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Rock glaciers of the contiguous United States: GIS inventory and spatial distribution patterns

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Abstract. Continental-scale inventories of glaciers are available, but no analogous rock glacier inventories exist. We present the Portland State University Rock Glacier Inventory (*n* = 10,343) for the contiguous United States, derived from the manual classification of remote sensing imagery (Johnson 2020, https://doi.pangaea.de/10.1594/PANGAEA.918585). Individually, these rock glaciers are found across widely disparate montane environments, but their overall distribution unambiguously favors relatively high, arid mountain ranges with sparse vegetation. While at least one rock glacier is identified in each of the 11 westernmost states, nearly 88% are found in just five states: Colorado (*n* = 3889), Montana (*n* = 1813), Idaho (*n* = 1689), Wyoming (*n* = 850), and Utah (*n* = 834). Mean rock glacier area is estimated at 0.10 km^2, with cumulative rock glacier area totaling 1008.91 km^2. Rock glaciers are assigned to a three-tier classification system based on area thresholds and surface characteristics known to correlate with downslope movement. Class 1 features (*n* = 7052, average area = 0.12 km^2) appear to be highly active, Class 2 features (*n* = 2416, average area = 0.05 km^2) appear to be intermediately active and Class 3 features (*n* = 875, average area = 0.04 km^2) appear to be minimally active. This geospatial inventory will allow past rock glacier research findings to be spatially extrapolated, help facilitate further rock glacier research by identifying field study sites, and serve as a valuable training set for the development of automated rock glacier identification and classification methods applicable to other large regional studies.

1 Introduction

The most well-known elements of the montane cryosphere are alpine glaciers and perennial snowfields (simply "glaciers" and "snowfields" hereafter). Two lesser known components of the montane cryosphere are rock glaciers and debris-covered glaciers, though presently there are no widely accepted formal definitions of either feature type that can be used to universally and unambiguously discriminate the two for all purposes. Most researchers consider rock glaciers to be flowing bodies of permafrost, composed of generally regular vertical distributions of coarse talus and granular regolith bound by interstitial ice (Clark et al. 1998, Berthling and Etzelmuller 2011). Virtually all rock glaciers form in cryo-conditioned landscapes, resulting from precipitation, meltwater or groundwater percolating into mechanically weathered debris and subsequently freezing (Francou et al. 1999, Berthling 2011). This interstitial ice is shielded from direct solar insolation and insulated from warm air temperatures during the melt season by the overlying regolith mantle (Jones et al. 2019a). Provided some fraction of the internal ice content remains frozen through the summer, additional ice is incorporated each winter until an active rock glacier, one that flows downslope via deformation of the internal ice-rock matrix, is formed. Researchers have generally defined debris-covered glaciers to simply be talus-covered massive ice glaciers, retaining discrete ice cores with relatively low internal concentrations of regolith (Berthling 2011). The surficial talus mantling of debris-covered glaciers is generally sourced from mass wasting of over-steepened lateral slopes, often formerly buttressed by the glacier body, but now unsupported and exposed to the elements due to glacial recession. Fully debris-covered glaciers are indistinguishable from the more traditionally defined rock glaciers through surface analysis alone, either in the field or based on remote sensing imagery, and can only begin to be recognized by direct coring or ground penetrating radar, though debris-covered glaciers with expansive surfaces of exposed ice in their accumulation zones are readily discriminated from rock glaciers. The semantics of classifying these two cryospheric feature types is occasionally debated, but is not something we seek to resolve with this inventory (Clark et al. 1998, Potter 1972, Haeberli et al. 2006, Berthling 2011). Our methods cannot discriminate between the fully mantled debris-covered glaciers and traditionally defined rock-glaciers and refer to them both collectively as "rock glaciers". Virtually all examples of both fully mantled debris-covered glaciers and traditionally defined rock glaciers have been shaped by a combination of glacial and periglacial forces at some point in their geologically recent history, suggesting that considering them here as a single feature type is a reasonable approach. In this regard we agree with the genetic rock glacier definition, "the visible expression of cumulative deformation by long-term creep of ice/debris mixtures under permafrost conditions", proposed by Berthling (2011).

The spatial distributions of glaciers and snowfields of the contiguous U.S. are well understood (RGI Consortium 2017, Fountain et al. 2017). Conversely, the distribution of rock glaciers of the contiguous U.S. is much less certain. Lacking the brilliantly reflective surfaces of glaciers and snowfields, which in late summer afford strong spectral contrast with immediately adjacent land cover, rock glaciers are challenging to identify remotely using automated methods, making spatial inventories difficult to compile (Millar and Westfall 2008). In this study we develop and present the Portland State University Rock Glacier Inventory (PSURGI) for the contiguous United States (Johnson 2020). This inventory will help further define the role of rock glaciers with respect to alpine climatology, ecology, geomorphology, hydrology, and engineering. Rock glacier responses to climate shifts are beginning to be understood with equal specificity to the climatic responses of glaciers, allowing past climatic conditions on short (Bodin et al. 2009, Sorg et al. 2015) and long time scales (Konrad et al. 1999, Stenni et al. 2007, Matthews et al. 2013) to be inferred from their present condition and distribution. The PSURGI will also help advance growing ecological interest in rock glaciers as climate refugia for cold-adapted flora and fauna (Caccianiga et al. 2011, Sulejman 2011, Millar et al. 2013b). Previously studied rock glaciers have shown they can control major fractions of local regolith transport (Kaab and Reichmuth 2005, Haeberli et al. 2006). Additionally, rock glacier meltwaters exhibit unique hydrographs (Bajewsky and Gardner 1989, Pauritsch et al. 2015, Jones et al. 2019b) and hydrochemistry signatures (Millar et al. 2013a, Fegel et al. 2016), as well as also volumetric discharge increases in late

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summer due to climate change (Caine 2010). From an anthropogenic perspective, rock glaciers represent unique engineering challenges, particularly with regard to the possibility of catastrophic collapse and debris flow generation (Iribarren and Bodin 2010, Lugon and Stoffel 2010, Bodin et al. 2017), but they also offer engineering opportunities as reservoirs of construction aggregate and water (Burger et al. 1999).

The regional or continental scale impacts of these and other rock glacier influences identified in previous research on individual rock glaciers cannot be inferred without an accurate rock glacier inventory at the same spatial scale. Smaller scale rock glacier inventories have been completed before (Table 1), but the rock glacier distribution across an area the size of the contiguous U.S. has never been quantified in a comprehensive manner. Where prior rock glacier inventories considered study areas most often measured in dozens, hundreds, or, occasionally, thousands of square kilometers, our rock glacier inventory evaluates a study area of over 3,000,000 km^2. This study addresses a pressing research question: What is the spatial distribution of rock glaciers of the contiguous U.S.?

2 Data and Methods

2.1 Study Region and Data Sources

We used Google Earth Pro 7.1.7 (Google Earth 2018) and ESRI ArcMap 10.4 software (ESRI 2017) to search for rock glaciers. Google Earth Pro provides imagery acquired at multiple dates from the early 1990s to present, orthorectified to accurate and easily manipulated three-dimensional surfaces. Quick access to multiple images of the same location, captured at different times of day, during different seasons, and across multiple years facilitated identification certainty. We relied on Google Earth Pro and the three-dimensional elevation models it provides for most identifications, supplementing with other plan-view imagery imported into ArcMap 10.4 when Google Earth Pro imagery was unsuitable due to cloud cover or other issues.

