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# Rock glaciers in the Eastern Cascades, Washington State, USA: Impacts of selected variables on spatial distribution and landform dimensions

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ABSTRACT

Recent regional-scale studies of rock glaciers have added much to our knowledge of rock glaciers and associated permafrost spatial distribution. In this study, we used Google Earth Pro imagery and selected field work to identify and classify 159 rock glaciers in the marine-influenced, continental margin, Eastern Cascades of Washington state in Western North America. Most rock glaciers are tongue-shaped, talus-derived, intact features. The majority are found in the Northeastern Cascades where temperatures are lower because of high elevations, high latitudes, and increasingly continental conditions. Most rock glaciers are also clustered around high peaks and ridges at the bases of cirque headwalls where steep, converging slopes provide ample debris. Dimensions of rock glaciers increase with increasing maximum elevation, area, relief, length, and slope of rocksheds. In comparison to other ranges, Eastern Cascades rock glaciers are generally small and low in spatial density, perhaps because of lower elevations and younger landscapes. Despite this, rock glaciers are significant components of the alpine/subalpine geomorphic continuum in the Eastern Cascades typically occupying late Pleistocene or Holocene cirques. Intact rock glaciers suggest that discontinuous permafrost currently exists down to ~1945 m elevation while relict features suggest that permafrost once extended down to ~1870 m elevation. As climate warms, slowly melting ice in rock glaciers will play a larger role in providing base flow for streams previously primarily supplied by snow and glacier melt.



## 1. Introduction

Rock glaciers are tongue- to lobe-shaped rock and ice features that show evidence of present or past, *en masse* creep on mountain slopes ranging from the Arctic to Antarctic (Vitek and Giardino, 1987; Barsch, 1996; Jones et al., 2018). These features have been identified and discussed, under various names, since at least 1883 (Humlum, 1982; Barsch, 1996). The formation of rock glaciers, and the resulting spatial distribution, depends on cold climate (and associated ice formation), ample debris supply, and steep topography sufficient for downslope movement (Wahrhaftig and Cox, 1959; Haeberli, 1985; Barsch, 1996). Ice, as well as frost-shattered debris, requires low temperatures found at high elevations, high latitudes, or poleward aspects (French, 2007; Etzelmüller and Frauenfelder, 2009). Such conditions are especially present in drier, continental or leeward settings where thin snow cover deters glacier formation and allows cold winter air to chill the interiors of rock glaciers, especially in those features composed of blocky debris with large pore spaces (King, 1986; Barsch, 1992; Haeberli et al., 2006). Debris supply is a function of the type of rock, area, relief, and length of slopes above rock glaciers (Chueca, 1992; Johnson et al., 2007; Janke and Frauenfelder, 2008). Steep, convergent topography is necessary for the delivery of blocky debris to the slopes below (Wahrhaftig and Cox, 1959; White, 1979; Brenning and Trombotto, 2006).

Rock glaciers may be classified by morphology–i.e., tongue-shaped, lobate, or complex (Wahrhaftig and Cox, 1959; Barsch, 1996), genesis–i.e., talus- or glacier-derived (e.g., Humlum, 1982, 1988), and activity levels–i.e., active, inactive, and relict (or "fossil") (Wahrhaftig and Cox, 1959; Barsch and King, 1975; Barsch, 1992). Active and inactive (collectively termed "intact") rock glaciers contain ice, either filling the interstices between debris or occurring as solid ice masses (Jones et al., 2019b). Toes of rock glaciers represent the approximate lower limits of discontinuous permafrost in alpine settings and, if in sync with current climate, represent the -1° to -2 °C mean annual temperature isotherm (Barsch, 1978; Haeberli, 1985; Janke, 2005). Relict rock glaciers lack ice at present but the positions of these features indicate the locations of discontinuous permafrost in the past (Urdea, 1998; Harrison et al., 2008).

Globally, rock glaciers have been identified in nearly all latitudinal zones (Martin and Whalley, 1987) and in all major mountain ranges (Barsch, 1996). In previous decades, it was assumed that rock glaciers were uncommon in marine settings (Thompson, 1962; Haeberli, 1985). This view has slowly changed with more regional-scale mapping and resulting inventories of rock glaciers, especially associated with the increased availability of high resolution satellite imagery (see Jones

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et al., 2018). Now, we recognize that marine-influenced, continental margin mountain belts oriented perpendicular to prevailing winds such as the Scandes of Norway (Lilleøren and Etzelmüller, 2011), Southern Alps of New Zealand (Brazier et al., 1998; Sattler et al., 2016), and Southern Andes of Chile (Falaschi et al., 2015) may have ample rock glaciers and adjacent permafrost. The western margin of the Western Cordillera in North America is a climatically-similar setting. There, rock glaciers have been identified in the Sierra Nevada of California (Millar and Westfall, 2008), Coast Range of British Columbia (Alley and Young, 1978; Slaymaker, 1993; Charbonneau and Smith, 2018), and Olympic Mountains of Washington state (a portion of the larger Coast Range) (Welter, 1987). In the Cascade Range of Washington state, rock glaciers were previously identified leeward of Mt. Rainier (but west of the Cascade Crest in the “Western Cascades”) (Crandell, 1969; Crandell and Miller, 1974) and in the “Eastern Cascades” (east of the Cascade Crest) (Thompson, 1962; Hopkins, 1966; Merrill, 1966; Libby, 1968; Beckey, 1973; Long, 1975; Beckey, 1977, 1981; Tabor et al., 1982; Goshorn-Maroney, 2012; Scurlock, 2021; Johnson, 2018; Johnson et al., 2020). Most of these sources only mentioned rock glaciers in passing; however, Goshorn-Maroney (2012) determined the activity characteristics of 15 of these features. Weidenaar (2013) identified and classified the morphologies, geneses, and activity levels of 103 rock glaciers. Johnson (2018) and Johnson et al. (2020) subsequently identified and classified surface characteristics of nearly 200 Eastern Cascades rock glaciers as part of a U.S.-wide study.

In this research, we used improved imagery and additional field work and analyses to expand on previous investigations to develop a more comprehensive understanding of the spatial patterns, physical dimensions, origins, and implications of rock glaciers in the Eastern Cascades. Specifically, we: 1) identified and mapped rock glaciers to determine the spatial distributions and physical dimensions; 2) classified the morphology, genesis, and activity of each of these features; 3) assessed the climate, topography, and debris supply variables potentially affecting rock glaciers to better understand the causes of the spatial distributions and dimensions; and 4) used our findings to discuss the geomorphic, permafrost, and hydrologic implications of rock glaciers in the Cascade Range.

## 2. Study area

The Eastern Cascades in Washington state stretch from the U.S. - Canada international boundary south to the Oregon - Washington state border, a distance of ~375 km (Fig. 1). The range extends eastward from the Cascade Crest (~115 km in the north to ~70 km in the south) to the Okanogan, middle Columbia, and Yakima rivers, respectively. We divide the Eastern Cascades into Northeastern and Southeastern components at the Yakima - Wenatchee river drainage divide (Fig. 1). The Puget Sound lies 70 to 90 km west of the Northeastern Cascades crest whereas the Pacific Ocean proper is more distant, ranging from 100 to 200 km west of the Southeastern Cascades crest (Fig. 1).

Pre-Cenozoic metamorphic and intrusive igneous rocks dominate the geology of the Northeastern Cascades whereas Cenozoic volcanic and sedimentary rocks comprise most of the Southeastern Cascades (Schuster, 2005). Terrain is more rugged and elevations are higher in the Northeastern Cascades than in its southern counterpart (Mitchell and Montgomery, 2006).

The north - south orientation of the range, combined with prevailing westerly winds, leads to increasingly continental conditions eastward of the Cascade Crest. This is especially true in the wider Northeastern Cascades. Summer temperatures are higher but winter temperatures and overall precipitation decline east of the Cascade Crest (Mass, 2008). Mean annual temperature and precipitation range from 0 °C and ~3600 mm near the Cascade Crest to 9 °C and ~760 mm in the lower, easternmost portions of the range (PRISM Climate Group, 2020). Most (75–85%) precipitation is associated with cyclonic storms and falls as snow between October and March (Mass, 2008; Western Regional Climate Center, 2020).

