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Zachary M. Seligman
The University of Montana

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ROCK-GLACIER DISTRIBUTION, ACTIVITY, AND MOVEMENT, NORTHERN ABSAROKA AND BEARTOOTH RANGES, MT, USA

By

Zachary M. Seligman

B.S., University of Colorado, Boulder, Colorado, 2005

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Approved by:

Perry Brown, Associate Provost for Graduate Education
Graduate School

Dr. Anna E. Klene, Chair
Geography

Dr. Ulrich Kamp,
Geography

Dr. Joel T. Harper
Geosciences

Seligman, Zach, M.S., Spring 2009 Geography

Rock-glacier Distribution, Activity, and Movement, northern Absaroka and Beartooth ranges, MT, USA

Chairperson: Anna E. Klene

Rock glaciers of the northern Absaroka and Beartooth Ranges have not previously been described. Six-hundred and sixty rock glaciers were hand digitized in a GIS and evaluated using 11 distributional characteristics. Beartooth rock glaciers were found to occur at higher elevations, receive more precipitation, and were subjected to colder temperatures. Additionally, logistic regression analysis was used to examine the predictive strength of the 11 descriptive parameters on rock-glacier activity. Elevation and average annual maximum temperatures were most strongly correlated with activity. Results were used to make inferences about permafrost distribution which coincided with estimates from previous studies. Finally, movement rates of four rock glaciers within the Black Canyon Basin of the Beartooth Mountains were estimated using photogrammetric techniques over a 51-year period. While movement rates were consistent with those determined in other Rocky Mountain locations, much of the results were inconclusive. Increased movement of the East Grasshopper rock glacier may be the result of increased glacier subsidence, while ‘uphill’ movement of the Beartooth rock glacier may be indicative of rock-glacier subsidence.

ACKNOWLEDGMENTS

Special thanks to Dr. Anna Klene for her help, guidance, patience and persistence. In addition, I greatly appreciate input from both Dr. Ulrich Kamp and Dr. Joel Harper. Thanks also to both Dan Seifert from the Custer National Forest Ranger District and Don Evans from the U.S. Forest Remote Sensing Application Center for providing funding and aerial photos. Special gratitude goes out to Greg Pederson for providing initial inspiration.

My family has, and always will be there for me. There is nothing stronger than that. Thanks guys!

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1 INTRODUCTION

Rock glaciers are relatively understudied, glacial or periglacial features found in many mountainous regions of the world. Morphologically, “rock glaciers can be defined as lobate or tongue-shaped debris-ice mixtures with very steep sides and similarly steep snout that slowly creep down-slope,” (Berger et al., 2004; pg. 233). They can also be described as both glacial or periglacial features, however this remains controversial. Some argue for a strictly periglacial origin where rock-glacier ice only forms interstitially as part of a rock-ice matrix (Barsch, 1992). Others support that rock glaciers form under a continuum of glacial to periglacial conditions (Ackert, 1998; Clark et al., 1998; Humlum, 1996). In either case, rock glaciers are important components of mountain landscapes and in regards to climate analysis, past and present.

Rock glaciers have been used to reveal information about past permafrost boundaries and paleotemperatures from their spatial distribution (Kerschner, 1978; Morris, 1981; Humlum, 1988; Brazier et al., 1998; Humlum, 1998; Aoyama, 2005; Johnson et al., 2007; Millar and Westfall, 2008). Other research has examined characteristics of rock-glacier age with respect to past glacial events (Zielinski, 1989) and geomorphologic rates (Berthling and Etzelmuller, 2007). Rock-glacier movement has been studied using both geodetic (Wahrhaftig and Cox, 1959; White, 1971; Chueca and Julian, 2005) and photogrammetric methodology (Kääb et al., 2007; Roer and Nyenhuis, 2007). Boreholes (Arenson et al., 2002) and refraction seismic and geoelectric measurements (Croce and Milana, 2002; Potter et al., 1998) have been used to assess structure. Rock-glacier hydrology is well studied in parts of the Andes due to the relatively arid environment and large numbers of rock glaciers (Schrott, 1996; Brenning, 2005; Lecomte et al., 2007), in the Austrian Alps (Krainer and Mostler, 2002) and the Colorado Front Range (Williams et al., 2006).

Recent temperature changes have resulted in glacier recession over many parts of the world (e.g. Haeberli and Beniston, 1998). In Glacier National Park, Montana, under continued warming trends, all glaciers are expected to disappear by 2030 with drastic ecological consequences (Hall and Fagre, 2003). Similar glacier recession has been observed for select glaciers of the Beartooth range, Montana (Seifert et al., 2009). The water stored in rock glaciers will become more critical as other sources of water are lost. Yet, in the northern Rocky Mountains where alpine glaciers are in decline, rock-glacier inventories are not complete. The results of this research will hopefully serve as baseline data for assessing the importance of rock glaciers with regards to alpine stream ecology and biodiversity, water resources, and climatic change in the northern Rocky Mountains.

1.1 Objectives

The purpose of this current study is three-fold. First, a survey of rock glaciers of the northern Absaroka and Beartooth ranges had not been previously performed. The closest studies, geographically, include studies from the Lemhi Range, Idaho (Johnson et al., 2007), the southern Absaroka Mountains, Wyoming (Potter, 1972; Potter et al., 1998; Ackert, 1998), the Colorado Rockies (White, 1971; Giardino, 1984; Benedict et al., 1986; Degenhardt et al., 2003; Refsnider and Brugger, 2007) and the Sierra Nevada, California (Millar and Westfall, 2008). Differences in rock glaciers between the two mountain ranges were evaluated with respect to several distributional parameters. Secondly, the effect of these parameters on modern and relict activity classification was assessed using binary logistic regression analysis. Finally, due to the availability of several photographs of the Black Canyon Basin (Beartooth Range), quantification of the horizontal surface movement of four rock glaciers over the years 1952 - 2003 was completed.

1.2 Study Area

The Absaroka and Beartooth ranges lay just north and northeast of Yellowstone National Park on the border between Montana and Wyoming and are the fourth and first highest mountain ranges in Montana, respectively (Figure 1). Geologically, the Absaroka Range is part of the larger Absaroka-Gallatin volcanic field, the largest volcanic field in the northern Rocky Mountains. Volcanism in this region occurred along two sub-parallel, northwest trending belts defined by hypabyssal plutons that extend for roughly 150 km (Chadwick, 1970). The Beartooth mountains are dominated by Pre-Cambrian granite, which was uplifted roughly 50 million years ago (Saros et al., 2003). Cirque glaciers, remnant of multiple Pleistocene glacial advances (Graf, 1971), line the ends of many of the prominent U-shaped alpine valleys, while rock glaciers are the principal feature in many of these same valleys.

Meteorological stations are scarce within the study area. Interpolated precipitation estimates from the “Parameter – elevation Regressions on Independent Slopes Model” (PRISM) for the Absaroka’s are approximately 100 – 130 cm/yr at the highest elevations, while the Beartooth’s receive roughly 150 – 180 cm/yr. PRISM used National Weather Service observations of temperature, precipitation, and digital elevation models (DEMs) to produce interpolations of climatic parameters on varying time-scales that were shown to reproduce climate patterns in mountainous terrain better than many other techniques (Daly et al., 2008). Averages calculated of mean January and July temperatures from 1991 – 2009 for the Monument Peak Snotel station (8850 ft: Natural Resources Conservation Service, 2009) were -9°C and 12°C respectively.

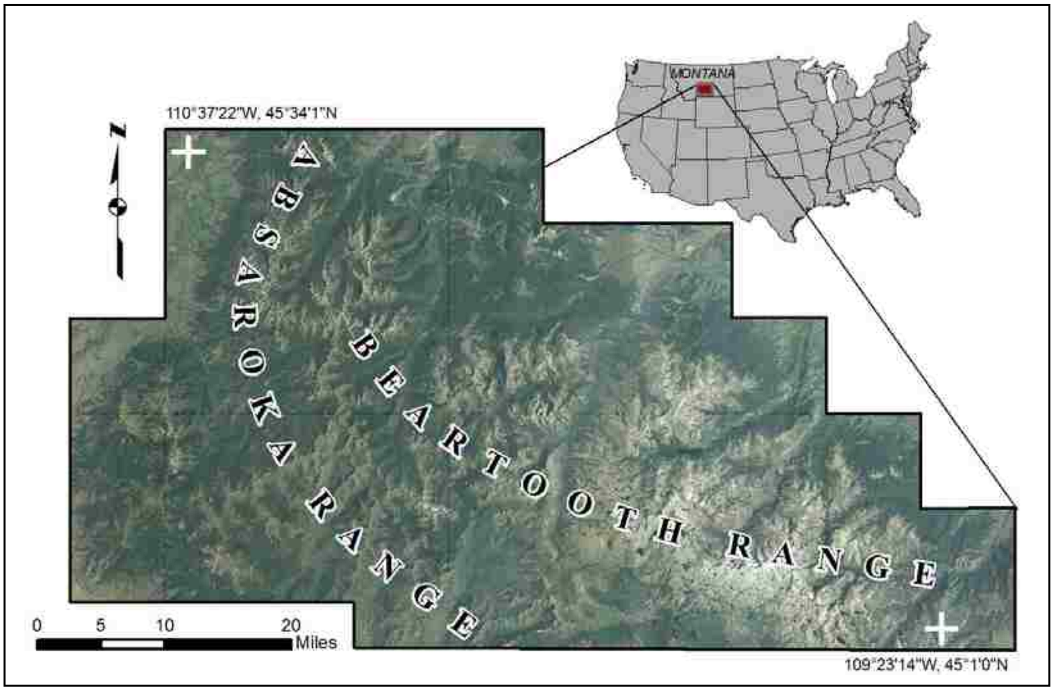

Figure 1: Outline of the study area for this project overlain on aerial photos. The study area includes most of the Absaroka/Beartooth Wilderness area designated by the US Congress in 1978.

2 ROCK-GLACIER DISTRIBUTION

2.1 Background

Geomorphic mapping of rock glaciers and subsequent analysis of their distributional characteristics are the first steps in determining relationships between rock glaciers and their various topographic and climatic controls. This fundamental interaction has led to many studies focused on understanding rock-glacier distribution. Rock-glacier inventories have aided in difficult land-cover classification in high mountain areas (Brenning and Trombotto, 2006). Additionally, inferences regarding chronologies of cold events have also been made from rock-glacier inventories (Luckman and Crockett, 1978; Kerschner, 1978; Brazier et al., 1998; Blagborough, 1999), as well as the relative distribution of modern and relict rock glaciers (Millar and Westfall, 2008; Brazier et al., 1998; Putnam and Putnam, 2009).

In this study, a variety of distributional characteristics were used to describe differences between Absaroka and Beartooth rock glaciers and to subsequently make inferences on glacial landscape evolution. These characteristics include: estimated annual insolation, mean slope, mean aspect, mean elevation, mean annual maximum temperature (T_{max}), mean annual minimum temperature (T_{min}), mean January maximum temperature ($T_{January}$), mean July maximum temperature (T_{July}), mean annual precipitation, lithology, and rock-glacier size.

2.2 Methods

2.2.1 Rock-Glacier Inventory

Digital aerial photos flown in August 2005 (1 × 1 m resolution; U.S. Farm Services Agency) were obtained for the study area. Initially, attempts were made to use Feature

Analyst$^{©}$, a commercial software add-on to ArcGIS$^{©}$, to identify rock glaciers; however, this was unsuccessful due to the inherent spectral similarity of rock glaciers to surrounding features. Instead, 660 rock glaciers and rock-glacier complexes were identified and hand-digitized. The following criteria were utilized to ensure consistency:

1) Rock glaciers appear as lobate or tongue-shaped flowing masses of ice, rock and debris (Humlum, 1996) and are different from talus fields, rock-falls, and moraines (Millar and Westfall, 2008). Talus fields show no distinct signs of flow, do not have a steep frontal slope, and often fan out instead of forming lobes or tear-dropped shapes. Moraines are symmetrical consolidated glacial debris, and rock avalanches, being the rapid displacement of debris are often small compared to rock glaciers, originate from a small or limited source area, and show no prolonged signs of movement. Protalus ramparts have been associated with rock-glacier development and can be differentiated as being wider than they are long (Johnson et al., 2007).

2) Signs of flow associated with rock glaciers include parabolic-shaped ridges and furrows on more developed rock glaciers (White, 1971) and a tear-drop (or 'tongue') shape associated with smaller, less complex rock glaciers.

3) Rock glaciers have a steep frontal slope (Roer and Nyenhuis, 2007).

4) Rock glaciers have a debris source such as a cirque or cliff above them (Humlum, 1996).

5) The presence of a cirque glacier or glacial cirque valley above a potential rock glacier is indicative of rock-glacier formation based on the model developed by Potter et al. (1998).

Additional criteria were considered in order to include potential relict rock glaciers.

1) A shallower, less defined frontal slope is indicative of loss of the ice core (Roer and Nyenhuis, 2007) or a non-rock glacier.
2) Thermokarst development upslope of the rock-glacier terminus is also indicative of ice core loss (Roer and Nyenhuis, 2007).
3) Encroachment of vegetation is indicative of relict, or at least inactive forms (Roer and Nyenhuis, 2007).

