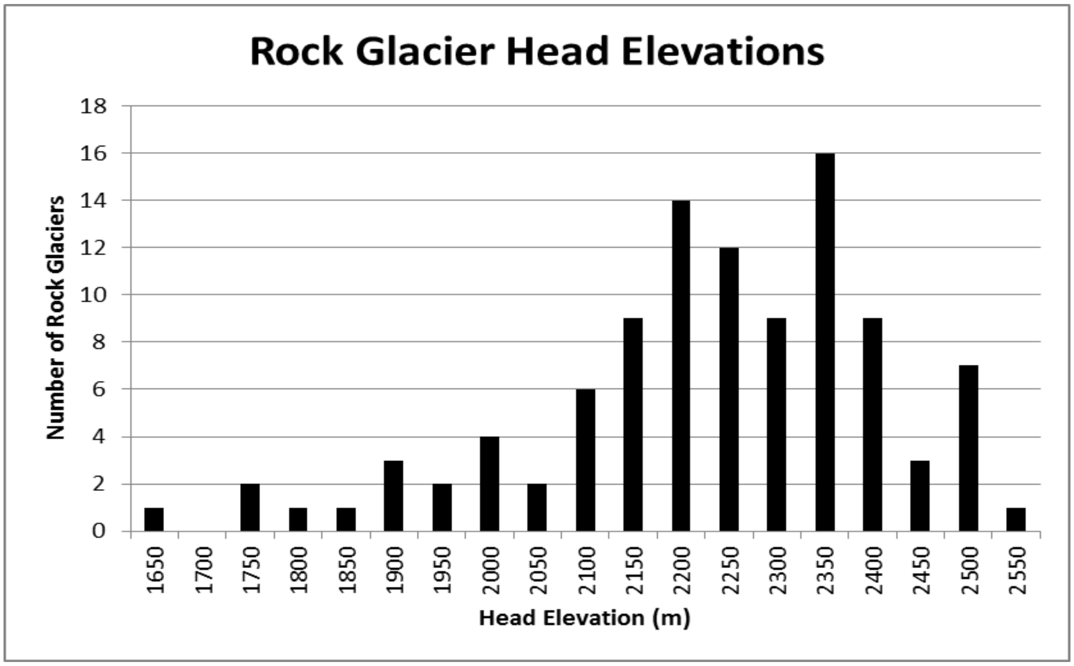

Figure **5-8**: Rock glacier head elevations in the Eastern Cascades.

Toe elevations were recorded and vary from 1540m to 2205m, however, they generally correlate to their respective rock glacier head elevations and do not provide useful material for analysis. The pattern of increasing numbers of rock glaciers existing at higher elevations is explained by a colder climate. Rock glaciers taper off above 2400m because the glacial threshold is near 2400m in the Eastern Cascades (Porter, 1977). Of the eight rock glaciers with head elevations near 2500m, five of them are glaciogenic. Rock glaciers do not occur in large numbers in the South Cascades (Figure 5-2) for latitudinal and elevational reasons. Many of the prerequisites for rock glacier formation are present in the South Cascades; however, the area is generally not sufficiently high enough to place rock glaciers below the -2°C isotherm. Given no change in other variables, climate would dictate that rock glaciers exist at lower elevations

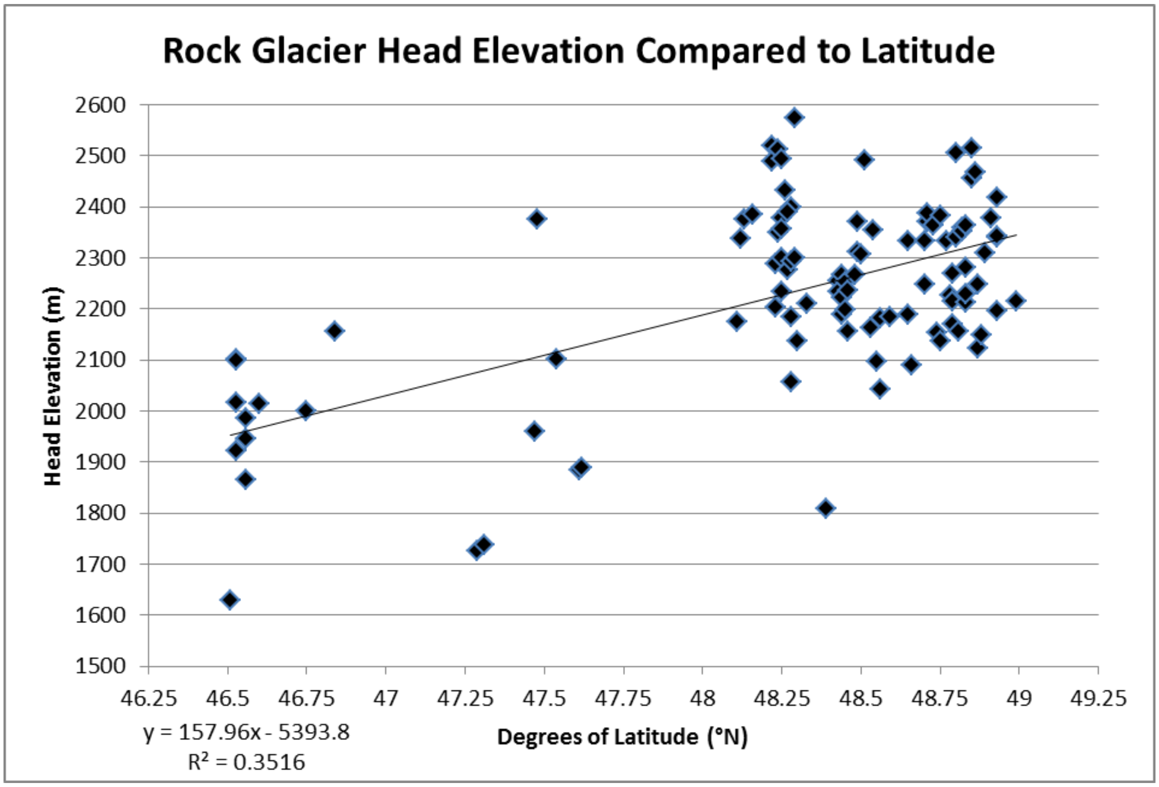

Figure **5-9:** Eastern Cascade rock glacier head elevation compared to latitude.

further north in the range. However, the opposite is illustrated in Figure 5-9. Rock glacier head elevations, on average, rise from 1950m at 46°30’N up to 2325m near the U.S.-Canada border (Figure 5-9). Rock glaciers are higher in elevation in the more northerly latitudes, partially due to an increase in the mean elevation of the Cascades going northward as well as increased continentality further north, causing warmer temperatures (Porter, 1977). Perhaps a certain threshold is also reached regarding rockfall in the North Cascades, below which it is not sufficient to sustain rock glacier growth. With a mean increase in range elevation, this threshold is higher in the North Cascades than in the South Cascades.

Elevation plays the largest role in determining rock glacier distribution in the Eastern Cascades, and in most other mountain ranges as well, which become colder with increasing elevation. In the Cascades, most rock glaciers exist no lower than 1800m (head elevation), regardless of what time period they formed. Three exceptions are found, two of which are near Blewett Pass and the other is near Darland Mountain in the South Cascades (Figures 5-3, 5-2). Both of the Blewett Pass rock glaciers are anomalies, with west aspects, low head elevations, large source areas, high rockfall, and basaltic rock (Windy Gully at 1732m and Table Mountain at 1727m). Local climate variance and shading seems to best support their existence at such low elevations. The Darland Mountain rock glacier (1630m) faces north, and exists due to extremely high amounts of basaltic rockfall in the surrounding area.

In other parts of the world, a strong correlation has been found between high-elevation areas and the existence of rock glaciers. Rock glaciers exhibit strong elevational gradients in the Rockies (Janke, 2007), Alps (Bodin, 2009), and Himalaya (Owen, 1998).

5.1.3 Aspect

The majority of Eastern Cascade rock glaciers face north to northeast, with only 29 facing between 270 and 360 degrees (Figure 5-10). No rock glaciers were recorded facing between 100 and 270 degrees. Sixty percent (64) of rock glaciers occur between 0 and 50° (Figure 5-10). The northerly aspect of Eastern Cascade rock glaciers is a result of decreased insolation on north-facing slopes at these mid-latitude, northern hemisphere sites, allowing colder temperatures and subsequent ice formation to dominate.

