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Author: Janke, Jason R.

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Colorado Front Range Rock Glaciers: Distribution and Topographic Characteristics

Jason R. Janke

Department of Earth & Atmospheric Sciences, Metropolitan State College of Denver, Campus Box 22, P.O. Box 173362, Denver, CO 80217-3362, U.S.A.
jjanke1@mscd.edu

Abstract

In the Colorado Front Range, rock glacier distribution has been noted on U.S. Geological Survey maps and in several publications; however, a comprehensive account of distribution is not available. When analyzed in a Geographic Information System (GIS), Digital Elevation Model variables (elevation, slope, or aspect) could reveal unique topographic characteristics of rock glaciers. The objectives of this study are to provide an accurate, complete account of rock glacier locations in a digital format, to compare topographic variables of rock glacier form and activity classes, and to evaluate glacier and rock glacier topographic information. Rock glacier locations were obtained from previous studies and were re-digitized on high-resolution digital orthophotos. Glacier distribution was determined through classification of a satellite image. Topographic information for rock glacier form and activity classes as well as for glaciers was obtained through zonal overlay in a GIS. Results indicate that tongue-shaped rock glaciers occur at higher elevations, have more northerly aspects, and have gentler slopes compared to lobate rock glaciers. Active, inactive, and fossil forms showed typical elevation and aspect gradients. Active rock glaciers are found at the highest elevations and most northern aspects. Inactive rock glaciers are found at lower elevations on all aspects with a tendency to face northeast, and fossil rock glaciers occur at the lowest elevations on all aspects. Topographic variables for all rock glaciers were statistically different compared to glacier locations; however, active tongue-shaped rock glaciers had similar topographic variables compared to glaciers, but lobate forms showed a significant difference. In the Front Range, active tongue-shaped rock glaciers are developed by glacial processes and active lobate forms are the product of periglacial processes.

Introduction

Rock glaciers, an important landform associated with the coarse debris system of alpine hillslopes, are found in major mountain regions of the world, with a significant percentage in mid-latitude chains with continental climates (Wahrhaftig and Cox, 1959; Birman, 1964; Potter, 1972; Jeannerret, 1975; Barsch and Treter, 1976; White, 1979; Höllermann, 1983; Calkin et al., 1987; Buchenauer, 1990; Lieb, 1991; Schrott, 1991; Schröder, 1992; Barsch, 1996). In the Front Range of the Rocky Mountains of Colorado, a continental climate (mean annual air temperature [MAAT] of −3.5°C and annual precipitation of 938 mm at 3739 m a.s.l.) favors rock glacier development (Losleben, 2004). Early rock glacier studies in the Front Range were descriptive and examined morphology (Ives, 1940; Outcalt and Benedict, 1965; Outcalt and MacPhail, 1965; Carroll, 1974). Later studies investigated motion on Arapaho, Taylor, and Fair rock glaciers and provided detailed maps (White, 1971, 1975, 1987; Benedict et al., 1986). White (1976) mapped the distribution of major tongue-shaped rock glaciers, and Wallace (1967) monitored motion and mapped several lobate rock glaciers in the valleys surrounding Niwot Ridge. Harbor (1984) provided rock glacier locations for the Blue Lake and Green Lake Valleys. U.S. Geological Survey (USGS) print maps have also displayed some rock glaciers in the Front Range. Braddock and Cole (1990) produced a geologic map of Rocky Mountain National Park at 1:50,000. Gable and Madole (1976) produced a geologic map of the Ward Quadrangle at 1:24,000 that included rock glaciers. However, a comprehensive digital database containing rock glacier locations is not available for the region (Fig. 1)

Topographic variables such as elevation, slope, and aspect have been shown to influence snow accumulation, freeze-thaw processes, and landform locations (Madole, 1972). Humlum (1998) has argued that rock glaciers and glaciers in Greenland share a similar regional climate; thus, a localized high supply of talus produced in topography with a low radiation budget produce rock glaciers. Sloan (1998) attempted to model sites of cirque rock glacier initiation using elevation, slope, aspect, curvature, and bedrock in the Selwyn Mountains of Canada and found that elevation exerted the most control, but the model was more successful at identifying areas where rock glaciers were not located. Morris (1981) used elevation, aspect, and bedrock jointing to explain differences in rock glaciers in the Blanca Massif section of the Sangre de Cristo Mountains of Colorado. Topographic characteristics of Front Range rock glaciers have not been examined.

Glacially derived or ice-cored rock glaciers form when debris from a rockfall covers a glacier, or when a glacier experiences excessive ablation during a stagnant period, allowing moraine or rock debris to melt out and occupy the surface (Wahrhaftig and Cox, 1959; Outcalt and Benedict, 1965; Potter, 1972; Whalley, 1974, Benedict, 1973; White, 1976; Ackert, 1998; Potter et al., 1998). In contrast, periglacial or ice-cemented rock glaciers

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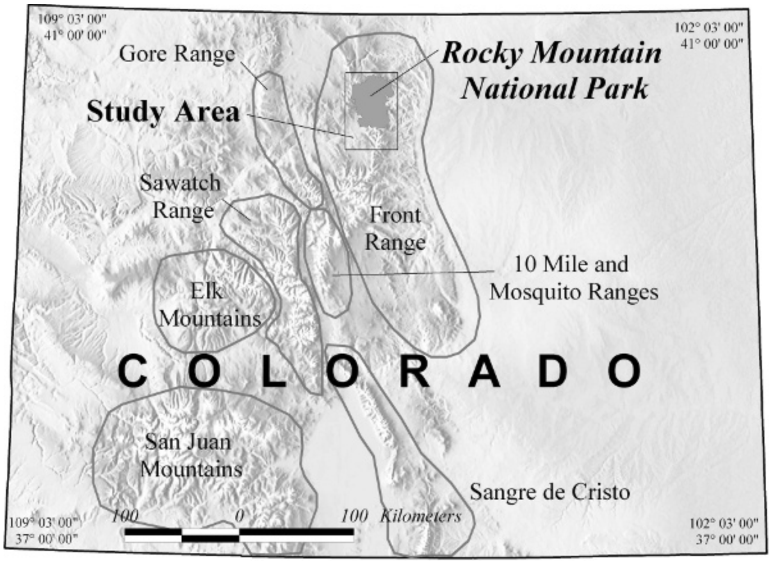

FIGURE 1. Location of the study area.

develop internal ice through refreezing of melting snow on an existing rockfall deposit or on a talus slope (Haeberli, 1985; Barsch 1987). Glacial and periglacial rock glaciers could have unique topographic variables that are connected to their origin.