We initially began evaluating all montane regions of the contiguous U.S., but quickly found no evidence of rock glaciers east of the Rocky Mountain States, therefore we focused our efforts on the 11 westernmost states (AZ, CA, CO, ID, MT, NM, NV, OR, UT, WA, WY). Climatologically, the study region is defined by four zones of the NOAA U.S. Climate Region system (Karl and Koss 1984): the Northwest Climate Region (hereafter “NW region”) of ID, OR and WA; the Southwest Climate Region (hereafter “SW region”) of AZ, CO, NM and UT; the West Climate Region (hereafter “W region”) of CA and NV; and the West North Central Climate Region (hereafter “WNC region”) of MT and WY. The major mountain range in each of the four regions is the Cascades, Southern Rockies, Sierra Nevada and Northern Rockies, respectively.

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2.2 Rock Glacier Identification

Because glaciers and rock glaciers are often co-located (Jones et al. 2019a, Knight et al. 2019, Millar and Westfall 2019), we used two GIS inventories that identify relevant features to inform target areas for our initial search for the rock glaciers; the Randolph Glacier Inventory (RGI) v6.0 (RGI Consortium 2017, Fountain et al. 2017) and the National Land Cover Database (NLCD) 2011 (Homer et al. 2015). The RGI is focused only on glaciers, whereas the NLCD identifies any perennial snow or ice feature. From this initial effort and our growing expertise in locating rock glaciers, we expanded our search areas to explore alpine regions far from any inventoried glaciers or perennial snow or ice features, but that could potentially host rock glaciers.

Rock glaciers were identified manually by their distinct surface characteristics (Aoyama 2005, Haeberli et al. 2006). These characteristics include ridge and swale surface banding resulting from differential flow rates and terminal and lateral slopes over-steepened beyond the angle of repose, presumably cemented by interstitial ice. Common mass wasting processes responsible for individual fragments of regolith traveling downslope result in accumulations at or below the angle of repose. Similar approaches to rock glacier identification, focusing on surface topography characteristics identified from aerial and satellite imagery, have been applied in other previous research (Eztelmuller et al. 2007, Janke 2007, Degenhardt 2009, Janke et al. 2015, Millar et al. 2019).

We focused our inventory efforts on identifying rock glaciers that, surficially, appear to contain appreciable internal ice fractions and are presently or were recently flowing downslope. We follow previous studies that omit features with expansive bare glacial ice in their accumulation zones as those are clearly debris-covered glaciers, but make no attempt to discriminate rock glaciers from fully mantled debris-covered glaciers (Bodin et al. 2010, Berthling 2011, Perucca and Angillieri 2011). After the exponentially larger study area than any previously investigated, a second major distinction between our rock glacier inventory and classification system and other previous U.S. rock glacier inventory efforts is that we intentionally attempt to exclude relict rock glaciers. We ignored potential candidate features lacking over-steepened terminal slopes and/or present evidence of advanced surficial soil development, such as expansive vegetation growth, both of which imply the rock glacier has a small internal ice fraction and/or has not flowed downslope recently.

When identifying a candidate rock glacier, plan-view images were initially viewed at 1:2000 scale or better. Once suspected ridge and swale flow banding and over-steepened terminal and lateral slopes were identified, image scale was greatly increased. All available clear sky images of the same scene were then evaluated, with plan views being replaced by oblique views from multiple angles and multiple scales and three-dimensional topography exaggerated by 50%. The perimeter of individual rock glaciers were manually delineated using Google Earth Pro. Usually, sharp changes in slope were evident, indicating a perimeter boundary between the thickened ice-bound regolith of the rock glacier and the surrounding

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unconsolidated talus of the adjacent slope. Additionally, lower rock glacier margins often abut well-vegetated terrain. The upper margins are often defined by a change in slope, from the steep slopes of exposed bedrock and unconsolidated talus in the rock glacier accumulation zone to the more gentle slope of the main body of the ice-thickened rock glacier.

Understandably, there can be some disagreement between analysts regarding rock glacier classification. To partially address this ambiguity all features identified as rock glaciers were subsequently assigned to a three-tier classification system based on surface characteristics known to correlate with downslope movement motivated by deformation of the internal ice-rock matrix (Figure 1). Class 1 rock glaciers appear to be highly active, exhibit unambiguous, complex and extensive ridge and swale flow banding, and have substantially over-steepened terminal and lateral boundaries. Class 2 rock glaciers appear to be intermediately active, exhibit some pronounced ridge and swale flow banding, and have somewhat over-steepened terminal and lateral boundaries. Class 3 rock glaciers appear to be minimally active, exhibit sparse ridge and swale flow banding, and have intermittently over-steepened terminal and lateral boundaries.

To characterize the topographic characteristics of the individual rock glaciers identified, elevation data were extracted from the USGS National Elevation Dataset (NED) ⅓ arc-second (≈ 10 m) digital elevation model (USGS 2017). Topographic variables of elevation, slope, aspect, and insolation were determined using Spatial Analyst tools in ArcMap 10.4 (ESRI 2017). Rock glacier area was calculated in km^2, while slope and aspect were calculated in degrees. Aspect was decomposed to an eastness and northness component (Nussear et al. 2009), and solar insolation was calculated in watt-hours per m^2. To characterize the climate of the rock glaciers, climate data, including air temperature and precipitation, were also extracted from PRISM 1981 - 2010 climate normals (PRISM 2017) using Spatial Analyst tools in ArcMap 10.4. PRISM data were also used to calculate several derivative atmospheric variables, such as fraction of precipitation falling as snow and mean vapor pressure deficit, using the Raster Calculator tool in ArcMap 10.4. These publicly available climate data have a spatial resolution of 800 m, with an average daily accumulated total precipitation bias of less than 2.5% in the western US, 1961 - 2001 (DiLuzio et al. 2008). Rock glacier classification and area clustering analysis using Moran's I-statistics helped further describe rock glacier spatial distributions (Cliff and Ord 1971, Senn 1976, Tiefelsdorf 2002).

3 Results

3.1 Overall Distribution

We identified 10,343 rock glaciers (Class 1 = 7052, Class 2 = 2416, Class 3 = 1021) across the western U.S. (Figure 2, Table 2), after removing 146 small (< 0.01 km^2) Class 3 rock glaciers following glaciological convention of area thresholds (Navarro and Magnusson 2017). Average rock glacier area is 0.10 km^2 and the average distance between each rock glacier and its nearest neighbor is 0.69 km. Contiguous U.S. rock glaciers have an average elevation of 3144.8 m, an average slope of 20.50º, an average eastness of -0.007, and an average northness of 0.066. Climatically, the average annual rock glacier

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precipitation is 350.2 mm, the average air temperature is 0.19 °C, the average dew point temperature is -8.37 °C, and the average vapor pressure deficit is 4.52 hPa. The overall rock glacier centroid (41.5350,-110.7072) is located in the southwest corner of the WNC region (Figure 2). The centroids of each of the three rock glacier classes (Class 1 = (41.5136, -110.5543), Class 2 = (41.7017, -111.0135), Class 3 = (41.2470, -111.0942)) can be contained by a minimum bounding area circle with a diameter of 57.3 km. Moran's I analysis shows rock glacier classifications and areas are significantly clustered (Table 3 and Table 4).