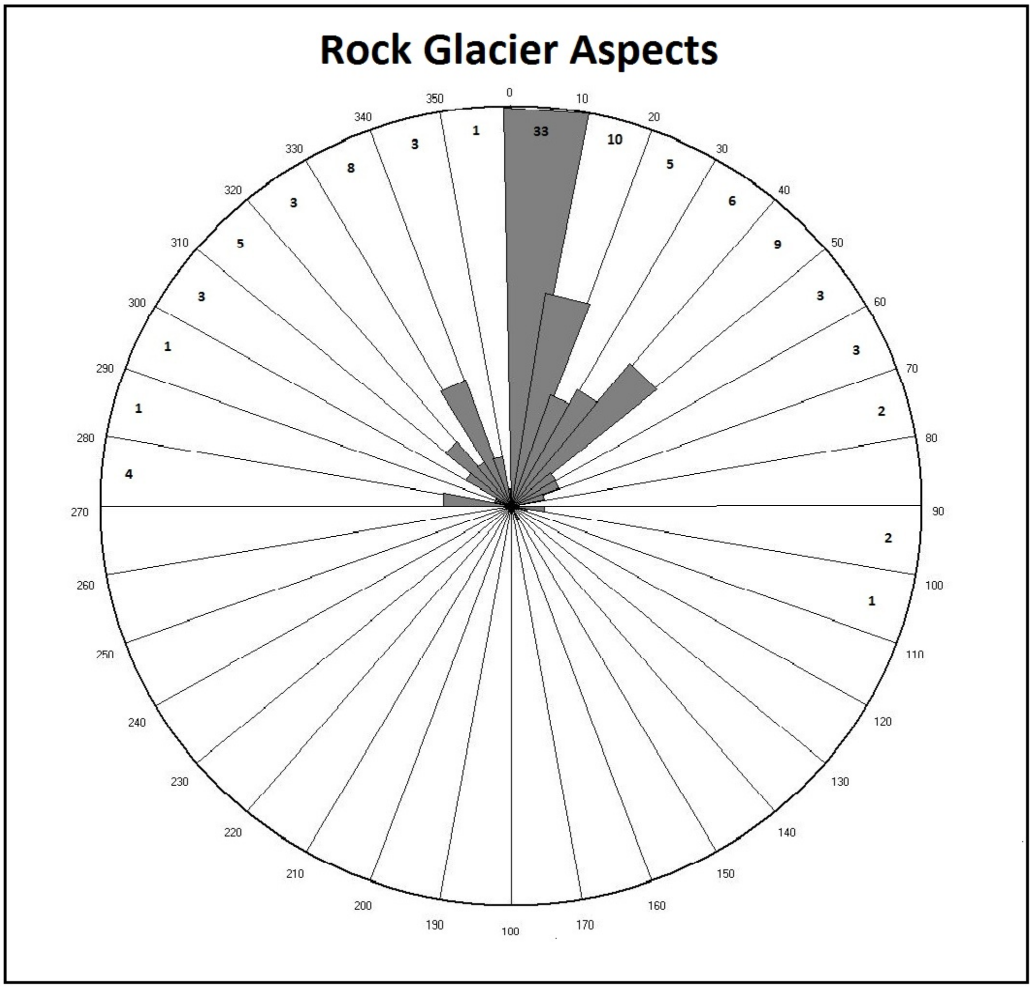

Figure **5-10:** Rock glacier aspects (in degrees) in the Eastern Cascades.

Rock glaciers often occur in vacated cirques, which also tend to face northward. Rock glaciers in the Eastern Cascades generally follow established trends for northern hemisphere glaciers and rock glaciers, which stay between 315 to 90 degrees (Evans, 1977). These results are similar to data from elsewhere in North America, such as the Rockies, showing a normal distribution (Janke, 2007).

5.1.4 Distance from crest:

Rock glaciers occur from 2 to 70km east of the Cascade crest (Figure 5-11). Mean distance from the Cascade crest is ~28km; however, the greatest number of rock glaciers occur approximately 40km east of the crest (Figure 5-11). Distance from the crest also influences rock glacier elevation, length and width, activity, and genesis type.

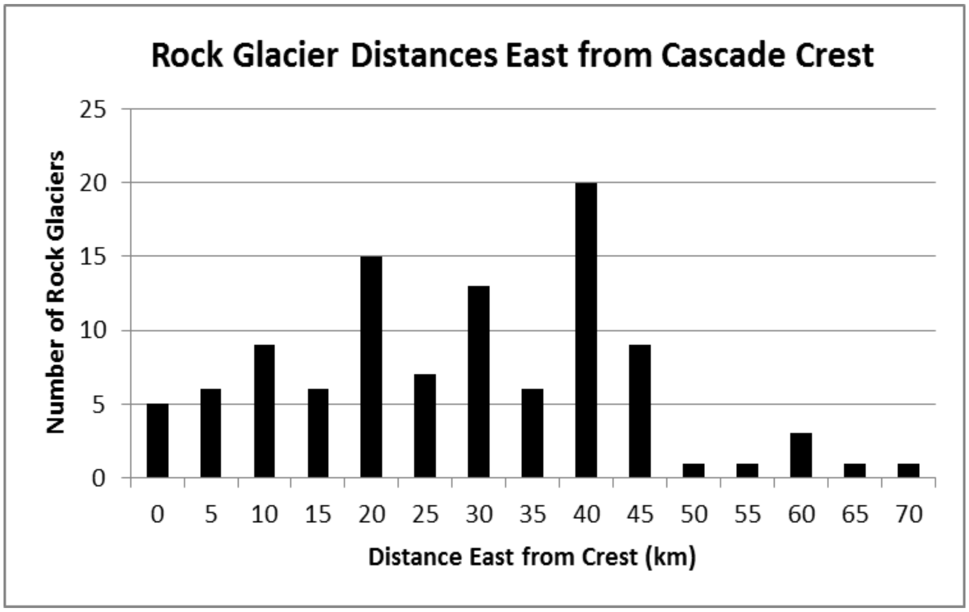

Figure **5-11**: Eastern Cascade rock glacier distances east from the Cascade crest.

Rock glaciers become more frequent further east of the crest because of the effects of continentality, which creates temperature extremes not seen in maritime climates. Colder winter temperatures and higher summer temperatures influence rock glacier development, with high summer temperatures being the limiting factor. Rock glacier density begins to fade >45km east of the crest, because of lower elevations in the far Eastern Cascades.

The width of the Cascade Range also plays a role in determining rock glacier distribution. The width of the Cascades affects how easily warm, moist air masses from the Pacific Ocean can penetrate inland during the winter months; a wider mountainous area prevents warm, moist air masses from entering more effectively than a smaller one. A strong rainshadow effect is the result of this phenomenon. The rainshadow effect is illustrated by areas near the Cascade crest receiving >100cm of precipitation per year, while the town of Twisp, WA 70km east of the Cascade crest receives ~37cm of precipitation per year (PRISM, 2012). A wider range allows sites east of the crest to receive the same amount of precipitation as an area further east from the ocean (i.e., more continental), while being closer to the ocean. Thus, rock glaciers further than 40km east of the Cascade crest receive <50cm of annual precipitation, which is conducive to maintained activity and growth. Therefore, more rock glaciers are able to exist further north because the North Cascades are wider than the South Cascades. A similar relationship between continentality and rock glacier distribution has also been noted in the Rockies and Alps (Janke, 2007; Roer, 2005).

Elevation also plays a key role in determining rock glacier distance from the Cascade crest (Figure 5-12). It is evident that head elevation rises eastward from the crest. This can be attributed to two separate factors. Rock glaciers that occur >30km from the Cascade crest also tend to occur in the northern ¼ of the state, where the average elevation of the range is higher. Also, although MATs are lower in the North Cascades in general because of northerly latitude and higher elevations, summer temperatures are also higher further inland. Rock glaciers occur at higher elevations in the North Cascades to escape higher summer temperatures, but also benefit from lower winter temperatures as well. This relationship has been observed in the Absaroka and Beartooth ranges of south-central Montana and north-central Wyoming, and the sub-ranges of the Colorado Rockies (Seligman, 2009; Janke, 2007). In both cases, rock glaciers were more prevalent at high elevations, limited by high summer temperatures.

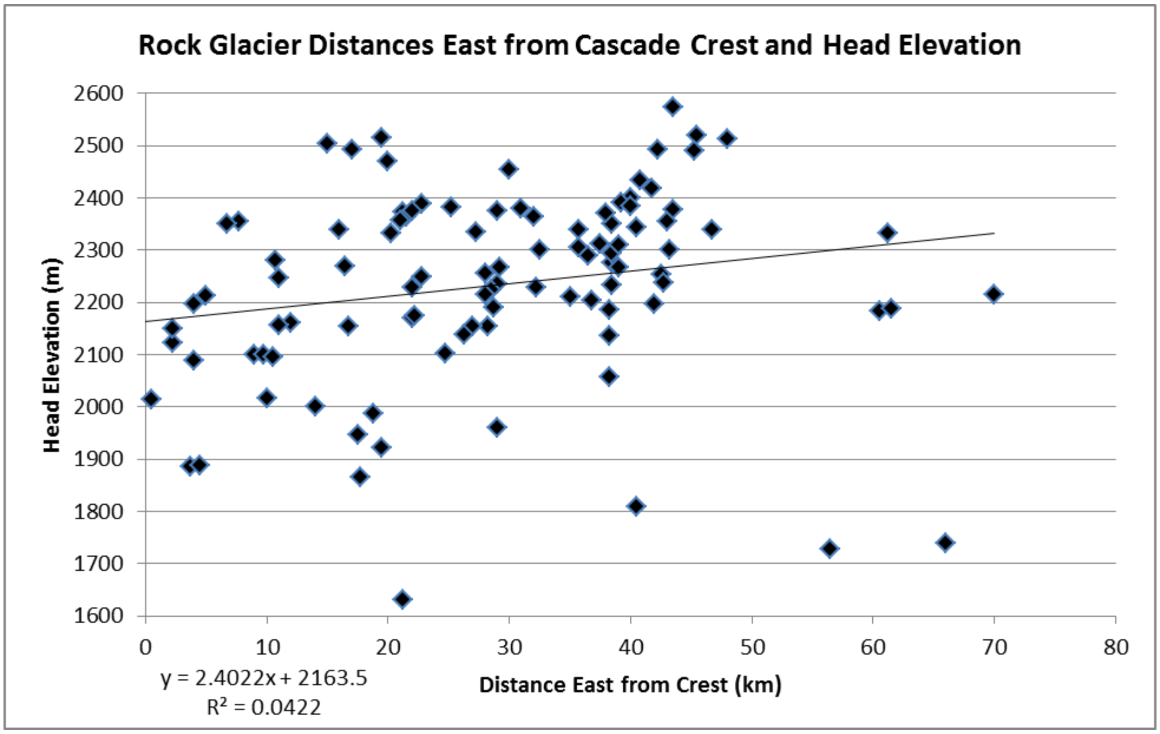

Figure **5-12:** Eastern Cascade rock glacier distance east from the crest compared to head elevation.