The relationship between topographic and rock glacier variables (form and activity classes) has not been examined in the Colorado Front Range. When examined in a Geographic Information System (GIS), Digital Elevation Model (DEM) variables (mean, maximum, minimum elevation, slope, and aspect) could establish unique rock glacier characteristics. Topographic factors that control shading and create cold temperatures may help explain rock glacier form and activity. The objectives of this research are threefold: (1) create for analysis a digital database of rock glaciers in the Front Range of Colorado in a GIS; (2) examine different topographic parameters for rock glacier form and activity classes; and (3) attempt to distinguish topographic variables of rock glaciers from glaciers.

Study Area

Located in the Front Range of Colorado, the study area (2710 km^2) encompasses Rocky Mountain National Park (Fig. 1). The park overlaps the Continental Divide and is bounded by the Never Summer and Mummy Ranges (Elias, 1995). The study area also includes the Indian Peaks Wilderness, running from South Arapaho Peak to Sawtooth Mountain, located south of the park. There are over 60 rugged, glaciated peaks that rise above 3350 m in the study area. Longs Peak, the highest point, stands at an elevation of 4345 m. In the Indian Peaks region, gently sloping periglacial interfluves usually extend east to west with Niwot Ridge being one of the most extensive (Ives and Fahey, 1971).

Methods

ROCK GLACIERS

A digital version of the geologic map produced by Braddock and Cole (1990) was obtained. Because several positional and attribute errors were created when the paper map was converted into a digital vector format, it served only as a reference from which a more detailed distribution would be obtained. Rock glaciers were identified on the Braddock and Cole (1990) map and a more detailed extent was re-digitized on USGS 1-m-resolution Digital Orthophoto Quadrangles (DOQs) at a common scale of 1:5000. Locations from the Ward Quadrangle were added using a tablet digitizer, and the precision and accuracy were later improved utilizing the orthophotos (Gable and Madole, 1976). For other locations, those noted in previous studies were added by on-screen digitizing. It is likely that many more small rock glaciers that were not clearly identifiable on the DOQs due to poor image contrast exist in the study area; the current estimate is conservative.

Activity status was determined through field verification, photogrammetric and field survey motion studies, and interpretation of aerial photographs (White, 1971; Janke, 2005a, 2005b). Rock glaciers were categorized into three activity types: (1) active, (2) inactive, and (3) fossil or relict (Whalley and Martin, 1992; Barsch, 1996). Although this classification scheme neglects other processes that operate on all rock glaciers, it is still commonly used in the literature (Giardino and Vitek, 1988). Active rock glaciers contain deforming ice, have a steep front slope, and have pronounced ridges and furrows. Inactive rock glaciers may also contain ice and are believed to have ceased moving. Their surface topography is often more subdued compared to active rock glaciers. Inactive rock glaciers have a gentler frontal slope, and the transition from the rock glacier surface to frontal slope is often more rounded compared to the sharp junction angle of active rock glaciers (Birkeland, 1973). Fossil rock glaciers likely contain no ice and are not moving. Geophysical methods were not used to test for ice presence; instead, vegetation cover was used to distinguish inactive and fossil forms. Fossil rock glacier surfaces contained greater than 75% vegetation cover on aerial photographs (Whalley and Martin, 1992; Barsch, 1996).

There are two major groups of rock glacier forms: tongue-shaped and lobate. Tongue-shaped rock glaciers have a longer length compared to width because they are confined by cirque or valley walls, whereas lobate rock glaciers have a shorter length compared to width because valley sides or walls contribute to their growth (Outcalt and Benedict, 1965). As a secondary indicator, transverse (perpendicular to flow and most widespread on tongue-shaped rock glaciers) and longitudinal (parallel to flow and often found on lobate rock glaciers) ridges were inspected to differentiate between forms (Fig. 2) (Wahrhaftig and Cox, 1959). After examining the dominant flow direction, surrounding topography, and ridge and furrow structure, measurements of width and length were taken, and each rock glacier was placed in the appropriate form class.

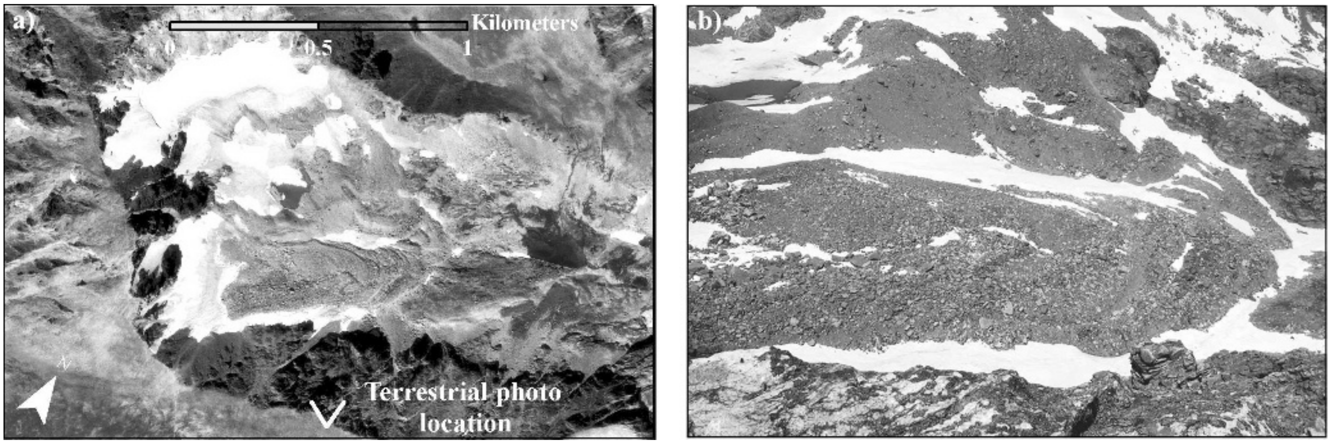

FIGURE 2. Arapaho rock glacier (tongue-shaped and active) located in the Colorado Front Range. (a) Shown in an aerial photograph (9/13/1999). (b) Shown in a terrestrial photo (7/11/2003).

GLACIERS

Glacier distribution was determined utilizing a minimum distance supervised classification of an Enhanced Thematic Mapper Plus (ETM+) image from 10 August 2002 in the Environment for Visualizing Images (ENVI 3.4) software. Low snow totals at high elevations and a dry summer during 2002 exposed glacial ice by melting most snow and firn. Therefore, glacial extent could easily be identified because snow and firn often overlay a glacial surface and compound spectral signatures. An overall classification accuracy of 87% was determined by comparing random points obtained from aerial photographs known to contain glaciers with the classified result. GIS glacier polygons were available; however, they were compiled from a variety sources, were generalized, and contained some positional errors due to different projections. The ETM+ image classification was utilized in this study because it was considered a more reliable data source compared to the GIS glacier data.