3.1.1 Regional Distributions

In the NW region, we identified 1993 rock glaciers (Class 1 = 1293, Class 2 = 512, Class 3 = 188)(Figure 5). Geographically, the average rock glacier size is 0.07 km^2, and the average distance between each rock glacier and its nearest neighbor is 0.99 km. Topographically, the average rock glacier elevation is 2629.6 m, the average slope is 20.7º, the average eastness is 0.000, and the average northness is 0.109. Climatically, the average annual rock glacier precipitation is 365.4 mm, the average air temperature is 1.06 °C, the average dew point temperature is -7.47°C, and the average vapor pressure deficit is 4.85 hPa. The NW region rock glacier centroid (44.8620, -115.2736) is located in the Sawtooth Mountains of Idaho (Figure 2). The NW region centroids of each of the three rock glacier classes (Class 1 = (44.7208, -114.9471), Class 2 = (45.0615, -115.7468), Class 3 = (45.2899, -116.2301)) can be contained by a minimum bounding area circle with a diameter of 106.3 km (Figure 5).

In the SW region, we identified 4870 rock glaciers (Class 1 = 3291, Class 2 = 1133, Class 3 = 446)(Figure 6). The average SW region rock glacier size is 0.09 km^2, and the average distance between each SW region rock glacier and its nearest neighbor is 0.59 km. Topographically, the average rock glacier elevation is 3490.35 m, the average slope is 20.70º, the average eastness is -0.013, and the average northness is 0.046. Climatically, the average annual rock glacier precipitation is 335.12 mm, the average air temperature is -0.09 °C, the average dew point temperature is -8.92 °C, and the average vapor pressure deficit is 4.50 hPa. The SW region rock glacier centroid (38.9385, -107.3569) is located in the Rocky Mountains of Colorado (Figure 2). The SW region centroids of each of the three rock glacier classes (Class 1 = (38.9066, -107.2755), Class 2 = (39.0867, -107.5456), Class 3 = (38.7968, -107.4786)) can be contained by a minimum bounding area circle with a diameter of 38.2 km (Figure 6).

In the W region, we identified 817 rock glaciers (Class 1 = 552, Class 2 = 181, Class 3 = 84)(Figure 7). The average W region rock glacier size is 0.12 km^2, and the average distance between each W region rock glacier and its nearest neighbor is 0.68 km. Topographically, the average rock glacier elevation is 3412.2 m, the average slope is 20.9º, the average eastness is -0.001, and the average northness is 0.082. Climatically, the average annual rock glacier precipitation is 367.79 mm, the average air temperature is 0.61 °C, the average dew point temperature is -9.52 °C, and the average vapor pressure deficit is 5.07 hPa. The W region rock glacier centroid (37.5421, -118.6340) is located in the Sierra Nevada of California (Figure 2).

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The W region centroids of each of the three rock glacier classes (Class 1 = (37.5506, -118.6616), Class 2 = (37.4045, -118.6486), Class 3 = (37.7828, -118.4209)) can be contained by a minimum bounding area circle with a diameter of 48.0 km (Figure 7).

In the WNC region, we identified 2663 rock glaciers (Class 1 = 1916, Class 2 = 590, Class 3 = 157)(Figure 8). The average WNC region rock glacier size is 0.11 km^2, and the average distance between each WNC region rock glacier and its nearest neighbor is 0.79 km. Topographically, the average rock glacier elevation is 2816.3 m, the average slope is 19.9º, the average eastness is -0.002, and the average northness is 0.067. Climatically, the average annual rock glacier precipitation is 361.1 mm, the average air temperature is -0.08 °C, the average dew point temperature is -7.7 °C, and the average vapor pressure deficit is 4.12 hPa. The WNC region rock glacier centroid (45.0184,-110.9847) is located in the Rocky Mountains of Montana (Figure 2). The WNC region centroids of each of the three rock glacier classes (Class 1 = (44.9688, -110.8858), Class 2 = (45.1258, -111.2233), Class 3 = (45.2200, -111.2951)) can be contained by a minimum bounding area circle with a diameter of 49.5 km (Figure 8).

4 Discussion

4.1 Spatial Distribution Patterns

Individually, contiguous U.S. rock glaciers are found across widely disparate montane environments, but their overall distribution unambiguously favors relatively high, arid mountain ranges with sparse vegetation. Rock glacier populations in those regions are denser, and the individual rock glaciers making up those populations are larger and exhibit surficial evidence of higher activity, than those of rock glaciers found in humid mountain ranges with copious vegetation. Rock glaciers of the NW region are largest and most densely concentrated in the Sawtooth Mountains of Idaho. Rock glaciers of the SW region are largest and most densely concentrated in the Front Range and San Juan Mountains of Colorado and the Uinta Mountains of Utah. Rock glaciers of the W region are largest and most densely concentrated in the Sierra Nevada of California. Rock glaciers of the WNC region are largest and most densely concentrated in the Beartooth Mountains of Montana and the Absaroka Range of Wyoming.

4.2 Inventory Accuracy

The completeness and accuracy of the inventory were qualitatively and quantitatively supported by numerous field observations and remote sensing classification verification by multiple GIS analysts familiar with the alpine cryosphere generally and rock glaciers specifically. The lead author personally visited more than 50 rock glaciers during field campaigns for related research, and more than 150 rock glaciers with precise coordinates listed in past peer reviewed research were examined remotely when developing our classification criteria. While developing the inventory, dozens of test areas

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measuring 500 km^2 or greater in all 11 western states were checked by two other well trained GIS analysts familiar with the alpine cryosphere for "missing" rock glaciers not originally identified by the lead author, and none were found. When considering the three-class rock glacier activity classification scheme, a test subset of 60 randomly selected rock glaciers were classified in isolation by five GIS analysts familiar with the alpine cryosphere generally and rock glaciers specifically. Classifications were then compared, yielding no significant differences between analyst interpretations. Class 1 rock glaciers showed a 92% agreement between analysts, Class 2 rock glaciers an 87% agreement between analysts, and Class 3 rock glaciers a 79% agreement between analysts.

As this rock glacier inventory is of unprecedented spatial extent, no analogous previous inventories exist for us to make direct and detailed GIS comparisons to over the entire study region. While smaller regional-scale rock glacier inventories have been compiled in the past, none of these inventories are publicly available as geospatial data sets. Coarse scale comparisons, however, were completed based on reported findings and figures published in previous studies presenting the aforementioned smaller regional rock glacier inventories. To compare our rock glacier inventory and previous regional rock glacier inventories we created polygons using the corner coordinates of low resolution regional study maps from peer-reviewed articles highlighting one Colorado rock glacier inventory (Janke 2007) and two California rock glacier inventories (Millar and Westfall 2008, Liu et al. 2013). Polygons representing the extents of maps from the smaller regional inventories were then used to select simple counts of rock glaciers identified in our inventory and compare them to counts of rock glaciers reported in the aforementioned studies. The 2007 Colorado inventory reported 28 "active" rock glaciers, the category in that study most similar to our Class 1 classification criteria, in and around Rocky Mountain National Park, while we identified 29 Class 1 rock glaciers in the same region. The 2008 California study reported 184 rock glaciers in the central Sierra Nevada, but used a more inclusive "rock-ice feature" definition, that deliberately includes relict rock glaciers, than our rock glacier classification criteria, while we identified 116 rock glaciers of any class in the same region. The 2013 California study (Liu et al. 2013) reported 67 "active" rock glaciers, a subset of features identified in the 2008 study and the category in that study most similar to our Class 1 classification criteria, while we identified 88 rock glaciers in largely the same study region. These three comparisons, and the agreement between the aforementioned inventories and our findings, greatly bolster our confidence in the overall accuracy of the PSURGI.

5 Data Availability

The PSURGI geospatial data (Johnson 2020) is available online via the PANGAEA data repository at https://doi.pangaea.de/10.1594/PANGAEA.918585.