2.2.2 Rock-Glacier Characterization

Digital elevation models (DEM's; 10 × 10 m resolution) were obtained from the United States Geological Survey (USGS). Aspect and slope layers were calculated from the DEM's using ArcGIS Spatial Analyst©. ArcGIS Solar Analyst©, which calculates incoming solar radiation based on a DEM, site specific latitude, and a sun map of the sky, was used to estimate mean annual incoming solar radiation for the study area (Fu and Rich, 1999). Temperature data (T_{min}, $T_{max,}$ $T_{January}$ and T_{July}) and mean annual precipitation were extracted from the 1971 - 2000 PRISM 30-year normal datasets. These datasets were reduced to sea level using the 1 × 1 km DEM corresponding to the PRISM data and a standard lapse rate of 6°C/1000 m, resampled to a 10 × 10 m cell size, and then elevated to new elevations using the USGS 10 × 10 m DEM. Absaroka and Beartooth lithologies were extracted from Spatial Databases for the Geology of the Northern Rocky Mountains (Zientek et al., 2005). Parameter data was 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. Linear mean aspect (ϴ) was calculated from surface mean aspect by the following equation:

$$\Theta = \left\{ \begin{array}{ll} \arctan(\sin/\cos) & \sin > 0, \cos > 0 \\ \arctan(\sin/\cos) + 180^{\circ} & \sin > 0, \cos < 0 \\ \arctan(\sin/\cos) + 360^{\circ} & \sin < 0, \cos < 0 \\ \arctan(\sin/\cos) - 180^{\circ} & \sin < 0, \cos > 0 \end{array} \right\}$$

Differences between rock glaciers of both the Absaroka and Beartooth mountain ranges were evaluated using a one-way ANOVA to test whether topographic and climatic parameters were significantly different between the two mountain ranges.

2.3 Results

A total of 270 and 390 rock glaciers were mapped for the northern Absaroka and Beartooth ranges, respectively (Figure 2). The mapped rock glaciers were not a complete inventory as only those features which were almost certainly rock glaciers were included (the author believes the majority of rock glaciers in the area were digitized). It is believed that the mapped rock glaciers are highly representative of the relative numbers of rock glaciers between the two ranges. Topographic and climatic parameters were significantly different between the two mountain ranges (Table 1) using ANOVA.

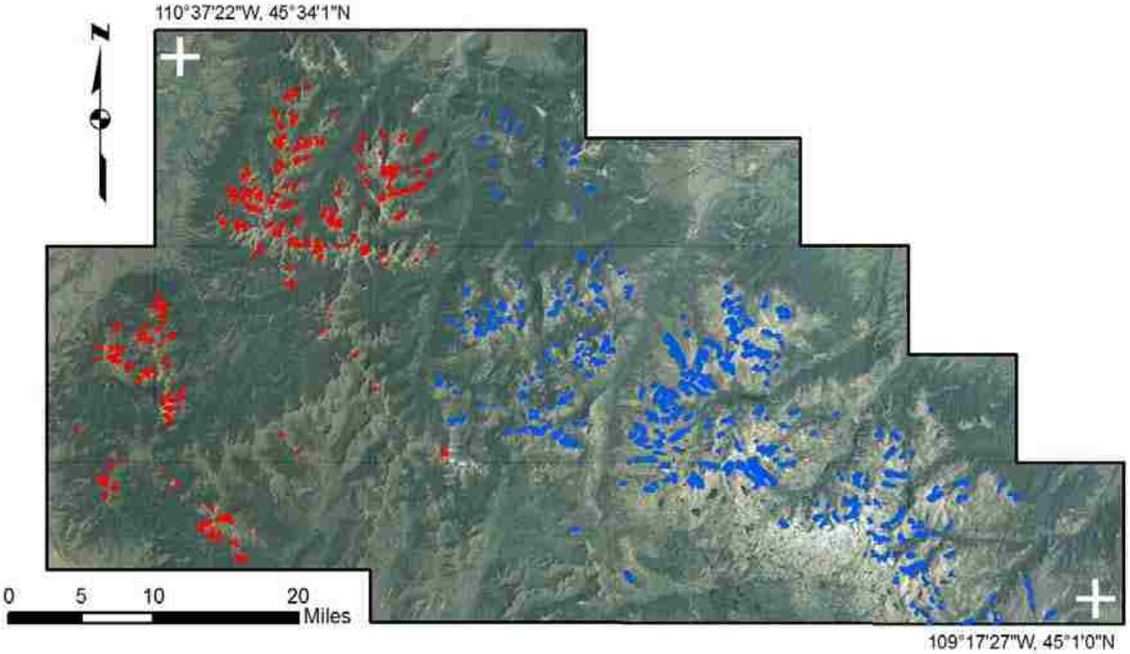

Figure 2: Map showing hand-digitized northern Absaroka (red) and Beartooth (blue) rock glaciers.

Beartooth rock glaciers were generally higher in elevation (~200 m) than rock glaciers of the northern Absarokas (Figure 3; Table 1). This reflects the fact that the Beartooth range is generally higher in elevation than the northern Absaroka's, having many peaks over 3800 m (~12,000 ft). Beartooth rock glaciers were also statistically significantly larger in size (Figure 4; Table 1). Roughly 5% of Beartooth rock glaciers were larger than any found in the Absarokas. Even excluding these outliers, differences in rock-glacier size were still significant.

Table 1: Table summarizing ANOVA results and mean, minimum, and maximum values for parameters between Absaroka and Beartooth rock glaciers. See text for complete description of each variable. Bolded p-values were significant at the 0.05 level. Samples sizes for the Absarokas and Beartooths were 270 and 360, respectively.

		Absaroka Rock-glaciers	**Beartooth Rock-glaciers**	**Difference (Absar-Bear)**	**ANOVA p-value**
Elevation (m)	*Mean*	2732	2929	-197	**0.000**
	Min	2093	2239	-146	
	Max	3072	3443	-371	
Area (m^2)	*Mean*	65274	143637	-78363	**0.000**
	Min	1444	3235	-1791	
	Max	471480	3281408	-2809928	
Slope (deg)	*Mean*	19	20	-1	0.067
	Min	5	5	0	
	Max	35	38	-3	
Insolation (kWh/m^2)	*Mean*	1337	1381	-44	**0.000**
	Min	923	987	-64	
	Max	1674	1742	-68	
T_{min} (°C)	*Mean*	-7	-8	1	**0.000**
	Min	-9	-11	2	
	Max	-2	-3	1	
T_{max} (°C)	*Mean*	7	5	2	**0.000**
	Min	5	2	3	
	Max	10	9	1	
$T_{January}$ (°C)	*Mean*	-4	-4	0	0.642
	Min	-12	-14	2	
	Max	8	7	1	
T_{July} (°C)	*Mean*	21	20	1	**0.000**
	Min	13	9	4	
	Max	32	32	0	
PPT (cm/yr)	*Mean*	89	103	-14	**0.000**
	Min	52	69	-17	
	Max	117	169	-52	
Lithology	*Mean*	N/A	N/A	N/A	**0.000**
	Min	N/A	N/A	N/A	
	Max	N/A	N/A	N/A	
Aspect	*Mean*	N/A	N/A	N/A	**0.036**
	Min	N/A	N/A	N/A	
	Max	N/A	N/A	N/A	

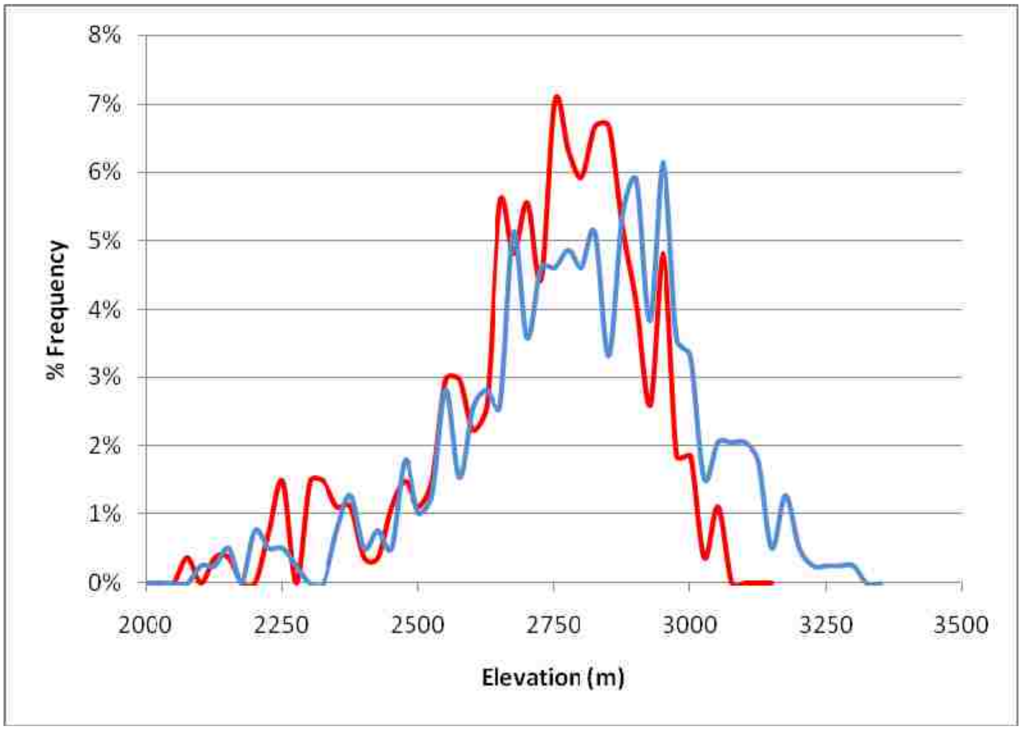

Figure 3: Distribution of mean elevation of rock glaciers in the Absaroka (red) and Beartooth (blue) ranges.

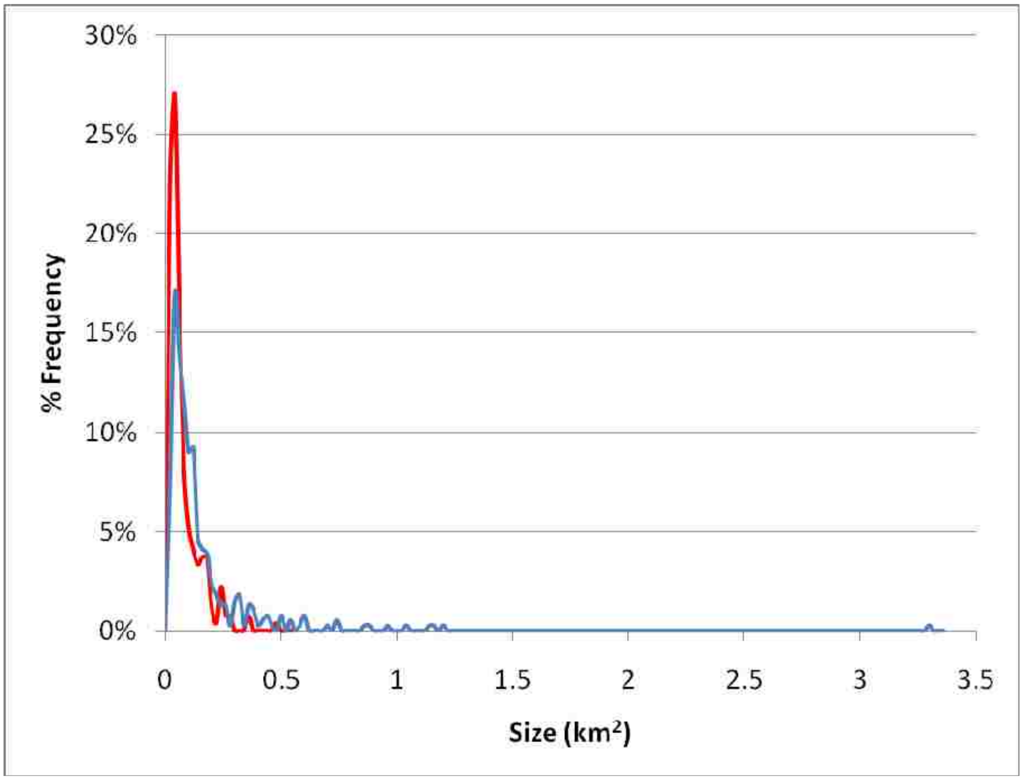

Figure 4: Distribution of mean area of rock glaciers in the Absaroka (red) and Beartooth (blue) ranges.

Beartooth rock glaciers also received ~ 3% higher levels of insolation (Figure 5; Table 1) and experienced slightly lower annual minimum and maximum annual average temperatures (Figure 6; Table 1), though differences in mean maximum January and July temperatures were more similar between ranges (Figure 7; Table 1). The Beartooth's were also estimated to receive more (+14 cm/yr) mean annual precipitation (Figure 8; Table 1). Lithologies were also significantly different between the two ranges; the Beartooth's being dominated by a mix of metamorphic rock types including: metamorphosed aluminous and sub-aluminous rocks, metamorphosed mafic or basic rocks, metamorphosed plutonic QAPF rocks and metamorphosed siliclastic sedimentary rocks (Figure 9; Table 1). While some northern Absaroka rock glaciers had similar lithology almost half were volcanic in origin. Additionally, a few rock glaciers were of a plutonic igneous origin in the northern part of the study area.

Means of rock-glacier slopes did not differ significantly between ranges (Figure 10; Table 1) with mean slopes of approximately 20°. Rock glaciers from both ranges were most common on N-NE facing aspects, but were found on all aspects (Figure 11; Table 1). Relative numbers of rock glaciers for each cardinal direction were virtually identical between mountain ranges (Table 2).