ZONAL STATISTICS AND SIGNIFICANT TESTS

In ArcGIS 9.0, USGS DEMs with a 10-m resolution were merged, and then slope and aspect were calculated. Rock glacier and glacier polygons were overlaid on the raster data, and zonal statistics utilizing the elevation and slope data were derived for each feature. Minimum, maximum, and mean values were calculated for cells that intersected each polygon. To compare means, *t*-tests were then run at the 95% confidence level. Mean aspect was calculated by interpretation of the aspect grid and manual derivation of a mean orientation. The orientation values were converted to vectors, and a mean direction, analogous to the mean value of a scalar set, was calculated. A set of significant tests designed for circular data were then run on the aspect data (Davis, 1986; Mardia and Jupp, 2000).

Results

ROCK GLACIER FORM AND ACTIVITY CLASSES

A total of 220 rock glaciers were identified in the study area. The majority of rock glaciers are lobate (170); 28 are active, 107 are inactive, and 85 are fossil (Fig. 3). Approximately 6.5% of lobate rock glaciers are active, 50.6% are inactive, and 42.9% are fossil, while 34.0% of tongue-shaped rock glaciers are active, 42.0% are inactive, and 24.0% are fossil. Although their average size is 2.5 times less than that of a tongue-shaped rock glaciers, lobate rock glaciers cover more area (42%) than tongue-shaped rock glaciers because they outnumber tongue-shaped forms. Tongue-shaped rock glaciers are found at slightly higher elevations, more northerly aspects, and gentler slopes compared with lobate rock glaciers (Table 1; Fig. 4). Each variable is significantly different at the 95% confidence level (Table 2).

Active rock glaciers occur at the highest elevations and have a north-northeast aspect; inactive rock glaciers are found at lower elevations on all aspects, with a tendency to face northeast; fossil rock glaciers occur at the lowest elevations and have the widest range of aspects (Table 3; Fig. 4). *T*-tests revealed that mean elevation is significantly different for each of the three classes. Active and inactive rock glaciers show similar aspects, but when comparing other activity classes, significantly different aspects are obtained. Rock glacier slope showed no significant difference for the three activity classes (Table 2).

ROCK GLACIERS VERSUS GLACIERS

Glaciers are located about 200 m higher and on more northerly slopes compared to rock glaciers (Table 4; Figs. 3 and 4). Rock glaciers occupy a larger area (19.93 km^2) compared to glaciers (1.55 km^2). At the 95% confidence level, mean elevation, aspect, and slope are all significantly different for all rock glaciers versus glaciers (Table 5).

In order to determine if active rock glaciers are related to glaciers, another set of statistical tests was run isolating unique form and activity classes (Table 5). When comparing all active rock glaciers versus glaciers, different elevations and slopes, but similar aspects, were obtained. Glaciers and active tongue-shaped rock glaciers showed similar elevations and aspects, whereas active lobate rock glaciers and glaciers displayed different aspects and elevations.

Discussion

GENERAL ROCK GLACIER ELEVATION AND ASPECT TRENDS

Along a latitudinal transect in North America, rock glaciers are found at increasing elevations from north to south. Active rock glaciers exist at 990 m in the Brooks Range, 1070 m in the Alaska Range, and 2125 m in Jasper National Park (Wahrhaftig and Cox, 1959; Luckman and Crocket, 1978; Calkin et al., 1987).

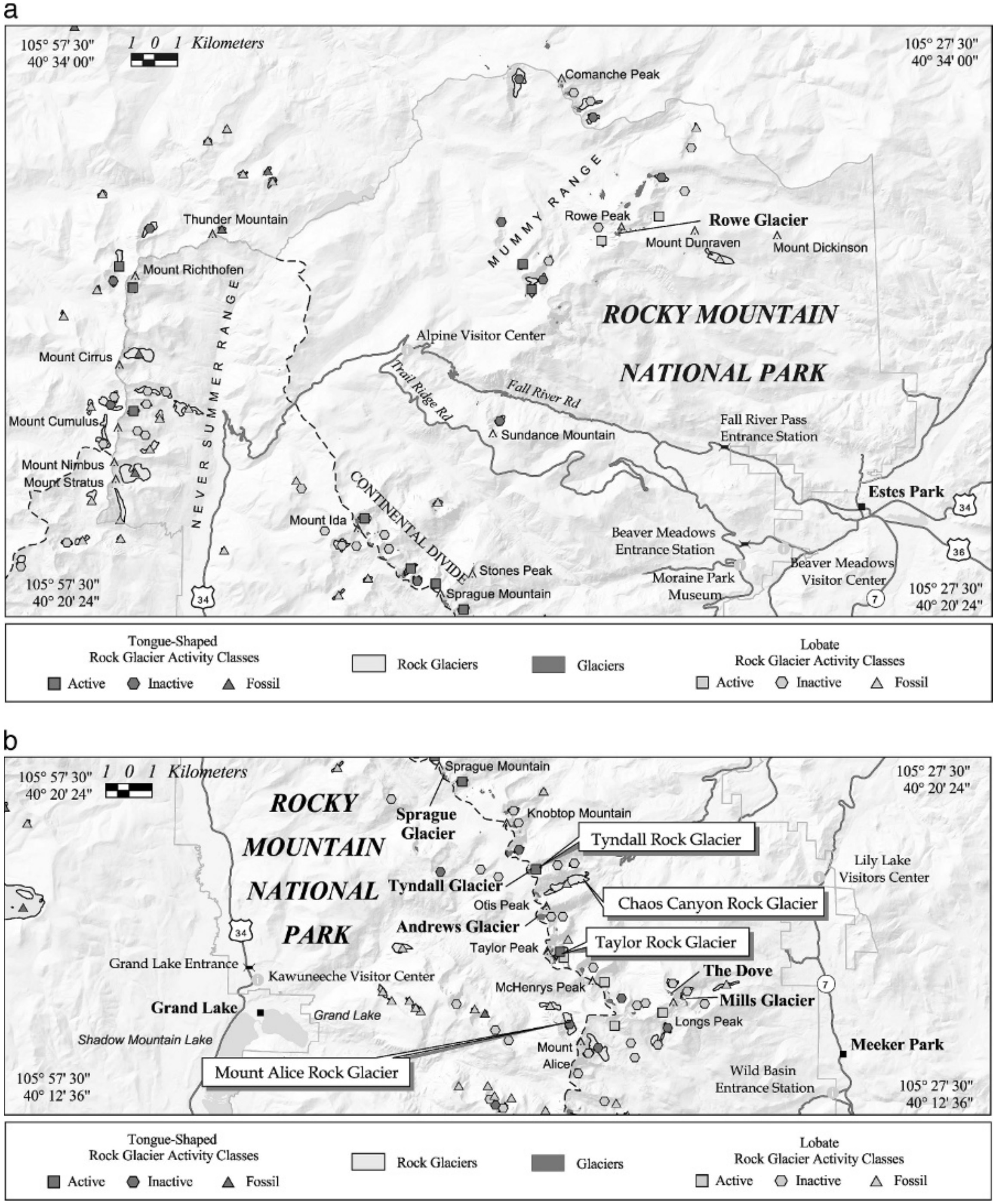

FIGURE 3. (a) Distribution of lobate, tongue-shaped, active, inactive, and fossil rock glaciers as well as glaciers in northern portion of the study area. (b) Distribution of lobate, tongue-shaped, active, inactive, and fossil rock glaciers as well as glaciers in central portion of the study area. See Figure 3c on following page.

