9-2019

Rock glaciers of the Beartooth and northern Absaroka ranges, Montana, USA

Zachary M. Seligman
University of Montana, Missoula

Anna E. Klene
University of Montana - Missoula

Frederick E. Nelson
Michigan State University

Recommended Citation

Seligman, ZM, Klene, AE, Nelson, FE. Rock glaciers of the Beartooth and northern Absaroka ranges, Montana, USA. Permafrost and Periglac Process. 2019; 1– 11. https://doi.org/10.1002/ppp.2019

Permafrost and Periglacial Processes

Rock glaciers of the Beartooth and northern Absaroka ranges, Montana, USA

Journal:	*Permafrost and Periglacial Processes*
Manuscript ID	PPP-19-0010.R1
Wiley - Manuscript type:	Special Issue Paper
Date Submitted by the Author:	14-Jun-2019
Complete List of Authors:	Nelson, Frederick; Michigan State University, Department of Geography, Environment, and Spatial Sciences; Northern Michigan University, Department of Earth, Environmental, and Geographical Sciences Klene, Anna; University of Montana, Department of Geography Seligman, Zachary; University of Montana, Geography
Keywords:	mapping, Montana, periglacial, rock glacier, Rocky Mountains, climate change

Rock glaciers of the Beartooth and northern Absaroka ranges, Montana, USA

Zachary M. Seligman,[1] Anna E. Klene,[1] and Frederick E. Nelson[2,3]

[1]Department of Geography, University of Montana, Missoula MT 59812, USA

[2]Department of Geography, Environment, and Spatial Sciences, Michigan State University, East Lansing MI 48824, USA

[3]Department of Earth, Environmental, and Geographical Sciences, Northern Michigan University, Marquette MI 49855, USA

Abstract

Six-hundred and sixty rock glaciers in the northern Absaroka and Beartooth Ranges of south-central Montana were digitized and evaluated using geographic information systems technology and an array of topographic and environmental parameters. Beartooth rock glaciers are larger, occur at higher elevations, receive more precipitation, and are subject to colder temperatures than northern Absaroka rock glaciers. Elevation is strongly correlated with rock glacier activity. Comparative analysis of these adjacent mountain ranges indicates that Beartooth geomorphic landscapes are shifting from predominantly glacial to periglacial regimes, and that the northern Absarokas have largely completed this transition. Because glaciers are declining in response to climatic warming, rock glaciers could soon become the most important source of ice in the region.

KEYWORDS

climate change, ground ice, mapping, Montana, periglacial, rock glacier, northern Absaroka Range, Beartooth Range, Rocky Mountains, water resources

1. INTRODUCTION

As global warming proceeds, water resources derived from glaciers and mountain snowpacks are increasingly threatened. Although rock glaciers have been studied for more than a century,[1] looming water deficits in many arid and semi-arid mountainous regions have intensified interest in these features. Because most rock glaciers are well insulated by a veneer of earth materials, the substantial ice volumes contained in them are being considered as alternative, longer-term sources of water.[2] Accompanying this increased interest is a burgeoning scientific literature concerned with rock glaciers, including a large number of regional inventories (e.g. [3,4,5,6,7,8,9]. Further evidence of the increasing scientific and societal importance of rock glaciers is the International Permafrost Association's recently established "Action Group on Rock Glacier Inventories and Kinematics".[10]

Basic mapping of periglacial landforms in the Middle and Northern Rocky Mountain physiographic provinces (pp. 365-404)[11] has not been carried out extensively, despite the widespread occurrence of periglacial features and recent technological advances that make such undertakings feasible. Although several localized rock-glacier studies have been conducted in parts of the U.S. states of Montana[12,13] and Wyoming,[14,15,16] there have been very few exhaustive inventories over extensive areas of this region. Johnson et al.[17] produced an inventory in the Lemhi Range in the adjacent state of Idaho, Legg[18] worked in Glacier National Park in Montana, and Florentine[19] documented a series of rock glaciers in southwest Montana that partially overlaps Seligman's[20] earlier study, albeit using highly divergent methods of data collection (cf. Section 3.1 below and Florentine (pp. 11-12)[19].

This paper represents the first such survey conducted in the northern Absaroka and Beartooth Ranges of Montana. Here, we summarize the differences between rock glaciers in the two ranges with respect to several topographic and environmental parameters based upon a survey by Seligman,[20] report similarities and differences in these parameters between the two ranges, and explore how the results can be interpreted in the context of Quaternary and contemporary climatic changes.

2. STUDY AREA

The Absaroka and Beartooth ranges span the border between the U.S. states of Montana and Wyoming (Figure 1), near Yellowstone National Park. These adjacent mountain ranges are among the highest in the region, and prominently display the effects of both glacial and periglacial processes. The Beartooth and northern Absaroka ranges are, respectively, the first and fourth highest mountain ranges in Montana.

[Figure 1 near here]

The Absaroka Mountains form part of the Absaroka-Gallatin volcanic field, the largest such field in the Middle and Northern Rocky Mountains. Volcanism in this region occurred along two subparallel, northwest trending belts defined by hypabyssal plutons that extend for roughly 150 km.[21] Topography developed in the Absarokas consists of the remnants of a highly dissected plateau displaying the rugged, sculpted results of extensive glaciation, including cirques, horn peaks, arêtes, U-shaped valleys, and prominent moraines. In this study we focus on the “Northern Absaroka Range” (hereafter “northern Absarokas”), which lies almost entirely within the state of Montana.[22] Of the many peaks rising above 3000 m.a.s.l. in the northern Absarokas, Tumble Mountain (3449 m) is the tallest; at least 10 peaks in the range exceed 3300 m. Rock glaciers are the most prominent periglacial landforms in the northern Absarokas. One feature at Galena Creek, south of the present study area, has played a prominent role in the history of rock-glacier research.[14-16, 23]

The Beartooth Mountains are dominated by metamorphosed Precambrian granite uplifted roughly 50 million years ago.[24] Granite Peak, at 3904 m.a.s.l., forms the highest topographic point in Montana, and several other peaks exceed 3800 m. Glaciated terrain on the northeast side of the Beartooths consists of deeply eroded glacial valleys (Figure 2A). Moraines occur in all valleys above 2750 m.a.s.l. In some major valleys they extend to below 1500 m and are considered to be of early to late Pinedale (Late Pleistocene) age. Younger moraines of Late Holocene age occur at the foot of existing glaciers and in cirques that were deglaciated recently (pp. F38).[25] Cirque glaciers, remnants of multiple Pleistocene glacial advances,[26] occur at higher elevations in the heads of the prominent U-shaped valleys. Ice-rich rock glaciers and talus accumulations are the principal currently active periglacial features within many of these valleys.

Discontinuous, high-elevation plateau-like surfaces are widespread in the Beartooths, separated by the large glacial troughs (pp. 381).[11] Except in the southwest part of the range, most of these tracts remained unglaciated throughout the Quaternary and are festooned with periglacial features, including tors, blockfields, large-diameter sorted patterned ground, and palsas.[27,28,29,30] A typical Beartooth Plateau surface is illustrated in Figure 2B. Permafrost has been reported in several non-rock-glacier locations in the Beartooth Plateau at elevations above 2950 m).[28-31]

[Figure 2 near here]

3. METHODS

3.1 Rock glacier inventory

Digital aerial photos with 1 × 1 m resolution, flown in August 2005,[32] were used to identify possible rock glaciers in the study area. A total of 660 rock glaciers and rock-glacier complexes were identified and hand-digitized. Several criteria were utilized to ensure consistency in the recognition of features as rock glaciers:

(1) Morphology. Rock glaciers appear as lobate or tongue-shaped flowing masses of ice (Figure 2C), rock, and debris,[33] and are morphologically distinct from talus fields, rockfalls, and moraines.3

(2) Indications of motion. Signs of flow associated with rock glaciers include parabolic ridges and furrows (Figure 2D) on better-developed features[34,35] and a teardrop or 'tongue' shape (Figure 2G) is often associated with smaller, less complex rock glaciers.

(3) Frontal slope. Active rock glaciers usually have steep frontal slopes (Figure 2E).[36]

(4) Debris provenance. Rock glaciers have identifiable debris sources (Figure 2F), such as cirques or cliffs above them.[33]

(5) Positional relation to glacial cirques. The presence of a cirque glacier or glacial cirque valley above a potential rock glacier (Figure 2G) is indicative of rock-glacier formation, based on the model developed by Potter et al.[16]

Figure 2 illustrates the primary morphological characteristics of rock glaciers in the study area.