5.2 Genesis

5.2.1 Glaciogenic Rock Glaciers

A total of 8 glaciogenic rock glaciers were found in the study area (Table 5-1). Glaciogenic rock glaciers occur within a narrow latitudinal zone, from 48°07'N to 48°49'N in the northern section of the study area (Table 5-1). Head elevations for glaciogenic rock glaciers range from 2266 to 2520m, with a mean of 2437m. Toe elevations range from 2066 to 2196m, with a mean of 2146m. Glaciogenic rock glaciers occupy a narrow range of aspects, from 0 to 65 degrees. They occur between 15 and 45.5km east of the crest, with a mean distance of 31km.

Table **5-1:** Eastern Cascade rock glacier genesis type comparison.

Rock Glacier Genesis Type	***Mean Head Elevation (m)***	***Mean Toe Elevation (m)***	***Mean Aspect (°)***	***Mean Distance from Crest (km)***	***Latitudinal Range (°N)***	***Total Number of Rock Glaciers***
Glaciogenic	2437	2146	28	31	48°7' - 48°49'	8
Gelifluction	2250	2042	69	32.25	46°31'- 48°55'	23
Debris	2202	1919	129	26.6	Entire study area	72

Three glaciogenic rock glaciers occur in the Sawtooth Range (Figure 5-4) on Mt. Bigelow and Star Peak (Figure 5-14), while the other five are isolated from each other. They occur at the highest elevations, and only in the North Cascades. The average elevation of the Cascade Range is not sufficiently high in the areas south of Stevens Pass and east of the Cascade crest to support glaciogenic rock glaciers in the present climate regime. They do not occur more than 45.5km from the crest as a result of increased snowfall requirements for glaciogenic rock glacier formation than their periglacial counterparts. Rock glaciers closer to the Cascade crest receive more snowfall than those further east. They also exclusively face north-northeast, which is the preferred orientation for ice glaciers in the northern hemisphere (Evans, 1977). This is mirrored in the Cascades, with glaciers preferentially facing north to northeast (Mitchell, 2005). Glaciogenic rock glaciers occur ~150m below the present glaciation threshold for the Eastern Cascades, 2600m (Porter, 1977). Glaciogenic rock glaciers have the most stringent requirements for formation of any of the genesis types, and are exclusively active (Clark, 1998) (Figure 5-13). They cannot be identified as inactive or relict without field verification (Corte, 1987). Glaciogenic rock glaciers differ from periglacial rock glaciers (i.e., gelifluction and debris) because they possess a layered ice core, as opposed to interstitial ice. As a result, an inactive or relict glaciogenic rock glacier cannot be identified without viewing the ice core.

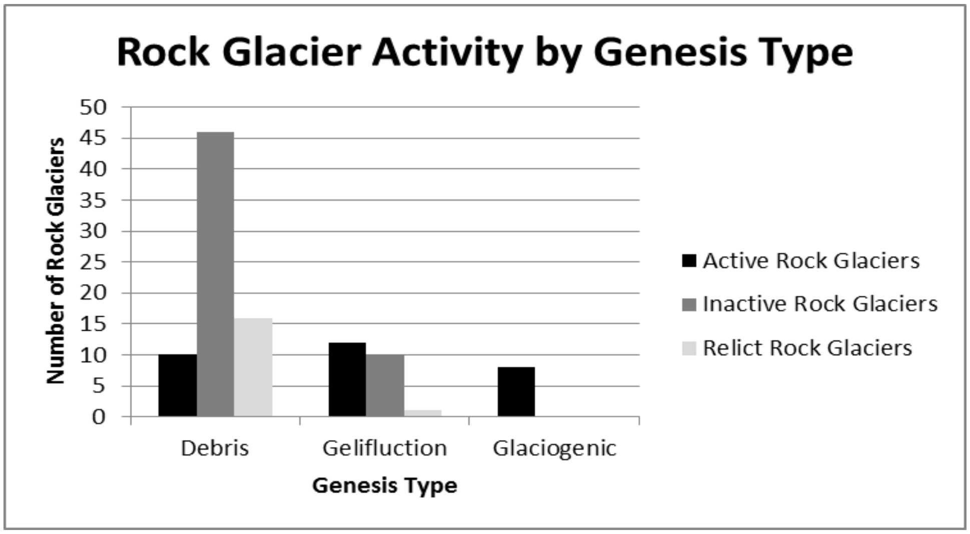

Figure **5-13:** Eastern Cascade rock glacier activity by genesis type.

Figure 5-14: Glaciogenic rock glacier on Star Peak, Sawtooth Range, North Cascades. View is towards the southwest.

5.2.2 Gelifluction Rock Glaciers

A total of 23 gelifluction rock glaciers were found in the study area (Table 5-1). They occur in a wide latitudinal zone, between 46°31’N and 48°55’N. Their head elevations range from 1809 to 2512m, with a mean elevation of 2250m. Toe elevations range from 1682 to 2205m, with a mean elevation of 2042m. Gelifluction rock glaciers also occupy a wide range of aspects, from 270 to 155 degrees, with a mean of 69 degrees. They occur between 0.5 and 60.5km from the crest, with a mean distance of 32.25km.

Gelifluction rock glaciers are nearly evenly split between active and inactive forms (Figure 5-13). Gelifluction rock glacier activity fits with general rock glacier trends in the Eastern Cascades, with more active forms further east of the crest (see section 5.3). A single relict form occurs 22km east of the crest (Saska Mountain, Figure 5-4), while inactive forms average 27.5km, and active forms are 39km east of the crest. The Saska Mountain relict form can be explained by its proximity to the crest, and its northwest facing aspect (315°). No other gelifluction rock glaciers face this direction. The combination of higher precipitation, northwest facing aspect, and cessation of rockfall supplying the adjacent boulder field explains its unique position. Activity increases eastward from the crest as precipitation declines creating a more favorable climate for rock glacier development. A fine example of an active gelifluction rock glacier is located in the Sawtooth Range on Oval Peak, 43.5km east of the crest (Figure 5-15).

The Eastern Cascades are remarkably similar to the northern Absaroka and Beartooth mountains of southern Montana regarding rock glacier genesis. In the higher elevation and generally colder Beartooths (i.e., North Cascades), glaciogenic rock glaciers comprise a higher percentage of rock glaciers than in the Absarokas (i.e., South Cascades). Rock glaciers in the Beartooths also generally face north-northeast (North Cascades), as opposed to Absaroka rock glaciers that face a variety of aspects (South Cascades). Favorable aspects and elevations of high basins in the Beartooths create ideal conditions for glaciogenic rock glaciers, which require a more rigorous set of climatic and topographic variables. Likewise, in the North Cascades, glaciogenic rock glaciers exist as a result of higher elevation and higher precipitation amounts. Gelifluction and debris-type rock glaciers are more common in the Absarokas than the Beartooths (Seligman, 2009). This is a result of the Absarokas receiving less winter snow because of a more continental location than the Beartooths. Periglacial rock glaciers (i.e., gelifluction) benefit from less precipitation and are also exhibit a wider array of aspects, and a larger elevation range. In the South Cascades and southern part of the North Cascades, periglacial rock glaciers are the only representatives to be found, as a result of lower elevations, a wide variety of aspects, and lower amounts of precipitation.

Figure **5-15:** Gelifluction rock glacier on Oval Peak, Sawtooth Range, North Cascades. View is towards the southwest.

5.2.3 Debris Rock Glaciers

A total of 72 debris rock glaciers (also called talus-derived or periglacial rock glaciers) were found in the study area (Table 5-1). They occur throughout the range, from 46°31’N to 48°59’N. Debris rock glacier head elevations range from 1630 to 2574m, with a mean elevation of 2202m. Toe elevations range from 1540 to 2182m, with a mean elevation of 1919m. They occupy the widest range of aspects of the three genesis types, from 270 to 100 degrees, with a mean aspect of 129 degrees. They range from 0 to 70km east of the crest, with a mean distance of 26.6km.

Debris-type rock glaciers were, by far, the most numerous in the study area. Their wide distribution east of the crest seems to be a result of ample rockfall. Steep couloirs and avalanche chutes tend to funnel more directed rockfall than to their gelifluction or glaciogenic counterparts, resulting in highly concentrated rockfall and long, tongue-shaped rock glaciers. Given the large number of inactive and relict forms within this class of rock glacier, it is not surprising that they have the lowest head elevations of the three genesis types. Active rock glaciers only comprise 16% of debris rock glaciers, while 52% of gelifluction and 100% of glaciogenic rock glaciers are active (Figure 5-13). Given their high rockfall and generally inactive state, the fact that debris rock glaciers also have a wide range of aspects logically follows. Debris-type rock glaciers are also the most flexible regarding climate, occurring as both the closest and farthest examples from the Cascade crest. Examples of debris rock glaciers abound in the Cascades, however, the form on Midday Mountain in the North Cascades illustrates the effect of couloirs on rockfall (Figure 5-16). Steep slopes directly below the couloirs on the north side of the mountain funnel rockfall, producing a characteristic tongue-shaped rock glacier.

Debris rock glaciers exhibit the widest range of aspect, elevation and spatial distribution. This is the case in the Rockies, Alps and Himalaya (Janke, 2007; Bodin, 2009; Shroder, 2000). Debris forms occur throughout the range, having little restriction compared to gelifluction or glaciogenic forms.