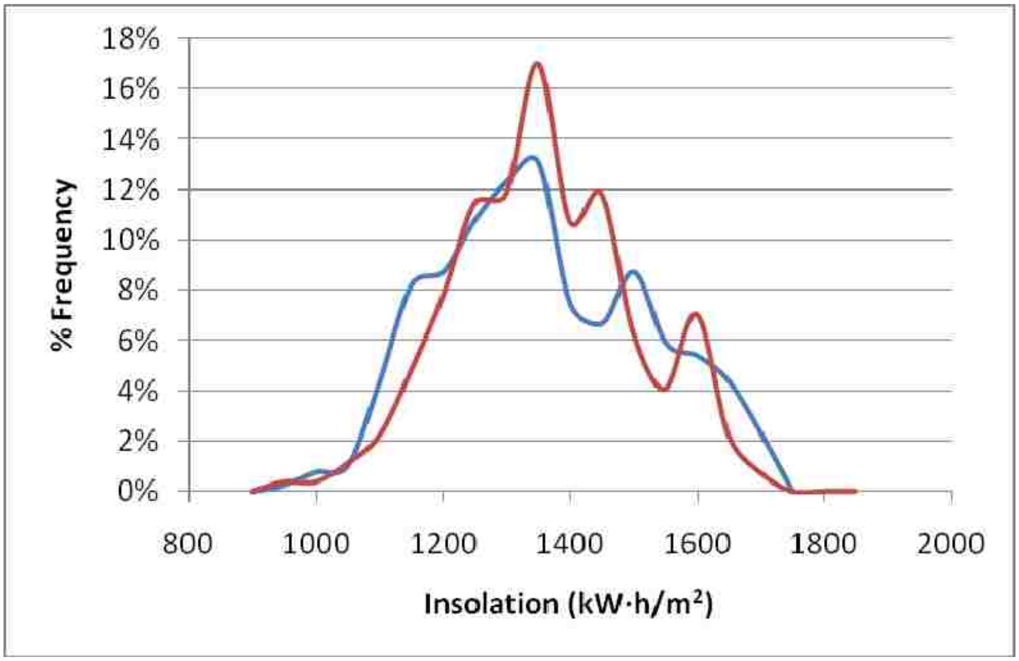

Figure 5: Distribution of mean insolation for rock glaciers in the Absaroka (red) and Beartooth (blue) ranges.

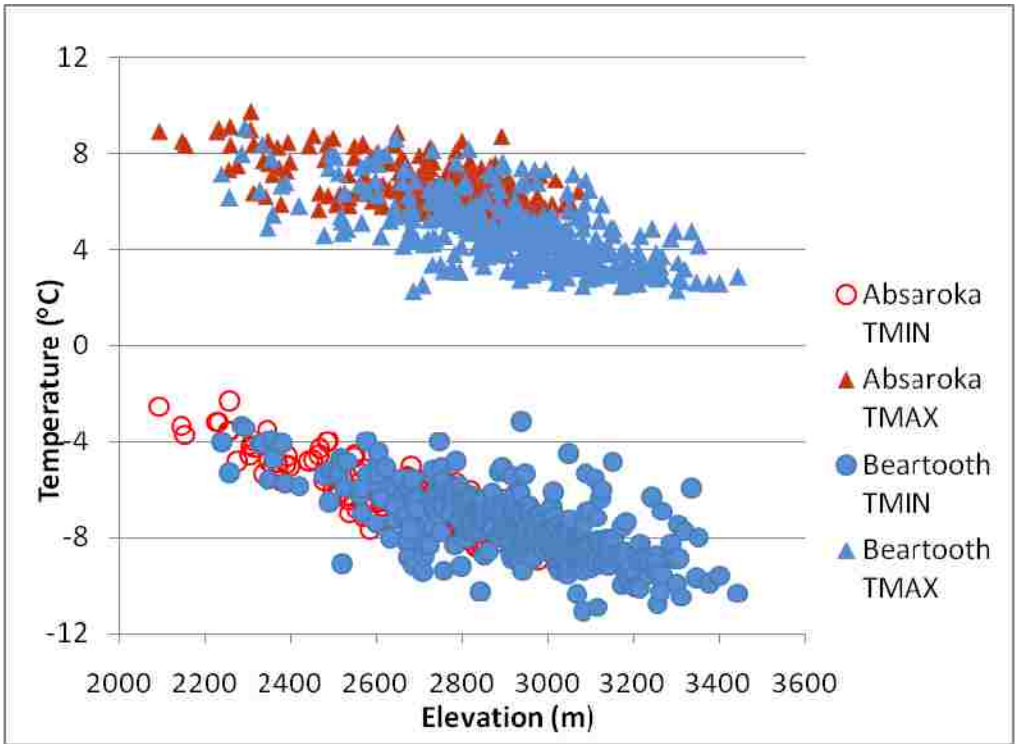

Figure 6: Distribution of T_{min} and T_{max} at each rock glacier in the two mountain ranges by elevation.

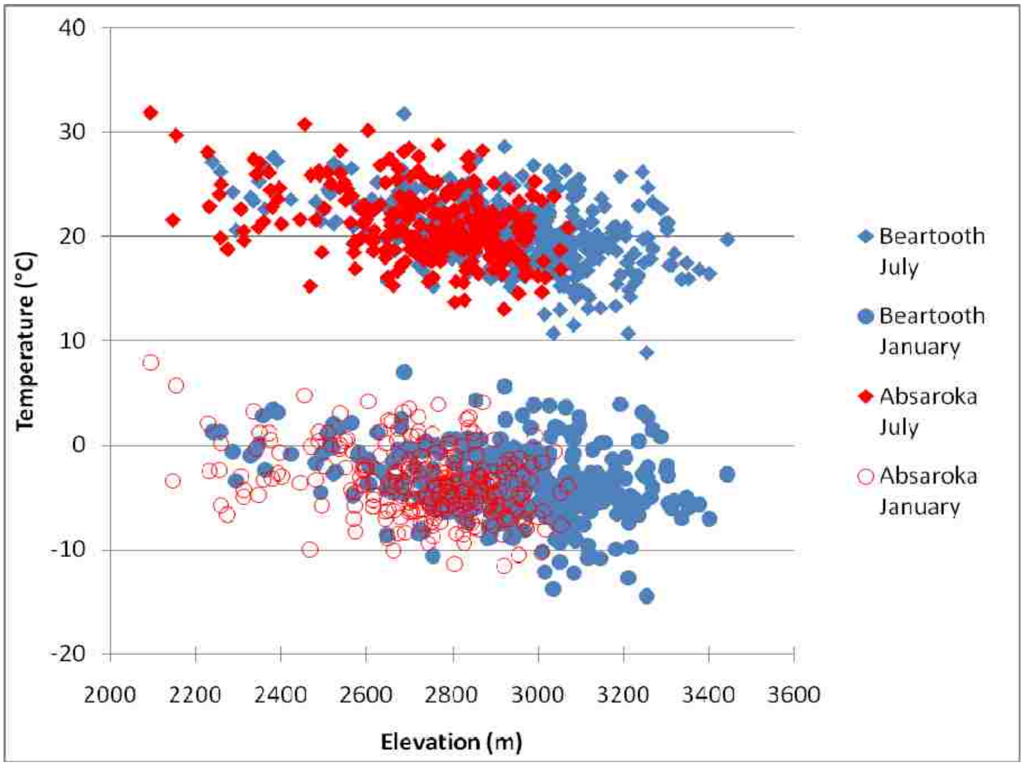

Figure 7: Distribution of $T_{January}$ and T_{July} at each rock glacier in the two mountain ranges by elevation.

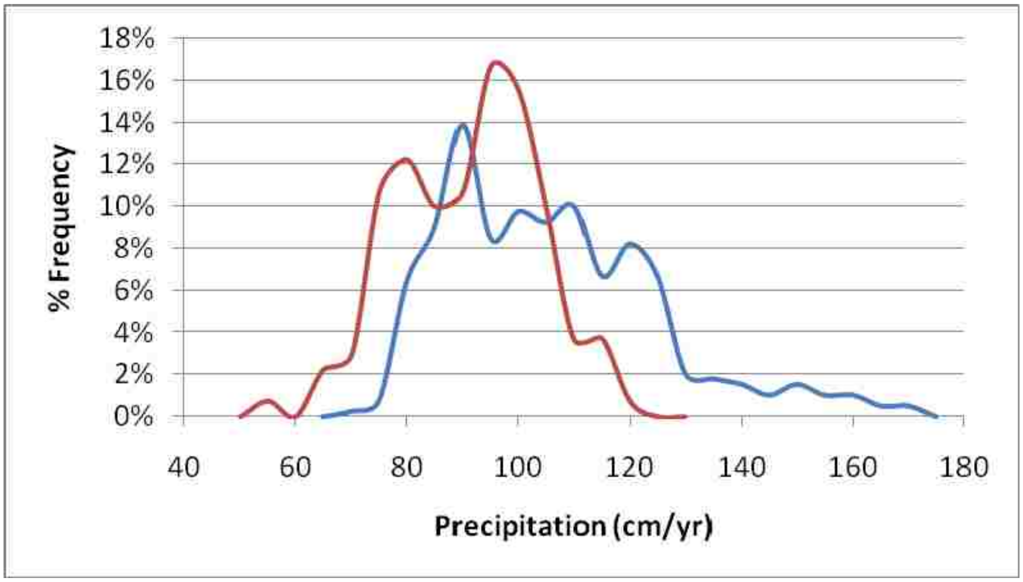

Figure 8: Distribution of mean annual precipitation for rock glaciers in the Absaroka (red) and Beartooth (blue) ranges.

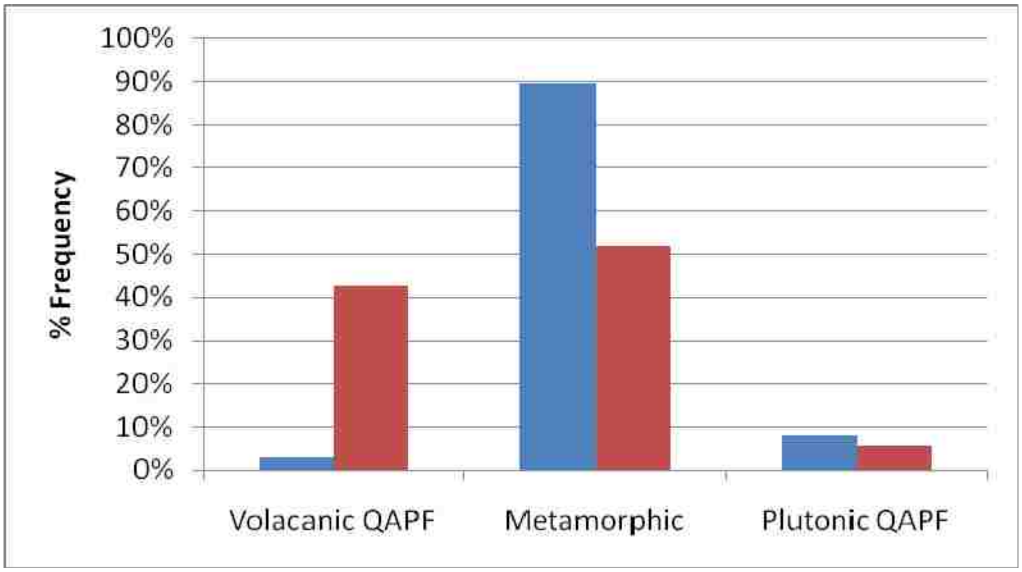

Figure 9: Distribution of lithologic types for rock glaciers in the Absaroka (red) and Beartooth (blue) ranges.

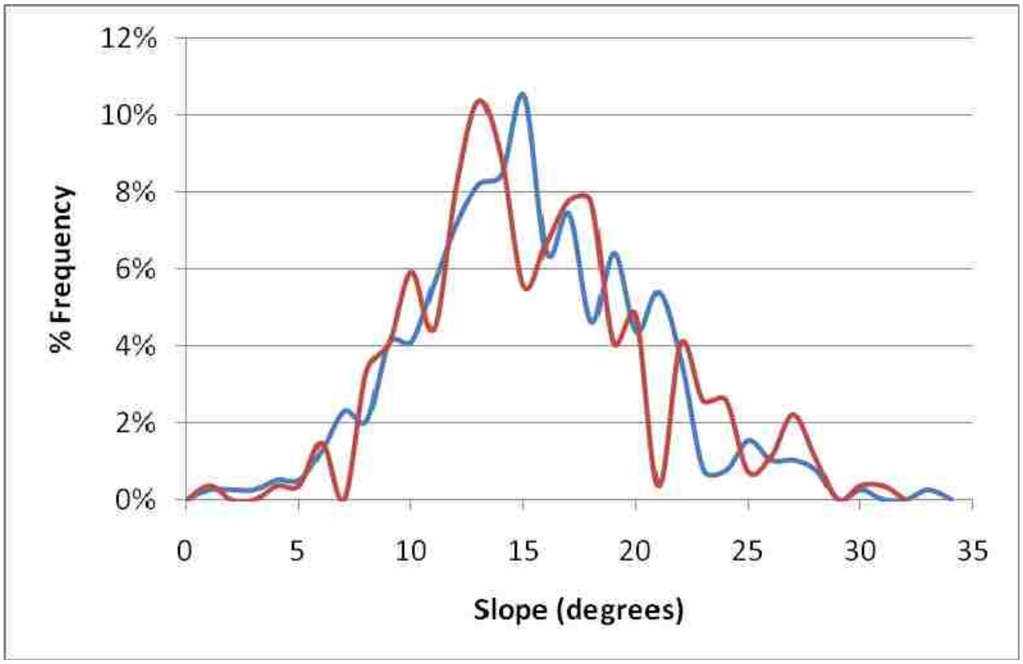

Figure 10: Distribution of rock-glacier slopes for Absaroka (red) and Beartooth (blue) ranges.

Table 2: Relative numbers of rock glaciers in each cardinal direction for Absaroka and Beartooth rock glaciers.