3.2 Topographic, geologic, and environmental parameters

Digital elevation models (DEMs) at 10 × 10 m resolution were obtained from the U.S. Geological Survey.[37] Slope and aspect layers were calculated from the DEMs using ArcGIS Spatial Analyst.[1] ArcGIS Solar Analyst was used to calculate incoming solar radiation, based on a DEM, at site-specific latitudes. A sun map of the sky was used to estimate mean annual incoming solar radiation for the study area.[38] Absaroka and Beartooth lithologies were extracted from Zientek et al.[39] Parameter data were extracted in ArcGIS for each pixel lying within each rock-glacier polygon. Pixel values within each individual rock-glacier polygon were averaged using ArcGIS Zonal Statistics. For analysis, means of each variable were used.

The direction faced by each rock glacier was calculated from “mean surface aspect” (the average aspect of DEM pixels within a rock glacier polygon) and statistical procedures designed for periodic (circular) data[40,41,42] were applied to the resulting data set. The Kuiper and Watson U^2 tests for departure from uniformity (the null hypothesis) were applied to the empirical frequency distributions of rock glacier orientation data for the two ranges. The two-sample Uniform-Scores test was applied to examine the proposition that the empirical frequency distributions of Absaroka and Beartooth rock glaciers differ.

Meteorological stations are scarce within the study area. Interpolated precipitation estimates from the “Parameter – elevation Regressions on Independent Slopes Model”

---

[1] ESRI, Redlands, CA.

(PRISM)[43] for the Absarokas are approximately 100–130 cm yr^{-1} at the highest elevations, while the Beartooths receive an estimated 150–180 cm yr^{-1}. PRISM used U.S. National Weather Service observations of temperature and precipitation, and employed digital elevation models (DEMs) to interpolate climatic parameters on varying timescales. This approach has been shown to reproduce climate patterns in mountainous terrain better than many other techniques.[44] Averages of January and July temperatures during the 1991–2009 period, calculated for the Monument Peak Snotel station (45.217°N, 110.333°W; 2697 m.a.s.l.) were -9°C and 12°C respectively.[45] Descriptive statistics for the topographic and environmental parameters are listed in Table 1.

[Table 1 near here]

3.3 Rock-glacier activity classification

Activity level was assessed in the field for 80 rock glaciers. An additional 40 rock glaciers were classified by activity level using only aerial photos, DEMs, and prior knowledge of field sites. Rock glaciers were evaluated according to a set of criteria derived from the literature (Table 2) that relate surface characteristics to recent movement and thus determine whether a rock glacier is modern or relict (this does not account for possible reactivation of "relict" features, which can be initiated by decreased temperature or increased water supply).[46] Specific criteria used include: (a) shallower, less well-defined frontal slopes Figure 2H) that indicate loss of ice cores[36]; (b) thermokarst development upslope of the rock-glacier terminus (Figure 2H), also indicative of ice core loss[36]; and (c) encroachment of vegetation (Figure 2I), indicative of relict, or at least inactive forms.[36]

To estimate the activity status of the 540 rock glaciers not investigated in the field or examined on air photographs, a logistic regression was performed using the 120 field- and remotely-verified rock glaciers. The five variables listed in Table 2 (elevation, area, slope, linearized aspect, potential insolation, and estimated precipitation), along with estimated temperature data and lithology (coded as two dummy variables) were used to build the regression model, which employed a backwards stepwise procedure. At each step the variable with the least weight was eliminated from the model until a desired *p* value <0.05 was reached. Further details are provided in Seligman.[20] Binary logistic regression produces logits, the logarithmically transformed odds of whether a selected binary categorical variable will occur based on input from independent variables.[47]

[Table 2 near here]

3.4 Elevation Trend

To assess if rock glaciers in the study area form part of a regional climate-related elevation trend, data from several previous studies in the USA's Pacific Northwest were used to examine the relation between rock-glacier elevation and increasing distance from the Pacific Ocean.

A 1056 km transect was constructed from Mt. Cameron (47.82°N, 123.32°W) in the Olympic Mountains of western Washington State to the approximate centroid of the combined northern Absaroka and Beartooth study areas in the east (45.25°N, 110.00°W). The mean elevation of a group of rock glaciers (1720 m) in the precipitation shadow of Mt. Cameron forms the westernmost data point in the transect.[48] Mean elevation of rock glaciers in the Cascade Mountains of Washington State (2120 m) was derived from features inventoried by

Weidenaar[49] in his “Lake Chelan”, “North Cascades Southern Part”, and “South Cascades” study areas. Rock glaciers in Idaho’s Lemhi Range were reported as lying at elevations “>2600 m”. The elevations of individual rock glaciers were not reported so that value was used.[17] This group of rock glaciers lies a substantial distance south of the transect; a cosine transformation was used to project this location onto the transect line.[50] Mean rock-glacier elevation was computed as 2760 m for lobate and tongue-shaped rock glaciers in the Tobacco Root Mountains of southwestern Montana,[51] and 2830 m in the combined Absaroka and Beartooth inventories. The average elevation of individual rock glaciers in the respective samples was used to compute an agglomerated mean elevation for each sample (i.e., for each data point).

Because uncertainties associated with data grouping exist in both the independent (latitudinal/longitudinal) and dependent (elevation) variables, error was partitioned between the two variables using a reduced major axis (RMA) line[52] to represent the relation between distance along the transect and mean elevation at the sample locations.

4. RESULTS

4.1 Rock glacier distribution

Figure 3 shows the distribution of the 270 Absaroka and 391 Beartooth rock glaciers. Topographic and climatic parameters are substantially different between the two mountain ranges (Table 2). Beartooth rock glaciers generally lie at higher elevations (~200 m) than those in the northern Absarokas (Figure 4; Table 1). This partly reflects the fact that parts of the Beartooth Mountains are higher in elevation than the northern Absaroka Range, with many peaks over 3800 m. Beartooth rock glaciers are also larger. Approximately 5% of Beartooth rock glaciers are larger than any found in the northern Absarokas. Slope angles of rock glaciers do not differ significantly between ranges, with mean slopes of approximately 20°.

[Figures 3 and 4 near here]

Lithology is significantly different between the two ranges. Layered granitic gneiss constitutes 90% of the bedrock in the Beartooths (pp. F15-F18)[25] and nearly 90% of Beartooth rock glaciers are derived from these and other less extensive metamorphic rocks. Although some northern Absaroka rock glaciers have lithological composition similar to those of the Beartooths, almost half are volcanic in origin. A few rock glaciers in the northern part of both ranges occur in rocks of plutonic igneous origin.

Florentine[13] concluded that the largest proportion of rock glaciers in her southwest Montana study area occurs in areas of foliated rocks, in which topography conducive to the creation of rock glaciers is best developed. Strongly foliated rocks also provide abundant clastic material to developing rock glaciers. Results from the current investigation are in agreement with Florentine's conclusions, with the majority of rock glaciers occurring in areas of layered metamorphic rocks (Figure 5).

[Figure 5 near here]

4.2 Influence of environmental parameters

Morris[53] concluded that preservation of ice cores within the rock glaciers of his southern Colorado study area was influenced by rockfall intensity and topoclimatic parameters, including elevation, reduction of incident radiation by topographic screening, and position of cirque headwalls with respect to wind-drifting and snow avalanches. Other studies have examined rock-glacier development and preservation through annual radiation receipts,[17] lithology and other geological controls, and morphology and topography.[54]

Results from the directional statistical analysis indicate the operation of strong topoclimatic controls over rock-glacier location in the northern Absarokas and Beartooths. Rock glaciers in both ranges appear to be controlled by the same topoclimatic factors. They are most common on N-NE facing exposures, although they occur over a wide range of aspect (Figure 6). Statistical descriptors for the sample circular frequency distributions are nearly identical (Table 3), and the relative numbers of rock glaciers in histogram bins around the circle are similar between the two ranges. Results from the Watson U^2 (pp. 180-182[40]; pp. 71)[41] and Kuiper (pp. 173-180[40]; pp. 66-67)[41] tests for preferred direction demonstrate that features in both ranges depart significantly from the uniform distribution. Rock glaciers in both ranges exhibit a strong preference for N to NE exposures, indicating that radiation receipts are an important factor in determining their locations. The two-sample Uniform Scores test (pp. 197-201[40]; pp. 122-123)[41] indicates that there is no statistical difference in the orientation of rock glaciers between the northern Absaroka and Beartooth ranges (Table 3). Beartooth rock glaciers were estimated to receive only about 3% higher levels of insolation than those in the northern Absarokas, consistent with the result from the Uniform Scores test. Beartooth rock glaciers were estimated to receive somewhat more (+14 cm yr^{-1}) mean annual precipitation than those in the northern Absarokas.

[Figure 6 and Table 3 near here]

4.3 Activity status

Only elevation, a surrogate for lapse-rate influenced temperature, emerged from the logistic regression as a strongly significant variable (inclusion of estimated temperature involved problems of colinearity). A Hosmer and Lemeshow[47] goodness-of fit-statistic was used to test whether observed values of rock-glacier activity differed from predicted. Predicted values did not differ from observed ($p = 0.233$). A traditional chi-squared test for model fit was also employed,[47] and showed a significant relation between predictor and response variables (p <<0.05). The resulting equation was used to calculate probabilities for the "modern" activity classification for the remaining 540 rock glaciers, which were then mapped to show the distribution of activity probability.