6 Conclusions

We present the most spatially extensive geospatial rock glacier inventory in the world to date, a powerful tool informing a wide range of research and management applications. The PSURGI exposes, for the first time at such an expansive spatial scale, what an ubiquitous component of the contiguous U.S. alpine cryosphere rock glaciers truly are. Despite their ubiquity, rock glaciers remain an under-studied and under-appreciated element of the alpine cryosphere (Duguay et al. 2015). The deeper understanding of where rock glaciers form and persist where provided by this inventory will aid ongoing refinement and future implementation of truly automated rock glacier detection methods. The ability to quickly, accurately and objectively identify rock glaciers from presently available remote sensing imagery, without relying on skilled visual image analysts or needing to address the inevitable interpretation disagreements between those analysts, would be an invaluable tool for climatologists, ecologists, water resource managers and many others (Brenning 2009).

7 Author Contributions

Gunnar Johnson designed the research project, created and analyzed the rock glacier inventory data, and wrote the manuscript. Heejun Chang and Andrew Fountain designed the research project and edited the manuscript

8 Author Contributions

The authors declare that they have no conflict of interest.

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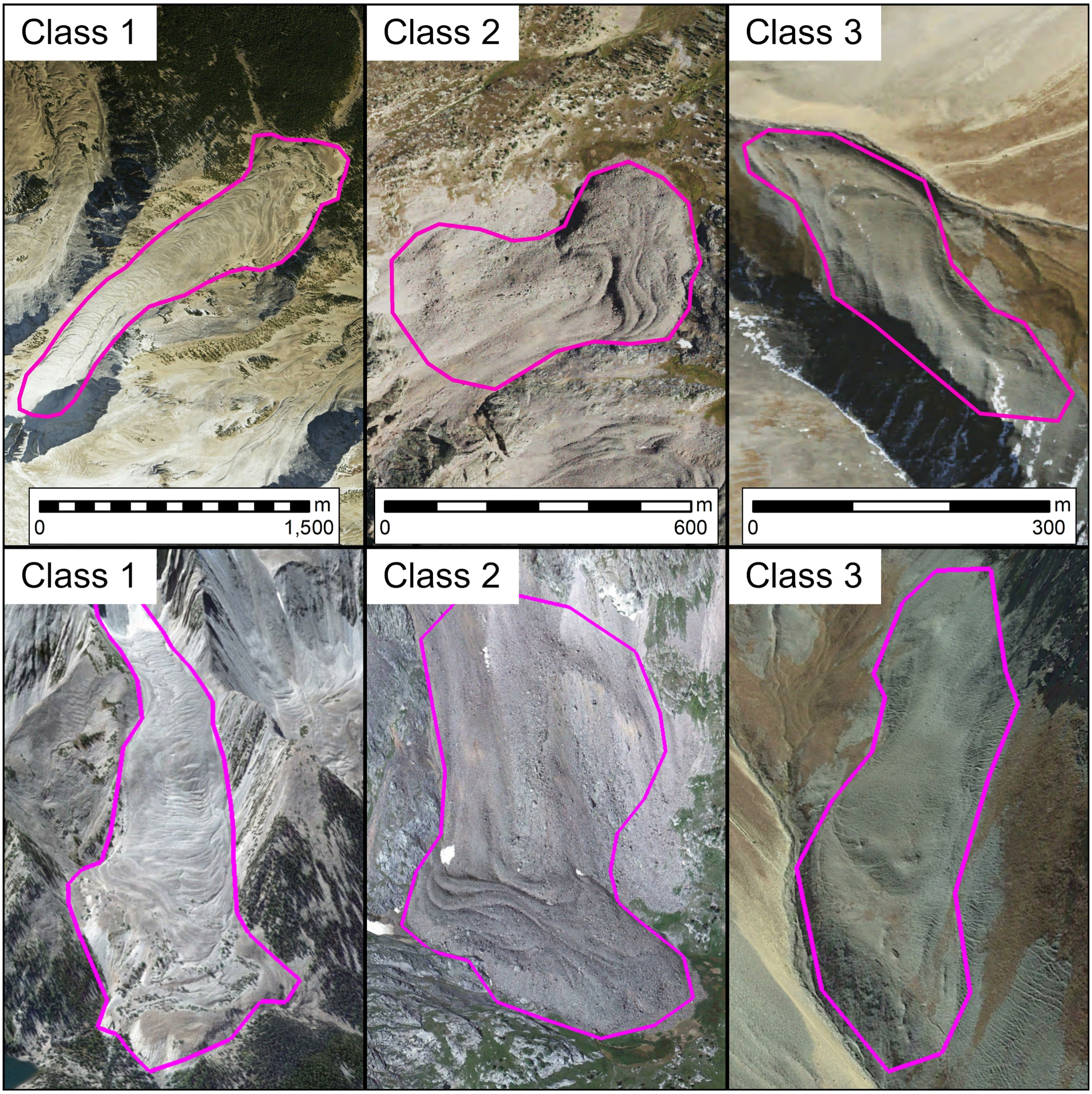
Figures



505 **Figure 1: Examples of each of the three rock glacier classes shown in both plan view (top panels) and oblique upslope view (bottom panels). Leftmost panels show a Class 1 rock glacier (appears to be highly active, exhibits unambiguous, complex and extensive ridge and swale flow banding, and has substantially over-steepened terminal and lateral boundaries). Center panels show a Class 2 rock glacier (appears to be intermediately active, exhibits some pronounced ridge and swale flow banding, and has somewhat over-steepened terminal and lateral boundaries.). Rightmost panels show a Class 3 rock glacier (appears to be minimally active, exhibits sparse ridge and swale flow banding, and has intermittently over-steepened terminal and lateral boundaries.). Note different scale bars for each plan view panel, and that scale varies across images in oblique view panels. Image credit: © Google Earth/Copernicus.**