Farther south, Galena Creek rock glacier occurs at 2700 m in the Absaroka Mountains of Wyoming, whereas in the San Juan Mountains, rock glaciers extend down to 3697 m (Potter, 1972; White, 1979). White (1971) showed that three active rock glaciers in the Front Range extend to 3330 m. According to a larger inventory in this study, active rock glaciers in the Front Range extend as low as 3526 ± 125 m.

When considering aspect, active rock glaciers have been shown to exist mainly on slopes facing the poles. In the Austrian and Swiss Alps, the preferred orientation of active rock glaciers is mainly in the northwest to northeast quadrant, whereas in the Southern Alps of New Zealand, the dominant orientation is south to south-southeast (Jeanneret, 1975; Buchenauer, 1990; Barsch, 1996). In the east-central Brooks Range, active rock glaciers had a preferred northerly orientation (Ellis and Calkin, 1979), and active rock glaciers in the Mount Sopris region in the Elk Mountains of Colorado are mainly facing north (Birkeland, 1973). Active Front Range rock glaciers demonstrate the same poleward trend with a dominant north-northeast orientation (Fig. 4).

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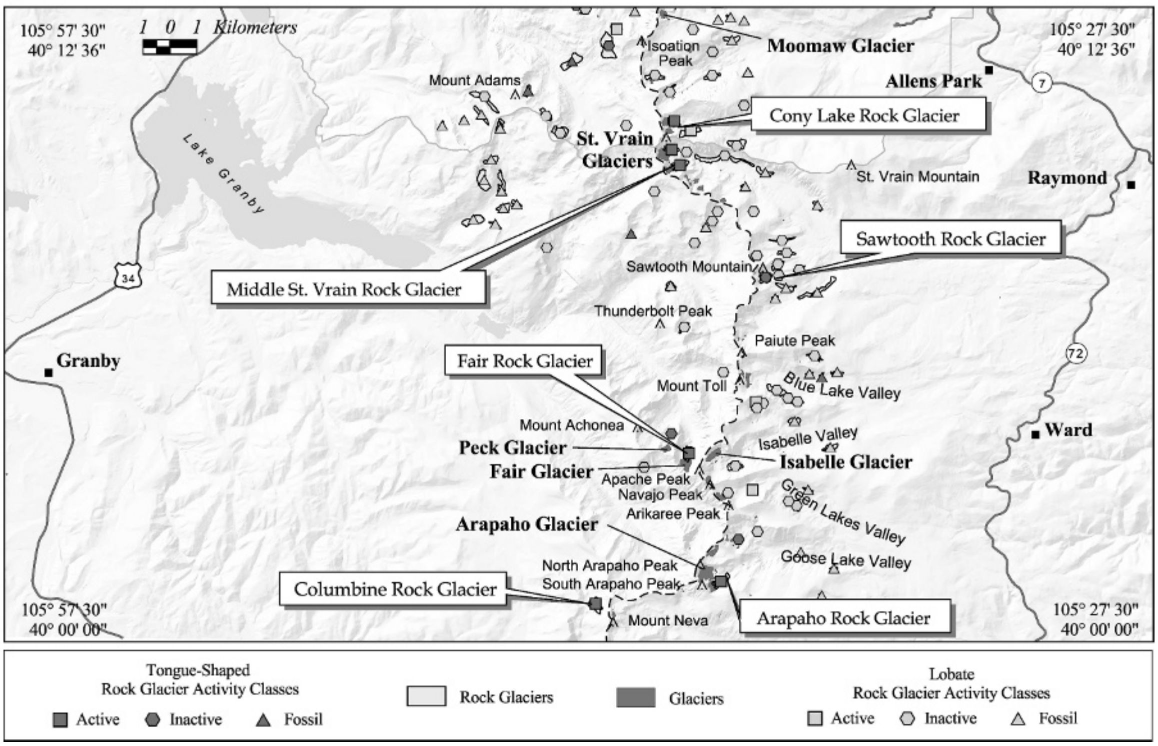

FIGURE 3c. Distribution of lobate, tongue-shaped, active, inactive, and fossil rock glaciers as well as glaciers in southern portion of the study area.

ACTIVE, INACTIVE, AND FOSSIL ROCK GLACIER COMPARISON

Active and inactive rock glacier categories show some overlap in elevation on the polar diagrams (Figs. 4 and 5), a common occurrence elsewhere (White, 1979; Sollid and Sörbel, 1992). A lack of a clear distinction is due to factors that are not represented by the topographic variables. This suggests that elevation and aspect must be coupled with other external variables such as debris supply, available meltwater, and climate to predict rock glacier activity. Debris supply is critical for rock glacier development. Without sufficient delivery, rock glaciers slowly become inactive as they creep away from their debris source. In a GIS environment, curvature and slope of contributing areas as well as relief of headwalls could be used to model rock accumulation. The type of supplied headwall rock can affect rock glacier size and activity. Matsuoka and Ikeda (2001) found that smaller rock glaciers are produced from materials that weather into fine pebbles, whereas larger rock glaciers have coarse boulders. Since pebbly rock glaciers are limited in their extent, their activity must also be restricted by rock type and size. Dominant geology of contributing areas could be classified on multispectral remote sensing imagery and then later be weighted to account for degrees of weathering or texture algorithms processed on digital imagery in order to classify surface rock size and then later be compared to activity. Without sufficient meltwater, periglacial rock glaciers may not be able to maintain an internal ice-cemented structure. Convexity or concavity of the landscape could be utilized in existing hydrologic models in an attempt to model flow accumulation. If sufficient accumulation is not met, a rock glacier may become inactive. A temporal dimension would also help differentiate activity classes as changes in precipitation and temperature will alter rock glacier activity. Climatic conditions during the Holocene could be estimated using existing permafrost predication models in an attempt to understand activity variation (Janke, 2005c). Similar techniques are being utilized in an attempt to model rock glacier locations and flow in the Swiss Alps (Frauenfelder, 2005).