The resulting map (Figure 7) and histogram (Figure 8) of probabilities show substantial differences between the two ranges. More than 30% of Beartooth rock glaciers have a 70% or higher probability of being modern, while only 8% of northern Absaroka rock glaciers do. Although elevation alone does not explain the variability in rock-glacier activities entirely, results from the logistic regression supports its use to estimate and analyze rock-glacier location. A larger proportion of rock glaciers in the Beartooths are of glaciogenic origin than in the northern Absarokas, and this may be a contributing factor to the higher incidence of "modern" rock glaciers in the Beartooth Range.

[Figures 7 and 8 near here]

4.4. Elevation trend

Results from the reduced major axis analysis demonstrate that a strong relation (r = 0.972) exists between rock-glacier elevation and distance from the Pacific Ocean along the transect

(Figure 9). Mean rock glacier elevation rises at a rate of about 1.0 m km^{-1} over the transect, an apparent response to the gradient of climatic continentality inland from the Pacific Ocean.

[Figure 9 near here]

5. DISCUSSION

5.1 Rock glacier elevation trend

Although a nearly 200 m difference exists between mean rock-glacier elevation in the Beartooth and northern Absaroka Ranges (Table 1), there is considerable overlap in their altitudinal frequency distributions (Figure 4). The difference in mean elevation between the two ranges appears to be controlled to a large extent by the existence of terrain at higher elevations in the Beartooths than in the northern Absarokas, as detailed in Section 4.1.

In a broader context, however, the mean elevation of rock glaciers in the study area is consistent with the gradient of rock-glacier elevation in the larger Pacific Northwest (PNW) region of the USA (Figure 9). This reflects a regional response to climatic continentality, as is the case with glacial cirques in the PNW (p. 72),[55] and is consistent with Humlum's[56,57] demonstration of a close relation between the elevation trends of rock glaciers and glacial equilibrium-line altitudes in Greenland. The rock-glacier elevation trend in the PNW is also similar to the trends of other periglacial features, including cryoplanation terraces,[58] blockfields,50 solifluction features,[59] and large-scale patterned ground in northwestern North America and elsewhere.[60] Viewed from this broader perspective, the difference in mean rock-glacier elevation between the Beartooths and northern Absarokas is a reflection of relatively local variations in topography, topoclimate, and lithology.

The relation between rock-glacier elevation and distance from moisture sources illustrated in Figure 9 should be considered the result of a preliminary analysis based on sparse data, and without differentiation between active/inactive features, glaciogenic/periglacial origin, or feature morphology. The increasing availability of detailed rock-glacier inventories in North America[2] should facilitate the application of sophisticated spatial-analytic techniques in the near future.

5.2 Glacial-Periglacial Transition

Evaluation of rock-glacier locational parameters in the Beartooth and northern Absaroka ranges provides insights into the glacial history of the region. Assuming that both ranges were subject to similar paleoclimatic trends owing to their proximity, deductions can be made regarding climatic effects on rock-glacier genesis, as well as controls on glacial landscape evolution.

According to Locke,[61] East Grasshopper Glacier, one of the larger glaciers in the Beartooth Range, currently falls below glacial climatic boundaries. This conclusion is supported by research documenting substantial thinning of this glacier since the mid-20th century.[62] The Beartooth Range currently contains only a few cirque glaciers similar to the Grasshopper Glacier (71 according to Graf[63] and 21 according to Locke),[61] and glaciogenic rock glaciers are presently the dominant glacial feature in many of these valleys. In contrast, the entire northern Absaroka Range currently contains only two possible cirque glaciers (on northern aspects of Mt. Cowen and Marten Peak), which may more appropriately be classified as snowfields (nine glaciers were present on these peaks according to Graf).[63] This relative distribution provides important context for analyzing potential shifts along the continuum from glacial to periglacial landscapes[64] in these two proximal mountain ranges.

Valleys in the Beartooth Mountains fit into a geomorphic model in which a landscape with a significant glacial component is transformed into one that is increasingly periglacial.[65] Most rock glaciers in the Beartooths have characteristics indicating a glaciogenic origin, as they are large in size and often have formed below cirque glaciers. Periglacial rock glaciers are, however, also common in the Beartooths.

Graf[63] described cirque glaciations as a series of cyclic events. As local climate becomes more glacial, accumulation exceeds ablation, and glaciers grow. If climate then becomes milder, ablation is greater than accumulation and glaciers recede. Local topography then exerts increasing influence on glacial systems relative to macroclimate through shading by cirque walls, topographically induced snow accumulation, and increased avalanching.[63] At this point in deglaciation, glaciers are at a minimum and are either retreating or disappearing, leaving more cirque headwall available for erosion. Eroded debris is subsequently added to the persisting glacial ice below, and as debris accumulation exceeds ice accumulation, glaciogenic rock glaciers can form. Through this process, glaciogenic rock glaciers are one step in the evolution of glacial landscapes.

Periglacial rock glaciers are the result of excessive debris accumulation in a cold, nonglacial environment[54] owing to avalanching of ice and rock. Consistently cold temperatures, not glacial geomorphology, constitute a primary control on formation (cf. [66]). In the northern Absarokas, most rock glaciers appear to be of periglacial origin, although glaciogenic rock glaciers can also be found in the Absaroka Range.[15,16] Periglacial rock glaciers are present on valley sides and may have begun their initial growth as pronival ramparts during more recent cold events, as hypothesized for morphologically similar rock glaciers in the nearby Lemhi Range.[17]

Analysis of the characteristics between ranges supports a conceptual model involving an ongoing shift from predominantly glacial to predominantly periglacial landscape processes in Beartooth valleys. Although there are many similarities between rock glaciers in the northern Absarokas and the Beartooths, those in the latter range are higher in elevation, receive more precipitation, and are subject to lower annual temperatures.[20] As warming followed the glacial maximum, climatic conditions in the Beartooths maintained a higher likelihood of sustaining glacial conditions and preserving glacial ice relative to the northern Absarokas. With continued warming and glacier recession, however, the shift toward periglacial conditions is becoming more apparent.

While glaciers are barometers of change in precipitation and temperature,[61,67] glaciogenic rock glaciers, by their existence, signal a decline in precipitation or an increase in temperature relative to previous conditions. In some areas, their frequent occurrence at elevations similar to glaciers appears to reflect the onset of conditions that are too dry to maintain contemporary glaciers.[68,69] Moreover, owing to the formation of an insulating rock mantle, rock glaciers may exhibit a slow response to changes in temperature. A marked increase in annual temperature would, therefore, have to persist over decades or even centuries[70] to yield a significant response.

Temperature increases in the instrumental climate record over the past century in areas of the nearby Canadian Rockies correspond to a decline in glacial mass balance.[71] Similarly, anomalous interaction of high summer temperatures and low winter snow accumulation has led to unprecedented glacial recession in Glacier National Park, Montana, beginning in the early 20th century.[72] Increased summer temperatures affecting glacier recession in other Rocky Mountain areas are likely to also be the source of changes in northern Absaroka and Beartooth high-elevation areas. In the wake of widespread glacier recession, rock glaciers may become the principal vestiges of glacial ice in the Beartooth region, as they appear to currently be in the northern Absarokas.

6. CONCLUSIONS

More than 650 rock glaciers were mapped within the study area and described using several topographic and climatic variables. Distinct differences are apparent between northern Absaroka and Beartooth rock glaciers with respect to size, elevation, precipitation, and lithology. The Beartooth rock glaciers are larger, higher in elevation, and receive more precipitation. Inferences from these comparisons indicate that, while Beartooth glacial geomorphology is shifting from glacial to periglacial, the higher elevations of the northern Absarokas are already governed largely by periglacial conditions.

Basic understanding of these rock glaciers is important because glacial decline is increasing in response to climate warming. Rock glaciers may soon become an important source of meltwater in the region. The inventory described here has potential to become a useful source of information about water resources in the Middle and Northern Rocky Mountains. Results from the analyses presented here can also serve as baseline data for assessing the importance of rock glaciers with respect to alpine stream ecology and biodiversity,[73] and climatic-driven changes[74] in the northern Absaroka and Beartooth Mountains.

ACKNOWLEDGMENTS

Dan Seifert of the Custer National Forest Ranger District and Don Evans from the U.S. Forest Remote Sensing Applications Center provided funding and aerial photos. Ryan Rock (University of Montana) provided helpful advice and assistance with literature. ZMS expresses special thanks to Greg Pederson for providing initial inspiration. We are grateful to two anonymous reviewers for comments and suggestions that led to improvements in the paper.