Late Pleistocene ice sheets covered parts of the Northeastern Cascades, ice fields and ice caps mantled higher portions of the Southeastern Cascades, and cirque glaciers developed in high elevations elsewhere (Porter et al., 1983; Kaufman et al., 2003). Latest Pleistocene and Holocene glaciers inhabited numerous cirques (Burke and Birkeland, 1983; Kaufman et al., 2003; Davis et al., 2009). Late 1990s to early 2000s U.S. Geological Survey (U.S.G.S.) 7.5′ topographic quadrangles reveal 39 named glaciers plus numerous snowfields present in the Eastern Cascades. Meltwater from these glaciers combines with snowmelt to form a major component of runoff to the Columbia River via the Smilkameen, Okanogan, Methow, Chelan, Entiat, Wenatchee, Yakima, Naches, and Tieton rivers (Fig. 1) (Dalton et al., 2013).

## 3. Methods

### 3.1. Identification of rock glaciers

Like other recent inventories (Rangecroft et al., 2014; Wang et al., 2017; Jones et al., 2018; Pandey, 2019), we used Google Earth (GE) to identify rock glaciers because of the large size of the study area, nearly seamless imagery coverage, vertical to oblique viewing perspectives, and multiple imagery dates. Rock glaciers were identified by: 1) locations at the bases of steep valley heads and sides near or above treeline; 2) lobate or tongue-shaped morphologies situated above immediate surroundings; 3) rocky debris compositions; 4) steep side and front slopes; and 5) transverse, curvilinear ridges and furrows that generally parallel the margins of the landforms (Wahrhaftig and Cox, 1959; White, 1976; Barsch, 1996; Jones et al., 2018). We used the presence of two more transverse, curvilinear ridges and associated furrows to differentiate mobile (or once mobile) rock glaciers from ubiquitous protalus ramparts that presumably have not flowed. Twenty (13%) rock glaciers were visited in the field (Fig. 1). Features were labeled by the immediate watershed and numbered (e.g., Miriam Creek 1).

### 3.2. Dimensions of rock glaciers

Once identified, we used Google Earth Pro (GEP) to measure the area, length, and width of each rock glacier (Fig. 2). Perimeters were outlined following the often distinct boundary along the flanks and toe, and the more subtle break-in-slope separating talus or till from the head of the rock glacier (Roer and Nyenhuis, 2007; Krainer and Ribis, 2012). Areas were calculated from the GEP perimeter measurements. Lengths were measured along the central flow line (Barsch, 1996) whereas widths were measured near the toe perpendicular to the flow line (Baroni et al., 2004).

### 3.3. Classification of rock glaciers

Using GEP and limited field observations, we classified rock glaciers into morphology, genesis, and activity groups. Morphology determination followed the modified classification of Barsch (1996) that included tongue-shaped, lobate, and complex subgroups of rock glaciers. Tongue-shaped rock glaciers are longer than wide whereas lobate rock glaciers are wider than long (Wahrhaftig and Cox, 1959; White, 1981). Complex rock glaciers were identified as two or more lobes of the same feature (Barsch, 1996). Genesis subgroups of rock glaciers were classified as either talus- or glacier-derived (Humlum, 1982, 1988). Talus-derived rock glaciers occur at the bases of taluses while glacier-derived features form in the till of moraines below present-day glaciers (Humlum, 1988). Because differentiation of active and inactive rock glaciers is very difficult when based solely on single-date imagery (Barsch, 1996; Lilleøren and Etzelmüller, 2011), we classified the activity of rock glaciers into either intact or relict subgroups based on surface and slope morphology, and vegetation cover (Haeberli, 1985). Intact rock glaciers

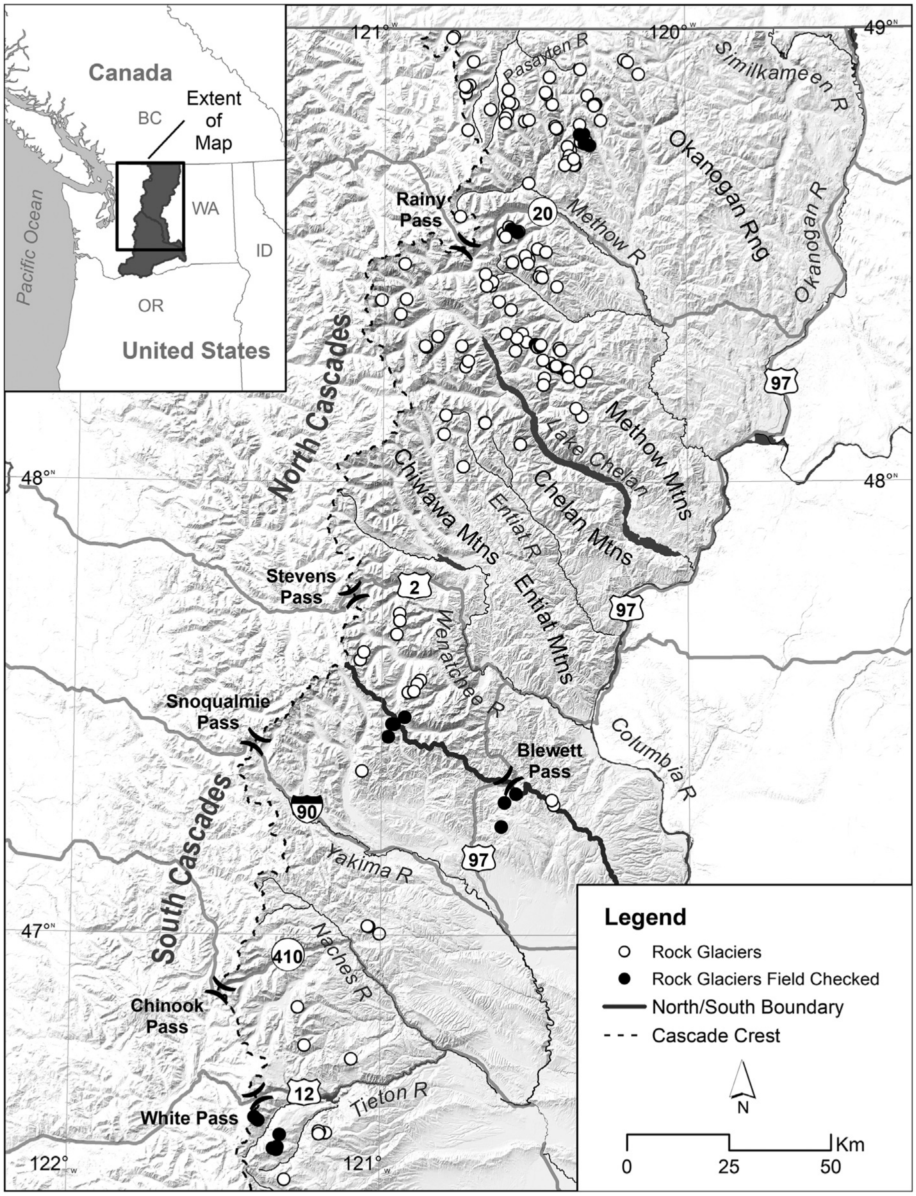


**Fig. 1.** Eastern Cascades study area and rock glaciers. Note the continental margin setting of the Cascade Range. Also note the majority of rock glaciers in the Northeastern Cascades.

are often "inflated" because they contain permafrost, have sparse to no vegetation cover, and margins that are at or near the angle of repose. Relict rock glaciers no longer contain ice therefore are more subdued with gentle slopes and ample vegetation cover (Barsch, 1996).

### 3.4. Variables potentially affecting rock glaciers

We assessed climate, debris supply, and topography variables potentially impacting each "rockshed" using GEP. For accuracy and clarity, we prefer "rockshed" to "source area" (Wahrhaftig and Cox, 1959), "talus shed" (Brenning et al., 2007), and "contributing area" (Janke and Frauenfelder, 2008). The cold climate necessary for the presence of perennial ice in rock glaciers results from higher latitudes, higher elevations, northerly aspects (in the northern hemisphere), and more continental locations (Guodong and Dramis, 1992; Luckman and Crockett, 1978). Latitude was calculated for the center of each rock glacier. Elevation was measured at the break-in-slope at the head (i.e., rock glacier initiation line altitude—Humlum, 1988 or rooting zone—Barsch, 1996) and toe of each rock glacier whereas the maximum elevation of each rockshed was determined as the highest point above each rock glacier (Fig. 2). Relative continentality was measured as the distance east from the Cascade Crest to the center of each rock glacier. Rock glacier and rockshed aspect was measured with the GEP ruler tool. These values were then averaged using the principles of circular statistics (Humlum, 2000). Individual aspect values for rock glaciers and rocksheds were modified to a 0-180° scale to aid in correlation analysis (see below).