	North (315 - 45°)	**East (45 - 135°)**	**South (135 - 225°)**	**West (225 - 315°)**
Absaroka	30%	30%	17%	23%
Beartooth	31%	31%	18%	20%

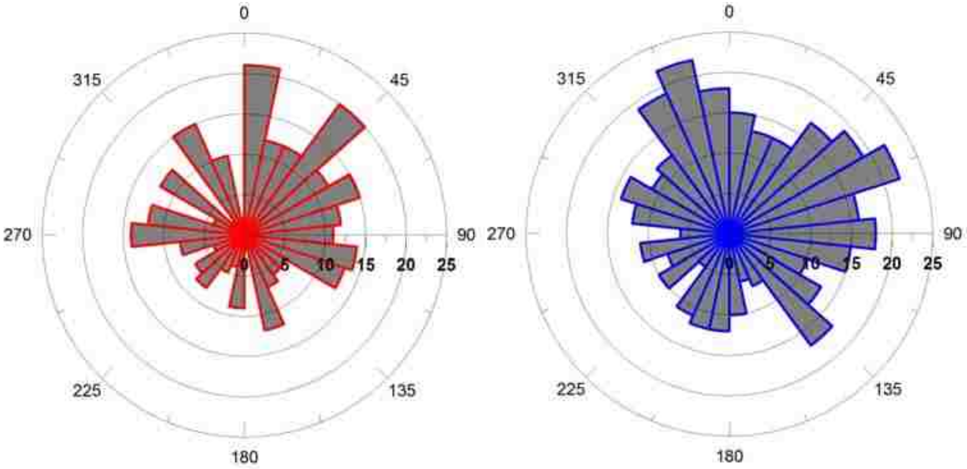

Figure 11: Distribution of rock-glacier aspects for Absaroka (red) and Beartooth (blue) ranges.

2.4 Discussion

Evaluation of distributional parameters between these two ranges provides potential for unique insight into the glacial history of this region. Assuming that both ranges were subject to roughly similar paleoclimatic trends due 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 (1989), East Grasshopper Glacier (one of the larger ice-fields of the Beartooth Range) currently falls below glacial climatic boundaries. This is supported by research documenting substantial surface subsidence of this glacier over the past 50 years (Seifert et al., 2009). The Beartooth Range currently contains a handful of cirque glaciers similar to the Grasshopper Glacier (71 according to Graf (1976) and 21 according to Locke (1989)); however, glaciogenic rock glaciers are presently the dominant glacial feature in many of these valleys. In contrast, the neighboring northern Absaroka's currently contain just two potential cirque glaciers (north aspects of Mt. Cowen and Martin Peak) which may more appropriately be classified as snow-fields (nine glaciers were present on these peaks according to Graf (1976)). This relative distribution is important context for analyzing potential shifts along the continuum from glacial and periglacial landscapes that occurs between these two proximal mountain ranges.

Graf (1976) describes 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 a stronger influence on glacial systems relative to climate through cirque shading, topographic snow accumulation, and increased avalanching

(Graf, 1976). 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 glacial landscape evolution.

In this study, the Beartooths seem to fit into a geomorphic model of what was once a predominantly glacial landscape can be transformed into one that is increasingly periglacial (Clark et al., 1998). Most rock glaciers of the Beartooths have characteristics of glaciogenic origin as they are large in size and often have formed below cirque glaciers. Periglacial rock glaciers, however, are still common in the Beartooths.

Periglacial rock glaciers are the result of excessive debris accumulation in a periglacial environment (Humlum, 2000) due to continual avalanching of ice and rock. Thus, consistent cold temperatures, not glacial geomorphology are a primary control on formation. In the northern Absarokas, most rock glaciers appear to be of periglacial origin. These rock glaciers are present on valley sides and may have begun their initial growth as protalus ramparts during more recent cold events, as is hypothesized for morphologically similar rock glaciers in the nearby Lemhi range (Johnson et al., 2007). However, even in the Absarokas there are many rock glaciers that are potentially glaciogenic.

Analysis of the characteristics between ranges supports the idea of an ongoing shift from predominantly glacial to periglacial landscape processes in the Beartooth's. The Beartooth's are higher in elevation, receive more precipitation, and are subjected to lower annual temperatures. As warming followed the glacial maximum, climatic conditions in the Beartooth's maintained a higher likelihood of sustaining glacial conditions and preserving glacial ice relative to the northern Absaroka's. However, with continued warming and glacier recession, the shift toward more periglacial conditions may become more apparent.

2.5 Conclusions

A total of 660 rock glaciers were mapped in the study area. Consequent analyses of distributional parameters showed distinct differences between Absaroka and Beartooth rock glaciers with regards to elevation, size, slope and topoclimatic variables. Overall, Beartooth rock glaciers were statistically higher, larger, received more precipitation, and were subject to lower temperatures than those in the Absaroka's.

Analyses of rock-glacier characteristics revealed interesting differences between mountain ranges. The comparative numbers of glaciers and the relative differences in the geomorphic position, size, and elevation of rock glaciers indicates that the northern Absarokas are closer to a periglacial-dominated landscape relative to the Beartooths which are clearly still highly influence by recent glacial activity.

If climatic warming continues and glacial ice extent continues to decrease, it is possible that the majority of remaining ice content will be associated with rock glaciers in the Beartooth's and similar Rocky Mountain locations.

3 ACTIVITY ANALYSIS AND LOGISTIC REGRESSION MODELING

A major application of rock-glacier distribution has been to reconstruct past climates from the relative distribution of modern and relict rock glaciers (Brazier et al., 1998; Hughes et al., 2003; Aoyama, 2005; Millar and Westfall, 2007; Roer and Nyenhuis, 2007; Putnam and Putnam, 2009). This study aims to estimate current lower limits of permafrost and evaluate the relative importance of a series of factors on rock-glacier ice preservation and activity in the region.

3.1 Background

Humlum (1998a: 378) describes the presence of rock glaciers to be "a complex function of responses to air temperature, insolation, wind and seasonal precipitation over a considerable period." Additional parameters are noted by Morris (1981), who compared altitude, insolation and cirque wall orientation to preservation potential of the rock-glacier ice matrix. In New Zealand, active rock glaciers favored relatively higher elevations and more southerly aspects (Brazier et al., 1998). In the same study, modern distribution of relict rock glaciers favored lower elevations on all aspects.

Determination of activity classification of rock glaciers is useful in estimating permafrost boundaries. Active and inactive rock glaciers can be used to assess boundaries of current permafrost distribution, while relict rock glaciers are used to evaluate past boundaries of permafrost (Pèwè, 1983; Barsch, 1996; Brazier et al., 1998). Following this rationale, the respective distribution of the lowest relict and modern rock glaciers might indicate past and present boundaries of mountain permafrost for the Absaroka/Beartooth region.

Logistic regression analyses have been used for many geomorphologic investigations; however, application towards rock glaciers has been limited (e.g. Brenning 2005; Brenning and Trombotto, 2006). In this study, a logistic regression model was created using the distributional data to produce probabilities of whether rock glaciers were either modern (active or inactive) or relict.

3.2 Methods

3.2.1 Rock-glacier Activity Classification

Activity level was assessed in the field at 80 rock glaciers in the summer and fall of 2008. An additional 40 rock glaciers were classified by activity level using only aerial photos, DEM's, and prior knowledge of field sites. Rock glaciers were evaluated according to a set of criteria derived from the literature (Table 3) that relate surface characteristics to recent movement and thus, determine whether a rock glacier is active, inactive or relict. Generally, rock glaciers with steep frontal and side slopes and little or no vegetation development were classified as modern, while rock glaciers with gentler frontal and side slopes (<35°) and heavy vegetation development were classified as relict. Additional detail is given in Table 3.

The relatively small sample size led to the decision to use binary logistic regression, which necessitated grouping the active and inactive rock glaciers into a 'modern' classification (Millar and Westfall, 2007).

Table 3: Criteria used to assess rock-glacier activity based upon work from several authors (Chueca and Julian, 2005; Roer and Nyenhuis, 2007; Millar and Westfall, 2007; Johnson et al., 2007; Clark et al., 1998).

	Modern		**Relict**
	Active	**Inactive**	
Surface	Dominantly smooth	Can be smooth with blocky sections; has circular or elongate pits	Dominantly blocky; Has a heavily pitted surface indicating thermokarst
Lichen	Little or no lichen	Crests of ridges are generally lichen covered, but the furrows remain bare	Rock surfaces are completely covered with Lichen
Surface Rocks	Angular, unweathered and size sorted	Not as well sorted, slightly weathered	Highly weathered and unsorted clasts
Front and Side Slopes	≥ 35°	≥ 35°	< 35°
Frontal Slope Stability	Unstable with fresh, large, angular boulders at their bases	Contains zones of stability and instability	Frontal slope is low angle and stable
Vegetation	No vegetation cover	Can be fully or partially covered with vegetation	Developed soils are completely colonized by vegetation

3.2.2 Logistic Regression

Binary logistic regression analysis was used to test the significance of nine variables (elevation, insolation, slope, aspect, area, lithology, T_{max}, T_{min}, and precipitation) on whether a feature was modern or relict. Further analyses examined the use of T_{July} and $T_{January}$ in place of T_{max} and T_{min}. The 120 field-verified and remotely-verified rock glaciers were used to build the regression model. All variables were continuous except lithology which was coded using two dummy variables. A backwards, stepwise procedure, which initially included all variables, was used. At each step, the variable with the least weight was eliminated from the model until a desired significance of $p < 0.05$ was reached.

Binary logistic regression produces logits, which are the logarithmically transformed ODDS of whether a selected binary categorical variable will occur based on input from independent variables (Hosmer and Lemeshow, 1989). In this study, logits of whether a modern rock glacier would occur were produced.

3.3 Results and Discussion

From the initial 9 parameters T_{max} and elevation were initially included in the final model:

$$\text{ODDS} = e^{[(0.009*\text{Elevation}) + (0.487*\text{Tmax}) - 28.622)]}$$

A Hosmer and Lemeshow ‘goodness of fit’ statistic (Hosmer and Lemeshow, 1989) was used to test whether or not observed values of rock-glacier activity differed from predicted. Predicted values did not differ from observed values (p = 0.233). In addition, a traditional chi-squared test for model fit was also employed (Hosmer and Lemeshow, 1989), showing significant relation between predictor and response variables (p<<0.05). The ODDS were divided by (1+ODDS) to calculate probabilities of modern activity classification. Probabilities for the remaining 540 rock glaciers were then mapped in a GIS to show respective distribution of activity probability (Figure 11). There were stark differences between the two ranges. Over 30% of Beartooth rock glaciers had a 70% or higher probability of being modern while only 8% of Absaroka rock glaciers did (Figure 12).

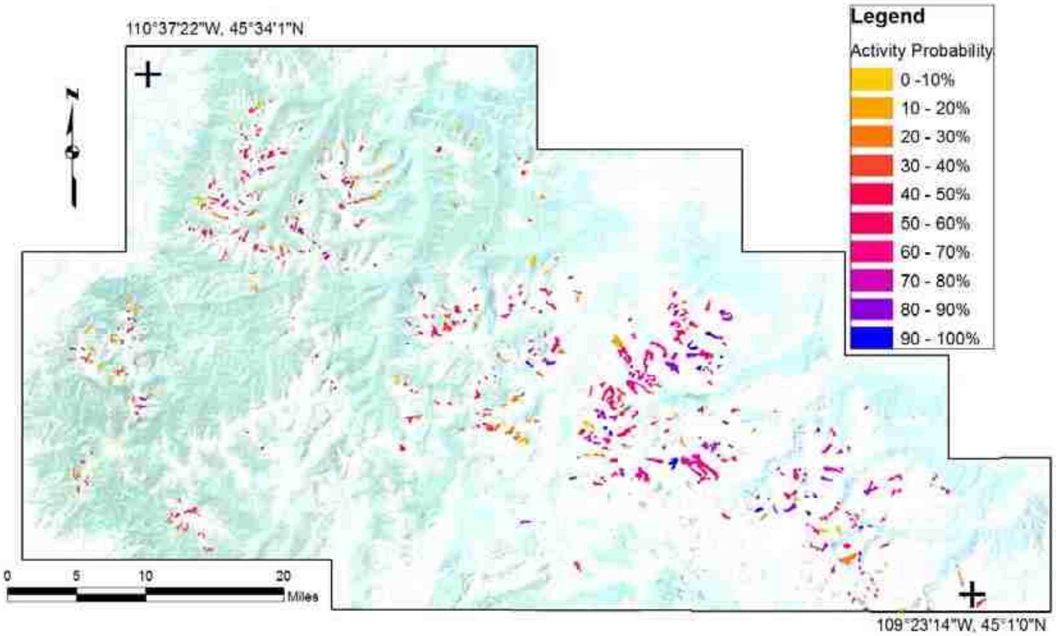

Figure 12: Map showing the probabilities of rock glaciers being classified as 'modern' in activity.