REFERENCES

---

[1] Kaufmann V. The evolution of rock glacier monitoring using terrestrial photogrammetry: The example of Äusseres Hochebenkar rock glacier (Austria). *Austrian Journal of Earth Sciences*. 2012; 105(2): 63-77.

[2] Jones DB, Harrison S, Anderson K, Betts RA. Mountain rock glaciers contain globally significant water stores. *Nature Geosciences*, 2018; 8: 2834. DOI:10.1038/s41598-018-21244-w

[3] Millar C, Westfall RD. Rock-glaciers and related periglacial landforms in the Sierra Nevada, CA, USA: Inventory, distribution and climatic relationships. *Quaternary International*, 2008; 188(1): 90-104.

[4] Kellerer-Pirklbauer A, Lieb GR, Kleinferchner H. A new rock glacier inventory of the eastern European Alps. *Austrian Journal of Earth Sciences,* 2012; 105: 78-93.

[5] Scotti R, Brardinoni F, Alberti S, Frattini P, Crosta GB. A regional inventory of rock glaciers and protalus ramparts in the central Italian Alps. *Geomorphology*, 2013; 186: 136-149. DOI: 10.1016/j.geomorph.2012.12.028

[6] Rangecroft S, Harrison S, Anderson K, McGrath J, Castel AP, Pacheco P. A first rock glacier inventory for the Bolivian Andes. *Permafrost and Periglacial Processes*, 2014; 25(4): 333-343. DOI: 10.1002/ppp.1816

[7] Janke JR, Ng S, Bellisario A. An inventory and estimate of water storage in firn fields, glaciers, debris-covered glaciers, and rock glaciers in the Aconcagua River Basin, Chile. *Geomorphology,* 2017; 296: 142-152. DOI: 10.1016/j.geomorph.2017.09,002

---

[8] Onaca A, Ardelean F, Urdea P, Magori, B. Southern Carpathian rock glaciers: Inventory, distribution and environmental controlling factors. *Geomorphology,* 2017; 293B: 391-404.

[9] Wang X., Liu L, Zhao L, Li Z, Liu G. Mapping and inventorying active rock glaciers in the northern Tien Shan of China using satellite SAR interferometry. *The Cryosphere* 2017; 11: 997-1014. DOI: 10.5194/tc-11-997-2017

[10] Delaloye R, Barboux C, Bodin X, Brenning A, Hartl L, Hu Y, Ikeda A, Kaufmann V, Kellerer-Piklbauer A, Lambiel C, Liu L, Marcer M, Rick B, Scotti R, Takadema H, Trombotto LD. Vivero S, Winterberger M. Rock glacier inventories and kinematics: A new IPA Action Group. In: Deline P, Bodin X, Ravenel, L. (eds.) *5th European Conference on Permafrost—Book of Abstracts, 23 June—1 July 2018. Chamonix, France: Laboratoire EDYTEM—UMR5204, Université Savoie Mont Blanc, 392-393,* 2018.

[11] Thornbury WD. *Regional Geomorphology of the United States*. New York: Wiley, 1965.

[12] Goolsby, JE. *East Rock Glacier of Lone Mountain, Madison County, Montana*. M.S. thesis, Montana State University, 1972.

[13] Florentine CE. *Regional context, internal structure, and microbial investigation of the Lone Peak Rock Glacier, Big Sky, Montana*. M.S. thesis, Montana State University, 2011.

[14] Potter N Jr. Ice-cored rock-glacier, Galena Creek, northern Absaroka Mountains, Wyoming. *Geological Society of America Bulletin,* 1972*;* 83(10): 3025-3058.

[15] Ackert P. Jr. A rock-glacier/debris-covered glacier system at Galena Creek, Absaroka Mountains, Wyoming. *Geografiska Annaler. Physical Geography, 1998;* 80A(3/4): 267-276.

---

[16] Potter N Jr, Steig EJ, Clark DH, Speece MA, Clark GM, Updike AB. Galena Creek rock-glacier revisited–-new observations on an old controversy. *Geografiska Annaler,* 1998; 80A(3-4): 251-265.

[17] Johnson BG, Thackray GG, Van Kirk R. The effect of topography, latitude, and lithology on rock-glacier distribution in the Lemhi Range, central Idaho, USA. *Geomorphology,* 2007; 91(1-2): 38-50.

[18] Legg BN. *Rock Glacier Morphology and Morphometry in Glacier National Park, Northwest Montana, USA.* M.S. thesis, Texas State University, 2016.

[19] Florentine C, Skidmore M, Speece M, Link C, Shaw CA. Geophysical analysis of transverse ridges and internal structure at Lone Peak Rock Glacier, Big Sky, Montana, USA. *Journal of Glaciology,* 2014; 60(221): 453-462. DOI: 10.3189/2014JoG13J160

[20] Seligman ZM. *Rock Glacier Distribution, Activity and Movement, Northern Absaroka and Beartooth Ranges, MT, USA.* M.S. thesis, University of Montana, Missoula, 2009. The present paper is based on data from this thesis. These data are available upon reasonable request from Prof. A.E. Klene (anna.klene@umontana.edu).

[21] Chadwick RA, Belts of eruptive centers in the Absaroka-Gallatin volcanic province, Wyoming and Montana. *Geological Society of America Bulletin,* 1970; 81(1): 267-274.

[22] Peakbagger. Northern Absaroka Range. https://www.peakbagger.com/range.aspx?rid=14410 Last accessed 13 January 2019.

[23] Barsch D. The problem of the ice-cored rock glacier. In: Giardino JR, Shroder JF, Vitek JD. (eds.) *Rock Glaciers*. Boston: Allen & Unwin, 45-53, 1987.

---

[24] Saros JE, Intelandi SJ, Wolfe AP, Engstrom DR. Recent changes in the diatom community structure of lakes in the Beartooth Mountain Range, U.S.A. *Arctic, Antarctic, and Alpine Research*, 2003; 35: 18-23.

[25] Simons FS, Armbrustmacher TJ, van Joy RM, Zilka MT, Federspiel FE, Ridenouer J. Beartooth Primitive Area and vicinity, Carbon, Park, Stillwater, and Sweet Grass Counties, Montana, and Park County, Wyoming: an evaluation of the mineral potential of the area. *U.S. Geological Survey Bulletin 1391-F*, Washington, DC, 1979, 125 pp.

[26] Graf WL Quantitative analysis of Pinedale landforms, Beartooth Mountains, Montana and Wyoming. *Arctic and Alpine Research,* 1971; 3(3): 253-261.

[27] Smith HTU. Cryopedologic phenomena in the Beartooth Mountains, Wyoming-Montana. *Geological Society of America Bulletin*, 1950; 60: 1503.

[28] Pierce WG. Permafrost and thaw depressions in a peat deposit in the Beartooth Mountains, northwestern Wyoming. *U.S. Geological Survey Professional Paper 424B*, 1961; 154-156.

[29] Johnson PL, Billings WD. The alpine vegetation of the Beartooth Plateau in relation to cryopedogenic processes and patterns. *Ecological Monographs*, 1962; 32(2): 105-135.

[30] Heidel B, Fertig W, Mellman-Brown S., Houston KE, Dwire KE. F*ens and their rare plants in the Beartooth Mountains, Shoshone National Forest, Wyoming*. General Technical Report RMRS-GRT-369. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, 110 pp.

[31] Collins EI, Lichvar RW, Evert EF. Description of the only known fen-palsa in the contiguous United States. *Arctic and Alpine Research*, 1984; 16(2): 255-258.

---

[32] United Farm Services Agency: National Agricultural Imagery Program (NAIP), Natural-color aerial photos of Montana (1 × 1 m resolution), 2005. http://nris.mt.gov/nsdi/orthophotos/naip_2005.asp Last accessed 4 January 2019.

[33] Humlum O. Origin of rock-glaciers: Observations from Mellemfjord, Disko Island, central West Greenland. *Permafrost and Periglacial Processes,* 1996; 7(4): 361-380.

[34] White SE. Rock-glacier studies in the Colorado Front Range, 1961-1968. *Arctic and Alpine Research* 1971; 3(1): 43-64.

[35] Chueca J, A Julián. Movement of Besiberris Rock Glacier, central Pyrenees, Spain: Data from a 10-year geodetic survey, *Arctic, Antarctic, and Alpine Research*, 2005; 37(2): 163-170.

[36] Roer I, Nyenhuis M. Rockglacier activity studies on a regional scale: Comparison of geomorphological mapping and photogrammetric monitoring. *Earth Surface Processes and Landforms,* 2007; 32(12): 1747-1758.

[37] United States Geological Survey National Mapping Program. Digital Elevation Models. https://catalog.data.gov/dataset/national-elevation-dataset-ned-1-3-arc-second-downloadable-data-collection-national-geospatial Last accessed 4 January 2019.