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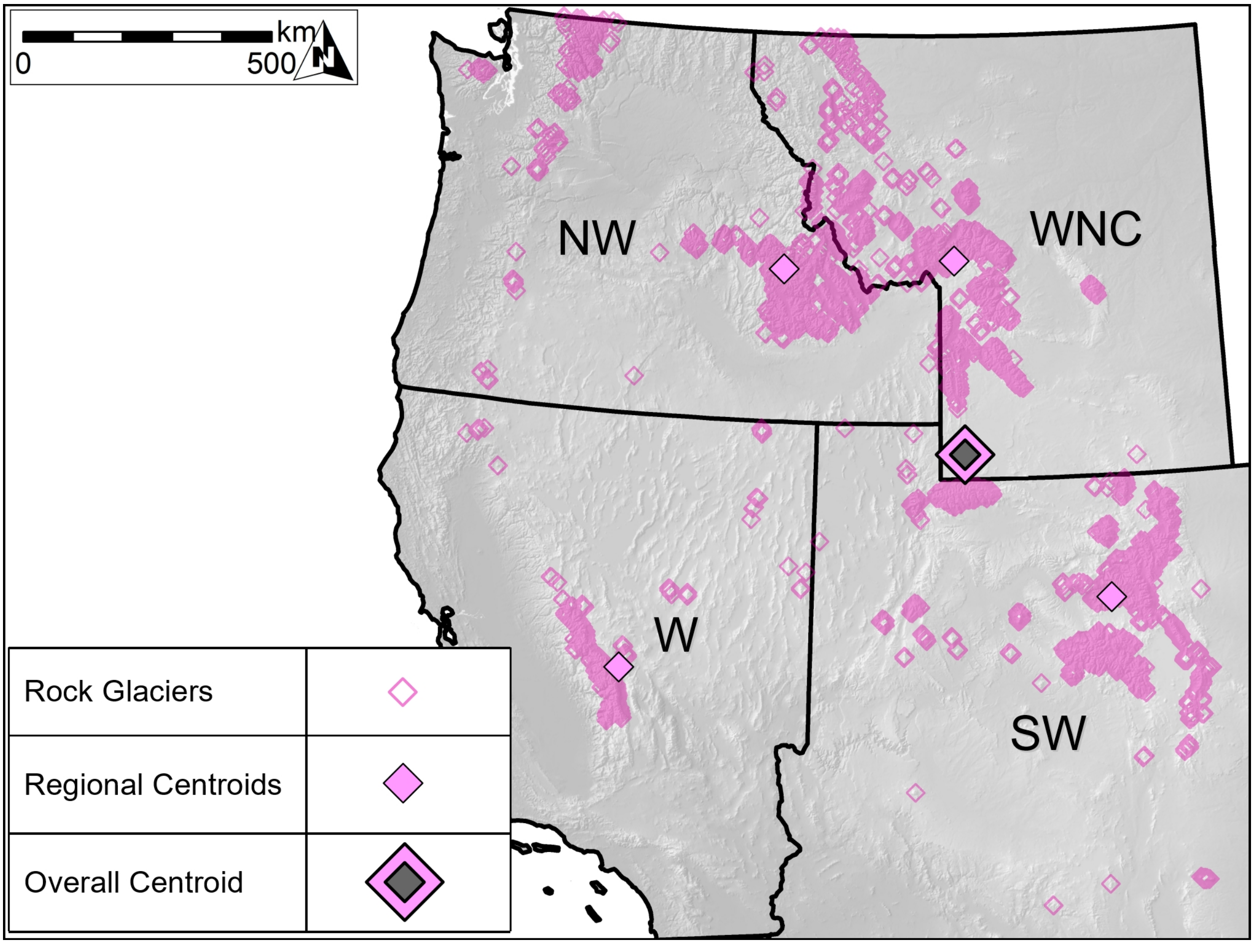

Figure 2: Locations of rock glacier inventory features (n = 10,343), as well as centroids for the entire inventory and NOAA Climate Region subsets. The largest rock glaciers, as well as highest rock glacier densities, are found in the relatively arid Southern Rocky Mountains. The Sierra Nevada of California and Uinta Mountains of Utah, climatologically similar to the Southern Rockies, also host large rock glaciers at high densities. Rock glaciers of the humid Cascade Mountains are smaller and less densely distributed, and only a few pockets of rock glaciers are found south of 35° N latitude. However, the western U.S. is generally defined by mountainous, high elevation terrain, and rock glaciers are found in all 11 western states.

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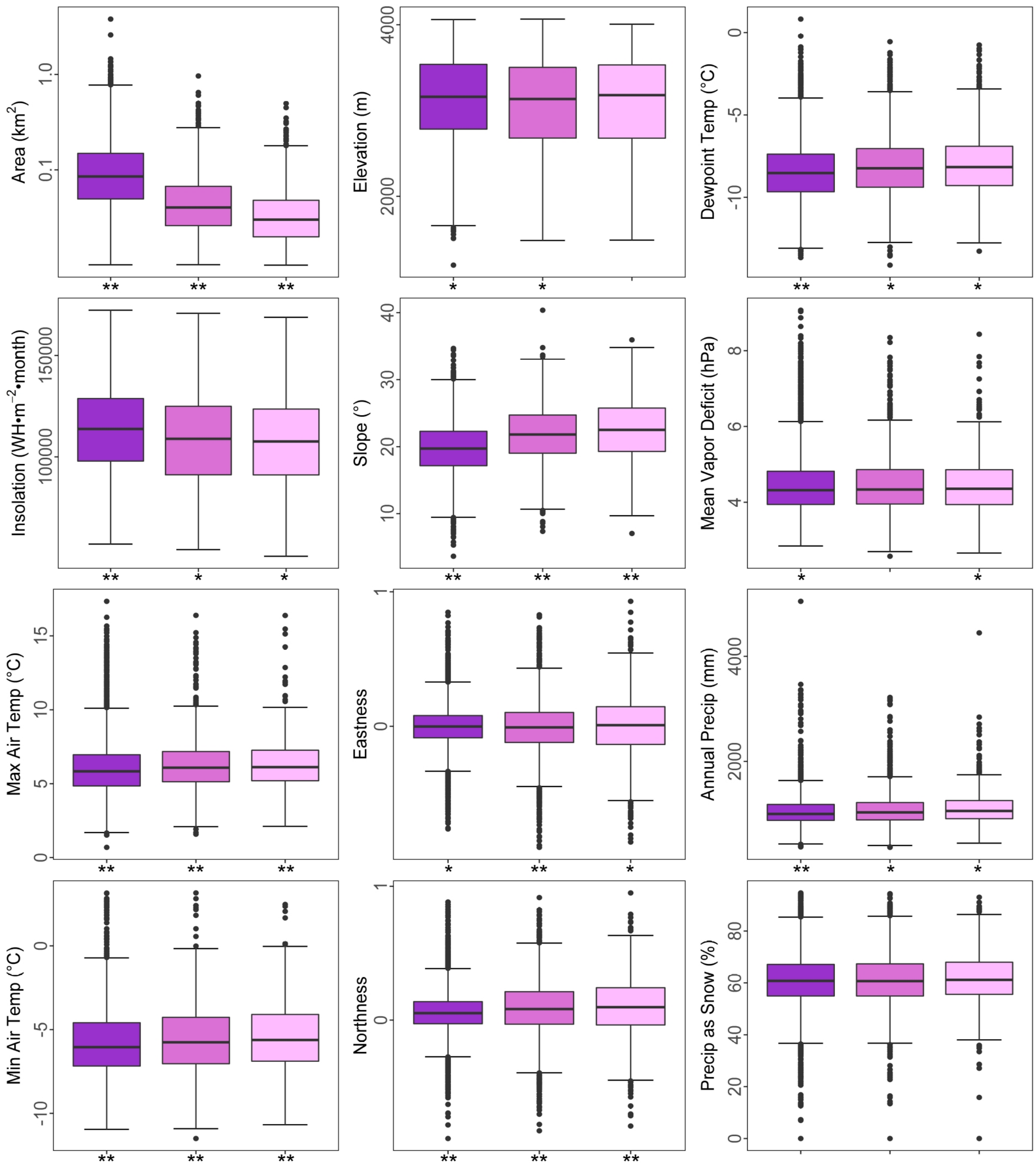

Figure 3: Geographic characteristics of Class 1 (dark purple, n = 7052), Class 2 (magenta, n = 2416) and Class 3 (light pink, n = 875) rock glaciers. Statistically significant differences (Tukey's HSD test, α = 0.05) are denoted with asterisks (different from one = *, different from both = **).