Active and inactive rock glaciers extend to lower elevations on north-facing slopes (315° to 45°) compared to south-facing slopes (135° to 225°) (Fig. 5); the same relationship exists in other portions of the world (Barsch, 1996). In theory, active rock

TABLE 1

Summary statistics calculated for all lobate and tongue-shaped rock glaciers. Mean elevation and slope are provided as well as standard deviation in parentheses. For aspect, the mean direction of vectors is given along with the circular variance in parentheses.

	Lobate			Tongue		
	Elevation (m)	Slope (°)	Aspect (°)	Elevation (m)	Slope (°)	Aspect (°)
Average minimum	3346.4 (±177.1)	7.2 (±5.4)	—	3397.6 (±129.8)	3.6 (±3.9)	—
Average maximum	3459.7 (±165.2)	42.2 (±11.2)	—	3566.5 (±114.7)	42.2 (±8.5)	—
Mean	3399.1 (±167.6)	21.6 (±6.7)	78.1 (0.51)	3474.0 (±115.2)	18.5 (±4.6)	48.5 (0.19)
Total area	11,684,100 m^2 (1168.41 ha)			8,242,700 m^2 (824.27 ha)		
Average size	68,328 m^2 (6.83 ha)			171,723 m^2 (17.17 ha)		

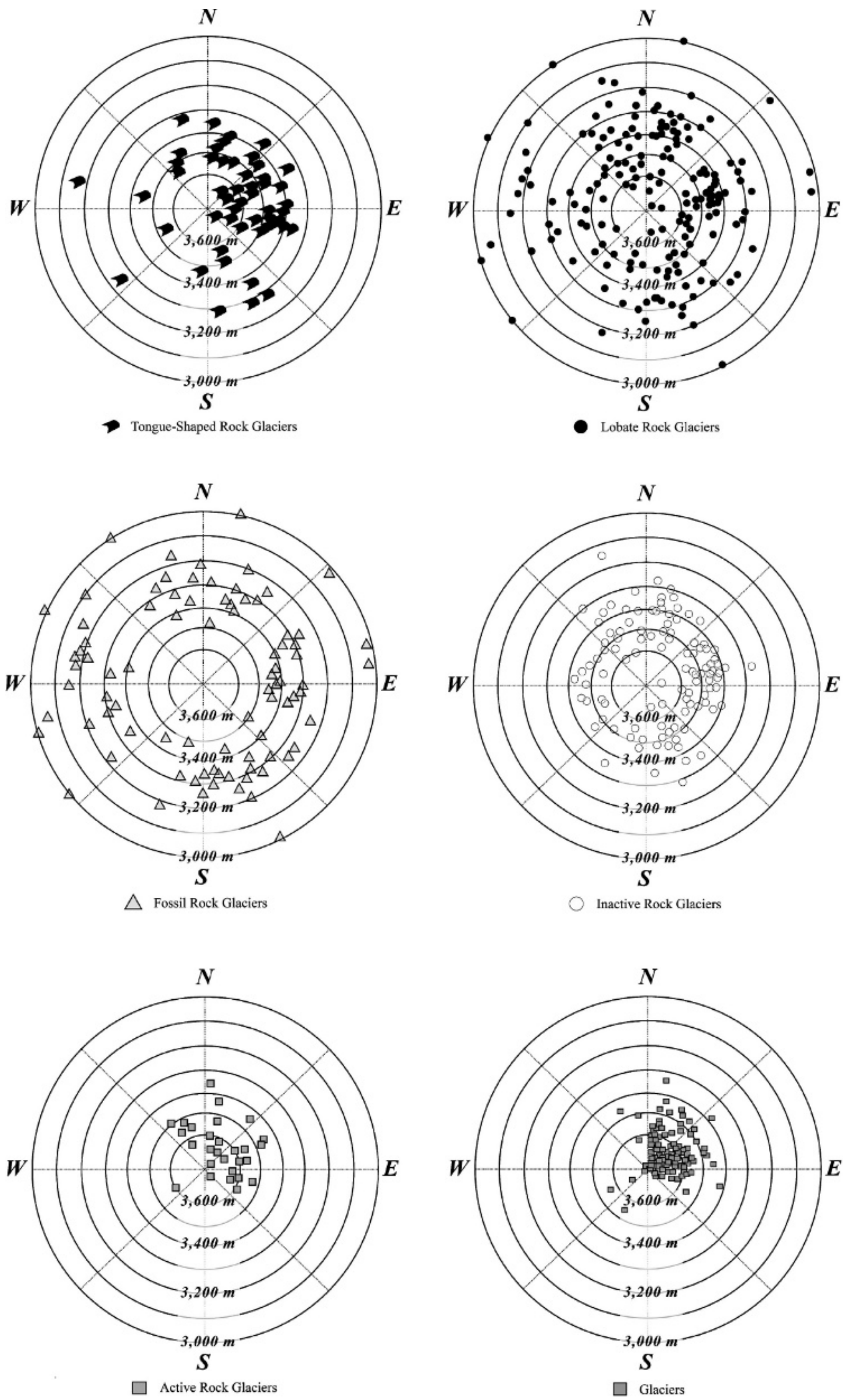

FIGURE 4. Polar diagrams comparing aspect and elevation for rock glacier forms and activity classes as well as glaciers.

glaciers should have a northern orientation; however, in the Front Range, a dominant north-northeast orientation exists. This is likely due to extensive cirque development on the eastern side of the Continental Divide in which rock glaciers subsequently occupied the valleys carved out by glaciers. Fossil rock glaciers display a unique trend that does not fit with the observed pattern of active and inactive rock glaciers (Fig. 5). On eastern slopes, fossil rock glaciers exist at higher elevations, but they occur at lower elevations on western slopes (Fig. 5). Perhaps this is explained by the fact that glaciation was more extensive and valleys were more deeply incised on the western side of the divide (Elias, 1995; Brocklehurst and Whipple, 2002). Given their lower elevation and densely vegetated surface, some Front Range fossil rock glaciers would likely be classified as debris covered glaciers that formed at the base of stagnant Wisconsin glaciers (Ackert, 1998).

TABLE 2

Statistical test results comparing rock glacier form and activity status.