[38] Fu P, Rich PM. Design and implementation of the Solar Analyst: An ArcView extension for modeling solar radiation at landscape scales. http://professorpaul.com/publications/fu_rich_1999_esri.pdf . Last accessed 4 January 2019.

[39] Zientek ML, Derkey PD, Miller RJ, Causey JD, Bookstrom AA, Carlson MH, Green NG, Frost TP, Boleneus DE, Evans KV, Van Gosen BS, Wilson AB, Larsen JC, Kayser HZ, Kelley WN, Assmus KC, *Spatial databases for the geology of the northern Rocky Mountains – Idaho,*

Montana, and Washington. Open File Report 2005 – 1235. U.S. Department of the Interior, U.S. Geological Survey, Idaho Geological Survey, Montana Bureau of Mines and Geology, 2005. http://pubs.usgs.gov/of/2005/1235/ Last accessed 4 January 2019.

[40] Mardia KV. *Statistics of Directional Data*. New York: Academic, 1972.

[41] Fisher NI. *Statistical Analysis of Circular* Data. Cambridge: Cambridge University Press; 1993.

[42] Kovach Computing Services. *Oriana*, version 4.02, 2013. http://www.kovcomp.com Last accessed 10 January 2019.

[43] PRISM (Parameter-Elevation Regressions on Independent Slopes Model). 30-arcsec NORMALS (1971 – 2000) for temperature and precipitation. http://www.prism.oregonstate.edu/ Last accessed 4 January 2019.

[44] Daly C., Halbleib M, Smith JI, Gibson WP, Doggett MK, Taylor JH, Curtis J, Pasteris JJ. Physiographically sensitive mapping of climatological temperature and precipitation across the conterminous United States. *International Journal of Climatology*, 2008; 28: 2031-2064.

[45] Natural Resources Conservation Service. Historical average temperatures for Site 635, Montana. https://wcc.sc.egov.usda.gov/nwcc/site?sitenum=635&state=mt Last accessed 4 January 2019.

[46] Giardino RF, Vitek JD. The significance of rock glaciers in the glacial-periglacial landscape continuum. *Journal of Quaternary Science*, 1988; 3(1): 97-103.

[47] Hosmer, D. and S. Lemeshow. 1989. *Applied Logistic Regression*. New York: Wiley.

[48] Welter SP. *Geomorphic Character, Age and Distribution of Rock Glaciers in the Olympic Mountains*, Washington. M.S. thesis, Portland State University, 1987.

---

[49] Weidenaar M. *Rock Glaciers in the Eastern Cascades, Washington*. Science honors thesis, Central Washington University, 2013.

[50] Park Nelson KJ, Nelson FE, Walegur MT. Periglacial Appalachia: Paleoclimatic significance of blockfield elevation gradients, eastern U.S.A. *Permafrost and Periglacial Processes,* 2007; 18(1): 61-73. DOI: 10.1002/ppp.574.

[51] Gustin AR. *The Distribution, Morphology, and Temporal Signature of Rock Glaciers in the Tobacco Root Mountains, Montana*. M.S. thesis, Indiana University, 2013.

[52] Till R. The use of linear regression in geomorphology. *Area*, 1973; 5(4): 303–308.

[53] Morris SE. Topoclimatic factors and the development of rock-glacier facies, Sangre de Cristo Mountains, southern Colorado. *Arctic and Alpine Research*, 1981; 13(3): 329-338.

[54] Humlum O. The geomorphic significance of rock-glaciers: Estimates of rock-glacier debris volumes and headwall recession rates in west Greenland. *Geomorphology,* 2000; 35(1-2): 41-67.

[55] Porter SC, Pierce K., Hamilton TD. Late Wisconsin mountain glaciations in the western United States. In: Wright HE Jr. (ed.) *Late-Quaternary Environments of the United States*, vol. 1 *The Late Pleistocene* (SC Porter, Ed.). Minneapolis: University of Minnesota Press, 1983.

[56] Humlum O. Altitudinal trends of talus-derived lobate rock glaciers on Disko, central west Greenland. *Geografisk Tidsskrift*, 1984; 84(1): 35-39.

[57] Humlum O. The climate significance of rock glaciers. *Permafrost and Periglacial Processes*, 1998; 9(4):375-395, DOI: 10.1002/(SICI)1099-1530(199810/12)9:4%3C375::AID-PPP301%3E3.0.CO;2-0.

---

[58] Nelson FE, Nyland KE. Periglacial cirque analogs: Regional trends of cryoplanation terrace elevation in eastern Beringia. *Geomorphology,* 2017; 293: 305-317. DOI: 10.1016/j.geomorph.2017.05.005

[59] Péwé TL. Quaternary Geology of Alaska. U.*S. Geological Survey Professional Paper 1975*; 835: 1-145.

[60] Graf K. Vergleichende Betrachtungen zur Solifluktion in verschiedenen Breitenlagen. *Zeitschrift für Geomorphologie Supplementband*, 1973; 16, 104-154.

[61] Locke WW. Present climate and glaciation of western Montana, USA. *Arctic and Alpine Research,* 1989*;* 21(3): 234-244.

[62] Seifert D, Chatelain E, Lee C, Seligman Z, Evans D, Fisk H, Maus P. *Monitoring alpine climate change: Beartooth Mountains, Custer National Forest. RSAC-0115-RPT1*. Salt Lake City, UT: Department of Agriculture, Forest Service, Remote Sensing Applications Center, 2009.

[63] Graf WL. Cirques as glacier locations. *Arctic and Alpine Research,* 1976; 8(1): 79-90.

[64] Pollard, W. Periglacial processes in glacial environments. In: Menzies J, van den Meer J. (eds.) *Past Glacial Environments*. Amsterdam: Elsevier, 537-564, 2017.

[65] Clark DH, Steig E, Potter N, Gillespie, AR. Genetic variability of rock-glaciers. *Geografiska Annaler, Physical Geography,* 1998; 80A(3/4): 175-182.

[66] Berthling I, Etzelműller B. The concept of cryo-conditioning in landscape evolution. *Quaternary Research,* 2011: 75: 378-384. DOI: 10.1016/j.qres.2010.12.011

---

[67] Shea JM, Marshall SJ. Atmospheric flow indices, regional climate, and glacier mass balance in the Canadian Rocky Mountains. *International Journal of Climatology*, 2007*;* 27(2): 233-247.

[68] Brazier V, Kirkbride M, Owens IF. The relationship between climate and rock-glacier distribution in the Ben Ohau Range, New Zealand. *Geografiska Annaler*, Physical Geography, 1998; 80A(3-4): 193-207.

[69] Humlum O. Active layer thermal regime at three rock-glaciers in Greenland. *Permafrost and Periglacial Processes,* 1998*;* 8(4): 383-408.

[70] Brenning A. Geomorphological, hydrological and climatic significance of rock-glaciers in the Andes of central Chile (33 – 35°S). *Permafrost and Periglacial Processes,* 2005; 16(3): 231-240.

[71] Luckman BH. Landscape and climate change in the central Canadian Rockies during the 20th century. *The Canadian Geographer*, 1998; 42(4): 319-336.

[72] Pederson GT, Fagre DB, Gray ST, Graumlich LJ. Decadal-scale climate drivers for glacial dynamics in Glacier National Park, Montana, USA. *Geophysical Research Letters,* 2004; 31: L12203. DOI: 10.1029/2004GL019770

[73] Thies H, Nickus U, Tolotti M, Tessadri R, Krainer K. Evidence of rock glacier melt impacts on water chemistry and diatoms in high mountain streams. *Cold Regions Science and Technology*, 2013; 96: 77-85. DOI: 10.1016/j.coldregions.2013.06.006

[74] Nachlinger J, Delany DL. Potential climatic refugia in semi-arid, temperate mountains: Plant and arthropod assemblages associated with rock glaciers, talus slopes and their forefield wetlands, Sierra Nevada, California, USA. *Quaternary International,* 2015; 387: 106-221.

		Absaroka Rock Glaciers	Beartooth Rock Glaciers	Difference (Absaroka minus Beartooth)
Elevation (m)	mean	2732	2929	197
	min	2093	2239	146
	max	3072	3443	371
Area (m^2)	mean	65,274	143,637	78,363
	min	1,444	3,235	1,792
	Max	471,480	3,281,408	2,809,928
Slope (degrees)	mean	19	20	1
	min	5	5	0
	max	35	38	3
Insolation (kWh/m^2)	Mean	1337	1381	44
	min	923	987	64
	max	1674	1712	68
Precipitation (cm)	mean	89	103	14
	min	52	69	17
	max	117	169	52

Table 1. Mean, minimum, and maximum values of topographic and environmental parameters, Absaroka and Beartooth rock glaciers.