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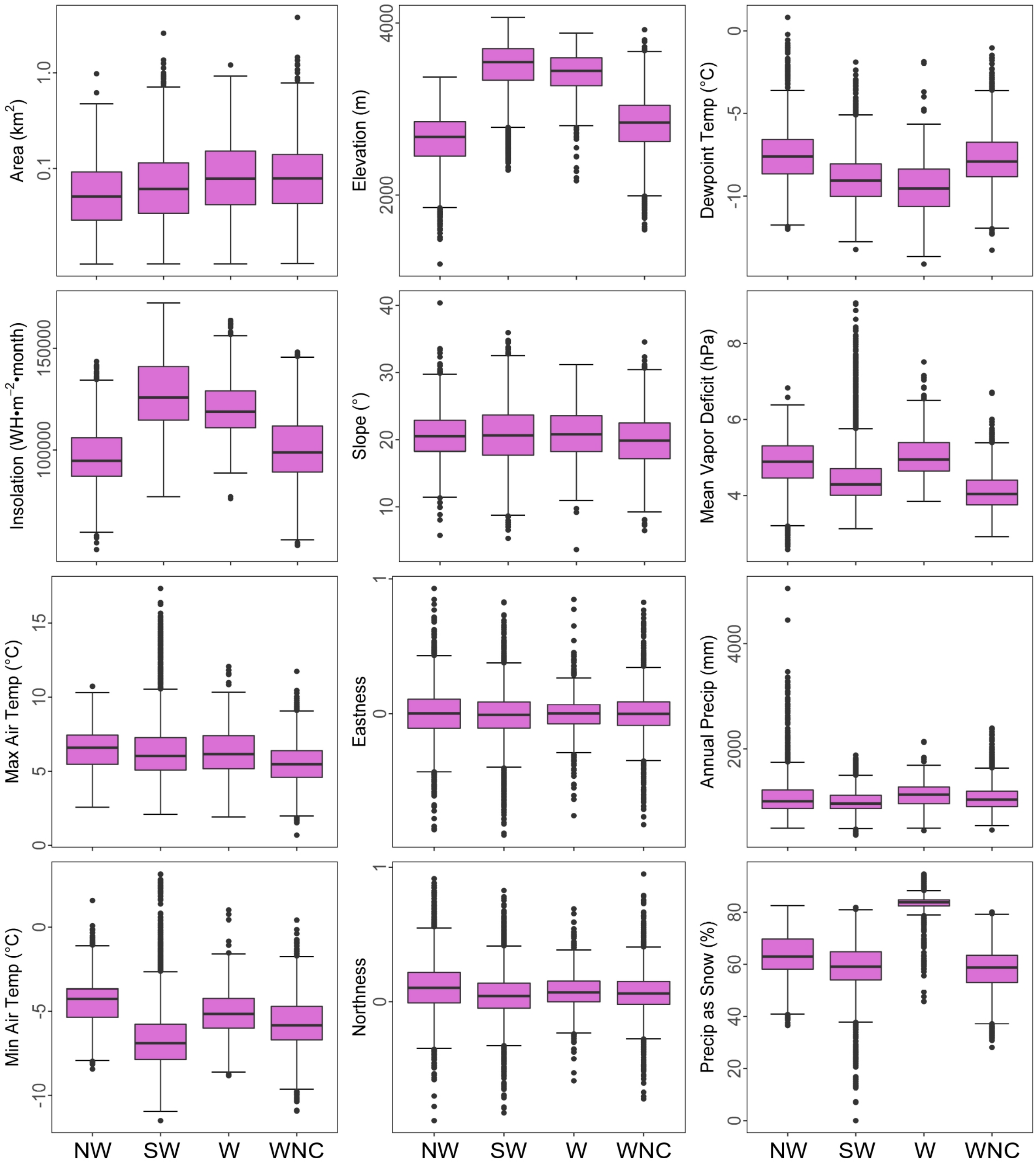

Figure 4: Geographic characteristics of rock glaciers by NOAA Climate Region.

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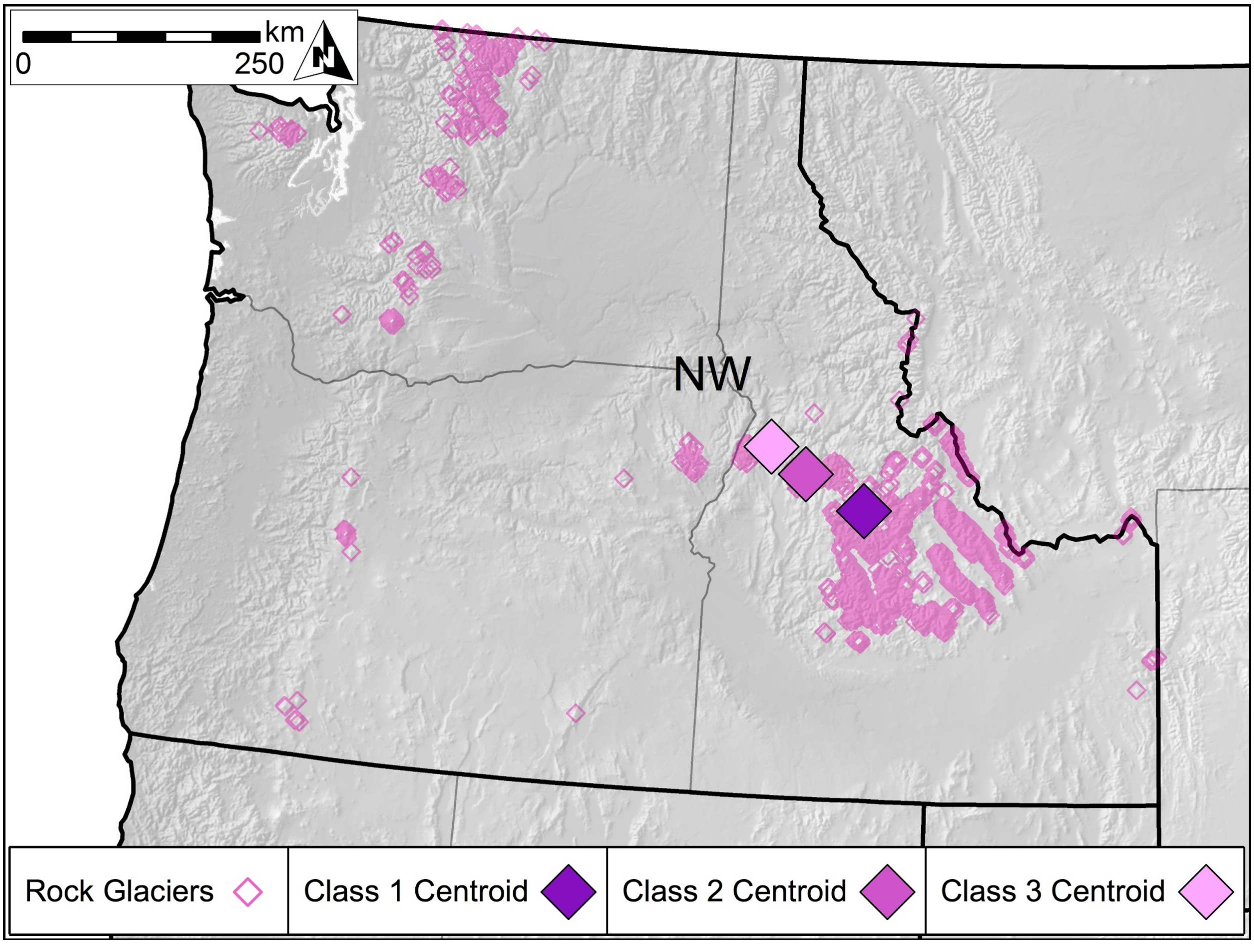

Figure 5: Locations of NW region rock glacier inventory features (n = 1993), as well as centroids for Class 1 (n = 1293), Class 2 (n = 512) and Class 3 (n = 188) features. Rock glaciers of the NW region are largest and most densely concentrated in the Sawtooth Mountains of Idaho.