Variables affecting debris supply include type of rock, relief, area, and length of rocksheds. Type of rock helps determine the debris size, which, in turn, affects the development of rock glaciers, especially in climatically marginal settings (Barsch, 1996). We determined type of rock from 1:100,000-scale Washington Geological Survey geologic maps. Relief was calculated as the elevation difference between the maximum elevation of a rockshed and the head elevation of a rock glacier (Fig. 2). The area of each rockshed area was determined with GEP by outlining the entire area that could potentially provide debris to the head of a rock glacier (Janke and Frauenfelder, 2008). Length of each rockshed was measured as the slope length extending from the highest point in a rockshed to the top of a rock glacier.

Topography variables included overall landform and slope of rocksheds. Caltopo (an online mapping software) and GEP were used

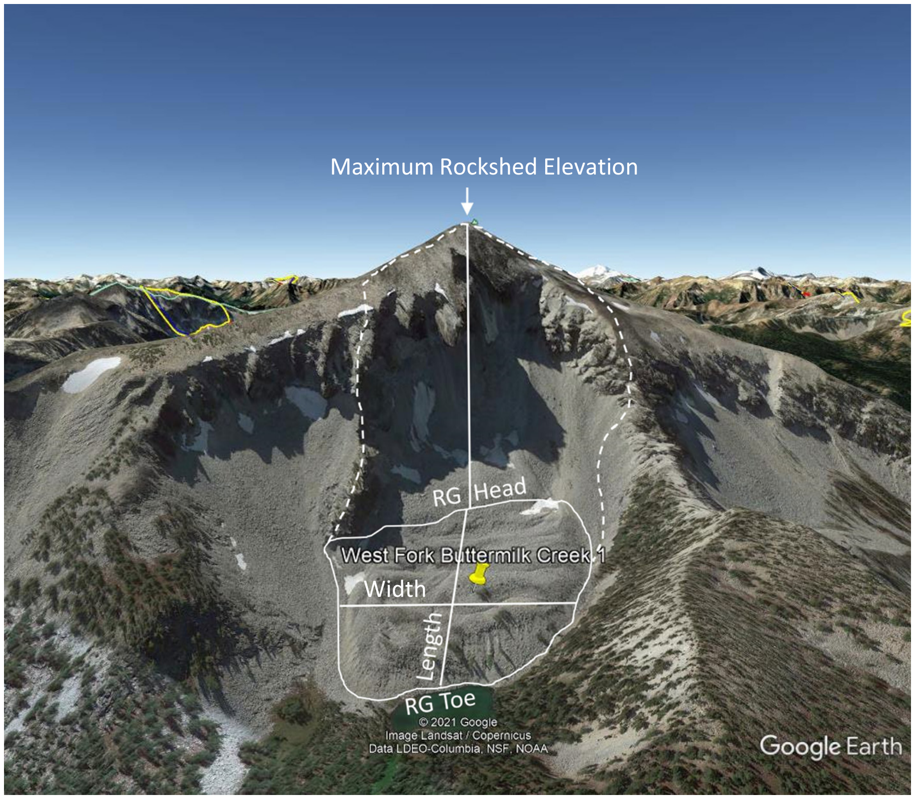


**Fig. 2.** Different measured elements of Eastern Cascades rock glaciers as illustrated by the West Fork Buttermilk Creek 1 rock glacier. Rock glacier area is outlined in solid white line. Rockshed area outlined in dashed white line. Google Earth Pro image.

to assess the landform (i.e., cirque headwall, cirque sidewall, landslide main scarp, and landslide minor scarp) on which each rock glacier formed. The slope of each rockshed was measured with GEP and expressed as a percentage.

### 3.5. Spatial distribution of rock glaciers

Spatial distribution was assessed in terms of density and distance between rock glaciers. Mean density of rock glaciers was calculated as the number of rock glaciers/ha above 1370 m elevation (the toe elevation of the lowest rock glacier in the Eastern Cascades) in each watershed (Onaca et al., 2017). The mean specific density of rock glaciers was calculated by dividing the total area of all rock glaciers in each watershed by the total watershed area above 1370 m (Gorbunov, 1983; Azocar and Brenning, 2010; Millar and Westfall (2019). The total area and > 1370 m elevation area was determined using ArcGIS Pro 2.2.0, a U.S.G.S. 1/3 arc-second digital elevation model (DEM), and the boundaries of Water Resource Inventory Areas (W.R.I.A.) for Washington State. Distance between rock glaciers was determined by measuring the distance from the center of a rock glacier to the center of its nearest neighbor.

### 3.6. Statistical analyses

We used STATISTIX software to conduct Spearman rank correlations on quantified climate, debris, and topography variables potentially affecting dimensions of rock glaciers. We then used a Kruskal-Wallis (three or more samples) or Mann-Whitney (two samples) test to determine whether significant differences exist between the measured variables of morphology, genesis, and activity groups members. Further, we used Spearman rank correlation to test the potential relationships of individual variables on members of morphology, genesis, and activity groups. We also used Spearman rank correlation to test the relationships between select pairs of variables potentially impacting the spatial distributions of rock glaciers. For all correlation and significance testing, we chose a significance level of $p < 0.05$.

## 4. Results

### 4.1. General patterns of rock glaciers

We identified 159 rock glaciers in the Eastern Cascades (Fig. 1). This total includes features independently identified by us as well as verification of those previously identified by Thompson (1962), Hopkins (1966), Merrill (1966), Libby (1968), Beckey (1973), Long (1975), Beckey (1977, 1981), Tabor et al. (1982), Goshorn-Maroney (2012), Weidenaar (2013), Johnson (2018), and Johnson et al. (2020), and Scurlock, 2021). We excluded features identified by those authors which did not meet our criteria.

Rock glaciers were found in nine watersheds in the Eastern Cascades, each of which is tributary to the Columbia River (Fig. 1; Table 1). Northeastern Cascades watersheds contain the most rock glaciers (85%) that cover the most area (87%), and have the largest individual mean areas (5.2 ha). They also have the highest densities (0.0003 rock glaciers/ha and 0.12%) and shortest distances between rock glaciers (1.9 km).

Tongue-shaped features are the most numerous (63%) and cumulatively cover the most area of the morphology types (65%) (Fig. 3; Table 2). However, complex rock glaciers have the largest mean areas (12.1 ha) and lengths (463 m). Lobate features are the widest with a mean of 291 m. Talus-derived rock glaciers are more numerous (148) and cumulatively cover more area (86%) than do glacier-derived features (Fig. 3; Table 2). Most features are intact (88%) which have a cumulative area of 633 ha (Fig. 3; Table 2). When combined, the most common rock glaciers in the Eastern Cascades are tongue-shaped, talus-derived, and intact.

**Table 1**
Spatial characteristics of rock glaciers in major watersheds of the Eastern Cascades.

| | # | Total Land Area Above 1370 m (ha) | Total Rock Glacier Area (ha) | Mean Rock Glacier Area (ha) | Mean Rock Glacier Density (#/ha) | Mean Rock Glacier Specific Density (%) | Mean Distance Between Rock Glaciers (km) |
|---|---|---|---|---|---|---|---|
| *Northeastern Cascades* | | | | | | | |
| Pasayton River | 22 | 50,885.3 | 96.3 | 4.4 | 0.0004 | 0.19 | 1.8 |
| Methow River | 49 | 239,026.9 | 239.7 | 4.9 | 0.0002 | 0.10 | 1.4 |
| Twisp River | 26 | 35,422.2 | 140.0 | 5.4 | 0.0007 | 0.40 | 1.3 |
| Lake Chelan | 22 | 127,773.5 | 116.4 | 5.3 | 0.0002 | 0.09 | 2.9 |
| Entiat River | 1 | 50,065.6 | 6.6 | 6.6 | 0.0001 | 0.01 | 4.7 |
| Wenatchee River | 15 | 129,922.9 | 71.5 | 4.8 | 0.0001 | 0.06 | 2.6 |
| Other | 0 | 8893.1 | 0 | 0 | 0 | 0 | 0 |
| Subtotal | 135 | 641,468 | 670.5 | 5.2 | 0.0003 | 0.12 | 1.9 |
| *Southeastern Cascades* | | | | | | | |
| Upper Yakima River | 6 | 89,142.2 | 35.6 | 5.9 | 0.0001 | 0.04 | 4.0 |
| Naches River | 6 | 70,362.8 | 22.5 | 3.8 | 0.0001 | 0.03 | 5.8 |
| Tieton River | 12 | 42,079.2 | 41.9 | 3.5 | 0.0003 | 0.10 | 1.5 |
| Other | 0 | 92,234.8 | 0 | 0 | 0 | 0 | 0 |
| Subtotal | 24 | 293,819.0 | 100 | 4.4 | 0.0005 | 0.04 | 3.2 |
| Total | 159 | 1,015,164.8 | 770.5 | 4.8 | | 0.0759 | 2.6 |

### *4.2. Impacts of variables on spatial distributions and dimensions of rock glaciers*

Table 3 shows variables assessed that have the potential to affect spatial distributions and dimensions of rock glaciers in the Eastern Cascades. We address each of the variables individually below.