	Modern, Active	Modern, Possibly Inactive	Relict
Surface	smooth	can be smooth with blocky sections; has circular or elongated pits	dominantly blocky; has heavily pitted surface indicative of thermokarst
Lichen	little or no lichen	crests of ridges lichenized; furrows lichen-free	rock surfaces completely lichen covered
Surface Clasts	angular, unweathered, size sorted	less sorted; slightly weathered	highly weathered; unsorted
Front and Side Slopes	≥ 35°	≥ 35°	< 35°
Frontal Slope Stability	unstable, with large fresh angular clasts at base	less sorted; slightly weathered	low angled; stable
Vegetation	no vegetation cover	partly or fully vegetated	well-developed soils; all surfaces colonized by vegetation

Table 2. Criteria used to assess rock-glacier activity, based on those developed by Clark et al.,**Error! Bookmark not defined.** Chueca and Julian,[35] Johnson et al.,[17] Millar and Westfall,[3] and Roer and Nyanhuis.[36] See Seligman[20] for further details.

Range	n	mean vector	normalized resultant length	median	circular variance	circular std. dev.	Watson U^2	Kuiper
Absaroka	270	39.0°	0.182	40°	0.818	105.7	0.504*	2.506†
Beartooth	391	36.0°	0.174	45°	0.826	107.2	0.631*	2.680†
Combined Sample	661	37.6°	0.178					

†significant at $p < 0.005$

*significant at $p < 0.01$

Two-sample Uniform Scores (Mardia-Watson-Wheeler) test for equality of populations

W = 0.163 $p = 0.922$

Table 3. Results from circular statistical tests. One-sample (Watson U^2 and Kuiper) circular statistical tests indicate that rock glacier orientation in both ranges differ significantly from the null hypothesis that samples were drawn from a uniform distribution. Sample statistics are very similar for the two ranges. Formal results from the two-sample Uniform Scores test indicate no difference in orientation between rock glaciers in the two ranges. Procedures used are described in detail in Mardia,[40] Fisher,[41] and Kovach Computing Services.[42]

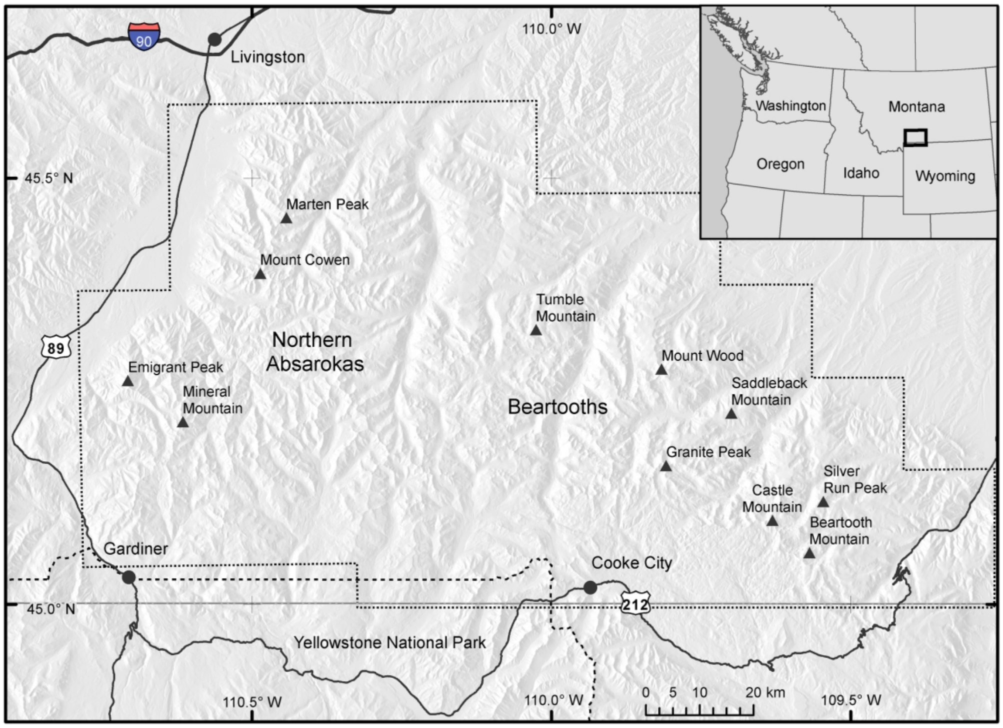

Figure 1. Shaded relief map of the study area (dotted outline), showing location north of Yellowstone National Park (dashed), along the Montana/Wyoming state border (long dashed line), with highways, cities, and locations mentioned in the text labeled. Inset map shows location of study area in the northwestern USA.

168x121mm (300 x 300 DPI)

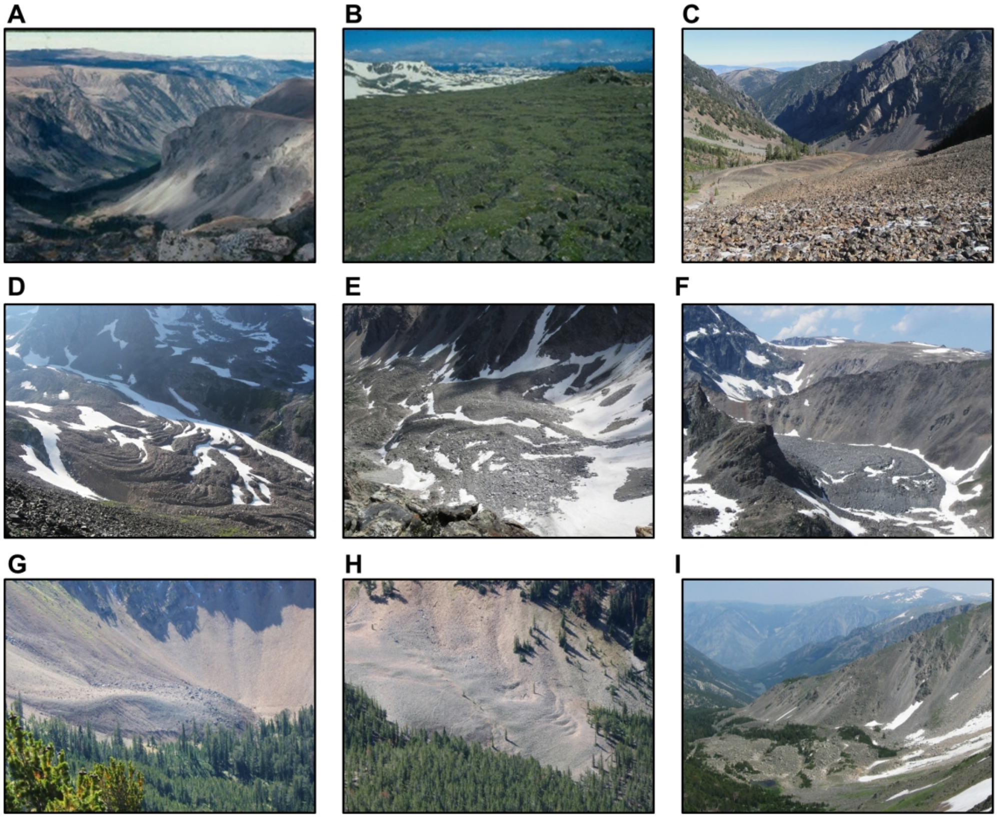

Figure 2. Morphological characteristics of rock glaciers and other periglacial forms in the study area. (A) Rock Creek Valley near U.S. Highway 212 in southeast portion of study area. Note cirque, possibly occupied by a glaciogenic rock glacier, on far valley wall, and talus forms in foreground. Photo by FEN, September 1985. (B) Plateau-like inter-valley surface near U.S. Highway 212 and Beartooth Basin Summer Ski Area. Note disintegrating tor and large-diameter sorted stripes. Photo by FEN, July 1978. (C) Emigrant Peak Rock Glacier, showing ridge-and-furrow microtopography indicative of movement. (D) Beartooth Mountain Rock Glacier, a glaciogenic feature, showing well-developed indications of activity. (E) Silver Run Rock Glacier, developed from ice glacier at higher elevation. (F) The Bear's Tooth Rock Glacier, showing steep frontal slope indicative of ice core and movement. (G) Arrastra Lake Rock Glacier, a tongue-shaped rock glacier ~1.5 km N of Mineral Mountain, showing sources of clastic material from backwall. (H) East Fork Emigrant Creek Rock Glacier, inactive rock glacier, showing shallow slopes, thermokarst pits, and encroachment by trees. (I) Saddleback Mountain Rock Glacier, inactive rock glacier, showing well-established forest atop the rock glacier. Photos C through I by ZMS, Summer 2008.