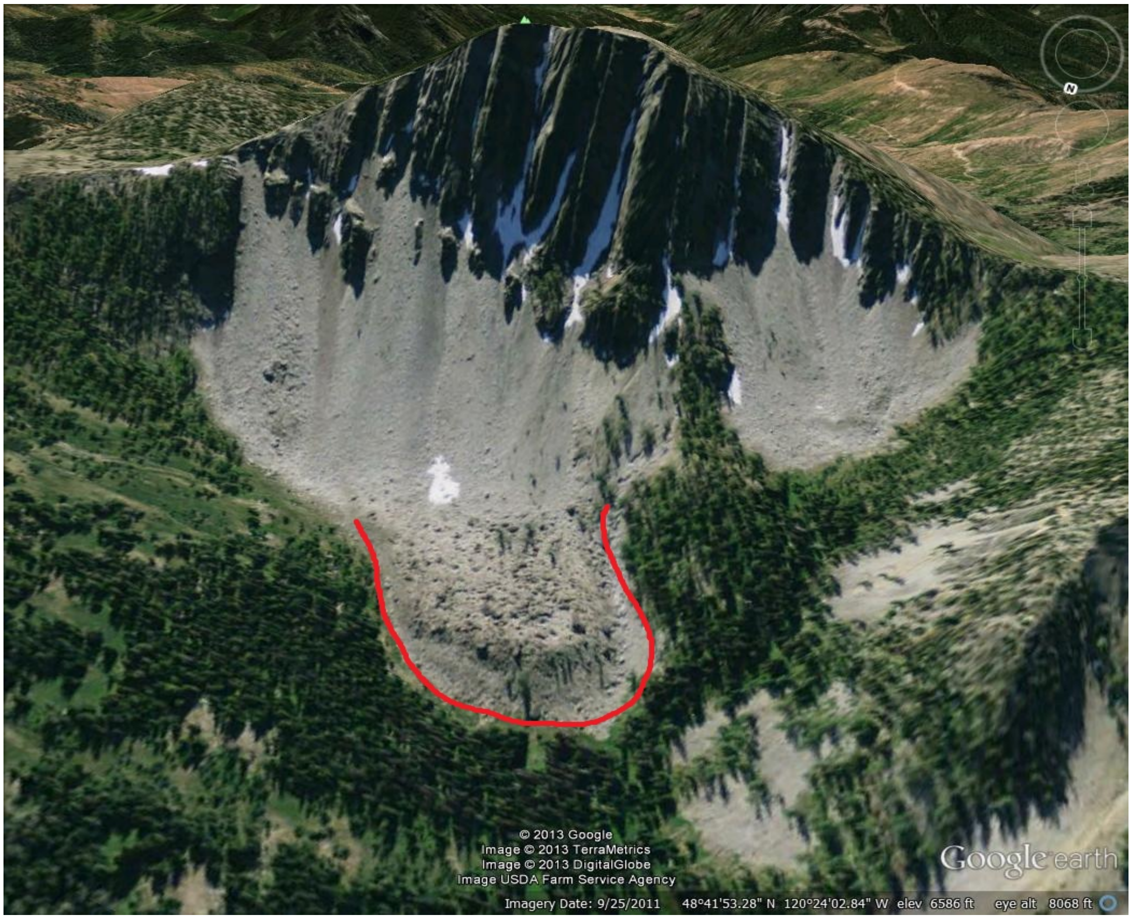

Figure **5-16:** Debris rock glacier on Midday Mountain, North Cascades. View is towards the south.

5.3 Activity

5.3.1 Active Rock Glaciers

A total of thirty (29% of total) active rock glaciers were found in the study area (Table 5-2). Active rock glaciers occur exclusively north of 48°N, with the southernmost active rock glacier on Pinnacle Mountain at 48°7’N. Head elevations for active rock glaciers range from 2096 to 2574m, with a mean elevation of 2376m. Toe elevations range from 1912 to 2205m, with a mean elevation of 2113m. Active rock glaciers face exclusively northwest to east-southeast (325 to 100°), with a mean aspect at 21°. Active rock glaciers occur between 10.5 and 61.5km east of the crest, with a mean distance of

35.5km. Only one cluster of active rock glaciers occurs, surrounding Star Peak (Figure 5-4). Twelve active rock glaciers occur in this area, less than 5km from Star Peak. One of these rock glaciers, on the north side of Courtney Peak, is a prime example of a fast-moving, active rock glacier (Figure 5-17). This cluster formed from a combination of abundant rockfall, a northwest-southeast orientation of the Sawtooth Range, a far distance from the crest, and low winter precipitation with low temperatures. Smaller clusters of two or three active rock glaciers occur elsewhere in the range, but do not exhibit the same characteristics as the large Star Peak cluster because of their lack of one or more of the previously mentioned factors.

Table **5-2:** Eastern Cascade rock glacier activity comparison between types.

Rock Glacier Activity Type	***Mean Head Elevation (m)***	***Mean Toe Elevation (m)***	***Mean Aspect (°)***	***Mean Distance from Crest (km)***	***Latitudinal Range (°N)***	***Total Number of Rock Glaciers***
Active	2376	2113	21	35.5	North of 48°	30
Inactive	2133	1878	356	25.5	46-49°	56
Relict	2169	1872	0	24.2	Near 46°, north of 48°	17

Active rock glacier distribution in the Eastern Cascades is based on temperature, primarily affected by elevation, aspect, latitude and continentality. The current 0°C isotherm is near 2100m in the North Cascades (PRISM, 2012). Active rock glaciers can only form at or under -2°C; however, they can continue to stay active at the 0°C isotherm once they have formed. Although elevation plays the largest role in determining temperatures that shape active rock glacier distribution, a north-facing aspect combined with a greater distance from the crest could push the microscale climate surrounding a rock glacier lower than 0°C, even when the general area surrounding the rock glacier has a MAT of 0°C. Given constant latitude and elevation, MATs generally decline moving east of the Cascade crest. This is illustrated by two rock glaciers at nearly the same elevation. The rock glacier on Buckskin Ridge (west side of Figure 5-6) has a MAT of 0.96°C, while the rock glacier on Arnold Peak (northeast corner of Figure 5-6) 65 km to the east has a MAT of 0.33°C (PRISM, 2012). On the microscale, a well-shaded, north-facing cirque has the potential to lower the MAT by several degrees due to blockage of solar insolation (Mitchell and Montgomery, 2005). In addition, rock glaciers further east of the crest are more subject to cold, dry, winter air masses traveling south from northern

Figure **5-17:** Active rock glacier on Courtney Peak, Sawtooth Range, North Cascades. View is towards the east.

regions. Low winter temperatures tend to determine active rock glacier distribution more than summer temperatures, because of the insulating effects of the debris cover (Degenhardt, 2009).

5.3.2 Inactive Rock Glaciers

A total of 56 (54% of total) inactive rock glaciers were found in the study area (Table 5-2). Inactive rock glaciers occur throughout the study area, from the southernmost on Darland Mountain (46°31’N), to the northernmost on Arnold Peak (48°59’N) (Figures 5-2, 5-6). Inactive rock glaciers are evenly spread in the study area, with as many occurring in the North Cascades as in the South Cascades. Inactive rock glaciers do not occur in large clusters, with four southeast of Hock Mountain constituting the largest single cluster (Figure 5-4). Head elevations range from 1630 to 2455m, with a mean elevation of 2133m. Toe elevations range from 1540 to 2164m, with a mean elevation of 1878m. Inactive rock glaciers have a wide range of aspects, facing from 270 to 155 degrees, with a mean aspect of 356 degrees. Inactive rock glaciers also have the widest range of distances east of the crest, from 0.5km to 70km. Mean distance from the crest is 25.5km.

Inactive rock glaciers tend to occur in the South Cascades and southern part of the North Cascades as a greater percentage of the total number than in the north part of the North Cascades. They occur at middle elevations as compared to active and relict rock glaciers, evidenced by the large rock glacier on Mt. Stuart (Figure 5-18). Inactive rock glaciers lack a strong latitudinal zone because of their transitional state from active to relict forms, meaning that they can occur anywhere in the range. This also explains the wide variance in elevations and aspects. Inactive rock glaciers occur closer to the crest than active rock glaciers, as a result of a colder past climate.

Inactive rock glaciers in the Eastern Cascades are similar to other Western Cordillera sites in elevational relationships with other forms, but differ slightly in mean aspect and are unique regarding distance from the crest. Inactive rock glaciers in the Eastern Cascades occur about 250m below active forms, however, they tend to have aspects nearer to northwest than active forms. Their distance east of the crest has a large effect on their distribution, which is not seen in most continental mountain ranges. The Colorado Front Range contains inactive rock glaciers with a dominant northeast aspect (56.8°) versus active forms that face closer to north (48.5°). They occur an average of

Figure **5-18:** Inactive rock glacier on Mt. Stuart, southern North Cascades. View is towards the northeast.

120m below active forms (3594m vs. 3477m) (Janke, 2007). Rock glaciers in the Front Range also are not affected by their distance from the continental divide, because the Rockies are already a continental mountain range.

5.3.3 Relict Rock Glaciers

A total of 17 (17% of total) relict rock glaciers were found in the study area (Table 5-2). Relict rock glaciers are concentrated in the far southern and far northern parts of the study area, with four occurring near Darland and Bear Creek Mountains in the southern Cascades (46°32’N), and the other thirteen occurring north of Saska Mountain (48°7’N). Relict rock glacier head elevations range from 1921 to 2300m, with a mean elevation of 2169m. Toe elevations range from 1720 to 2072m, with a mean elevation of 1872m. Relict rock glacier aspects range from 300 to 75 degrees, with a mean of 0 degrees. Distances from the crest range from 4 to 42km, with a mean distance of 24.2km.

The lack of relict rock glaciers in the middle part of the range can be attributed to the distance east of the crest and the effects of microclimates. Rock glaciers in the southern part of the North Cascades generally occur in well-shaded environments (with the exception of the Mt. Stuart rock glacier), and are located further than average east of the crest (with the exception of the French Ridge rock glaciers) (Figure 5-3). The occurrence of relict forms in the North Cascades points to the large number of rock glaciers there to begin with, and that they exist at lower elevations than their inactive and active counterparts (Figures 5-3, 5-4, 5-5). Relict forms are generally large, as a result of their maturity, as illustrated by the Hock Mountain rock glacier (Figure 5-19). Active and inactive forms tend to be smaller, with active forms being the smallest.