#### *4.2.1. Latitude*

Latitudes of rock glaciers in the Eastern Cascades range from 46.5°N to nearly 49° with most rock glaciers (77%) concentrated in the Northeastern Cascades, north of 48°N (Fig. 1). Complex, glacier-derived, and intact rock glaciers are found at the highest latitudes (Table 3). Latitude is not significantly correlated with the overall data set or the

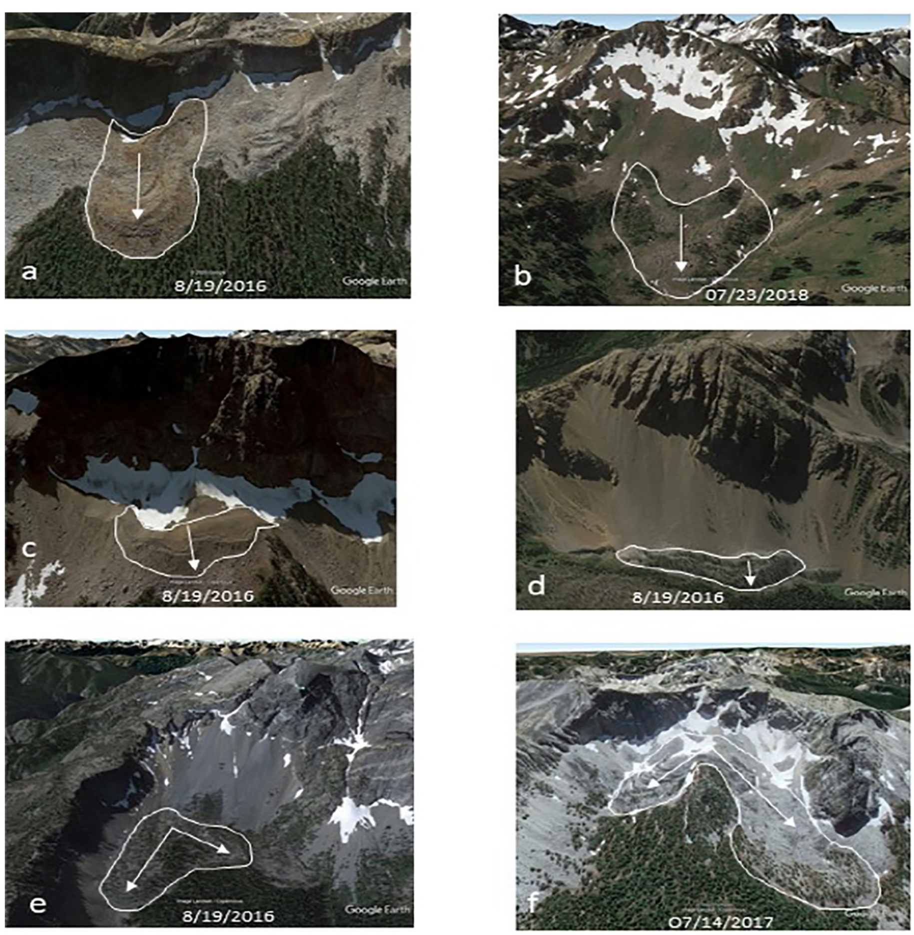


**Fig. 3.** Examples of different morphology, genesis, and activity classes of rock glaciers (outlined) in the Eastern Cascades: a. tongue-shaped, talus-derived, intact Varden Creek 1; b. tongue-shaped, talus-derived, relict Trout Creek 3; c. lobate, glacier-derived, active Margerum Creek 1; d. lobate, talus-derived, intact Chuchawanteen Creek 1; e. complex morphology, talus-derived, relict Pinnacle Creek 1; and f. complex morphology, talus-derived, active East Fork Buttermilk Creek 2. Arrows indicate primary flow direction. Imagery dates shown near bottom center of each image. Google Earth Pro images.

**Table 2**
Dimensions of different morphology, genesis, and activity group members of rock glaciers in the Eastern Cascades.

| | # | Cumulative Area (ha) | Mean RG area (ha) | Mean RG Length (m) | Mean RG width (m) |
|---|---|---|---|---|---|
| Overall | 159 | 770.5 | 4.9 | 282 | 185 |
| *Morphology* | | | | | |
| Tongue-shaped | 100 | 502.1 | 5.0 | 342 | 125 |
| Lobate | 51 | 171.5 | 3.4 | 136 | 291 |
| Complex | 8 | 96.9 | 12.1 | 463 | 264 |
| Subtotal | 159 | 770.5 | | | |
| *Genesis* | | | | | |
| Talus-derived | 148 | 695.5 | 44.7 | 281 | 184 |
| Glacier-derived | 11 | 75.0 | 6.8 | 285 | 202 |
| Subtotal | 159 | 770.5 | | | |
| *Activity* | | | | | |
| Intact | 140 | 632.7 | 4.5 | 274 | 180 |
| Relict | 19 | 137.8 | 7.2 | 339 | 224 |
| Subtotal | 159 | 770.5 | | | |

**Table 4**
Correlations between variables and dimensions of rock glaciers in the overall data set. Significant correlations at $p < 0.05$ are shown in bold. Significant correlations at $p < 0.01$ are indicated with bold and asterisk.

| Variable | Dimension | Overall dataset |
|---|---|---|
| Maximum Elev. of Rockshed | RG Area | **0.35*** |
| | RG Length | **0.25*** |
| | RG Width | **0.19** |
| Area of Rockshed | RG Area | **0.55*** |
| | RG Length | **0.25*** |
| | RG Width | **0.50*** |
| Relief of Rockshed | RG Area | **0.39*** |
| | RG Length | **0.17** |
| | RG Width | **0.38*** |
| Length of Rockshed | RG Area | **0.41*** |
| | RG Length | **0.19** |
| | RG Width | **0.38*** |
| Slope of Rockshed | RG Area | **0.41*** |
| | RG Length | **0.19*** |
| | RG Width | **0.38** |

morphology, genesis, or activity group dimensions (Tables 4, 5 & 6); however, latitude does have a statistically significant relationship with rock glacier head elevation and rockshed maximum elevation (Table 7, Fig. 4) suggesting that an increase in latitude is associated with an increase in rock glacier head and rockshed maximum elevations.

### *4.2.2. Distance East of the Cascade Crest*

Rock glaciers range from less than 1 to 69 km east of the Cascade Crest with a mean of nearly 25 km (Fig. 1; Table 3). Complex, glacier-derived, and intact subgroups are found furthest east of the Cascade Crest. Distance east of the Cascade Crest is not significantly correlated with the overall data set or morphology, genesis, or activity group dimensions (Tables 4, 5 & 6); however, like latitude, distance east has a statistically significant, positive relationship with rock glacier head elevation and rockshed maximum elevation (Table 7; Fig. 5) suggesting that an increase in distance east is associated with an increase in head and maximum elevations.