165x135mm (299 x 299 DPI)

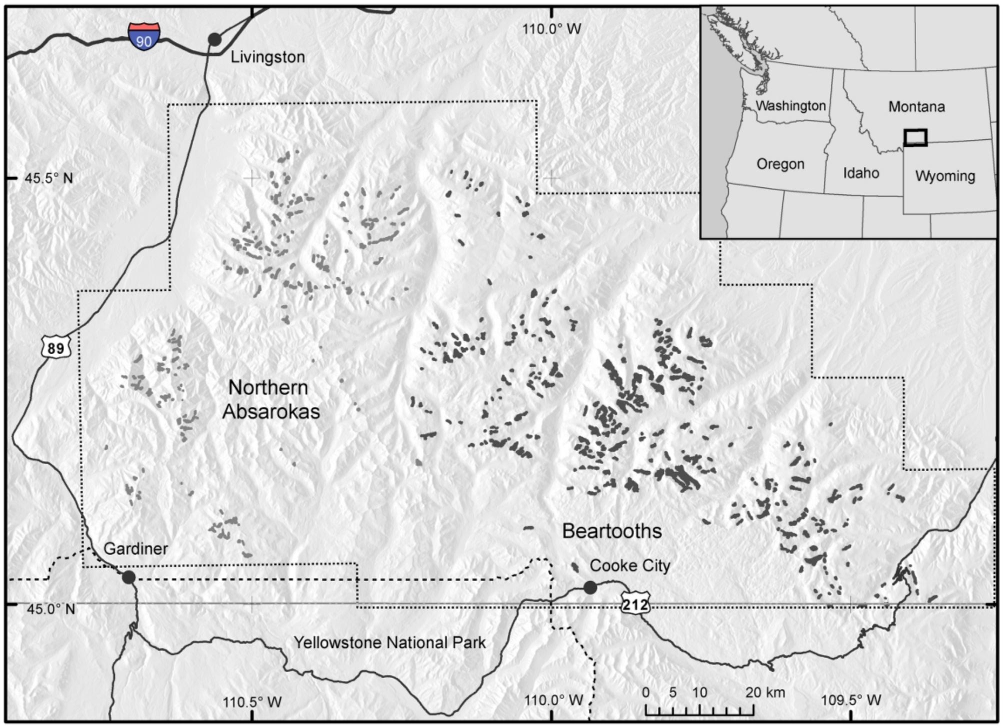

Figure 3. Map showing hand-digitized rock glaciers in the northern Absaroka (left, light gray) and Beartooth (right; dark gray) ranges. The study area (dotted), Yellowstone National Park (dashed), the Montana/Wyoming state borders (long dashed line), are shown and highways and cities labeled. Inset map shows location of study area in the northwestern USA.

168x121mm (300 x 300 DPI)

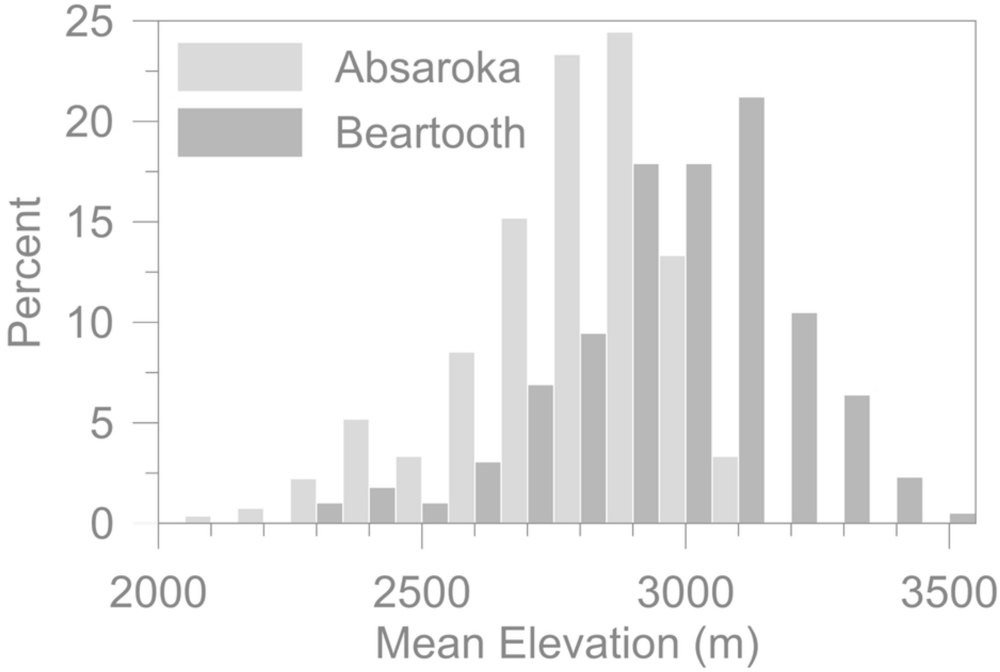

Figure 4. Percentage frequency of mean elevation of rock glaciers in the northern Absaroka and Beartooth ranges A difference of means test indicated that rock-glacier elevation is significantly different in the two ranges ($p < 0.0001$).

79x53mm (300 x 300 DPI)

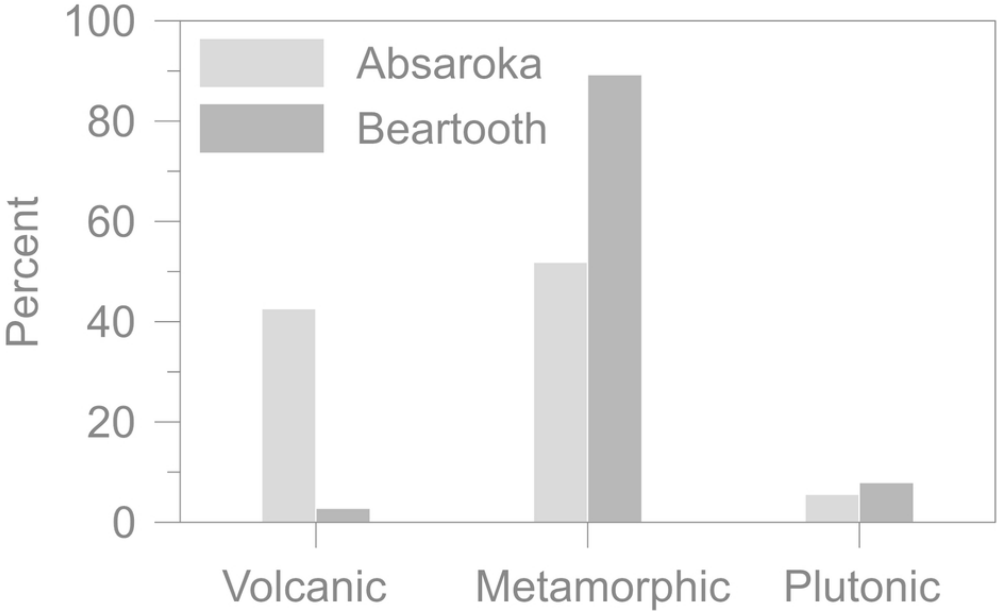

Figure 5. Percentage frequency of rock glaciers by lithology in the northern Absaroka and Beartooth ranges.

79x49mm (300 x 300 DPI)

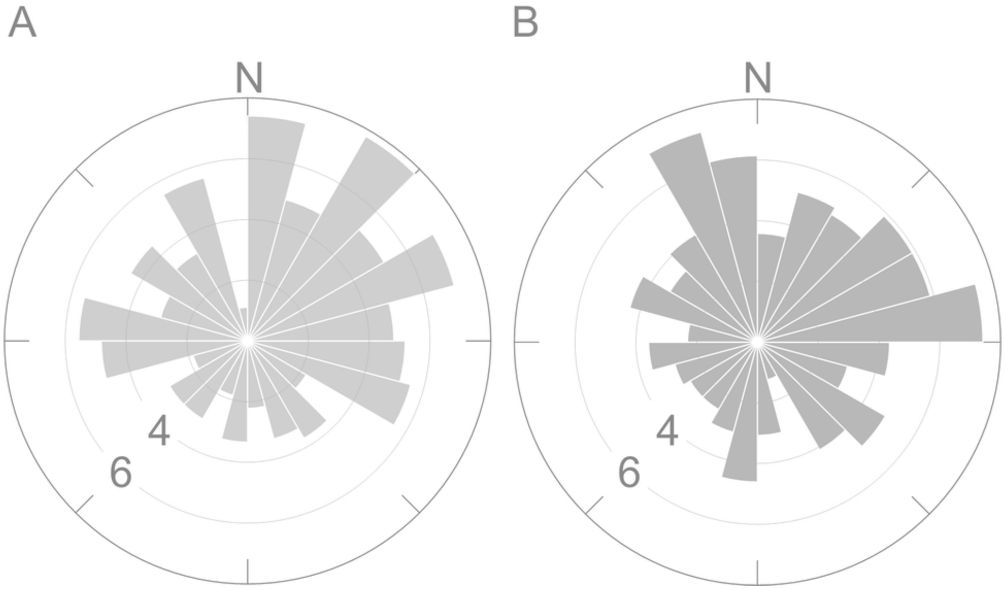

Figure 6. Percentage frequency of aspect (15° bins) of rock-glaciers in the (A) northern Absaroka and (B) Beartooth Ranges.