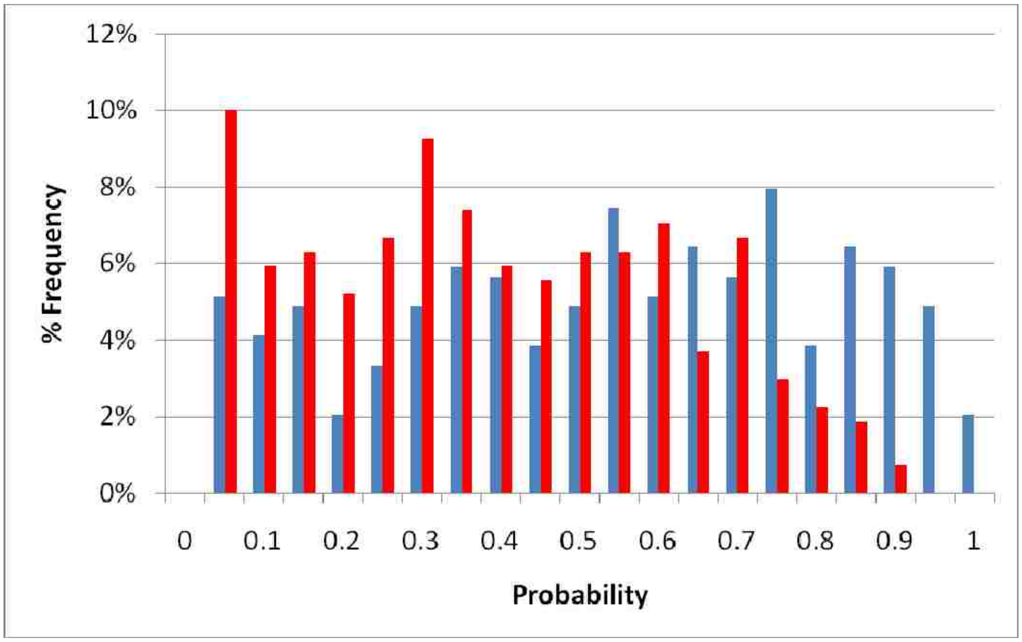

Figure 13: Probability of a rock glacier having modern activity for the northern Absarokas (red) and Beartooths (blue).

While these results support the expected relationship between elevation, temperature, and ice preservation in rock glaciers, temperature is largely a function of altitudinal gradients due to atmospheric lapse rates. Both T_{max} and elevation have significant weight in the model, however the two variables are correlated (Pearson correlation coefficient = -0.771). Beyond issues of co-linearity, the appropriateness of T_{max} for this study was questioned during analysis.

T_{max} is defined as an annual mean calculated from average maximum monthly temperature. This makes it difficult to interpret whether cold, warm, or transitional season temperatures are ultimately affecting and predicting rock-glacier activity. Similar ambiguity exists by using T_{min}, mean monthly lows which are also averaged annually. Comparison to mean maximum temperatures from January and July (standard variables for examining temperatures influences on glacial behavior) were subsequently used to evaluate whether yearly extremes of cold and warm temperatures were correlated with rock-glacier activity. In this new analysis, elevation remained significantly related to rock-glacier activity, but neither $T_{January}$ nor T_{July} were. Additionally the fact that PRISM data are modeled using elevation as a primary factor in interpolation may render it inappropriate for inclusion as an independent variable in this regression analysis.

Previous research shows that preservation of ice within rock glaciers is dependent on cold winter temperatures (Brazier et al., 1998; Millar and Westfall, 2007). While $T_{January}$ was not included in the regression model, the fact that elevation was highly related to activity supports these previous studies (Figure 13); as colder temperatures can be inferred at higher elevations due to atmospheric lapse rates, though that is not necessarily true in mountainous regions. Results from an ANOVA test comparing means of the 11 different parameters between modern and relict rock glaciers support Figure 13 which shows that mean elevations of modern rock glaciers are significantly higher ($p = 3.92\times10^{-5}$) than those of relict rock glaciers. It seems that while elevation alone does not entirely explain the variability in rock-glacier activity, logistic regression results further support the use of altitudinal boundaries of rock glaciers in estimating their location.

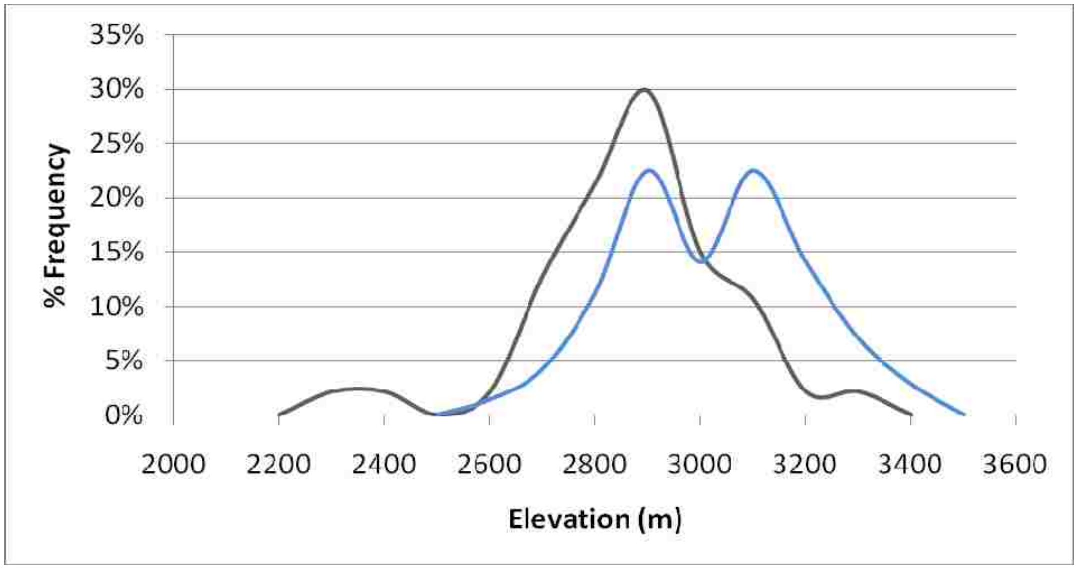

Figure 14: Distribution of elevation for modern (blue) and relict (black) rock glaciers.

3.3.1 Permafrost Distribution

Previously the lower altitudinal limits of continuous mountain permafrost were estimated for the Absaroka/Beartooth region by Harris (1986), where ice in peat was observed in the Beartooth's at 2400 m. Ensuing general lower limits of continuous and sporadic mountain permafrost were estimated to be ~2600 m and ~1500 m, respectively for latitudes of about 45° N (Harris, 1986).

The lowest field-observed relict rock glacier was located in the Absarokas and had a minimum elevation of 2100 m which coincides with previous estimates of lower permafrost limits for Wisconsinan times in northern Wyoming (Mears, 1981). While Harris (1986) estimated the current lower limit of mountain permafrost to be ~2600 m, estimates of current permafrost boundaries in this study based on minimum elevations of modern rock glaciers were 2500 m and 2800 m for Absaroka and Beartooth rock glaciers, respectively. The mean of these two values was 2650 m which is slightly higher, but comparable to estimates made by Harris (1986). However, this range of values is slightly lower than was proposed by Pèwè (1983), who suggested a 1000 m upward shift since the late Wisconsinan; which would put current levels for the study area at roughly 3000 m. Rock-glacier age, a critical component of paleoclimatic investigation using rock glaciers, was not determined in this study. Thus, only relative inferences can be made by comparisons with previous research (Figure 14).

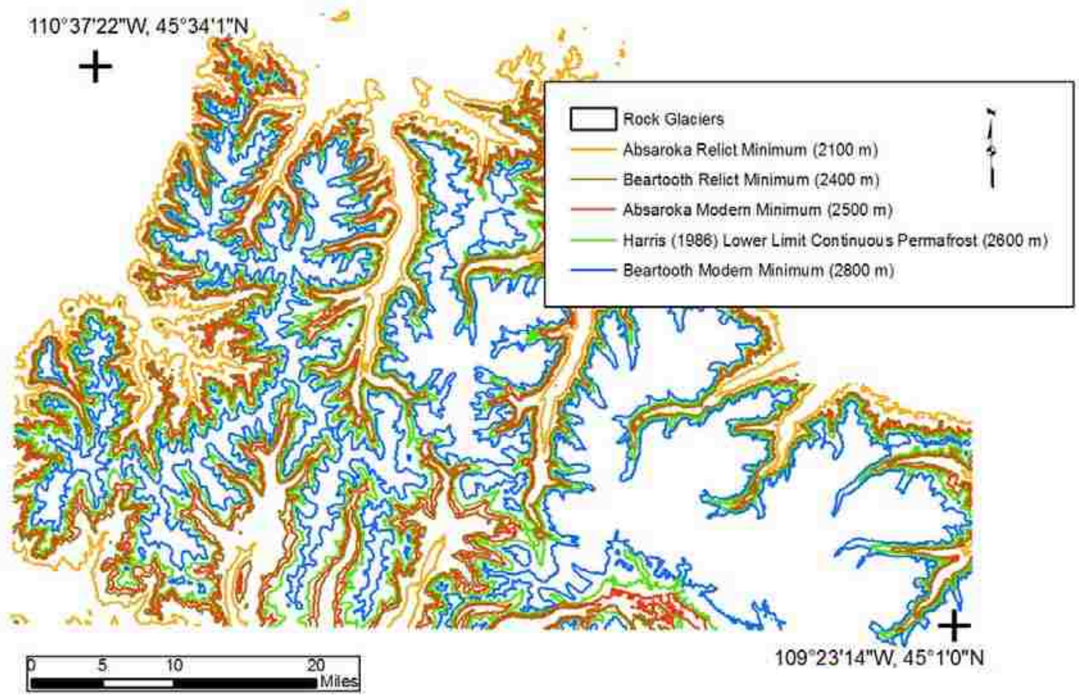

Figure 15: Map showing the relative position of estimated permafrost boundaries on the landscape.

The elevations of the probability distribution of modern rock glaciers were mapped along with minimum elevations of relict and modern rock glaciers (Figure 15). By tracing the 'Beartooth Modern Limit' (Figure 15), one finds that it crosses probability isolines ranging from 10% - 70% which may or may not improve estimates of permafrost boundaries.

The implications of these estimates are many-fold. As was described in Chapter 2 glacier/rock glacier ratios imply that the Beartooth range is geomorphically shifting towards more periglacial processes. Regional estimates of permafrost boundaries may assist in understanding potential future shifts in permafrost as near surface temperatures in the mountains of the western USA are projected to increase by 0.8 – 1.7°C by 2050 (de Jong et al., 2009). Increasing temperature trends would further promote Beartooth deglaciation as the northern Absarokas are already deglaciated. In addition, ice within rock glaciers may also decrease, leading to fewer active rock glaciers, though rates of this decline will be slowed due to insulative properties of the rock mantle.

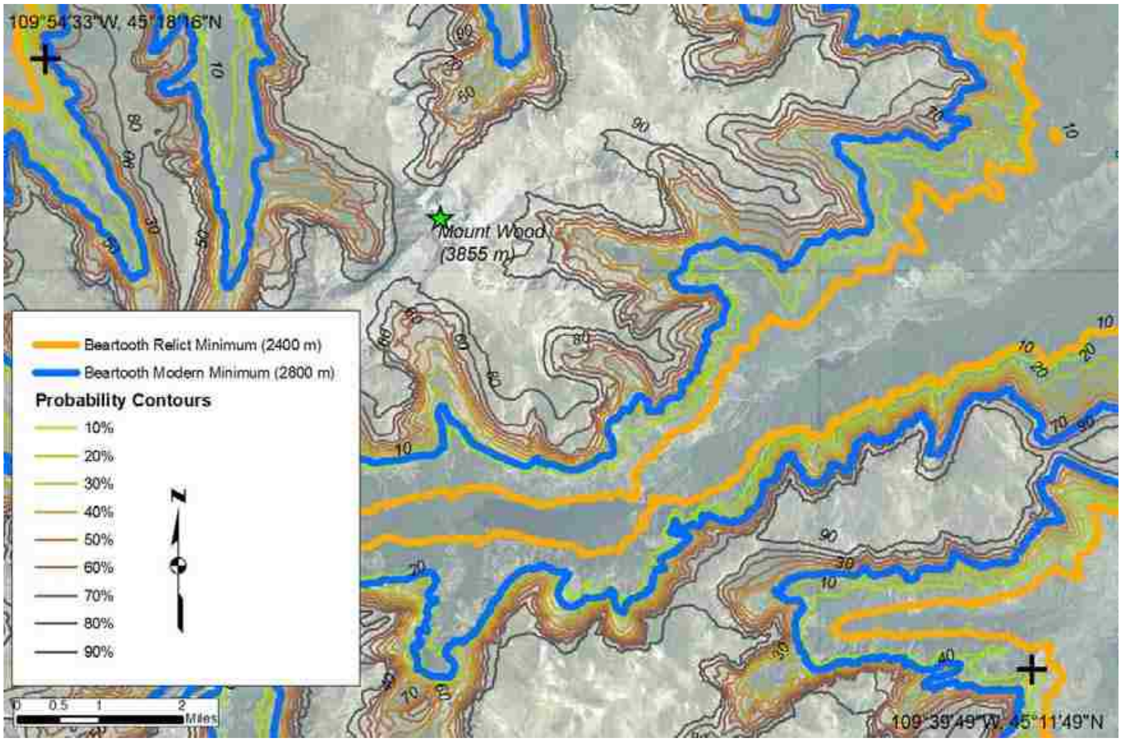

Figure 16: Close-up map of Mt. Wood area (Beartooths) showing estimated activity probability compared with boundaries estimated from minimal altitudinal extents of modern and relict rock glaciers.

3.3.2 *Insolation and Temperature*

It was originally hypothesized that elevation and insolation would be primary controls on rock-glacier activity, and while elevation was most significant, T_{max} was more significant ($p < 0.05$) than insolation. Results do not discount insolation completely, however. Comparison of mean insolation values was statistically significant ($p < 0.05$) by aspect (Figure 16). Additionally, plotting the observed modern and relict rock glaciers with respect to elevation and aspect shows a greater occurrence of modern rock glaciers on north-facing slopes than the relict distribution (Figure 17; Table 4).