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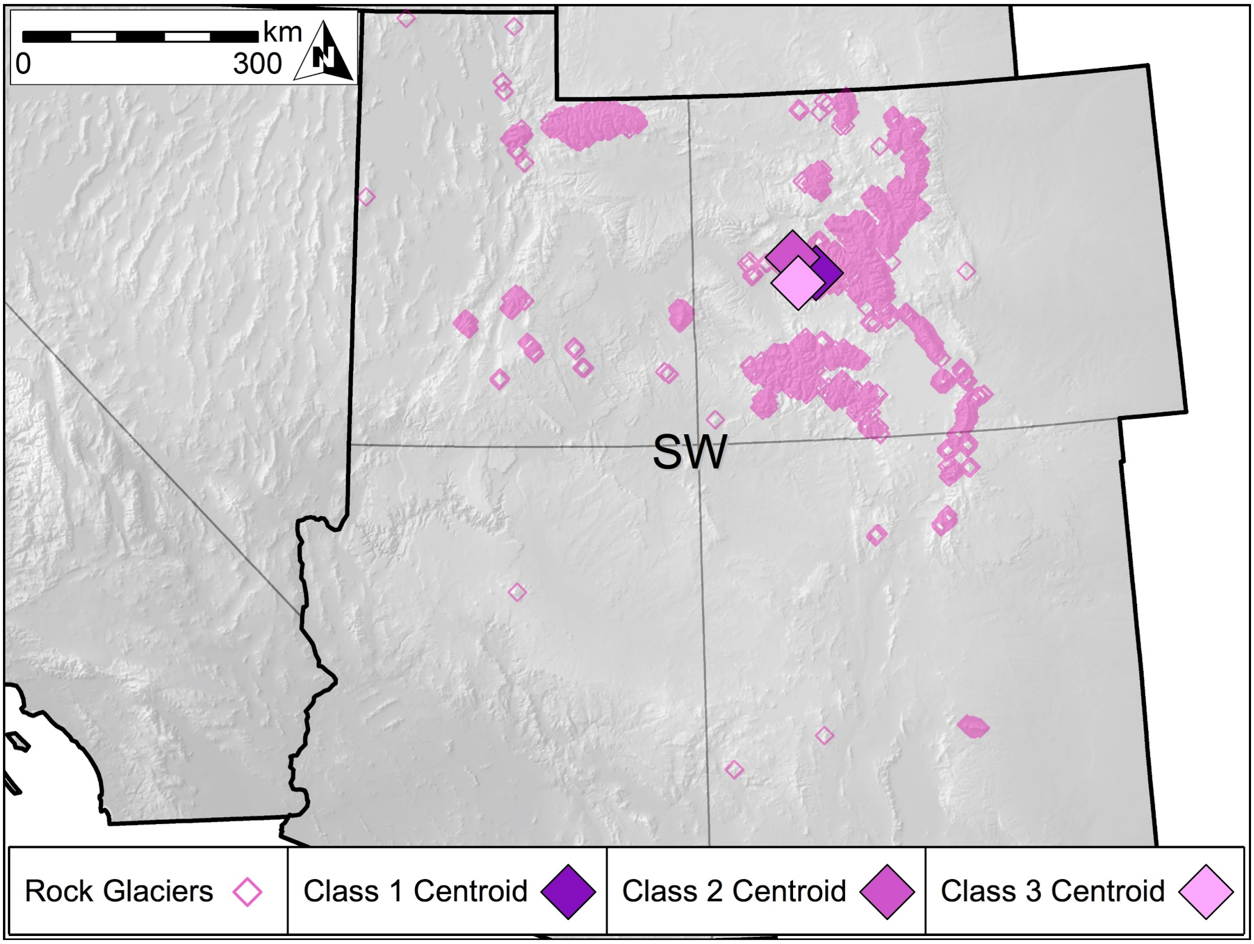

Figure 6: Locations of SW region rock glacier inventory features (n = 4870), as well as centroids for Class 1 (n = 3291), Class 2 (n = 1133) and Class 3 (n = 446) features. Rock glaciers of the SW region are largest and most densely concentrated in the Front Range and San Juan Mountains of Colorado and the Uinta Mountains of Utah.

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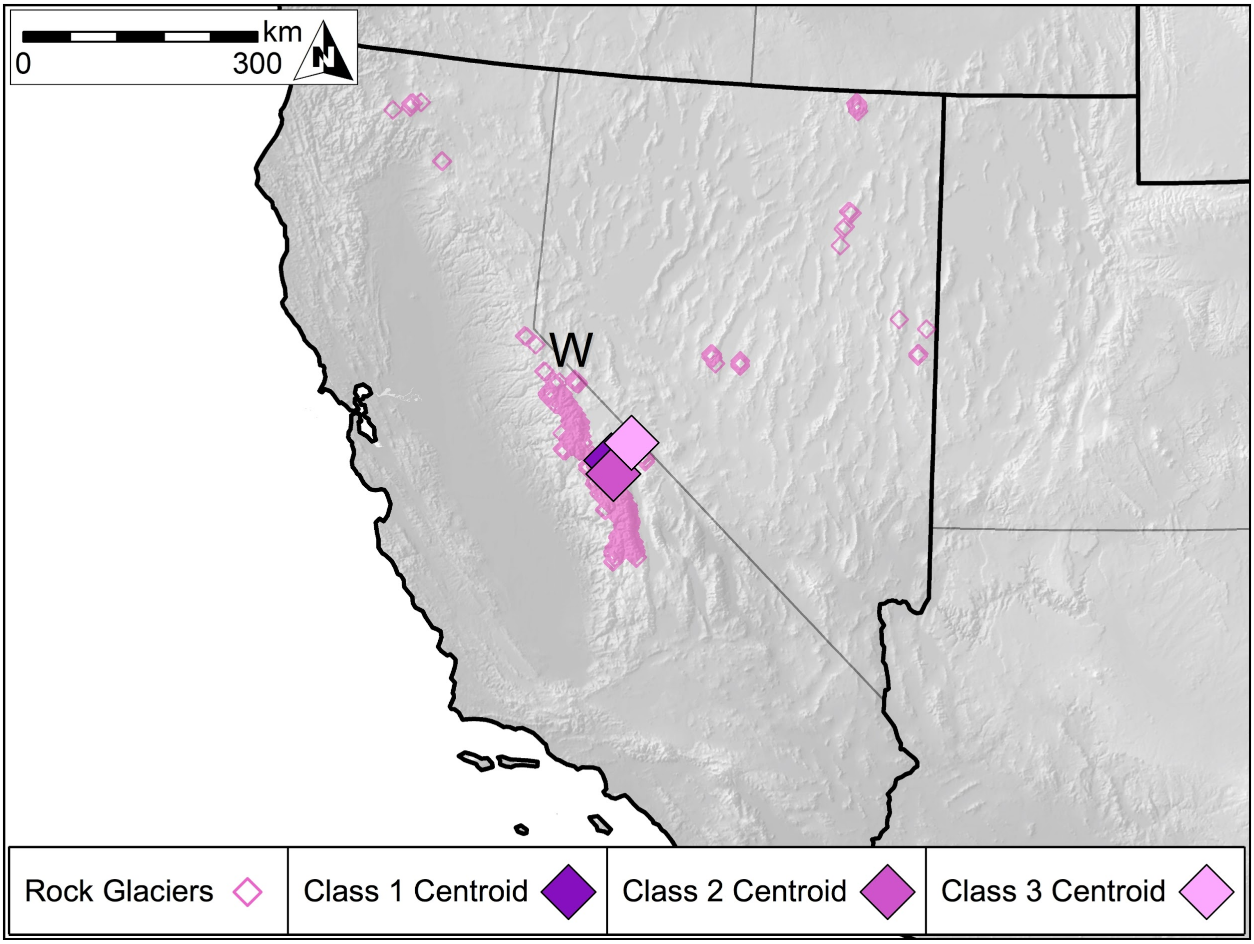