81x48mm (300 x 300 DPI)

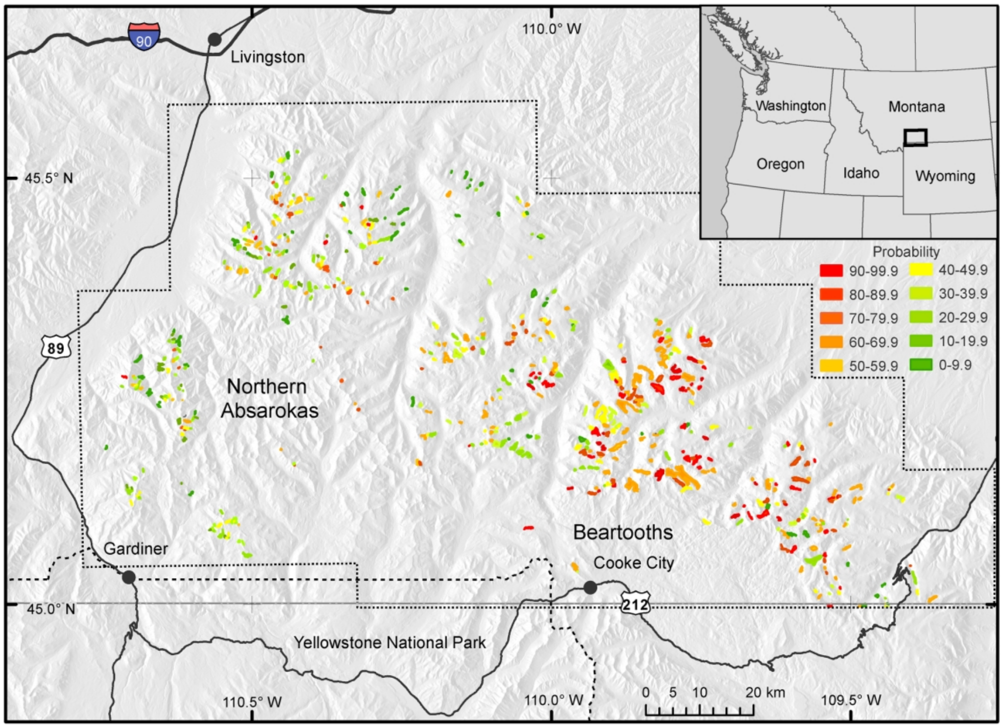

Figure 7. Map of the probabilities of rock glaciers being classified as "modern" (Table 2). The study area (dotted), Yellowstone National Park (dashed), and Montana/Wyoming state border (long dashed line), are shown and highways and cities labeled. Inset map shows location of study area in the northwestern USA.

168x121mm (300 x 300 DPI)

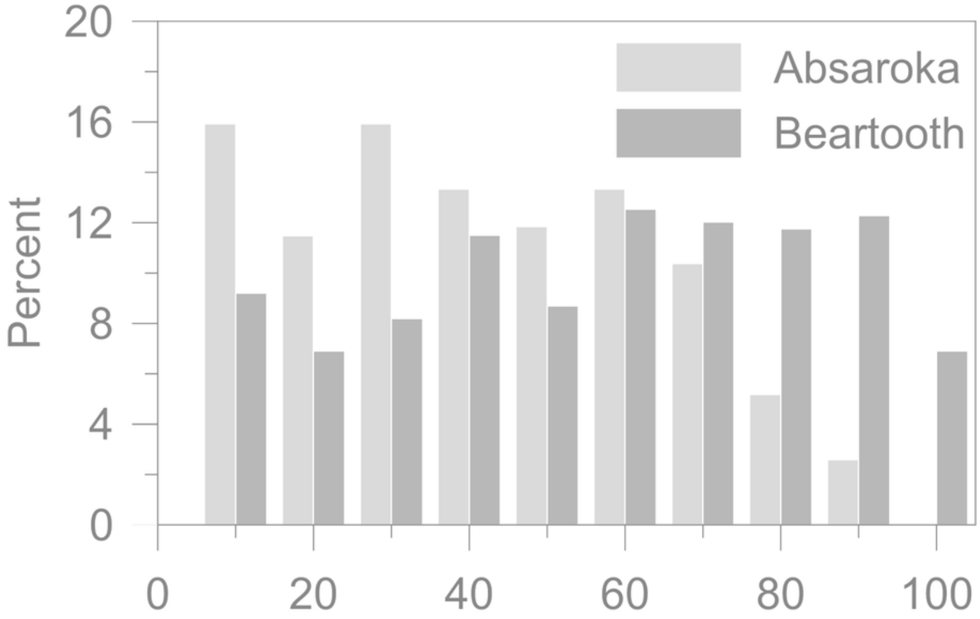

Figure 8. Percentage frequency of the probability of rock glaciers predicted to be “modern” in the Absaroka and Beartooth ranges.

79x49mm (300 x 300 DPI)

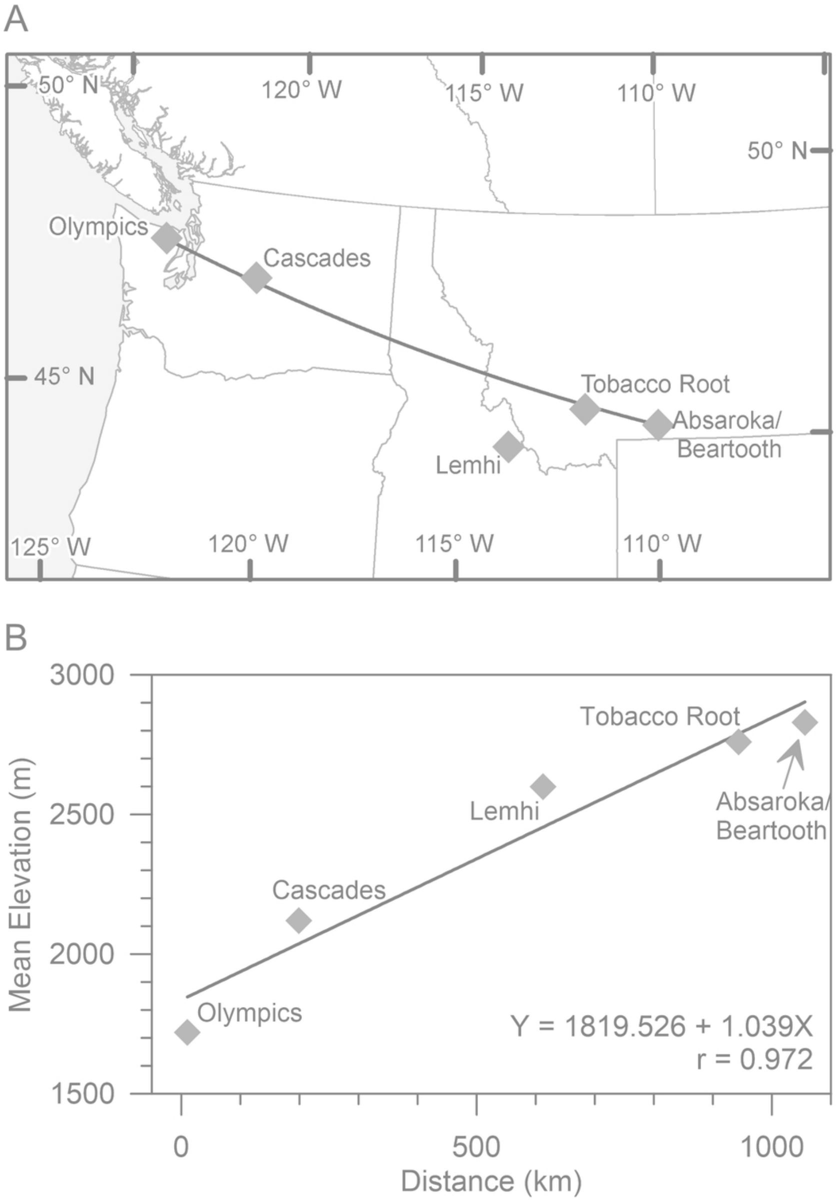

Figure 9. (A) Map of rock-glacier locations along a linear transect from the Olympic Mountains of Washington state to the northern Absaroka/Beartooth study area in Montana. Data from additional transect locations in the Cascades, Lemhi,and Tobacco Root Mountains were used. See text for details. (B) Graph of the elevations of mean rock-glacier elevation against distance from Pacific moisture sources along the transect in (A). Reduced major axis line indicates that rock-glacier elevation increases at a rate of 1.04 m km-1 from west to east along the transect..

79x114mm (300 x 300 DPI)