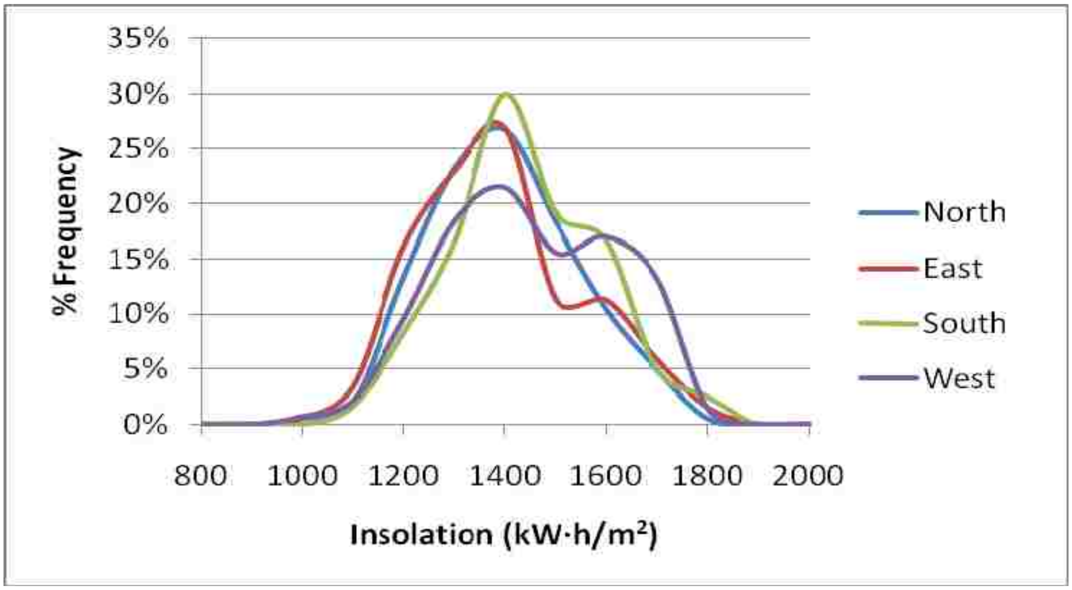

Figure 17: Relationship between mean insolation and aspect for all 660 rock glaciers. Mean insolation values (kW·h/m^2) for each respective orientation were: North (1346), East (1340), South (1388), and West (1397).

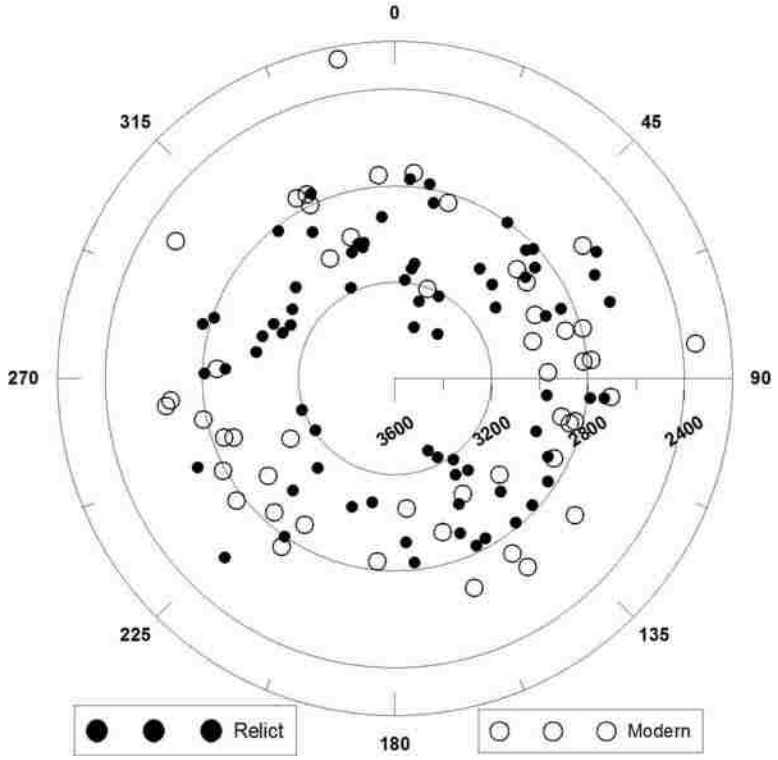

Figure 18: Comparison between modern and relict rock glaciers plotted by elevation (m) and orientation.

Table 4: Relative numbers of relict and modern rock glaciers for each cardinal direction.

	North (315 - 45°)	**East (45 - 135°)**	**South (135 - 225°)**	**West (225 - 315°)**
Relict	20%	37%	20%	22%
Modern	29%	25%	26%	19%

Previous research from southern Colorado shows preservation of the rock-glacier ice matrix to be primarily controlled by rock-fall intensity and topoclimatic parameters such as elevation, radiation reduction, and position of the cirque headwall with respect to wind-drifting and snow avalanching (Morris, 1981). Other studies have looked at rock-glacier development and preservation with regards to annual insolation and lithology (Johnson et al., 2007), lithology and geological controls (Ikeda and Matsuoka, 2006), and morphology and topography (Humlum, 1988). Controls on rock-glacier initiation and growth are not understood in great detail, however (Humlum, 2000).

In this study, interestingly, estimated insolation was not a strong predictor of activity. This is most likely the result of insulating properties of the rock mantle which have been suggested to greatly reduce ablation rates (Potter et al., 1998). It was also hypothesized that there would be a correlation between temperature and insolation, but none was found. The solar insolation calculated in Solar Analyst© is an estimated value that does not take complex atmospheric variability into account; observational solar radiation measurements might show trends more highly correlated to surface temperatures.

While glaciers are barometers of change in precipitation and temperature (Locke, 1989; Shea and Marshall, 2007), glaciogenic rock glaciers, by their existence, signal a decline in precipitation relative to previous conditions. This is due to their frequent occurrence in areas and at elevations similar to glaciers, but generally too arid for current glacier formation (Brazier et al., 1998, Humlum, 1998b). In addition, due to the formation of a rock mantle, rock glaciers exhibit slow response to changes in temperature. A marked increase in annual temperatures, thus, would need to have persisted for decades to centuries (Brenning, 2005) in order to harvest a response.

Temperature increases in the instrumental climate record over the past 100 years for areas in the Canadian Rockies correspond to a decline in glacial mass balance (Luckman, 1998). Similarly, anomalous interaction of high summer temperatures and low winter accumulation has led to unprecedented glacial recession in Glacier National Park, Montana that began in the early-20th century (Pederson et al., 2004). Increased summer temperatures that are affecting glacier recession in other Rocky Mountain areas are most likely affecting northern Absaroka and Beartooth alpine areas, though because modern rock glaciers are dependent on cold winter temperatures for their ice preservation, in the wake of massive glacier recession, rock glaciers may become the principal vestiges of glacial ice in the Beartooth region as they may already be in the northern Absarokas.

3.4 Conclusions

This study utilized activity data from 120 rock glaciers to predict activity classification on a larger data set of 540 rock glaciers through logistic regression analysis. T_{max} (mean annual maximum temperatures) and elevation had the strongest predictive value for whether a rock glacier would be modern (active or inactive) as opposed to relict. However, further analysis using January and July temperature data suggested that T_{max} may be inappropriate for this study due to their co-linearity with elevation and the inability to differentiate whether cold, warm, or seasonal temperature trends affect rock-glacier activity.

Predicted probabilities of rock-glacier activity were compared to minimum rock-glacier elevations as a proxy for permafrost presence. Estimates from this study coincide with previous estimates from Harris (1986) where lower limits of continuous permafrost were approximated to be present at ~ 2600 m. In the current study, minimum elevations for modern relict rock glaciers in the northern Absarokas and Beartooths were 2500 m and 2800 m respectively. The mean of these two elevations is 2650 m, which is slightly higher but comparable to estimates from Harris (1986).

Originally it was hypothesized that solar insolation would be a determining factor, however no strong correlation with activity was observed. This is most likely the result of insulative characteristics of the rock-glacier rock mantle.

Finally, with continuing climate warming and glacial recession, the slow response of ice within rock glaciers may prove to be an important asset to alpine ecosystems. Presumably this is already the case in the Absarokas and will become increasingly more important in the Beartooths.

4 ROCK-GLACIER MOVEMENT

4.1 Background

Ground-based approaches as well as air- and space-borne techniques exist for monitoring rock-glacier kinematics with high resolution (Haeberli, 2006). Movement quantification in the Colorado Front Range has been done using surveying (White 1971). Similar studies were carried out in the Pyrenees (Chueca and Julian, 2005) and the Alps in Austria (Krainer and Mostler, 2000), where surface velocities were on the order of 0.1 m/yr and roughly 2.5 m/yr, respectively. Some of the highest rock-glacier velocities have been observed in the Andes, up to 100 m/yr (Corte, 1987). Photogrammetry is the technique most commonly used for monitoring rock-glacier movement (Haeberli, 2006) and can help describe horizontal as well as vertical displacement of rock-glacier surface features most efficiently and with high resolution (Kääb et al., 1997, Berger et al., 2004).

Comparison between climate and rock-glacier morphology and movement is controversial due to conflicting reports of evident and obscure correlations on varying time scales (Kääb et al., 1997; Bachrach et al., 2004). Other research has shown rock-glacier climate sensitivity to fluctuate over the length of the rock glacier (Konrad et al., 1999). Ablation rates were found to be higher near the cirque and decreased to near zero towards the terminus due to the increasing thickness of the debris layer near the terminus.

4.2 Methods

Digitally ortho-rectified and geo-referenced aerial photographs of the Black Canyon Basin (Figure 18) were obtained for the years 1952, 1981, 1987, 1995, and 2003 from the USFS's Remote Sensing Application Center (RSAC).

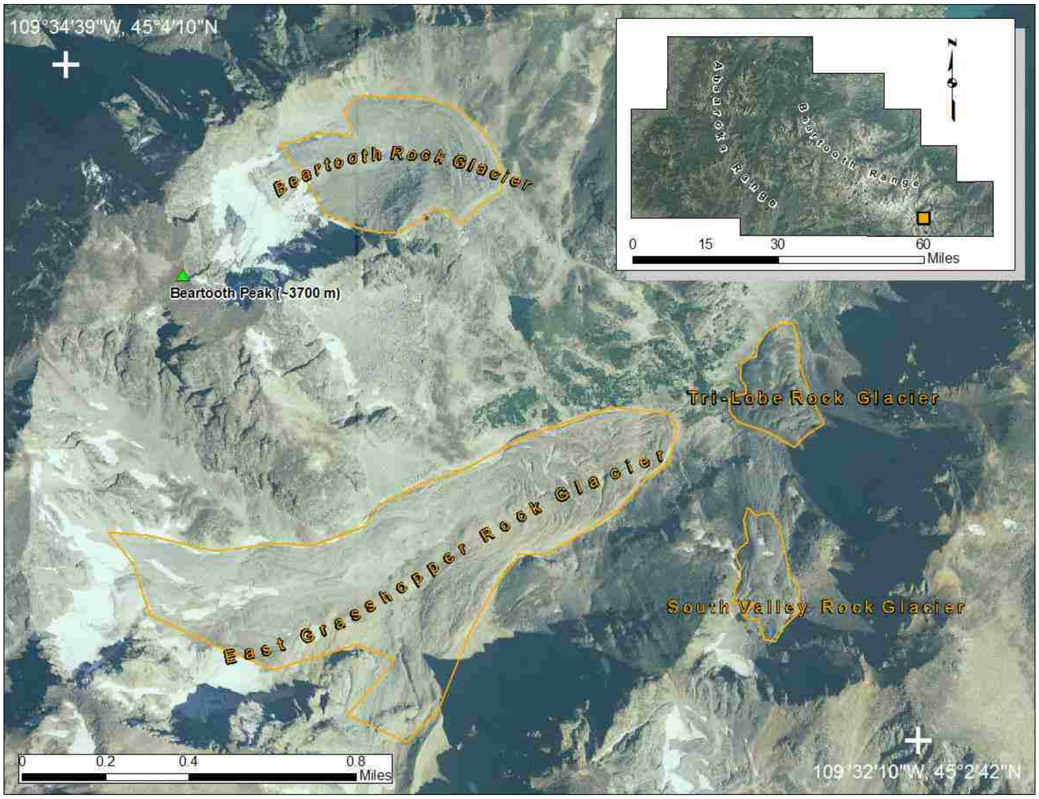

Figure 19: Map showing the four rock glaciers (Beartooth, East Grasshopper, South Valley, and Tri-Lobe) included in photogrammetrical analysis.

Only four rock glaciers were analyzed because other potential rock glaciers had either poor photo resolution or had orthorectification inaccuracies. For each of the rock glaciers, distinctive surface boulders were identified and tracked by digitizing a line, with each point on the line representing the location of the boulder at one time slice (Figure 19).

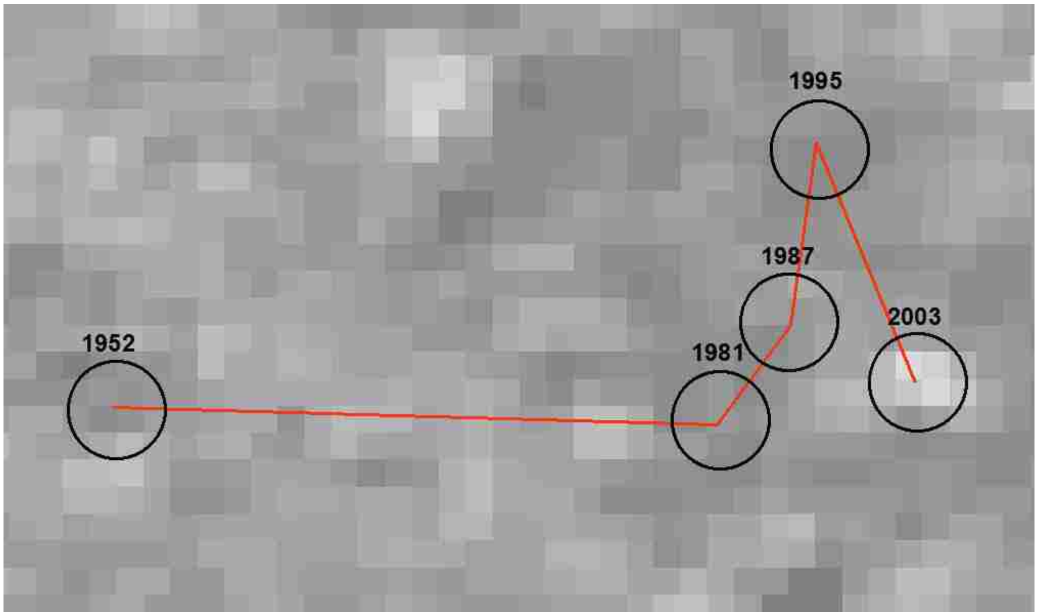

Figure 20: Movement vector on the East Grasshopper rock glacier. The lighter pixels in the 2003 circle represent the boulder that was tracked using this particular poly-line. Other circles represent the position of that boulder in previous years.