### *4.2.3. Elevation*

Head elevations of rock glaciers range from 1573 to 2338 m with an average of 2012 m (Fig. 7; Table 3). Complex, glacier-derived, and intact subgroups have the highest head elevations. Head elevations of relict rock glaciers are, on average, 56 m lower than those of intact features. Maximum elevations of rocksheds range from 1699 to 2859 m with a mean of 2249 m (Table 3). Complex, glacier-derived, and relict rock glaciers have the highest rockshed elevations. Rockshed maximum elevation has statistically significant, very weak to weak relationships with overall rock glacier area, length, and width (Table 4). Rockshed maximum elevation also has statistically significant differences in dimensions within the morphology and genesis subgroups (Tables 5 & 6). With one exception, rock glacier dimensions increase with increases in rockshed maximum elevation (Table 6). As noted above, rock glacier head elevation and rockshed maximum elevation each have statistically significant, positive correlations with rock glacier latitude and rock glacier distance east of the Cascade Crest (Figs. 4 & 5). Further, rock glacier head elevation has a statistically significant, positive correlation with rockshed maximum elevation suggesting that rock glacier head elevations increase with rising rockshed maximum elevations (Table 7; Fig. 6).

### *4.2.4. Aspect*

Individual aspects of rock glaciers range from 0-359°. The overall data set mean is 3° and most face north (Fig. 7; Table 3). Means of rock glacier subgroups range from north northwest (353°) to north northeast (27°). Aspects of rocksheds are mostly northeast-facing

**Table 3**
Averages for variables potentially affecting different members of morphology, genesis, and activity groups of rock glaciers in the Eastern Cascades. Landforms of rocksheds are stated as modes. The remainder of variables are expressed as means.

| | Overall | Tongue-Shaped | Lobate | Complex | Talus-Derived | Glacier-Derived | Intact | Relict |
|---|---|---|---|---|---|---|---|---|
| Latitude (°) | 48.21 | 48.13 | 48.34 | 48.44 | 48.20 | 48.28 | 48.23 | 48.08 |
| Distance East (km) | 24.6 | 25.5 | 21.4 | 32.8 | 24.2 | 29.8 | 25.6 | 16.8 |
| Head Elev. of RG[1] (m) | 2011 | 2008 | 2004 | 2104 | 2003 | 2126 | 2018 | 1962 |
| Toe Elev. of RG (m) | 1935 | 1915 | 1965 | 1985 | 1927 | 2044 | 1943 | 1868 |
| Aspect of RG (°) | 3 | 353 | 15 | 23 | 1 | 27 | 4 | 355 |
| Max. Elev. (m) of RS[2] | 2249 | 2233 | 2256 | 2412 | 2238 | 2367 | 2246 | 2270 |
| Aspect of RS (°) | 42.7 | 40.0 | 49.1 | 29.4 | 41.9 | 51.4 | 43.1 | 39.9 |
| Landform | HW[3] | HW | HW | HW | HW | HW | HW | HW |
| Slope of RS (%) | 46.3 | 45.5 | 48.0 | 46.0 | 46.2 | 48.3 | 46.1 | 47.7 |
| Area of RS (ha) | 18.2 | 5.0 | 20.7 | 32.3 | 16.8 | 36.8 | 17.2 | 25.6 |
| Relief of RS (m) | 271 | 261 | 280 | 344 | 267 | 329 | 264 | 326 |
| Length of RS (m) | 571 | 555 | 576 | 749 | 562 | 702 | 559 | 668 |
| Type of Rocks | II[4] | II | S[5] | M[6] | II | II | II | II |

RG[1] = rock glacier.
RS[2] = rockshed.
HW[3] = Headwall.
II[4] = Intrusive igneous.
S[5] = Sedimentary.
M[6] = Metamorphic.

**Table 5**
Two-tailed test results to showing those morphology, genesis, and activity group members with significant differences ($P < 0.5$) in dimensions. Significant differences shown in bold.

| | Tongue-shaped vs. Lobate vs. Complex Morphologies | Talus- vs. Glacier-Derived Geneses | Intact vs. Relict Activities |
|---|---|---|---|
| Distance East of Crest | **H = 6.54** | Z = 1.55 | **Z = 2.50** |
| | ***p* = 0.04** | *p* = 0.12 | **p = 0.01** |
| Head Elevation of Rock Glacier | H = 2.55 | **Z = 2.47** | Z = 1.61 |
| | *p* = 0.28 | **P = 0.01** | *p* = 0.11 |
| Modified Aspect of Rock Glacier | **H = 10.71** | Z = 0.09 | Z = 0.37 |
| | ***p* = 0.01** | *p* = 0.39 | *p* = 0.72 |
| Length of Rockshed | **H = 61.23** | Z = 0.99 | **Z = 5.51** |
| | ***p* = 0.00** | *p* = 0.32 | **p = 0.00** |

with a mean orientation of the overall data set of ~43 ° (Fig. 7; Table 3). Lobate and complex morphologies, glacier-derived, and intact activity members are most oriented toward cooler, northerly aspects. Rock glacier modified aspect has a statistically significant, strong to very strong relationship with rockshed modified aspect of the overall data set as well as members of the morphology, genesis, and activity groups (Table 7; Fig. 8). This suggests that aspects of rock glaciers are strongly associated with aspects of rocksheds.

#### 4.2.5. Area of rockshed

Areas of rocksheds range from <1 ha to nearly 238 ha with a mean of ~18 ha (Table 3). Rockshed areas are largest for complex, glacier-derived, and relict subgroups. Areas of rocksheds for the overall data set have statistically significant, positive, weak to moderate correlations with rock glacier area, length, and width (Table 4) suggesting that dimensions grow with increasing area of rocksheds. No significant differences exist between the members of the groups.

#### 4.2.6. Relief of rockshed

Relief of rocksheds ranges from 34 to 878 m with a mean of 271 m (Table 3). Complex, glacier-derived, and relict rock glaciers have, on average, the greatest relief. Whereas no significant differences exist between members of the groups, (Table 5), relief in rocksheds for the overall data set has statistically significant, positive, very weak to weak correlations with rock glacier area, length, and width (Table 4). This suggests that the dimensions of the overall data set increase with increased relief.

#### 4.2.7. Length of rockshed

Lengths of rocksheds range from 83 to 1920 m with an average length of nearly 572 m (Table 3). Complex, glacier-derived, and relict subgroup rocksheds have the greatest lengths. Significant differences exist between members of the morphology and activity groups (Table 5). Lengths of rocksheds of the overall data set, as well as members of the morphology and activity groups, have statistically significant, positive, very weak to very strong correlations with area, length, and width of rock glaciers suggesting that dimensions of rock glaciers increase with increasing length of rocksheds (Table 6).

#### 4.2.8. Slope of rockshed

Slopes of rocksheds range from 20 to 63% with a mean of just over 46% (Table 3). Whereas rockshed slopes are greatest for lobate, glacier-derived, and relict features, no significant differences exist between members of the groups (Table 5). Overall slopes of rocksheds have statistically significant, positive, very weak to moderate correlations with areas, lengths, and widths of the overall rock glacier data set (Table 4) suggesting that the dimensions of rock glaciers grow with increased slope of rocksheds.

#### 4.2.9. Type of rock

Intrusive igneous rocks (i.e., granite, granodiorite, tonalite, trondhjemite, and diorite) are the most numerous (33%), and are associated with the largest and longest, rock glaciers of the study area (Table 8). This is especially true in the Northeastern Cascades. Extrusive igneous rocks (i.e., andesite, basalt, dacite, and diabase) more commonly compose Southeastern Cascades rock glaciers. All types of rocks (i.e., igneous, sedimentary, and metamorphic) are found in the morphology, genesis, and activity groups.

#### 4.2.10. Landform

Most Eastern Cascades rock glaciers (91%) form in cirques, especially on headwalls (Fig. 3; Table 3). Cirque headwall rock glaciers are, on average, much larger and longer than those formed on cirque sidewalls or landslide scarps (Table 8). Cirque headwalls are therefore the most common birthplaces for tongue-shaped rock glaciers whereas lobate forms are more common on cirque sidewalls. Nearly all landslide scarp features are tongue-shaped. All landforms result in talus-derived rock glaciers while only cirque headwalls harbor glacier-derived rock glaciers.