	Lobate vs. tongue-shaped rock glaciers	Active vs. inactive rock glaciers	Active vs. fossil rock glaciers	Inactive vs. fossil rock glaciers
Area (m^2)				
t	2.39	0.38	0.86	1.11
t critical 2-tailed ($\alpha = 0.05$)	2.01	2.01	1.98	1.98
Probability	0.02	0.70	0.39	0.27
Elevation (m)				
t	3.57	4.71	11.24	10.55
t critical 2-tailed ($\alpha = 0.05$)	1.98	2.04	2.02	1.98
Probability	0.00	0.00	0.00	0.00
Aspect (°)				
F	3.90	1.38	4.26	2.31
F critical 2-tailed ($\alpha = 0.05$)	2.74	2.01	2.11	1.82
Probability	0.01	0.18	0.00	0.02
Slope (°)				
t	3.64	0.33	0.15	0.29
t critical 2-tailed ($\alpha = 0.05$)	1.98	2.04	2.03	1.97
Probability	0.00	0.74	0.88	0.78

LOBATE VERSUS TONGUE-SHAPED FORMS

In the Blanca Massif of the Sangre de Cristo Mountains, inspection of polar diagrams reveals a dominant northern orientation for both lobate and tongue-shaped forms (Morris, 1981). In the San Juan Mountains, White (1979) found no significant difference in altitude, slope, or aspect for lobate and tongue-shaped rock glaciers. Lobate rock glacier elevations in the San Juan Mountains also had low variance compared to tongue-shaped rock glaciers because lobate rock glaciers do not extend great distances down valley floors. Aspect for San Juan lobate and tongue-shaped rock glaciers was more northerly compared to the Front Range. In the Front Range, tongue-shaped rock glaciers have a northeast (48.5°) aspect, whereas lobate forms have an east-northeast (78.1°) orientation. A significant difference between Front Range rock glacier form classes exists for elevation, slope, and aspect. This suggests that radiation parameters may play an important role for tongue-shaped and lobate rock glacier locations in the Front Range compared to the San Juan Mountains. In the San Juan Mountains, weathering of igneous rocks (as opposed to weathering of metamorphic rocks) and greater snowfall accumulation may help explain the form variation. Front Range tongue-shaped rock glaciers also showed a 50-m greater range between average minimum and average maximum elevations because they extend greater distances down cirque floors. Front Range tongue-shaped and lobate rock glaciers also had slightly greater but similar slopes compared to San Juan rock glaciers, providing a unifying criterion to improve spectral rock glacier detection models (Janke, 2001).

ROCK GLACIERS VERSUS GLACIERS ANALYSIS

Since glaciers are located higher than rock glaciers, these findings support the fact that cooler temperatures, higher snow accumulation, and a lower production of talus is needed for glaciers, while rock glaciers may exist at lower elevations under a variety of aspects because they have a protective layer of debris insulating an internal ice structure. Rock glaciers have a lower mean slope than glaciers because remaining glacier surfaces are found clinging to shaded, steeper slopes.

The aforementioned analysis of rock glacier topographic variables indicated that active tongue-shaped rock glaciers have statistically similar elevations and aspects compared to glaciers, suggesting that most active tongue-shaped Front Range rock glaciers are glacially derived. Active lobate rock glaciers have different elevations and aspects compared to glaciers, indicating

TABLE 3

Active, inactive, and fossil rock glacier topographic information.

	Active rock glacier		
	Elevation (m)	Slope (°)	Aspect (°)
Average minimum	3525.8 (±125.1)	6.2 (±6.4)	—
Average maximum	3668.0 (±93.9)	42.8 (±9.1)	—
Mean	3594.7 (±109.6)	20.6 (±6.4)	48.5 (0.87)
Total area	1,938,400 m^2 (193.84 ha)		
Average size	84,278 m^2 (8.43 ha)		
	Inactive rock glacier		
	Elevation (m)	Slope (°)	Aspect (°)
Average minimum	3424.3 (±110.5)	5.7 (±4.8)	—
Average maximum	3541.9 (±111.3)	43.5 (±10.9)	—
Mean	3477.1 (±105.2)	21.0 (±6.5)	56.4 (0.68)
Total area	8,685,700 m^2 (868.57 ha)		
Average size	78,961 m^2 (7.89 ha)		
	Fossil rock glacier		
	Elevation (m)	Slope (°)	Aspect (°)
Average minimum	3227.4 (±151.4)	7.4 (±5.5)	—
Average maximum	3358.5 (±138.7)	40.3 (±10.4)	—
Mean	3288.7 (±137.1)	20.8 (±6.4)	273.1 (0.44)
Total area	9,302,700 m^2 (930.27 ha)		
Average size	108,171 m^2 (10.81 ha)		

TABLE 4

Elevation, aspect, and slope data for glaciers and rock glaciers.

	Glaciers			Rock glaciers		
	Elevation (m)	Slope (°)	Aspect (°)	Elevation (m)	Slope (°)	Aspect (°)
Average minimum	3624.0 (±168.3)	18.6 (±11.7)	—	3359.3 (±168.5)	6.7 (±5.5)	—
Average maximum	3684.3 (±180.7)	43.9 (±17.1)	—	3482.3 (±160.8)	41.9 (±10.6)	—
Mean	3651.6 (±170.8)	30.7 (±12.3)	48.8 (0.24)	3416.3 (±160.2)	21.0 (±6.6)	70.5 (0.74)
Total area	1,555,200 m^2 (155.52 ha)			19,926,800 m^2 (1,992.68 ha)		

that active lobate rock glaciers are more likely a product of periglacial processes. These findings support the photo-interpretation of Outcalt and Benedict (1965), who found that "cirque-floor" rock glaciers originate as debris covered tongues of glaciers, and "valley-walled" rock glaciers contain interstitial ice from buried snow beneath rockfall debris.

Similar observations have been reported in the Swiss Alps (Lieb, 1991; Krainer, personal communication, 2005). In the Selwyn Mountains, Sloan (1998) found that active cirque-floor rock glaciers were likely to contain late Wisconsin glacier ice because they predated Little Ice Age moraines. Valley-walled rock glaciers were found lower than Little Ice Age moraines and were unlikely to contain glacially derived ice.

Rock glaciers are transitional landforms that are derived and are currently affected by both periglacial and glacial processes (Giardino and Vitek, 1988). For example, field evidence indicates that Arapaho rock glacier has experienced both glacial and periglacial processes. The rock glacier contains both interstitial ice, indicated by tightly frozen sands and muds near the toe, and an ice core with thickness ranging from 1 to 9.8 m near the rock glacier head (White, 1971; Benedict, 1973). High production of cirque headwall talus in the Mount Sopris region could produce an ice-cemented structure capable of producing flow (Birkeland, 1973). Stagnant glacial ice could also be "regenerated" by periglacial processes as melting snow and internal ice percolates and refreezes on an existing internal ice structure down-glacier. Some Mount Sopris rock glaciers have tilted trees on the surface, indicating reactivation possibly due to this process or from warmer temperatures that induced temperate ice-flow conditions (Birkeland, 1973). Considering the statistical analysis and close proximity to modern glaciers, it is likely; however, that active tongue-shaped Front Range rock glaciers and glaciers are strongly interconnected.

TABLE 5

Statistical test results comparing glaciers with rock glaciers.