The total number of lines digitized per rock glacier was based on the size of the rock glacier as well as the ability to identify specific boulders on sequential photos (Table 5). The mean distance traveled by boulders between successive photo periods was determined for each rock glacier.

Table 5: Sample sizes of boulders per rock glacier used to determine rock-glacier movement.

Rock glacier	Number of Boulders Tracked
Tri-Lobe Rock-glacier	88
East Grasshopper Rock-glacier	218
Little Monster Rock-glacier	65
Beartooth Rock-glacier	94
Reference Vectors	91

Photo error was estimated by comparing the movement of rock-glacier boulders to the ‘movement’ of large boulders outside rock-glacier boundaries that were assumed to be stationary; these are called reference vectors hereafter. The same set of reference vectors were used for each rock glacier.

4.3 Results

4.3.1 Reference Vectors

T–test’s were used to compare means of X and Y coordinates for reference vectors among sequential photos. Results showed that positions of reference boulders did not vary significantly from one year to the next ($p < 0.05$). While the photos, in general, were very well aligned, distortion at photograph edges was widespread. This made the potential for tracking movement of boulders often difficult and thus, inaccurate at times.

4.3.2 South Valley Rock Glacier

The South Valley rock glacier has a mean elevation of 3185 m and holds a northerly aspect. Field analysis revealed this rock glacier to be inactive which is partially supported by movement analysis. In periods one (1952-1981), three (1987-1995) and four (1995-2003), photo error was significantly higher than or equal to rock-glacier movement (Figure 20). In period two (1981-1987), however, comparing means of movement and reference vectors showed rock glacier movement to be significant. Values of annual displacement rates can be calculated by subtracting photo error movement from rock-glacier movement as both were observed to be moving in the same direction. For period two, rock-glacier movement was 7 cm/yr for the 6-year period.

This suggests the South Valley rock glacier was active in period two, however, due to photo error, results regarding other periods were inconclusive.

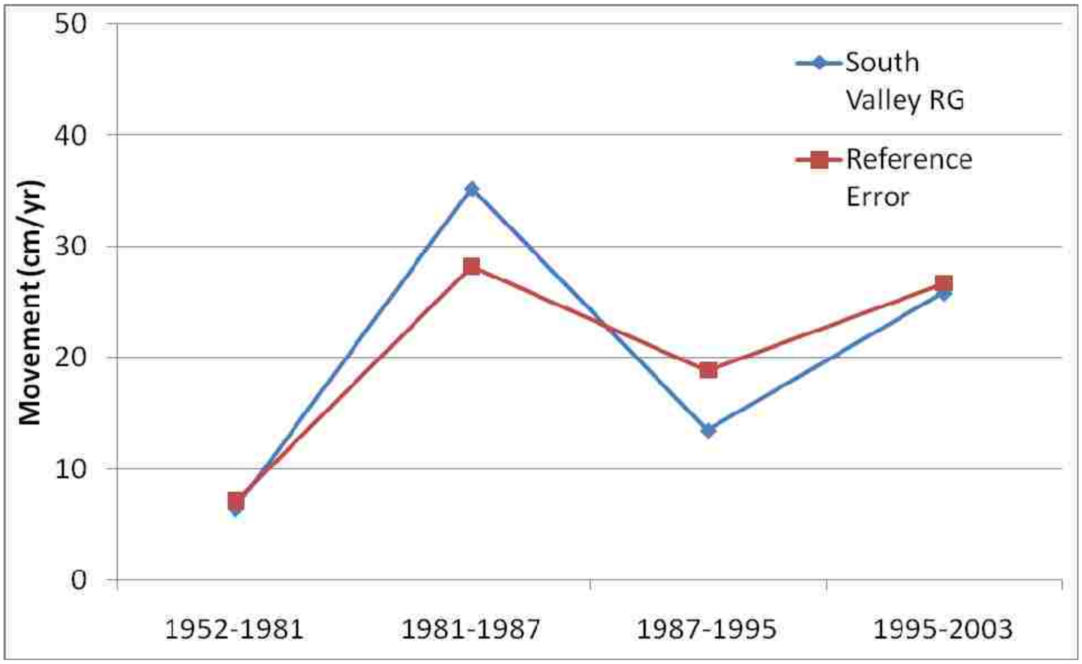

Figure 21: Surface movement of the South Valley rock glacier (1952 - 2003).

4.3.3 Tri-Lobe Rock Glacier

The Tri-lobe rock glacier is the lowest in elevation of the four rock glaciers coming to a terminus at the western end of Black Canyon Lake. It has a mean elevation of 2906 m and a northwesterly aspect. In all four periods, photo error was either equal to or greater than potential rock-glacier movement, suggesting that this rock glacier had not moved throughout the study period (Figure 21). This is consistent with field observations where the Tri-Lobe rock glacier was classified as inactive due to its steep front slope, weathered surface features and extensive alpine vegetation cover.

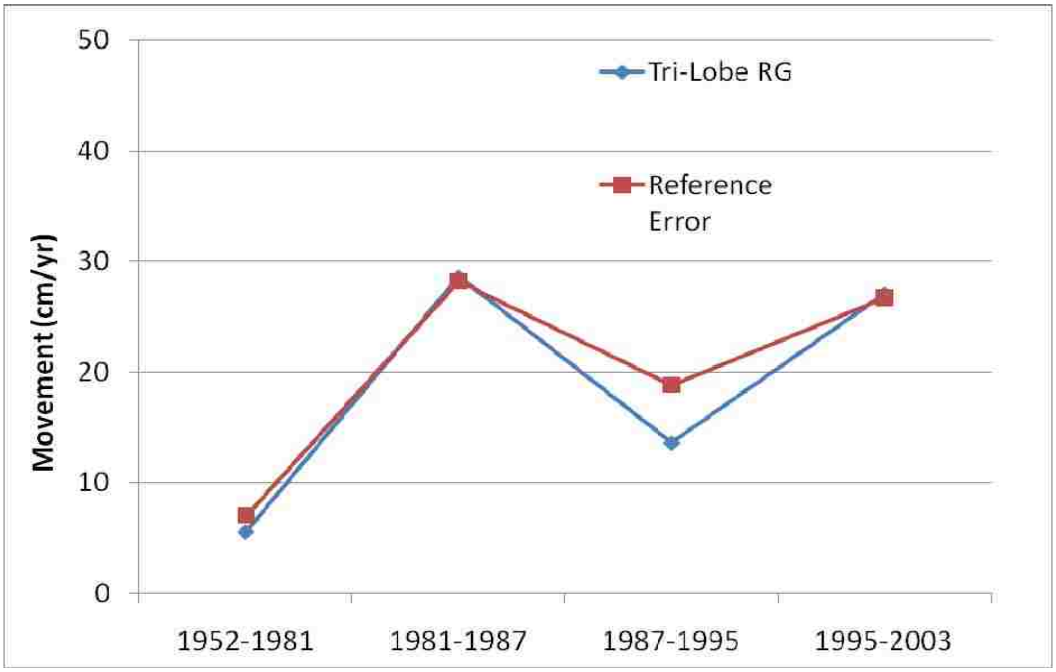

Figure 22: Surface movement of the Tri-Lobe rock glacier (1952 - 2003).

4.3.4 Beartooth Rock Glacier

The Beartooth rock glacier gets its name from the Beartooth Glacier below which it formed. The rock glacier sits at 3224 m and has a mean directional aspect facing east. It was classified as active due to a steep, unstable frontal slope, no vegetation, and a smooth surface with fresh angular clasts. For periods one, two, and three (1952 – 1995), reference vector movement was equal or greater than rock-glacier movement (Figure 22). In period four, however, rock-glacier movement was significant in comparison to reference vectors ($p < 0.05$) at 9.2 cm/yr; but was 'backwards' or uphill. This may be the result of surface subsidence; causing boulders to appear to be moving backwards when they are actually lowering or settling in the z-direction. Further climatic and photogrammetric analyses are necessary in order to explore these hypotheses.

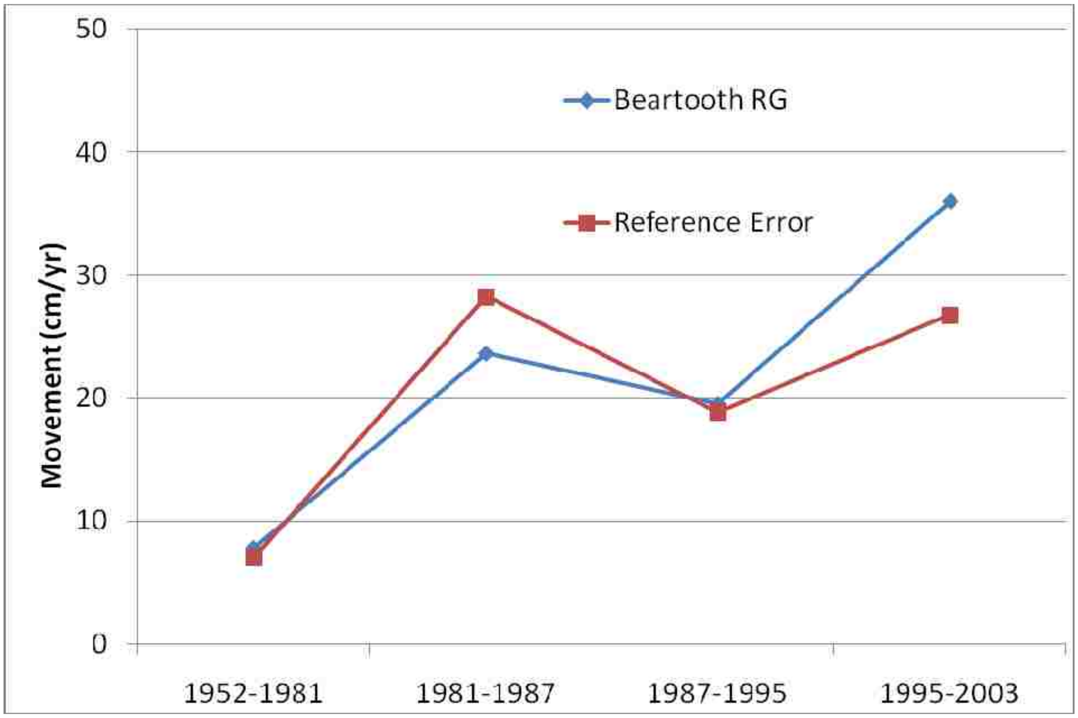

Figure 23: Surface movement of the Beartooth rock glacier (1952 - 2003).

4.3.5 East Grasshopper Rock Glacier

The East Grasshopper rock glacier is one of the largest in the Beartooth Range. It has a northeast aspect and a mean elevation of 3117 m. It was classified as active due to the steepness and instability of its frontal and side slopes. There was vegetation on some developed soils, but due to the size of this particular rock glacier, it is possible that some regions were inactive. Period one shows displacement rates of 4.3 cm/yr. In periods two, and four, p-values showed no difference between means and photo error was greater than rock-glacier movement. Period three, however, shows an increased rate of 8.0 cm/yr

(Figure 23). Overall, in period one total displacement equaled 125 cm over 29 years. In period three (1987-1995), a duration one quarter the length of period one, the rock glacier moved 64 cm, which is half the distance covered in period one.

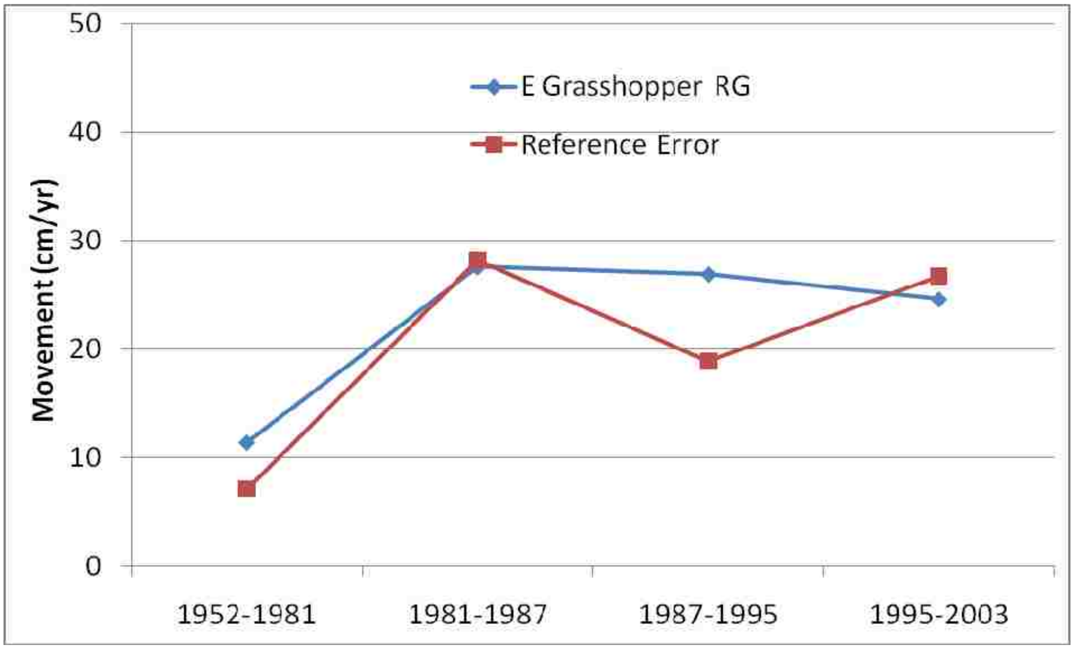

Figure 24: Surface movement of the E Grasshopper rock glacier (1952 - 2003).