545 **Figure 7: Locations of W region rock glacier inventory features (n = 817), as well as centroids for Class 1 (n = 552), Class 2 (n = 181) and Class 3 (n = 84) features. Rock glaciers of the W region are largest and most densely concentrated in the Sierra Nevada of California.**

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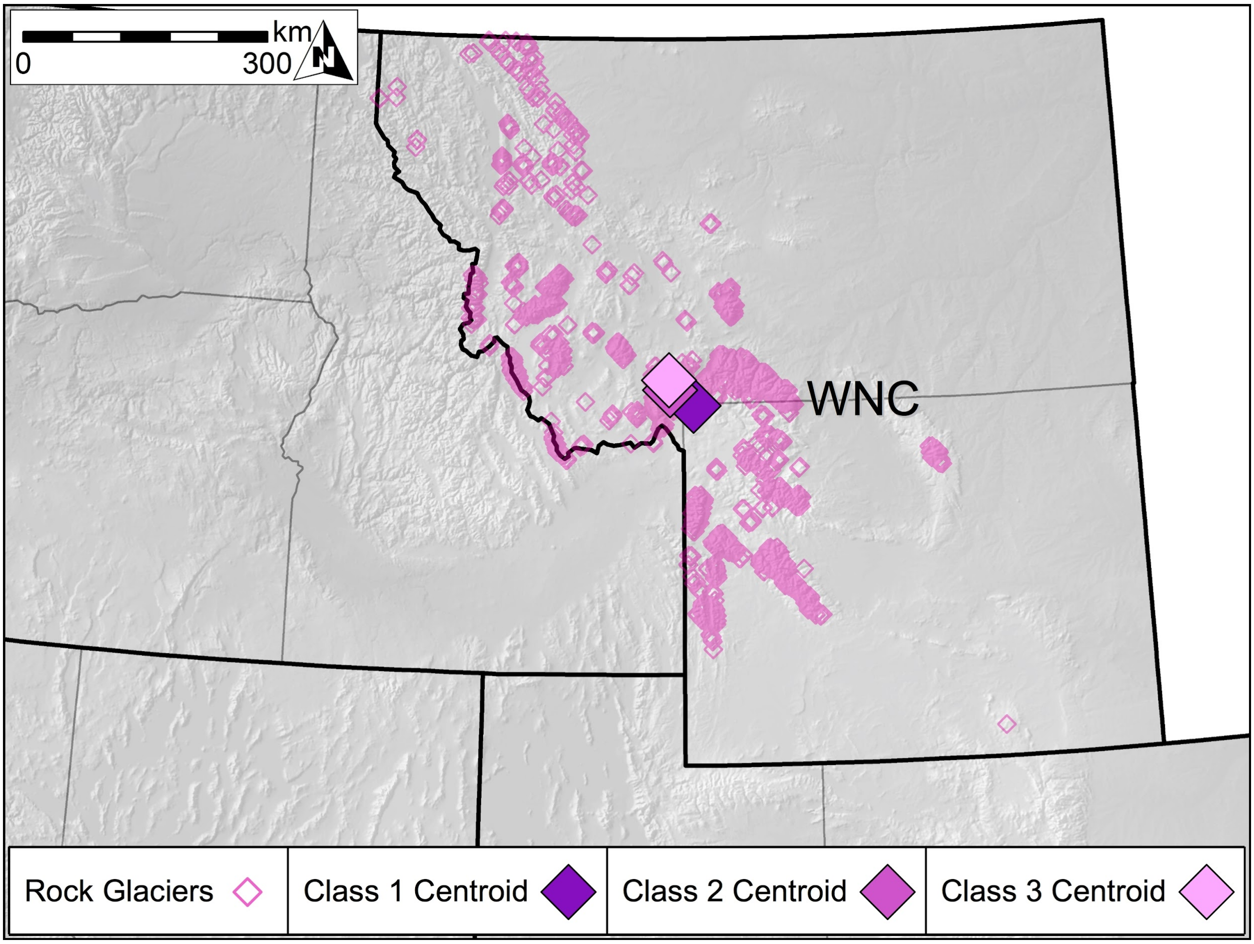

550 **Figure 8: Locations of WNC region rock glacier inventory features (n = 2663), as well as centroids for Class 1 (n = 1916), Class 2 (n = 590) and Class 3 (n = 157) features. Rock glaciers of the WNC region are largest and most densely concentrated in the Beartooth Mountains of Montana and the Absaroka Range of Wyoming.**

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Tables

560 **Table 1: Notable previous rock glacier inventories evaluated during comprehensive literature review. Only inventories that identified > 50 rock glaciers (i.e. at least regional scale) are included here, though sporadic smaller local inventories have been compiled.**

Continent	Primary Investigator(s)	Rock Glaciers Identified
Asia	Bolch and Gorbunov (2014)	72
Europe	Cremonese et al. (2011)	4795
	Baroni et al. (2004)	216
	Delaloye et al. (1998)	321
	Frauenfelder et al. (2005)	84
	Imhof (1996)	80
	Keller-Pirklbauer et al. (2012)	1647
	Kenner and Magnusson (2017)	239
	Krainer and Ribis (2012)	3145
	Lambiel and Reynard (2001)	239
	Scotti et al. (2013)	1514
	Seppi et al. (2012)	705
North America	Millar and Westfall (2008)	289
	Humlum (2000)	400
	Janke (2007)	220
	Janke and Frauenfelder (2008)	180
	Liu et al. (2013)	67
South America	Angillieri (2010)	155
	Falaschi et al. (2014)	488
	Falaschi et al. (2015)	177
	Rangecroft et al. (2014)	94

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Table 2: Rock glacier counts by NOAA climate region. The SW and WNC regions account for nearly 73% of rock glaciers identified.

NOAA Region	Class 1 (count (mean area))	Class 2 (count (mean area))	Class 3 (count (mean area))	Total Rock Glaciers (count (mean area))
NW region	1293 (0.09 km^2)	512 (0.05 km^2)	188 (0.04 km^2)	1993 (0.07 km^2)
SW region	3291 (0.12 km^2)	1133 (0.05 km^2)	446 (0.04 km^2)	4870 (0.09 km^2)
W region	552 (0.16 km^2)	181 (0.06 km^2)	84 (0.05 km^2)	817 (0.12 km^2)
WNC region	1916 (0.13 km^2)	590 (0.06 km^2)	157 (0.05 km^2)	2663 (0.11 km^2)
All regions	7052 (0.12 km^2)	2416 (0.05 km^2)	875 (0.04 km^2)	10,343 (0.10 km^2)

Table 3: Moran's I statistics for rock glacier class. Spatial clustering is most severe in the W region.

NOAA Region	Moran's Index	z-score	p-value	Pattern
NW region	0.100	3.904	< 0.001	Clustered
SW region	0.099	8.596	< 0.001	Clustered
W region	0.176	4.179	< 0.001	Clustered
WNC region	0.119	5.982	< 0.001	Clustered
All regions	0.106	11.686	< 0.001	Clustered

Table 4: Moran's I statistics for rock glacier area. Spatial clustering is most severe in the W region.

NOAA Region	Moran's Index	z-score	p-value	Pattern
NW region	0.159	6.228	< 0.001	Clustered
SW region	0.101	8.902	< 0.001	Clustered
W region	0.175	4.184	< 0.001	Clustered
WNC region	0.116	6.095	< 0.001	Clustered
All regions	0.116	6.905	< 0.001	Clustered