In this study, only 16.5% of the rock glaciers were classified as relict. This is a result of two causes. Not all relict rock glaciers can be readily identified from satellite and aerial imagery, because some may be completely overgrown with vegetation and difficult to distinguish, contributing to the low number. Conversely, slow soil formation on some inactive rock glaciers may have led to them being wrongly classified as inactive

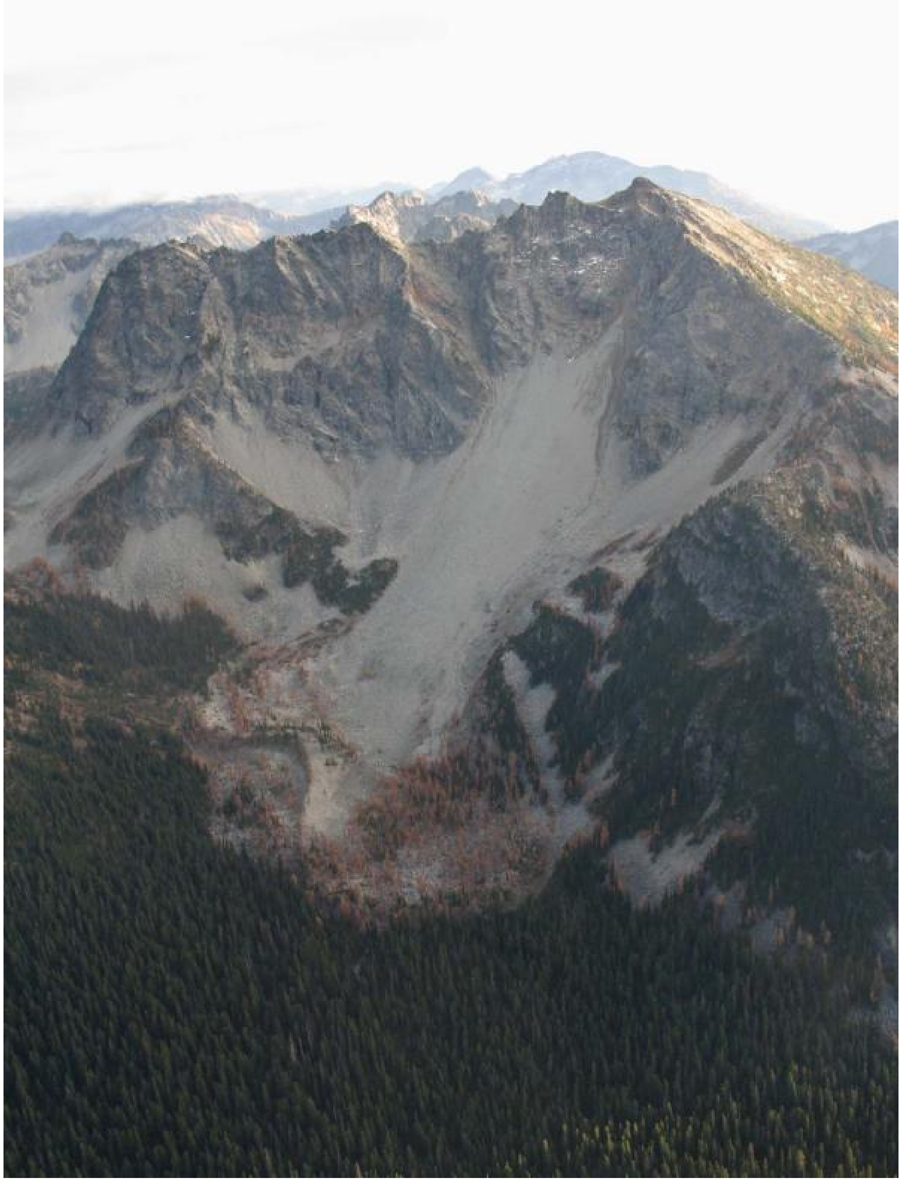

Figure **5-19:** Relict rock glacier on Hock Mountain, North Cascades (© John Scurlock).

rock glaciers. Further, the climate of the Cascade Range (see below) may have been conducive to active rock glaciers in the recent past (<200 years), which has not given active and inactive rock glaciers time to become relict. Relict rock glaciers are common features in continental mountain ranges. Compared to other ranges in the Western Cordillera, the Eastern Cascades lack significant numbers of relict rock glaciers. In the Colorado Front Range, out of 220 total rock glaciers, 85 (43%) of them are relict (Janke, 2007), while in another part of the Rockies, 15 out of 48 rock glaciers (31%) are relict (Johnson, 2007). I believe this is a result of the relatively recent formation of many Eastern Cascade rock glaciers (see below).

5.4 Age

Eight rock glaciers were visited in the field and were dated via dendrochronology, lichenometry and weathering rinds (Table 5-3).

5.4.1 Shoe Lake Rock Glacier (South Cascades)

The Shoe Lake rock glacier was the southernmost visited rock glacier (Figure 5-2), and nearest to the Cascade crest (0.5km east). Much of the rock glacier is bare of any vegetation, and only a few small trees grow near the base of the rock glacier toe. The sampled tree on the Shoe Lake rock glacier is 2m tall, and has 29 annual rings (Table 5-3). Adding to this a reasonable stabilization period of 150 years, dendrochronology suggests the Shoe Lake rock glacier became inactive in the mid to late 20th century, putting it in a young age group. An additional lag time of 10-20 years is required, for tree ecesis (Luckman, 2000). Therefore, the revised date with a lag time of 170 years is ~1810 AD, when climatic change on the Shoe Lake rock glacier occurred.

The lichen dates suggest the Shoe Lake rock glacier is much older than indicated by the tree dates. This seems to be a result of slow soil formation and poor growing conditions for trees. Field observations indicate very little soil development in the furrows of the rock glacier. Therefore, the lichen date seems more accurate because of the tolerance of lichen to extreme climates, placing it with its counterparts in the southern part of the North Cascades (Table Mountain and West Lake Ann). Assuming a lag time of 150 years in addition to the lichen growth time, an age of 240 years is obtained, indicating that the rock glacier began to stabilize at 1770 AD. This date corresponds well with the LIA, which lasted until 1850 AD (Steinman et al, 2012). Weathering rinds were not obtained from the Shoe Lake rock glacier.

5.4.2 Table Mountain Rock Glacier (Southern North Cascades)

The Table Mountain rock glacier, in the Wenatchee Range (Figure 5-3), is similarly bare of vegetation, except near the base, where multiple 6m tall subalpine firs are growing. An age of 68 years was determined here, based on tree rings (Table 5-3). Dates obtained from lichen showed an age of approximately 70 years, a near match with the tree dates. In this case, the soil on the lobes of the rock glacier is well-developed and conducive for tree growth. With the addition of a 150-year lag time, (in addition to a 20-year tree ecesis period) the approximate date of a changing climate on the Table Mountain rock glacier is 1783 AD. Weathering rinds were also obtained on the toe of the Table Mountain rock glacier. A rind thickness of 1.4mm on Yakima Valley deposits on the Colman and Pierce (1981) curve corresponds to 300ka, which also represents the limit of the curve. The Table Mountain rock glacier contains rinds with a mean thickness of 2.1mm, indicating a much older age, approaching 450ka.

Table **5-3:** Eastern Cascade Rock Glaciers sampled for tree, lichen and weathering rind data.

Rock Glacier	**Latitude/ Longitude**	**Gen. Type**	**Act. Type**	**Head Elev. (m)**	**Tree Species**	**Tree Ring Age (actual)**	**Tree Ring Age + lag Time**	**Toe Mean Lichen Diam. (mm)**	**Lichen Age**	**Lichen Age + lag Time**	**Rock Type**	**Toe Mean Wx Rind Thickness (mm)**
Shoe Lake	46°35'42"N, 121°23'51''W	Ge	In	2014	Mtn Hemlock	29 years	195±5 years	41.53	~90 years	~250 years	Andesite	2.49
Table Mountain	47°17'34"N, 120°35'57''W	De	In	1727	Subalpine Fir	68 years	233±5 years	33.15	~70 years	~230 years	Basalt	2.1
Windy Gully	47°18'41"N, 120°33'42"W	De	In	1738	N/A	N/A	N/A	27	~58 years	~218 years	Basalt	3.02
West Lake Ann	47°27'56"N, 120°57'55"W	De	In	1961	Western Larch	72 years	237±5 years	41.48	~90 years	~250 years	Serpentine	N/A
Mount Stuart	47°28'51"N, 120°55'27"W	De	In	2376	Subalpine Larch	225 years	390±5 years	141.5	>160 years	>310 years	Granodiorite	N/A
Courtney Peak	48°15'46"N, 120°26'55"W	Ge	Act	2433	N/A	N/A	N/A	N/A	N/A	N/A	Granite	N/A
Gray Peak	48°16'8"N, 120°28'29"W	De	In	2390	N/A	N/A	N/A	33.29	~80 years	~240 years	Gneiss	12.38
West Oval Lake	48°16'51'', 120°28'1"W	De	In	2400	Western Larch	390 years	555±5 years	37.3	~70 years	~240 years	Granite	N/A

Lichen growth curve based on O'Neal (2003). Weathering rind curve based on Colman and Pierce (1981).