	Glaciers vs. all rock glaciers	Glaciers vs. all active rock glaciers	Glaciers vs. active tongue-shaped rock glaciers	Glaciers vs. active lobate rock glaciers
Area (m^2)				
t	7.34	6.51	9.37	2.69
t critical 2-tailed ($\alpha = 0.05$)	1.97	2.07	2.13	2.31
Probability	0.00	0.00	0.00	0.03
Elevation (m)				
t	13.24	2.12	0.31	3.06
t critical 2-tailed ($\alpha = 0.05$)	1.96	1.68	1.81	1.71
Probability	0.00	0.04	0.77	0.00
Aspect (°)				
F	8.36	0.88	0.65	2.44
F critical 2-tailed ($\alpha = 0.05$)	3.84	2.03	2.06	2.18
Probability	0.00	0.56	0.52	0.03
Slope (°)				
t	8.49	5.95	1.66	10.10
t critical 2-tailed ($\alpha = 0.05$)	1.97	2.00	2.26	1.98
Probability	0.00	0.00	0.13	0.00

Conclusions

Valuable topographic information can be easily obtained by integration of data sources within a GIS. Through a detailed analysis of rock glacier form and activity, it was determined that tongue-shaped rock glaciers are found at higher elevations and slopes that are more northern compared with lobate rock glaciers. Active, inactive, and fossil forms showed typical elevation and aspect gradients. Active rock glaciers are found at the highest elevations and most northern aspects. Inactive rock glaciers are found at lower elevations on all aspects with a tendency to face northeast, and fossil rock glaciers occur at the lowest elevations on all aspects.

The analysis of all Front Range rock glaciers versus glaciers revealed that some unique elevations, slopes, and aspects exist for each landform. Glaciers are mostly smaller, are found at higher elevations, and are restricted to more northern and northeastern slopes. Because these remaining small ice masses are mostly attached to steep cirque walls, their slope is usually steeper than the blocky accumulations of a rock glacier. Rock glaciers are larger, more abundant, and many are believed to contain ice, thus they could provide a small source of water in a future warmer, drier climate.

Active tongue-shaped rock glaciers have elevations and aspects similar to glaciers, but active lobate forms have different elevations and aspects. This relationship suggests that most tongue-shaped Front Range rock glaciers are glacially derived. The ice in temperate Rocky Mountain glaciers is rarely older than 300 years (Little Ice Age); however, because rock glaciers have an insulated debris layer, rock glacier ice is likely to be much older (Clark et al., 1996; Birkeland, 1973). As a result, ice cores from tongue-shaped rock glaciers may provide a record of climatic change through a good portion of the Holocene.

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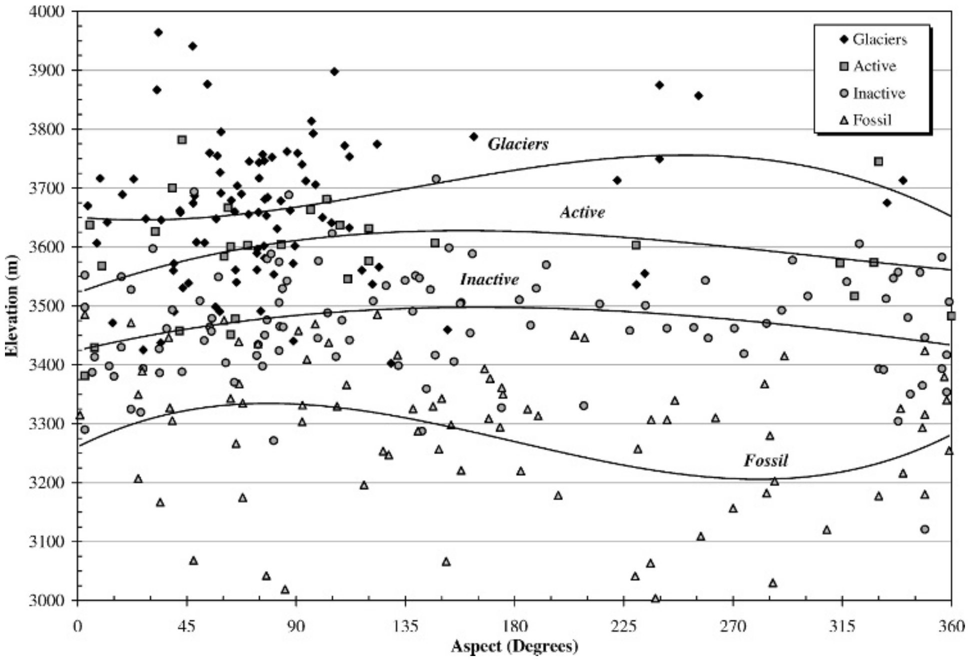

FIGURE 5. Scatterplot of elevation versus aspect for active, inactive, and fossil rock glaciers and glaciers. Trendlines are 3rd order best-of-fit polynomials.

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References Cited

Ackert, R., 1998: A rock glacier/debris-covered glacier system at Galena Creek, Absaroka Mountains, Wyoming. *Geografiska Annaler Series A–Physical Geography*, 80A(3–4): 267–276.

Barsch, D., 1987: The problem of the ice-cored rock glacier. *In* Giardino, J. R., Shroder, J. F., and Vitek, J. D. (eds.), *Rock glaciers*. London: Allen and Unwin, 45–53.

Barsch, D., 1996: *Rock glaciers: indicators for the present and former geoecology in high mountain environments*. Berlin: Springer-Verlag.

Barsch, D., and Treter, U., 1976: Zür verbreitung von periglazialphänomenen in Rondane/Norwegen. *Geografiska Annaler*, 58A: 83–93.

Benedict, J., 1973: Origin of rock glaciers. *Journal of Glaciology*, 12: 520–522.

Benedict, J., Benedict, R., and Sanville, D., 1986: Arapaho rock glacier, Front Range, Colorado, U.S.A.: a 25 year resurvey. *Arctic and Alpine Research*, 18: 349–352.

Birkeland, P., 1973: Use of relative age-dating in a stratigraphic study of rock glacier deposits, Mount Sopris, Colorado. *Arctic and Alpine Research*, 5: 401–416.

Birman, J., 1964: *Glacial geology across the crest of the Sierra Nevada, California*. Boulder, Colorado: Geological Society of America, Special Paper 75, 80 pp.

Braddock, W., and Cole, J., 1990: Geologic map of Rocky Mountain National Park and vicinity, Colorado. U.S. Geological Survey Miscellaneous Investigations Series I-1973, scale 1:50,000.

Brocklehurst, S., and Whipple, K., 2002: Glacial erosion and relief production in the eastern Sierra Nevada, California. *Geomorphology*, 42(1–2): 1–24.