## 5. Discussion

### 5.1. Causal variables, spatial patterns, and dimensions

#### 5.1.1. Climate

Similar to studies elsewhere (Luckman and Crockett, 1978; Matsuoka, 2003; Janke, 2007; Onaca et al., 2017; Wang et al., 2017; Ran and Liu, 2018), we found that rock glaciers in the Eastern Cascades are found in more northerly latitudes with increased continentality, higher elevations,

**Table 6**
Correlations between variables and rock glacier dimensions for morphology, genesis, and activity group members. Only those variables with significant differences in dimensions are shown. Significant correlations at $p < 0.05$ are shown in bold. Significant correlations at $p < 0.01$ are indicated with bold and asterisk.

| Variable | Dimension | Tongue shaped | Lobate | Complex | Talus derived | Glacier derived | Intact | Relict |
|---|---|---|---|---|---|---|---|---|
| Max. Elev. of RS[1] | RG Area | **0.3033** | **0.3129** | 0.5238 | **−0.3205** | **0.6273** | **0.3246** | **0.5333** |
| | RG Length | **0.2826*** | 0.2049 | 0.6190 | **0.2278** | 0.5545 | **0.2139** | **0.4702** |
| | RG Width | 0.1476 | 0.2453 | 0.5238 | **0.1709** | 0.5455 | 0.1639 | **0.5529** |
| Length of RS | RG Area | **0.4136*** | **0.4158*** | 0.0238 | **0.3963*** | 0.1543 | **0.3370*** | **0.8088*** |
| | RG Length | **0.2156** | **0.3353** | 0.0476 | **0.1876** | 0.2909 | 0.1116 | **0.6421*** |
| | RG Width | **0.4701*** | **0.3188** | 0.1429 | **0.3763*** | 0.2818 | **0.3690*** | **0.4932** |

Max. Elev. of RS.[1] = Maximum Elevation of Rockshed.

**Table 7**
Correlations between variables of overall data set as well as members of morphology, genesis, and activity groups. Significant correlations at $p < 0.05$ are shown in bold. Significant correlations at $p < 0.01$ are indicated with bold and an asterisk.

| | Overall | Tongue-Shaped | Lobate | Complex | Talus-Derived | Glacier-Derived | Intact | Relict |
|---|---|---|---|---|---|---|---|---|
| Latitude – Head Elevation of RG[1] | **0.39** | **0.4943** | **0.29** | −0.67 | **0.43** | 0.08 | **0.35** | **0.54** |
| Latitude – Max. Elevation of RS[2] | **0.45** | **0.57** | 0.26 | −0.29 | **0.50** | 0.31 | **0.42** | **0.65** |
| Distance East – Head Elevation of RG | **0.37** | **0.24** | **0.5431** | **0.83** | **0.34** | 0.58 | **0.37** | 0.20 |
| Distance East – Max Elevation of RS | **0.23** | 0.14 | **0.40** | 0.2619 | **0.22** | −0.04 | **0.26** | −0.07 |
| Head Elevation of RG – Max Elevation of RS | **0.69*** | **0.77*** | **0.52*** | 0.52 | **0.70*** | 0.47 | **0.73*** | 0.392 |
| Mod. Aspect of RG– Mod. Aspect of RS | **0.71** | **0.65*** | **0.75*** | 0.67 | **0.70*** | **0.62** | **0.87*** | **0.68*** |

Head Elevation of RG[1] = Head Elevation of Rock Glaciers.
Max. Elevation of RS[2] = Maximum Elevation of Rocksheds.

and more northerly aspects. Of these variables, only elevation (especially rockshed maximum) has a statistically significant, positive relationship with the dimensions of rock glaciers. High elevations enhance frost action and the creation of talus, as well as ice formation within talus and till at the bases of the slopes. Elevation also significantly combines with latitude and distance east of the crest to explain broader spatial patterns of rock glaciers. Head elevations of rock glaciers rise with increasing latitude, a pattern that runs counter to climate logic and findings elsewhere (Guodong and Dramis, 1992; Janke, 2007; Azocar and Brenning, 2010; Lilleøren and Etzelmüller, 2011; Sattler et al., 2016; Wang et al., 2017; Ran and Liu, 2018). The limited latitudinal range (~2.5°) and the higher topography (i.e., maximum elevations of rocksheds) in the Northeastern Cascades may be the cause of this–i.e., higher elevations may result in higher cirque floors (Hassinen, 1998; Barr and Spagnolo, 2015), and most rock glaciers in the Eastern Cascades form in cirques. Head elevations of rock glaciers also rise eastward, either as a result of climate (i.e., summer temperatures rise with increasing continentality therefore forcing rock glaciers to rise) (Luckman and Crockett, 1978) or as a reflection of rising elevations of cirque floors (Porter, 1964). The effects of maximum elevations of rocksheds are also evident in the clusters of rock glaciers around high peaks and ridges in the Eastern Cascades, a pattern noted elsewhere (Barsch, 1996; Baroni et al., 2004). Conversely, low elevations (with associated higher temperatures) (e.g., found at 46.75 to 47.25°, and 47.5 to 48° latitudes) are typically devoid of rock glaciers (Fig. 1). These results suggest that the lower maximum elevations relative to other ranges may also play a role in the generally low density of rock glaciers in the Eastern Cascades compared to those elsewhere (Bolch and Gorbunov, 2014; Falaschi et al., 2014; Onaca et al., 2017). Most rock glaciers in the Eastern Cascades, like others in the northern hemisphere (Humlum, 1988; Janke, 2007; Charbonneau and Smith, 2018), face north where minimal insolation results in lower temperatures. This

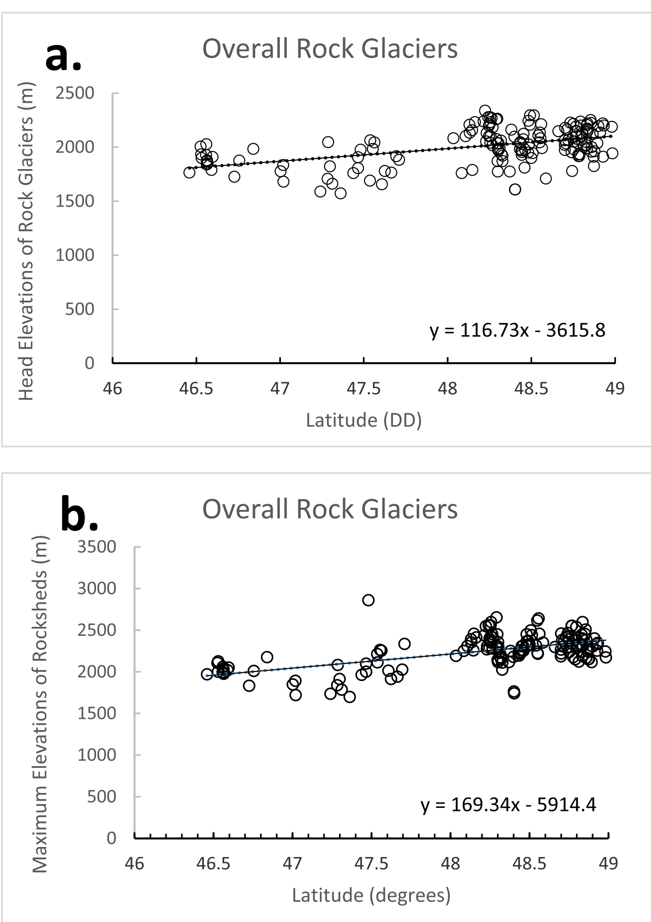


**Fig. 4.** Head elevations of rock glaciers (a.) and maximum elevations of rocksheds (b.) at different latitudes, overall data set.