5.4.3 Windy Gully Rock Glacier (Southern North Cascades)

The Windy Gully rock glacier, at the north end of Table Mountain in the Wenatchee Range, is nearby the Table Mountain rock glacier (5km northeast), and is at a similar elevation. The Windy Gully rock glacier (Figure 5-3) did not have any trees growing on its surface. Poor soil formation in furrows and on the toe likely precluded tree growth. This most likely results from where the rock glacier gained its name; from field observations, the gully the rock glacier is located in is usually quite windy. The breeziness of the gully blows soil parent material down valley, but does not allow it to settle. Lichen samples gave a minimum age of 58 years (Table 5-3). A revised age with lag time reveals ~1803 AD as the date of a changing climate. Weathering rinds were also obtained, with average thicknesses of 3mm. When applied to the Colman and Pierce (1981) curve, the age is >300ka. If the curve continues linearly up to 3mm, the rock glacier could be >600ka. On both the Table Mountain and Windy Gully rock glaciers, extremely old ages could have only been obtained if the general area was not glaciated. This is substantiated by Tabor et al (1982), which shows glaciation nearby, 10km to the northwest in the Stuart Range, however, the Table Mountain complex has no evidence of glaciation.

5.4.4 West Lake Ann Rock Glacier (Southern North Cascades)

The West Lake Ann rock glacier was a unique case for rock type, being the only rock glacier composed of serpentine (Table 5-3). Dendrochronology was successful, however, the first tree sampled may have been already rooted in an older inactive section of the rock glacier because it was the only tree in the area taller than 10m. The other tree was found to be 72 years old. Lichen dates were similar to the tree dates, giving an age of

90 years (Table 5-3). With tree ecesis taken into account, both dates fall near 90 years. With lag time, climate appears to have changed near 1771 AD. Weathering rinds were non-existent on the West Lake Ann rock glacier.

5.4.5 Mount Stuart Rock Glacier (Southern North Cascades)

The Mount Stuart rock glacier was the largest rock glacier visited in field, nearly ½km in length (Figure 5-3). The rock glacier has some of the tallest trees and largest lichens observed on a rock glacier in the Cascades. Dendrochronological measurements indicate an age of 225 years for the rock glacier. Likewise, lichen diameters are too large for the O'Neal growth curve, which stops at 80mm. Lichen diameters of up to 170mm were observed, with an average of 141.5mm. This corresponds to an age older than 160 years, where the O'Neal growth curve stops. Using the tree ring date with an average lag time, the Mount Stuart rock glacier started changing activity states at 1621 AD, a much older age than the previously mentioned rock glaciers to its south (Shoe Lake, Table Mountain, Windy Gully, West Lake Ann). Its head elevation is also still above the 0°C isotherm (2376m) for this area of the Cascades. The major factor limiting this rock glacier seems to be rockfall. From field observations, the rock glacier has almost decoupled itself from its source area, a high cirque on the northwest side of Mount Stuart (Figure 5-18). Weathering rinds were non-existent on the Mount Stuart rock glacier.

5.4.6 Courtney Peak Rock Glacier (North Cascades)

The Courtney Peak rock glacier is the only active rock glacier visited in the field (Figure 5-17). The rock glacier is devoid of trees, lichen or weathering rinds (Table 5-3). It has a fairly steep front slope (40°) and well defined ridges and furrows. Its head elevation is still well above the current 0°C isotherm for the North Cascades, therefore it can be expected that this rock glacier will stay active for some time into the future.

5.4.7 Gray Peak Rock Glacier (North Cascades)

The Gray Peak rock glacier is on a high, west-facing slope in the Sawtooth range of the North Cascades (Figure 5-4). Trees were observed growing around the edges of the rock glacier, but not within or on the surface as a result of poor soil development on the rock glacier. Lichen measurements averaged 33.2mm, corresponding to an age of 70 years (Table 5-3). Coupled with a lag time of 150 years, this rock glacier seems to be an LIA feature, changing states at 1791 AD. Weathering rinds were obtained from the Gray Peak rock glacier, averaging 12.38mm. However, there is no rind curve for gneissic rocks in the Cascades. Even if the granitic curve developed by Porter (2008) is used, it only goes up to 3mm. This suggests that the rock glacier is well older than the maximum 3,000 years indicated on the Porter curve. If a weathering rind curve for gneissic rocks is developed, future researchers can use these data.

5.4.8 West Oval Lake Rock Glacier (North Cascades)

The West Oval Lake rock glacier was the final field-examined rock glacier. Tree cores and lichen measurements were both successfully taken, giving ages of 555 and 230 years with lag time, respectively (Table 5-3). This rock glacier presents an interesting case, because the lichen and tree dates do not match. I believe this can be explained by the mismatch between lichen growth rates on the western and eastern sides of the Cascade range. The West Oval Lake rock glacier is 40km east of the crest, in the Sawtooth Range northeast of Lake Chelan (Figure 5-4). This a relatively dry area of the range, averaging only ~140cm of precipitation per year, versus the Mt. Stuart rock glacier, which receives ~190cm of precipitation, and the Shoe Lake rock glacier, which receives ~210cm of precipitation per year (PRSIM, 2012). This should drastically reduce lichen growth rates, especially during the summer months. In this case, the tree date seems more reliable. The West Oval Lake rock glacier is by far the oldest inactive form visited in the field. Coupled with a 150 year lag time, this rock glacier started changing states in the late 15th century ~1456 AD at the beginning of the LIA (Table 5-3). The rock glacier is still well above the 0°C isotherm (2400m), therefore I believe rockfall is the limiting factor, similar to the Mount Stuart rock glacier. Field observations indicate that the rock glacier advanced sufficiently far from its source cliff, and was unable to continue due to a lack of rockfall. Weathering rinds were non-existent on this rock glacier.

5.4.9 Entire Eastern Cascades

Rock glaciers visited in the field can be split into two groups. The first group, with five rock glaciers (Shoe Lake, Table Mountain, Windy Gully, West Lake Ann, Gray Peak) will be called the late Little Ice Age group. All of these rock glaciers started becoming inactive at the end of the LIA, in the late 18th to early 19th century. They seem to have been almost entirely climate driven. The second group (Mount Stuart, West Oval Lake) does not seem to have been limited by climate, instead becoming inactive in the beginning-middle of the LIA. Instead, these rock glaciers were limited by the source of their growth, rockfall. Rockfall may have been limited by a change in climate, which would slow weathering rates, or by a slowing of jointing and stabilization of the cliff or rockwall.

5.5 Paleoclimatic Implications

Three distinct categories for rock glaciers in the Eastern Cascades are shown below, based on latitude.

5.5.1 South Cascades

In the South Cascades, the Shoe Lake rock glacier (head elev. 2014m) indicates that a MAT of 0°C existed there as recently as the early 20th century. PRISM data indicates the MAT for 1895-1924 was -0.2°C. The current 1981-2010 MAT at the Shoe Lake rock glacier is 1.9°C, and the current 0°C isotherm exists at 2250m in much of the South Cascades (PRISM, 2012). According to these data, the South Cascades in this specific area have risen 2°C in the last 100-150 years.

5.5.2 Southern Part of North Cascades

For the southern part of the North Cascades, the current 0°C isotherm lies at 2100m. In the Table Mountain area, a MAT of 0°C probably existed until the late 18th century. Current MATs at 1750m on Table Mountain are 3.6°C. Both of these rock glaciers are extremely well shaded by surrounding cliffs, and although they both face northwest-west, the microclimate surrounding them must have been conducive to their growth. Therefore, I propose that the area was not under the 0°C isotherm in general, but that microclimates surrounding the rock glaciers provided them with sufficiently cold temperatures to sustain an active state. Temperature rise at Table Mountain most likely rose in tandem with other areas of the Cascades, a near 2°C increase. The sites immediately surrounding the Table Mountain and Windy Gully rock glaciers accounted for another 0.6-1.6°C of cooling, as a result of their microclimates. In the Mt. Stuart/Lake Ann area, the 0°C isotherm seems more representative of the range as a whole. Mt. Stuart has already been discussed as a special case involving rockfall, so only Lake Ann will be considered here. The West Lake Ann rock glacier became inactive sometime before 1920, probably in the latter half of the 19th century. The current MAT for the rock glacier is 2.3°C. This would imply a 2°C rise in temperature over the last 100-150 years, similar to that seen at Shoe Lake.

5.5.3 North Cascades

In the North Cascades, the current 0°C isotherm lies between 2050-2100m, depending on distance east of the Cascade crest. The head elevations of both the Gray Peak and West Oval Lake rock glaciers lie above the current 0°C isotherm. There is field evidence that both still contain an ice core, however, they have both stopped moving. Both have meltwater streams coming from the toe, and have relatively steep front slope angles (30° and 33°, respectively). While the head elevations of both rock glaciers lie above the 0°C isotherm, their toes have a MAT of 0.6°C. Both of these rock glaciers became inactive within the last 70-150 years. Thus, it seems that temperatures have risen about 2°C since the mid to late 19th century, which is consistent with the results from the South Cascades and southern North Cascades.

5.5.4 Greater Eastern Cascades and Regional Correlations

Inactive and relict rock glaciers can be extrapolated to include much of the past climate of the Eastern Cascades. Relict rock glaciers in the study area (of which the Mt. Stuart rock glacier is the closest form visited in the field) have an average elevation near 1900m (Table 5-2). Given that the amount of vegetation cover is >50%, and that tree height generally exceeds 10m, this would indicate that the 0°C isotherm has been above 1900m for at least 200 years. With inactive forms averaging near 2000m, this would indicate that the 0°C isotherm has been above this elevation for at least 100 years.