4.4 Discussion and Conclusions

This study attempted to quantify the movement of four rock glaciers in the Beartooth Range using photogrammetric methods within a GIS. Statistically, error was large enough to render much of the analysis inconclusive. The Tri-lobe rock glacier is essentially inactive with no significant movement found either in the field or from air-photo analysis. In contrast, movement rates of the East Grasshopper rock glacier may have increased over time and are consistent with movement rates observed at other Rocky Mountain rock glaciers (White, 1971; Benedict et al., 1986; Potter et al., 1998).

Successive observation of the air photos does indicate potential subsidence and ‘flattening’ of the upper section of the Beartooth rock glacier. In the 1952 photo (Figure 24), the 1952 and 2005 glacier termini are labeled, respectively. GIS measurements show over 100 m of horizontal recession. Additionally, in 1952 the terminal moraine section of the rock glacier is defined by a sharp crest. Comparison with the 2005 photo (Figure 25) also shows the position of the sharp crest for 1952; however, there appears to have been some amount of subsidence and erosion because the crest is not as easily defined. This additional analysis supports the theory that apparent ‘backwards’ movement may be the result of subsidence of the rock-glacier surface, though further investigation is necessary.

With respect to the East Grasshopper rock glacier, current research shows dramatic surface thinning of its associated cirque glacier (Seifert et al., 2009). Previous research concerning basal sliding of rock glaciers suggests increased cirque glacier ablation is correlated with increased rock-glacier movement due to lubrication of sliding surfaces (Krainer and Mostler, 2000).

1952

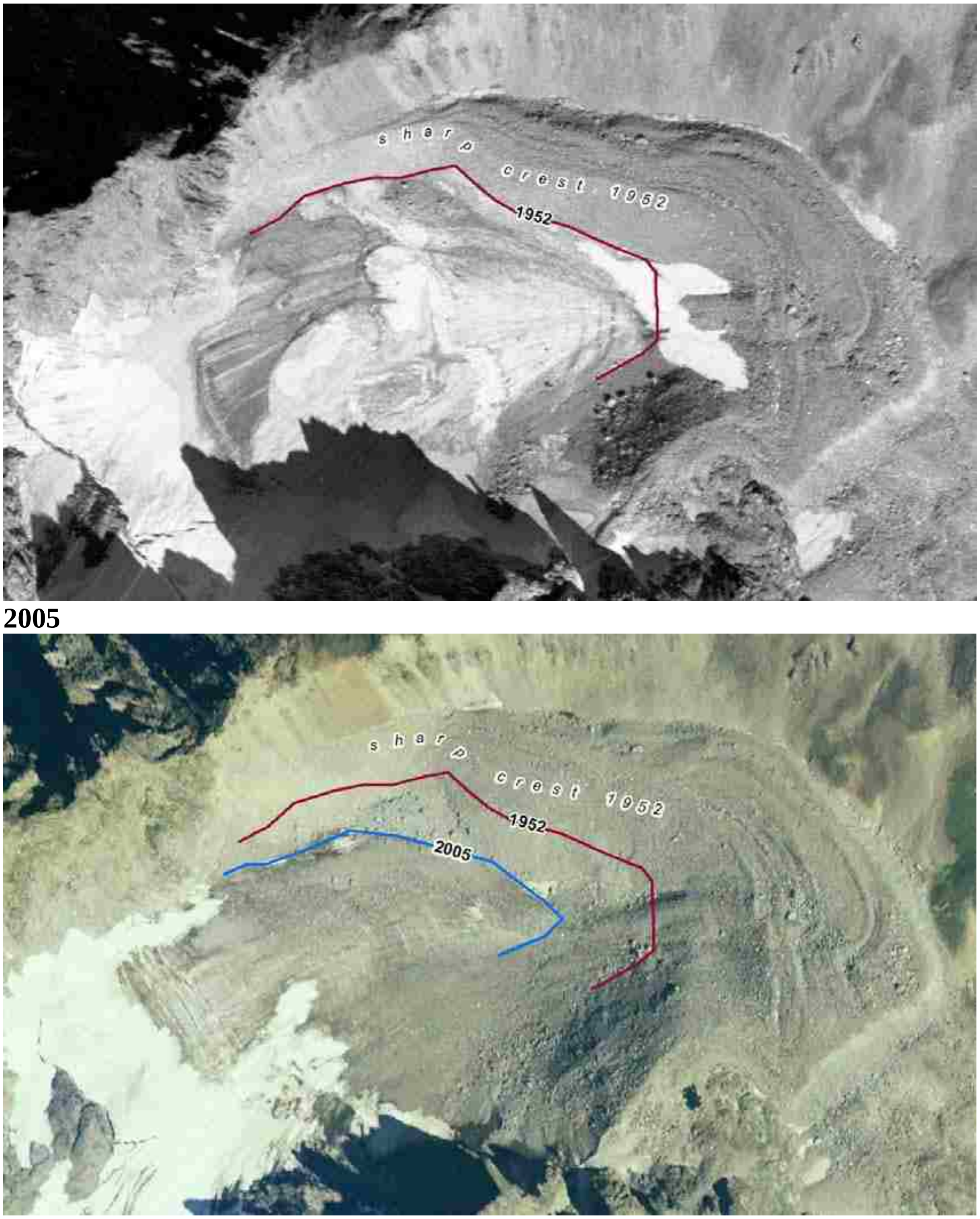

Figure 25: Aerial photos of the Beartooth rock glacier (1952 top and 2005 bottom) with the glacier terminus in 1952 shown in red and the 2005 glacier terminus in blue. Up-valley recession was from 80 – 120 m. In the 1952 photo, there is a clearly defined sharp crest on the terminal moraine that is labeled; in 2005, the crest is not as prominent.

5 CONCLUSIONS AND FUTURE RESEARCH

5.1 Conclusions

5.1.1 Distribution

Over 660 rock glaciers were mapped within the study area and then described using 11 topographic and climatic variables. Distinct differences were apparent in temperature, elevation, precipitation, insolation, and lithology between northern Absaroka and Beartooth rock glaciers. The Beartooth rock glaciers were higher in elevation and subject to more precipitation and lower temperatures. Inferences from these comparisons suggest that while Beartooth geomorphology is shifting from glacial to more periglacial, the northern Absarokas are already largely periglacial. Basic understanding of these rock glaciers is important because glacial decline is increasing due to climate warming and rock glaciers may soon become the dominate source of ice in the region, particularly in the Beartooths.

5.1.2 Activity Analysis

Of the 660 rock glaciers that were mapped, 120 were assessed for activity level. This sub-sample was used to build a binary logistic regression that 1) determined which parameters had the strongest relationship to rock-glacier activity and 2) could be used to extrapolate activity probabilities onto the larger dataset. The parameters that were most important in activity prediction were rock-glacier elevation and T_{max} (average annual maximum temperature). That T_{max} was modeled using elevation as a primary factor in interpolation essentially disqualifies it as an appropriate independent variable. In addition, by using T_{max}, it was unclear whether cold, warm or other seasonal temperature trends affect rock-glacier activity. Subsequent analysis of January and July temperatures was inconclusive in that no correlation was found between temperature data for these months and rock-glacier activity.

5.1.3 Permafrost Boundary Estimates

Predicted activity probabilities from the logistic regression were mapped and compared with previous methods to estimate past and present permafrost boundaries. Modern permafrost limits were similar to those found in the region by Harris (1986) but varied due to inclusion of logistic regression results.

5.1.4 Movement

Quantification of surface movement of four rock glaciers in the Beartooth Range through photogrammetric techniques proved to be largely inconclusive, however, some findings were reached. The South Valley rock glacier moved 7 cm/yr from 1981 – 1987. Displacement rates of the East Grasshopper rock glacier increased: from 1952 – 1981, rates were 4.3 cm/yr, and from 1987 – 1995, rates were 8.0 cm/yr. In contrast, no significant movement was observed for the Tri-Lobe rock glacier as photo error was similar to rock-glacier movement. Statistically significant movement of the Beartooth rock glacier was observed, though it appeared to be ‘backwards’ or uphill. As this methodology only quantified horizontal surface movement, apparent uphill movement could actually be subsidence.

5.2 Future Research

5.2.1 Lithology

In this study, while Beartooth lithologies were fairly uniform, differences between Absaroka rock glaciers were found that should be explored further. For example, rock glaciers off the north cirque of Martin Peak were composed of metamorphosed mafic igneous rocks (gneiss) which often produced blocky, dark surfaces with large clasts similar to Beartooth rock glaciers (Figure 25). In contrast, to the south, on the north side of Emigrant Peak, rock glaciers were dominated by volcanic QAPF rocks (basalt, andesite, dacite, rhyolite, conglomerate; Figure 26) with clasts that were lighter in color, smaller, more angular, and subsequently more tightly packed. Further research is warranted as differences in clast size and mineralogy may influence insulative properties, energy balance, and air and water flow.

Figure 26: Metamorphic rocks shown in the north cirque of Martin Peak. The rock glacier is in the mid-ground and the right bottom corner of the photo.

Figure 27: Volcanic QAPF rocks on a north gulley of Emigrant Peak. Furrows and ridges can be seen down-slope on the lower one-third of this very large rock glacier.

5.2.2 Climatic Data Analysis

Logistic regression analysis found T_{max} and elevation to be strongly related to activity classification. However, insolation contained limited predictive value. Additionally, there was no significant relationship between temperature data and estimated insolation. These variables were based upon model estimates of temperature and DEMs instead of in situ observations and thus need to be treated with caution. Verification of these data through field measurements of temperature and insolation would improve our understanding of these variables and their interaction.

Analysis of historical climate data could be useful in evaluating recent, regional climatic changes, and whether or not rock-glacier movement is related to these changes.

Analysis of site-specific climate data was outside the scope of this current study, although there are a variety of stations in the region with records that go back into the late 19th and early 20th centuries (Appendix A).

5.2.3 Hydroecology and Water Resources

Similar to glaciers, rock glaciers can act as a source of year-round water in high alpine catchments where late summer precipitation is minimal (Johnson et al., 2007). Schrott (1996) determined that rock glaciers can contribute up to 30% of river discharge during summer months, while other research has shown Andean rock glaciers to store an estimated water equivalent of 0.3 km^3 per 1000 km^2 of mountainous area (Brenning, 2005). The amount of water in rock glaciers is often difficult to estimate due to the inherent variability and difficulty in determining exact genesis and subsequent depth and distribution of ice in rock glaciers. Hence, another approach summarizes rock glacier hydrologic input more specifically by evaluating isotopic pathways in rock-glacier runoff (Williams et al., 2006).

While the effects of deglaciation receive high levels of attention, hydrologic contribution from rock glaciers is less understood, though becoming increasingly more important. Milner et al. (2009) reviews some major ecological effects of deglaciation to include changes in fluvial, solute, sediment and thermal regimes which also directly influence channel stability and habitat. Thus, future biodiversity of stream communities in cold environments can be severely affected by changes in water source contribution.

As the potential increases for rock glaciers to be the primary source of ice in Rocky Mountain alpine catchments, it may be beneficial to further understand how rock glaciers influence different morphologic regimes of streams and rivers as well as ecological communities relative to glaciers. In this way, associated changes in habitat and channel stability can be more accurately anticipated.

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APPENDIX A

Table A: Climate stations proximally located to the northern Absaroka and Beartooth ranges.

Station Name	Station Type	Elevation (ft.)	Period of Record	Temp.	Precip.	Snowfall
Livingston 12S	COOP	4870	1951-present	x	√	√
Emigrant	COOP	5000	1950-1968	x	√	√
Jardine	COOP	6450	1951-1976	√	√	√
Gardiner	COOP	5280	1956-present	√	√	√
Yellowstone Park	COOP	6240	1894-present	√	√	√
Tower Falls	COOP	6270	1948-present	√	√	√
Lamar Ranger St	COOP	6470	1922-present	√	√	√
YNP N	COOP	N/A	1946-1967	√	√	√
Cooke City 2W	COOP	7560	1967-present	√	√	√
Crandal Creek	COOP	6720	1913-present	√	√	√
Red Lodge 1NW	COOP	5580	1894-present	√	√	√
Mystic Lake	COOP	6570	1924-present	√	√	√
Nye	COOP	5030	1954-1962	√	√	√
Mcleod	COOP	5130	1951-1990	x	√	X
Cole Creek	SNOTEL	7850	1971- present	√	√	√
Burnt Mtn.	SNOTEL	5880	2001-present	√	√	√
Placer Basin	SNOTEL	8830	1980-present	√	√	√
Box Canyon	SNOTEL	6670	1979-present	√	√	√
Monument Peak	SNOTEL	8850	1980-present	√	√	√
Fisher Creek	SNOTEL	9100	1967-present	√	√	√
NE Entrance	SNOTEL	7350	1967-present	√	√	√
E Boulder Mine	SNOTEL	6335	2008-present	√	√	√
White Mill	SNOTEL	8700	1974-present	√	√	√