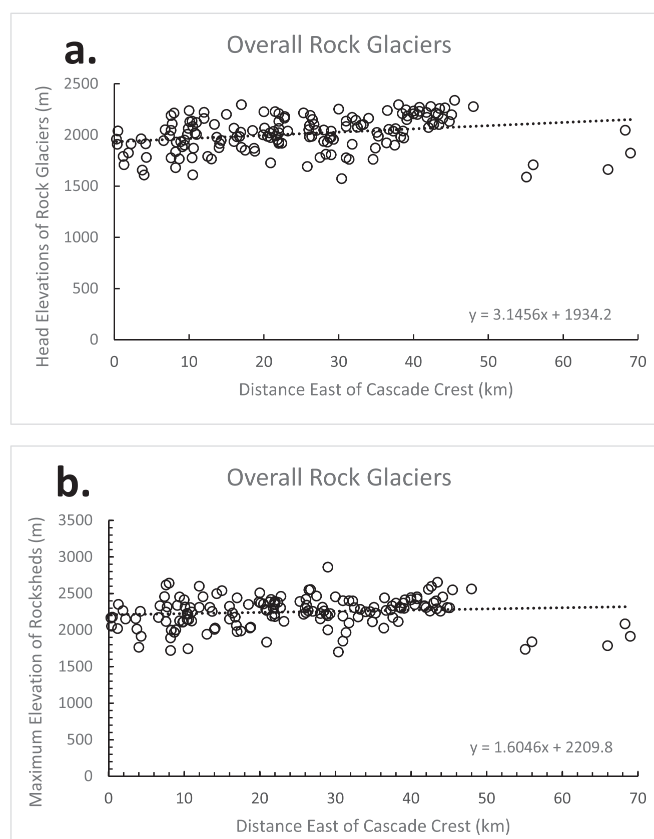


**Fig. 5.** Head elevations of rock glaciers (a.) and maximum elevations of rocksheds (b.) at different distances east of Cascade Crest, overall data set.

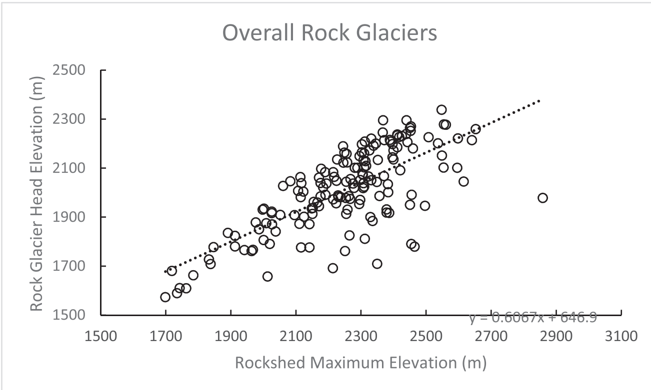


**Fig. 6.** Head elevations of rock glaciers at different maximum elevations of rocksheds, overall data set, Eastern Cascades.

pattern may be complicated by orientations of mountain ranges (Ran and Liu, 2018).

*5.1.2. Topography*

As in other glaciated ranges (Outcalt and Benedict, 1965; Luckman and Crockett, 1978; Lytkin, 2020), most rock glaciers in the Eastern Cascades form in cirques, primarily at the bases of headwalls and sidewalls. These cirques are generally northeast-facing, with floors generally rising to the east (Porter, 1964). Statistical analysis suggests that aspects of the cirque wall rocksheds play a very significant role in the aspects of rock glaciers. Cirque headwalls are ideal for the formation of rock glaciers because their slopes are often sheltered from sunlight thus promoting frost-action weathering. When these slopes become mantled in frost-fractured debris, the steep gradients and converging forms are conducive to creep delivery to valley floors (Wahrhaftig and Cox, 1959; Luckman and Crockett, 1978; Barsch, 1996; Brenning et al., 2007; Falaschi et al., 2015). These characteristics help explain why rock glaciers in the Eastern Cascades that originate at the bases of cirque headwalls have, on average, greater areas and lengths than those forming in other landform settings. These settings also tend to produce tongue-shaped rock glaciers whereas sidewalls, because of more laterally uniform deposition, result in wider, lobate forms. Despite the cirque origins of most rock glaciers in the Eastern Cascades, most are talus-derived highlighting the importance of post-glacial "paraglacial" landscape relaxation processes that resulted in ample deposition of rockfall debris (Ballantyne, 2002; Knight et al., 2018; Jones et al., 2019a). The relatively few glacier-derived, tongue-shaped rock glaciers also originated in cirques.

*5.1.3. Debris supply*

Based on the discussion above, it would seem that each cirque in the Eastern Cascades would contain a large, tongue-shaped rock glacier. This is certainly not the case. One explanation lies in the variable

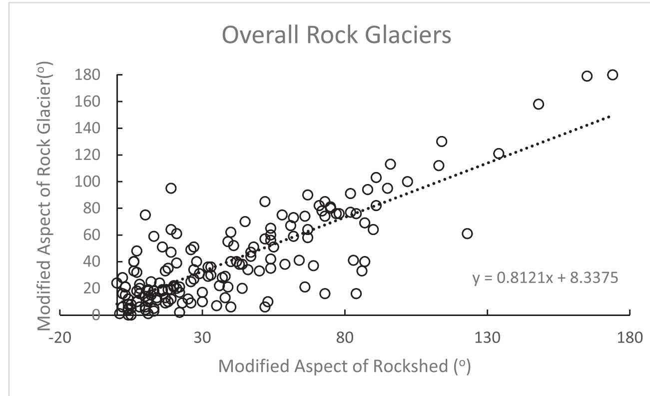


**Fig. 8.** Modified aspects of rock glaciers at different modified aspects of rocksheds, overall Eastern Cascades data set.

geology of the cirques. The large, blocky debris that best promotes cooling, which leads to ice formation and subsequent creep in rock glaciers, often results from the weathering of resistant, crystalline rocks like granite and gneiss, and from massively bedded rocks such as sandstone and limestone (Evin, 1987; Chueca, 1992; Matsuoka and Ikeda, 2001; Haeberli et al., 2006; Falaschi et al., 2014). Such lithologies, while present in the Eastern Cascades, are not universal. Hard, block-producing rocks also result in high relief in rocksheds (Whalley, 1984) which also favors the development of rock glaciers (Luckman and Crockett, 1978; Matsuoka and Ikeda, 2001) (see below). Cirques lacking rock glaciers contain talus cones or aprons, and often protalus ramparts. In cirque-free areas, far from the Cascade Crest, rock glaciers are present but scarce. There, they form on the main and minor scarps of landslides in block-forming basalts. The typical low relief of main and minor scarps, and associated lesser amounts of debris, results in smaller rock glaciers than those found in cirques. Dimensions of rock glaciers in the Eastern Cascades are also affected by the area, relief, length, and slope of rocksheds. Area, length, and width of rock glaciers in the overall data set grow with increases in each of these variables. This is especially true of length of rockshed which has significant relationships with the overall data set as well as the morphology and activity groups. We, like others (e.g., Smith, 1973; Janke and Frauenfelder, 2008; Bolch and Gorbunov, 2014), also found that greater relief of rocksheds is associated with longer rock glaciers.

*5.1.4. Age*

With a mean area of 4.9 ha, rock glaciers in the Eastern Cascades are relatively small compared to those of other ranges–e.g., Basin Ranges in Western North America (Millar and Westfall, 2019), Scandes (Lilleøren and Etzelmüller, 2011), and the Himalaya (Jones et al., 2018; Pandey, 2019). This may reflect the climate, topography, or debris supply

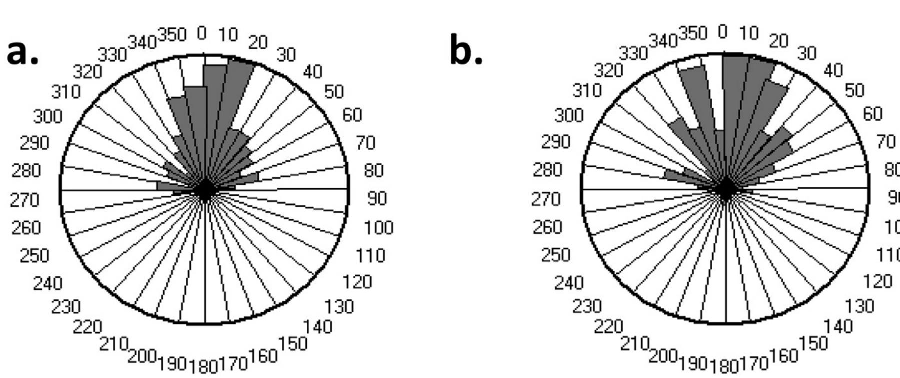


**Fig. 7.** Aspects for: **a.** rock glaciers and **b.** rocksheds of the overall Eastern Cascades data sets.

**Table 8**
Dimensions, types of rocks, and landforms of morphology, genesis, and activity groups of rock glaciers.

| | Intrusive Igneous | Sed. | Extrusive Igneous | Met. | Cirque Headwall | Cirque Sidewall | Slide Main Scarp | Slide Minor Scarp |
|---|---|---|---|---|---|---|---|---|
| # | 52 | 42 | 34 | 31 | 118 | 26 | 12 | 3 |
| Mean area (ha) | 5.7 | 3.9 | 4.4 | 5.3 | 5.2 | 3.6 | 2.6 | 1.9 |
| Mean length (m) | 300 | 269 | 292 | 267 | 300 | 191 | 259 | 554 |
| Mean Width (m) | 187 | 198 | 131 | 223 | 180 | 243 | 117 | 154 |
| Tongue-Shaped # | 37 | 23 | 25 | 15 | 76 | 11 | 10 | 3 |
| Lobate # | 13 | 17 | 8 | 13 | 34 | 15 | 2 | 0 |
| Complex # | 2 | 2 | 1 | 3 | 8 | 0 | 0 | 0 |
| Talus-Derived # | 44 | 42 | 33 | 27 | 105 | 26 | 12 | 3 |
| Glacier-Derived # | 8 | 0 | 1 | 4 | 13 | 0 | 0 | 0 |
| Intact # | 45 | 37 | 31 | 27 | 140 | 24 | 9 | 3 |
| Relict # | 7 | 5 | 3 | 4 | 14 | 3 | 2 | 0 |