Taking all of these areas together, it seems that the 0°C isotherm has risen in elevation by 250-300m over the last 100-150 years. The present glaciation threshold for the Eastern Cascades is ~2400m (Porter, 1977). This has also risen by at least 200m in the last 100 years (Porter, 1977). Marcott et al (2008) found that temperatures have risen at least 0.6°C in the central Oregon Cascades since the end of the LIA, or an increase of 300m in elevation. Glaciation threshold in the southern Coast Mountains of British Columbia has also risen nearly 100m in the last 100 years, or 0.2°C (Koch et al, 2009). This is also consistent with other mid-latitude mountain ranges. In the Alps of Switzerland, researchers have found an increase of 250m in the 0°C isotherm since 1890 (Roer et al, 2005). Average winter temperatures in this area of the Alps have increased from -1.2°C to 0.9°C over the same period (1890-present), a more than 2°C increase. Mountain and alpine areas have also generally risen in temperature faster than the rest of the world average for the 20th century, which stands at about 1°C of temperature rise (IPCC, 2007). Because rock glaciers are static and cannot retreat upslope like ice glaciers, they lose their ice cores and become inactive, but often only after a substantial lag time of 100-150 years. Little Ice Age data for the Cascades and elsewhere suggest that a global, rather than a regional force is at work. I conclude that 19th and 20th century temperature change has much to do with rock glacier change in the Eastern Cascades.

SECTION 6

CONCLUSIONS

In this study I identified 103 rock glaciers in the Eastern Cascades, an increase of 84 from previous studies. Rock glaciers exist in large numbers in the North Cascades, but less so in the South Cascades because of lower elevations, more southerly latitudes, and closer distances to the crest. Debris type rock glaciers are most common, followed by gelifluction, and glaciogenic forms. Debris types are the most widespread as a result of their relative tolerance to climatic factors, while glaciogenic forms occur furthest from the crest and in a narrow latitudinal range north of 48°N. Gelifluction types also generally occur in the North Cascades because of more stringent requirements than debris-type rock glaciers. The most common activity types are inactive, active, and relict, in that order. Active rock glaciers occur further north and further east of the Cascade crest, while inactive and relict forms are more widespread and occur closer to the crest, and are representative of the South Cascades.

Many of the rock glaciers in the Eastern Cascades are Little Ice Age features, determined by the date of their inactivity. Still others are likely much older forms, with unknown causes regarding their inactive and relict states. Dendrochronology and lichenometry were found to be useful dating techniques on Eastern Cascade rock glaciers. Five rock glaciers produced tree cores ranging from 45-390 years, while lichen diameters ranged from 27-141.5mm, indicating ages between 58 to greater than 160 years. Weathering rinds were not useful as absolute dates, because of the lack of a dating curve for the Cascade Range. However, rinds functioned as a relative age dating technique between similar rock types. Using a rind curve developed in the Yakima Valley, the Windy Gully rock glacier was found to be significantly younger than the Table Mountain rock glacier, at 450,000 and 600,000 years, respectively.

The past climate of the high Eastern Cascades can be inferred through rock glaciers, which indicate a rise in the 0°C isotherm elevation of 250-300m in the last 100-150 years, a 2°C increase. This is consistent with trends from other mid-latitude mountain ranges, as well as glacial data from the greater Cascades.

SECTION 7

FURTHER RESEARCH

Many questions remain to be answered regarding rock glaciers in the Eastern Cascades. There were many possible candidates for rock glaciers that were not included in this study because they did not match all of the rock glacier identification criteria. These forms could be mapped to show transitional forms of talus accumulations or incipient rock glaciers. More mapped rock glaciers could also be visited to be field-verified regarding their genesis and activity types, because airphotos do not always show exact detail. Specifically, glaciogenic rock glaciers could be visited to determine their activity state, and more could be dated in the field. A rock glacier database with lichen, dendrochronology and weathering rinds could also be set up to better determine paleoclimates in the Eastern Cascades. Weathering rinds and lichen dating analyses could benefit from having curves developed for the Eastern Cascades. Such curves will provide further insight into paleoclimates and rock glacier formation.

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APPENDIX A

Rock glacier data (from south to north)

South Cascades (Figure 5-2)

Name	Lat/Long	Head Elevation (m)	Toe Elevation (m)	Aspect	Aspect (°)	Length (m)	Width (m)	Genesis	Activity	Distance from Crest (km)
Darland Mtn 1	46°31'3.75"N, 121°10'38.84"W	1630	1540	N	0	298	81	Debris	Inactive	21.25
Bear Creek Mtn 1	46°31'43.27"N, 121°20'5.25"W	2101	1927	N	0	183	132	Gelifluction	Inactive	9
Darland Mtn 2	46°31'44.85"N, 121°11'50.85"W	1921	1720	NNW	337.5	376	114	Debris	Relict	19.5
Bear Creek Mtn 3	46°31'46.57"N, 121°19'14.44"W	2016	1754	N	0	321	166	Debris	Relict	10
Bear Creek Mtn 2	46°31'50.52"N, 121°19'31.69"W	2100	1797	NE	45	379	240	Debris	Relict	9.75
Divide Ridge 3	46°33'44.85"N, 121°11'24.80"W	1946	1865	E	90	141	66	Gelifluction	Inactive	17.5
Divide Ridge 1	46°33'47.97"N, 121°10'41.52"W	1987	1742	N	10	206	128	Debris	Relict	18.75
Divide Ridge 2	46°33'52.87"N, 121°11'26.32"W	1865	1810	NE	10	198	76	Debris	Inactive	17.75
Shoe Lake	46°35'42.28"N, 121°23'51.29"W	2014	1880	NNE	15	216	143	Gelifluction	Inactive	0.5
Rattlesnake Peaks	46°45'20.84"N, 121°14'32.50"W	2000	1787	ENE	40	447	185	Debris	Inactive	14
Nelson Ridge	46°50'23.53"N, 121°15'52.41"W	2155	1965	N	0	213	121	Debris	Inactive	16.75

North Cascades: Southern Part (Figure 5-3)

Name	Lat/Long	Head Elevation (m)	Toe Elevation (m)	Aspect	Aspect (°)	Length (m)	Width (m)	Genesis	Activity	Distance from Crest (km)
Table Mtn 1	47°17’34.06”N, 120°35’57.66”W	1727	1632	NW	315	289	38	Debris	Inactive	56.5
Windy Gully	47°18’41.27”N, 120°33’42.72”W	1738	1585	W	270	251	97	Debris	Inactive	66
W Lake Ann	47°27’56.67”N, 120°57’55.33”W	1961	1785	N	0	198	126	Debris	Inactive	29
Mt. Stuart	47°28’51.83”N, 120°55’27.18”W	2376	1755	WNW	300	436	279	Debris	Inactive	29
Jack Ridge	47°32’16.10”N, 120°54’48.65”W	2102	1615	N	20	446	182	Debris	Inactive	24.75
French Ridge 1	47°36’26.40”N 121°4’27.03”W	1885	1622	N	0	258	204	Debris	Inactive	3.75
French Ridge 2	47°37’27.03”N, 121°3’32.21”W	1888	1705	WNW	292.5	186	100	Debris	Inactive	4.5

North Cascades: Lake Chelan Area (Figure 5-4)

Name	Lat/Long	Head Elevation (m)	Toe Elevation (m)	Aspect	Aspect (°)	Length (m)	Width (m)	Genesis	Activity	Distance from Crest (km)
Saska Mtn	48°7’0.94”N, 120°39’0.34”W	2175	1926	NNW	315	263	274	Gelifluction	Relict	22.25
North Navarre Peak	48°7’41.72”N, 120°20’05.39”W	2339	2087	N	0	169	204	Gelifluction	Inactive	46.75
Pinnacle Mtn	48°7’54.13”N, 120°39’54.82”W	2375	2066	NNE	10	583	118	Glaciogenic	Active	22
Sunrise Peak	48°9’45.92”N, 120°21’52.67”W	2384	2113	N	340	411	111	Debris	Inactive	40
Mount Bigelow East	48°13’23.15”N, 120°21’4.02”W	2520	2185	NNE	22.5	344	136	Glaciogenic	Active	45.5
Mount Bigelow West	48°13’30.68”N, 120°21’23.01”W	2490	2121	N	0	419	165	Glaciogenic	Active	45.25
Baldy Creek 1	48°13'47.08"N, 120°27'54.49"W	2203	2000	NNE	330	323	134	Debris	Relict	36.75
Baldy Creek 2	48°13'48.02"N, 120°28'7.52"W	2289	2009	NE	45	265	184	Debris	Inactive	36.5
Raven Ridge	48°14’32.25”N, 120°19’52.16”W	2512	2159	N	10	329	138	Gelifluction	Active	48
Star Peak 1	48°14’49.83”N, 120°23’46.81”W	2377	2077	NNE	55	328	155	Gelifluction	Active	43.5
Baldy Mtn	48°14'29.09"N, 120°27'25.63"W	2350	2205	N	0	208	137	Gelifluction	Active	38.5
Baldy Mtn 2	48°14'46.39"N, 120°27'30.93"W	2233	2007	N	0	330	120	Debris	Inactive	38.5
Star Peak 2	48°14'58.53"N, 120°24'10.85"W	2301	2107	ENE	55	309	180	Gelifluction	Active	43.25
Star Peak 3	48°14'59.18"N, 120°24'25.77"W	2356	2177	N	20	207	166	Gelifluction	Active	43
Star Peak 4	48°15'10.83"N, 120°25'2.96"W	2493	2181	ENE	60	523	349	Glaciogenic	Active	42.25
Courtney Peak	48°15'46.46"N, 120°26'55.39"W	2433	2178	NNE	10	267	309	Gelifluction	Active	40.75
North Fork Prince Creek 2	48°16'30.61"N, 120°29'42.03"W	2276	2072	NNW	337.5	191	276	Debris	Relict	38.5
North Fork Prince Creek 1	48°16'39.92"N, 120°29'31.86"W	2293	2013	NNW	315	228	116	Debris	Relict	38.5
North Fork Prince Creek 4	48°16'45.46"N, 120°30'29.77"W	2185	1996	N	0	255	236	Debris	Active	38.25
North Fork Prince Creek 3	48°16'48.75"N, 120°30'8.43"W	2056	1887	NNE	345	234	194	Debris	Inactive	38.25
West Oval Lake	48°16'51.73", 120°28'16.79"W	2400	2164	NNW	350	232	149	Debris	Inactive	40
Gray Peak	48°16'8.81"N, 120°28'29.07"W	2390	2134	W	280	275	97	Debris	Inactive	39.25
Moore Mtn	48°17'22.64"N, 120°33'52.19"W	2300	1958	WNW	300	420	172	Debris	Relict	32.5
Oval Peak	48°17'27.10"N, 120°24'56.48"W	2574	2182	ENE	67.5	465	239	Debris	Active	43.5
Battle Mtn	48°18'0.31"N, 120°29'0.23"W	2136	1954	N	0	200	115	Debris	Inactive	38.25
Boulder Butte	48°19'44.73"N, 120°35'41.21"W	2211	1752	NNW	337.5	226	104	Debris	Inactive	35
Williams Butte	48°23'14.74"N, 120°30'57.93"W	1809	1682	W	270	105	217	Gelifluction	Inactive	40.5

North Cascades: U.S.-Canada Border (Figure 5-6)

Name	Lat/Long	Head Elevation (m)	Toe Elevation (m)	Aspect	Aspect (°)	Length (m)	Width (m)	Genesis	Activity	Distance from Crest (km)
Hidden Meadows	48°25'57.78"N, 120°39'34.54"W	2256	1929	NNW	337.5	177	511	Gelifluction	Inactive	28
South Lake	48°26'1.15"N, 120°38'42.29"W	2235	1988	E	90	251	132	Debris	Inactive	29
Twisp Lake 2	48°26'26.48"N, 120°39'4.01"W	2190	1957	NNE	30	200	314	Gelifluction	Inactive	28.75
Twisp Lake 3	48°26'31.12"N, 120°38'26.73"W	2223	1905	N	0	219	789	Debris	Inactive	28.5
Twisp Lake 1	48°26'39.35"N, 120°39'12.63"W	2266	1838	N	0	252	96	Debris	Relict	29.25
Abernathy Ridge 2	48°27'12.99"N, 120°29'10.03"W	2253	2088	ENE	45	288	147	Debris	Inactive	42.5
Hock Mtn	48°27'32.34"N, 120°39'48.86"W	2155	1729	NNW	337.5	530	256	Debris	Relict	28.25
Abernathy Ridge 1	48°27'46.84"N, 120°28'50.98"W	2237	1886	ENE	45	336	120	Debris	Inactive	42.75
Abernathy Ridge 3	48°27'5.67"N, 120°28'33.63"W	2198	1944	N	0	420	338	Debris	Relict	42
Abernathy Peak	48°28'56.23"N, 120°31'22.48"W	2266	2141	E	45	266	124	Glaciogenic	Active	39
Lamont Lake 2	48°29'30.44"N, 120°31'41.03"W	2371	2132	N	0	386	91	Gelifluction	Active	38
Lamont Lake 1	48°29'30.90"N, 120°31'16.34"W	2312	2111	N	0	301	138	Gelifluction	Inactive	37.5
Storey Peak	48°30'28.60"N, 120°27'48.61"W	2306	1903	N	10	339	285	Debris	Inactive	35.75
North Gardner Mtn	48°30'53.76"N, 120°29'29.87"W	2492	2196	N	20	504	133	Glaciogenic	Active	17
Shelokum Mtn	48°31'32.68"N, 120°32'14.90"W	2162	1724	WNW	305	468	197	Debris	Inactive	12
Silver Star Mtn 2	48°32'29.36"N, 120°35'51.28"W	2354	2067	W	270	294	148	Debris	Inactive	7.75
Silver Star Mtn 1	48°33'12.11"N, 120°33'14.64"W	2096	1988	N	15	339	199	Gelifluction	Active	10.5
Porcupine Peak 2	48°33'44.11"N, 120°43'35.25"W	2042	1834	NNW	330	275	223	Debris	Inactive	-2
Porcupine Peak 1	48°33'53.25"N, 120°43'14.67"W	2182	1768	NNW	340	285	180	Debris	Inactive	-2

North Cascades: Highway 20 Area (Figure 5-

Name	Lat/Long	Head Elevation (m)	Toe Elevation (m)	Aspect	Aspect (°)	Length (m)	Width (m)	Genesis	Activity	Distance from Crest (km)
Old Baldy	48°35'36.55"N, 119°57'28.10"W	2184	2062	N	40	275	154	Gelifluction	Active	60.5
Clark Peak 1	48°39'13.29"N, 119°55'4.89"W	2332	2083	NNE	45	343	121	Debris	Active	61.25
Clark Peak 2	48°39'14.64"N, 119°54'50.83"W	2189	2026	NNE	35	256	98	Debris	Active	61.5
County Line	48°39'22.04"N, 120°41'36.89"W	2089	1888	N	0	168	97	Debris	Inactive	4
Midday Mtn	48°42'0.39"N, 120°24'4.64"W	2332	1912	NNW	337.5	214	164	Debris	Active	20.25
McLeod Mtn 1	48°42'28.63"N, 120°23'34.22"W	2372	1988	NW	315	274	181	Debris	Inactive	21.25
McLeod Mtn 2	48°42'3.21"N, 120°22'28.38"W	2249	1992	NE	45	161	1019	Debris	Inactive	22.75
McLeod Mtn 3	48°42'48.30"N, 120°22'15.96"W	2388	2066	N	15	129	341	Debris	Inactive	22.75
Sunrise Peak North	48°43'56.75"N, 120°22'59.15"W	2363	2173	N	0	157	68	Debris	Active	21.5
Sherman Peak 1	48°44'37.27"N, 120°19'04.52"W	2153	1689	NNE	30	332	172	Debris	Relict	27
Sherman Peak 2	48°44'45.34"N, 120°19'58.52"W	2138	1950	NE	30	153	159	Gelifluction	Inactive	26.25
Sherman Peak 3	48°45'2.88"N, 120°20'54.65"W	2382	2078	NW	325	279	101	Debris	Active	25.25
Three Pinnacles 1	48°46'47.59"N, 120°25'38.32"W	2228	1869	NE	55	407	329	Debris	Relict	22
Big Craggy Peak	48°46'5.11"N, 120°20'20.25"W	2334	1998	N	0	1034	181	Debris	Active	27.25
Eightmile Peak	48°47'23.67"N, 120°21'6.77"W	2214	1798	N	10	315	172	Debris	Inactive	28
Monument Peak 3	48°47'29.23"N, 120°30'45.12"W	2269	2069	N	45	252	90	Gelifluction	Inactive	16.5
Monument Peak 1	48°47'47.43"N, 120°32'3.18"W	2505	2101	E	65	630	156	Glaciogenic	Active	15
Monument Peak 2	48°47'57.80"N, 120°31'11.55"W	2340	1852	N	20	289	256	Debris	Inactive	16
Three Pinnacles 2	48°47'7.69"N, 120°26'2.20"W	2170	1884	E	75	258	200	Debris	Relict	22
Rolo Peak	48°48'45.59"N, 120°35'31.58"W	2157	1952	N	20	237	138	Debris	Inactive	11
Lost Peak	48°49'2.63"N, 120°27'25.47"W	2358	2180	N	0	255	164	Glaciogenic	Active	21
Buckskin Ridge 1	48°49'21.45"N, 120°38'53.69"W	2351	1998	NE	30	195	125	Debris	Inactive	6.75
Osceola Peak	48°49'49.86"N, 120°35'29.13"W	2280	1986	NNW	10	157	128	Debris	Inactive	10.75
Fool Hen Mtn 2	48°49'53.22"N, 120°18'6.02"W	2365	2140	N	0	266	136	Debris	Inactive	32
Buckskin Ridge 2	48°49'56.41"N, 120°40'2.31"W	2213	1951	W	270	255	108	Debris	Inactive	5
Fool Hen Mtn 3	48°50'4.96"N, 120°17'52.58"W	2229	2046	N	325	257	219	Debris	Inactive	32.25
Many Trails Peak 2	48°51'1.60"N, 120°27'40.74"W	2516	2101	E	100	172	119	Debris	Active	19.5
Fool Hen Mtn 1	48°51'10.32"N, 120°19'33.46"W	2455	2139	WNW	315	304	108	Debris	Inactive	30
Many Trails Peak 1	48°51'21.57"N, 120°27'43.43"W	2469	2133	N	30	125	365	Gelifluction	Active	20
Point Defiance	48°51'59.17"N, 120°35'20.69"W	2247	2057	N	10	147	149	Debris	Relict	11
Holman Peak 2	48°52'16.82"N, 120°43'41.12"W	2123	1901	NNE	40	153	246	Debris	Inactive	2.25
Holman Peak 1	48°52'30.00"N, 120°44'1.80"W	2150	1765	N	0	292	195	Debris	Inactive	2.25
Preston Ridge	48°53'7.97"N, 120°13'39.96"W	2310	2035	N	35	227	169	Debris	Inactive	39
Corral Lake	48°54'39.79"N, 120°20'58.60"W	2379	2097	N	30	198	196	Debris	Active	31
Remmel Mtn 1	48°55'36.79"N, 120°11'28.76"W	2419	2205	E	20	418	174	Gelifluction	Active	41.75
Van Peak	48°55'39.98"N, 120°16'13.80"W	2340	2163	NNW	325	136	188	Debris	Inactive	35.75
Smoky Mtn	48°55'40.08"N, 120°42'18.69"W	2197	1840	N	15	113	373	Debris	Relict	4
Remmel Mtn 2	48°55'55.52"N, 120°12'11.95"W	2343	2170	E	70	164	155	Gelifluction	Active	40.5
Arnold Peak	48°59'51.23"N, 119°54'0.09"W	2216	1990	NNW	0	230	145	Debris	Inactive	70