variables discussed above. It also raises the issue of age playing a role in the dimensions of rock glaciers in the Eastern Cascades. Previous research has shown that older rock glaciers are larger (Luckman and Crockett, 1978; Barsch, 1996; Lilleøren and Etzelmüller, 2011; Onaca et al., 2017). Extensive late Pleistocene and Holocene glaciation (Porter et al., 1983; Burke and Birkeland, 1983; Kaufman et al., 2003; Davis et al., 2009) in the Eastern Cascades could be the cause of relatively young rock glaciers. Because they mostly occupy cirques, rock glaciers likely post-date the last cirque glaciation. Unfortunately, few dates exist (relative or absolute) on cirques in the Eastern Cascades (Miller, 1969; Waitt Jr. et al., 1982; Bilderback, 2004; Heard, 2012). Assuming formation following retreat of alpine glaciers in the late Pleistocene (Haeberli, 1985; Calkin et al., 1987; Barsch, 1996), rock glaciers in the Eastern Cascades should be younger than about 13.7 ka (Riedel, 2017). Depending on the climate, topography, and debris supply characteristics of each site, some rock glaciers may have required much of the latest Pleistocene and Holocene to develop (Barsch, 1996) whereas others could have formed in as few as several hundred years (Vere and Matthews, 1985; Humlum, 1999). Preliminary absolute and relative dating results from the 20 rock glaciers visited in the field supports this general youthfulness—i.e., generally treeless or young tree ring ages, a lack of overlying tephras, small lichen diameters, and narrow weathering rinds (Weidenaar, 2013; Lillquist, unpublished data). The smaller sizes of non-cirque rock glaciers suggest that landslides that created their rocksheds occurred since the last glaciation or that the variables present there are not conducive to extensive rock glacier growth.

### *5.2. Implications*

This research, combined with that of Millar and Westfall (2008) in the Sierra Nevada Range, Welter (1987) in the Olympic Range, and Charbonneau and Smith (2018) in the Coast Range, shows that rock glaciers are present throughout much of the continental margin, marine-influenced, Western Cordillera. The Cascade Range (including the Eastern Cascades) has long been thought of as being dominated by glaciers (Beckey, 2003). However, this research has shown that rock glaciers are present in every major watershed in the Eastern Cascades; therefore, rock glaciers are potentially important in shaping geomorphic and hydrologic patterns in the region.

Evidence of glaciers (past and present) and rockfall characterizes subalpine and alpine zones in the Eastern Cascades. Steep cirque walls are commonly mantled with talus. Rock glaciers and protalus ramparts often form at the bases of these taluses. Despite being relatively less common, rock glaciers also form in till at the bases of glaciers. In both situations, rock glaciers, along with glaciers and various forms of mass wasting (i.e., rockfall, debris flows, landslides, and avalanches), play a key role in the transport of debris from cliffs to valley floors in alpine settings (Whalley, 1974; Barsch and Jakob, 1998; Humlum, 2000; Janke et al., 2013; Kummert et al., 2017). As an illustration of the potential importance of these features to the geomorphology of the Eastern Cascades, rock glaciers in the Swiss Alps may account for 15–20% of all mass movements (Barsch, 1977). Rock glaciers here, as elsewhere, are key components of alpine and subalpine geomorphology (e.g., Giardino and Vitek, 1988; Shroder et al., 2000; Monnier and Kinnard, 2015). The roles as part of the glacier ≥ debris-covered glacier ≥ rock glacier continua should only increase with time as mountain temperatures rise and glaciers recede (Jones et al., 2019a)–i.e., paraglacial processes operating during deglaciation should enhance rock glacier development (Knight et al., 2018). Despite finding that rock glaciers are relatively uncommon in the till downslope of Eastern Cascades glaciers, we expect that, with predicted climate change, glacier-derived rock glaciers will increase.

As noted earlier, the termini of intact rock glaciers may be used to estimate the lowermost occurrences of contemporary, discontinuous permafrost (Barsch, 1996; Haeberli et al., 2006; Schmid et al., 2015). Toe elevations of relict rock glaciers (currently lacking ice) indicate past permafrost locations (Urdea, 1998; Frauenfelder and Kääb, 2000). Relict rock glaciers in the Eastern Cascades likely started forming following retreat of alpine glaciers in the late Pleistocene or early Holocene. They suggest that the discontinuous permafrost line was located at approximately 1870 m elevation, and that the mean annual air temperature (MAAT) there was ~ − 1.0 °C (Janke, 2005). Intact rock glaciers likely formed during the early Neoglacial and perhaps as recently as the Little Ice Age. The mean toe elevations, combined with an environmental lapse rate of 6.5 °C/1000 m (Barry, 2008), suggest that MAAT's have risen about 0.5 °C since the earlier rock glaciers became relict.

Snow and glacier melt forms a large component of stream and river discharge in the Cascade Range. In a warming world, snowmelt will occur earlier and glaciers will recede (Moore et al., 2009; Elsner et al., 2010). This is already occurring in the Cascade Range. Over time, diminished snowmelt and glacier melt will result in lower base flow, especially in late summer. Late summer meltwater from these sources is often key for maintaining adequate base flow conditions for salmonids. Meltwater derived slowly from ice-containing, intact rock glaciers may help replace some of the previously-supplied glacier meltwater (Brenning, 2005). Water stored as ice in intact Eastern Cascades rock glaciers, combined with water potentially stored in talus and protalus rampart ice, may play an increasing role in stream base flow in the coming decades. As glacier equilibrium line altitudes rise thus diminishing the amount of land area above, less climatically sensitive rock glaciers will assume greater roles in providing late season, mountain stream flow. This will have local ecological effects as well as ecological and human impacts further downstream (e.g., Millar et al., 2013; Millar et al., 2015; Tampucci et al., 2017; Jones et al., 2019b; Brighenti et al., 2020).

## 6. Conclusions

This study is the first comprehensive assessment of 159 rock glaciers, and the variables that affect the spatial distribution and physical dimensions of these features, in the marine-influenced, continental margin Eastern Cascades. Regional patterns of rock glaciers reflect the combined influence of elevation, latitude, and distance east of the Cascade Crest. At more local scales, rock glaciers are present primarily on northeast-facing cirques. Dimensions of rock glaciers are shaped primarily by variables associated with debris supply (i.e., types of rocks and area, relief, and length of rocksheds) as well as local climate (rockshed and rock glacier elevation), and topography (landform and slope of rocksheds). Correlations between the climate, debris, and topography variables and dimensions of rock glaciers are stronger and more numerous for the overall data set than for the members of the morphology, genesis, and activity groups. Given the relatively small sizes of rock glaciers in the Eastern Cascades and the results of research elsewhere, landform age may play a role in rock glacier dimensions. The presence of rock glaciers in every major Eastern Cascades watershed suggests that they play a key, heretofore unrecognized, role in the geomorphic continuum of the range. Relict rock glaciers indicate that discontinuous permafrost was present to 1870 m elevation. Intact rock glaciers suggest that discontinuous permafrost exists down to about 1945 m elevation in the Eastern Cascades. In a warming world, these intact features, will play an increasing role in shaping geomorphic and hydrologic patterns.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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