Buchenauer, H., 1990: Gletscher- und Blockgletschergeschichte der westlichen Schobergruppe (Osttirol). *Marburger Geographisches Schriften*, 117: 1–376.

Calkin, P., Haworth, L., and Ellis, J., 1987: Rock glaciers of Central Brooks Range, Alaska, U.S.A. *In* Giardino, J., Shroder, J., and Vitek, J. (eds.), *Rock glaciers*. London: Allen and Unwin, 65–82.

Carroll, T., 1974: Relative age dating techniques and a Late Quaternary chronology, Arikaree Cirque, Colorado. *Geology*, 2: 321–325.

Clark, D., Steig, E., Potter, N., Fitzpatrick, J., Updike, A., and Clark, M., 1996: Old ice in rock glaciers may provide long-term climate records. *EOS, Transactions, American Geophysical Union*, 77(23): 217–222.

Davis, J., 1986: *Statistics and data analysis in geology*. New York: John Wiley and Sons.

Elias, S., 1995: *The ice-age history of national parks in the Rocky Mountains*. Washington, D.C.: Smithsonian Institution Press.

Ellis, J., and Calkin, P., 1979: Nature and distribution of glaciers, neoglacial moraines, and rock glaciers, east-central Brooks Range, Alaska. *Arctic and Alpine Research*, 11: 403–420.

Frauenfelder, R., 2005: *Regional-scale modelling of the occurrence and dynamics of rockglaciers and the distribution of paleopermafrost*. University of Zürich: *Schriftenreihe Physische Geographie Glaziologie und Geomorphodynamik*, 45: 70 pp.

Gable, D., and Madole, R., 1976: Geologic map of the Ward quadrangle, Boulder County, Colorado, U.S. U.S. Geological Survey Geological Quadrangle Map GQ-1277, scale 1:24,000.

Giardino, J. R., and Vitek, J. D., 1988: The significance of rock glaciers in the glacial-periglacial landscape continuum. *Journal of Quaternary Science*, 3(1): 97–103.

Haeberli, W., 1985: Creep of mountain permafrost: internal structure and flow of alpine rock glaciers. *Mitteilungen der Versuchsanstalt für Wasserbau, Hydrologie und Glaziologie*, 77: 1–142.

Harbor, J. M., 1984: *Terrestrial and lacustrine evidence for Holocene climatic/geomorphic change in the Blue Lake and Green Lake Valleys of the Colorado Front Range*. M.A. thesis. Department of Geography, University of Colorado, Boulder.

Höllermann, P., 1983: Blockgletscher als Mesoformen der Periglazialstufe. Studien aus europäischen und nordamerikansichen Hochgebirgen. *Bonner Geographische Abhandlung*, 67: 1–73.

Humlum, O., 1998: The climatic significance of rock glaciers. *Permafrost and Periglacial Processes*, 9: 375–395.

Ives, J. D., and Fahey, B. D., 1971: Permafrost occurrence in the Front Range, Colorado Rocky Mountains, U.S.A. *Journal of Glaciology*, 10(58): 105–111.

Ives, R., 1940: Rock glaciers in the Colorado Front Range. *Geological Society of America Bulletin*, 51: 1271–1294.

Janke, J. R., 2001: Rock glacier mapping: a method utilizing enhanced TM data and GIS modeling techniques. *Geocarto International*, 16(3): 5–15.

Janke, J. R., 2005a: Long-term flow measurements (1961–2002) of Arapaho, Taylor, and Fair rock glaciers, Front Range, Colorado. *Physical Geography*, 26(4): 313–336.

Janke, J. R., 2005b: Photogrammetric analysis of Front Range rock glacier flow rates. *Geografiska Annaler: Series A, Physical Geography*, 87(4): 515–526.

Janke, J. R., 2005c: Modeling past and future permafrost distribution in the Colorado Front Range. *Earth Surface Processes and Landforms*, 30(12): 1495–1508.

Jeanneret, F., 1975: Blockgletscher in den Südalpen Neuseelands. *Zeitschrift für Geomorphologie*, 19: 83–94.

Lieb, G., 1991: The horizontal and vertical distribution of rock glaciers in the Hohe Tauern, Austria. *Zeitschrift für Geomorphologie*, 35: 345–365.

Losleben, M., 2004. D-1 (3743 m) Climate Station: Temperature and Precipitation Data (1952–2004) (http://culter.colorado.edu/exec/nwtdataqs.cgi?category=KEYWORD&search=meteorology).

Luckman, B., and Crockett, R., 1978: Distribution and characteristics of rock glaciers in the southern part of Jasper National Park, Alberta. *Canadian Journal of Earth Sciences*, 15(4): 540–550.

Madole, R. F., 1972: Neoglacial facies in the Colorado Front Range. *Arctic and Alpine Research*, 4: 119–130.

Mardia, K., and Jupp, P., 2000: *Directional statistics*. New York: John Wiley and Sons.

Matsuoka, N., and Ikeda, A., 2001: Geological control on the distribution and characteristics of talus-derived rock glaciers. *Annual Report of the Institute of Geosciences, University of Tsukuba, Japan*, 27: 11–16.

Morris, S., 1981: Topoclimatic factors and the development of rock glacier facies, Sangre de Cristo Mountains, southern Colorado. *Arctic and Alpine Research*, 13(3): 329–338.

Outcalt, S., and Benedict, J., 1965: Photo-interpretation of two types of rock glaciers in the Colorado Front Range, U.S.A. *Journal of Glaciology*, 5: 849–856.

Outcalt, S., and MacPhail, D., 1965: *A survey of Neoglaciation in the Front Range of Colorado*. Series in Earth Sciences 4. Boulder: *University of Colorado Studies*,4: 124 pp.

Potter, N., 1972: Ice-cored rock glacier, Galena Creek, northern Absaroka Mountains, Wyoming. *Geological Society of America Bulletin*, 83: 3025–3068.

Potter, N., Steig, E., Clark, D., Speece, M., Clark, G., and Updike, A., 1998: Galena Creek rock glacier revisited—New observations on an old controversy. *Geografiska Annaler Series A–Physical Geography*, 80A(3–4): 251–265.

Schröder, H., 1992: Aktive blockgletscher im zentralen teil des nördlichen Tienschan. *Petermanns Geographische Mitteilungen*, 136: 109–119.

Schrott, L., 1991: Global solar radiation, soil temperature and permafrost in the Central Andes, Argentina: a progress report. *Permafrost and Periglacial Processes*, 2: 59–66.

Sloan, V. F., 1998: *The distribution, rheology, and origin of rock glaciers, Selwyn Mountains, Canada*. Ph.D. dissertation. Department of Geological Sciences, University of Colorado: Boulder,

Sollid, J., and Sörbel, L., 1992: Rock glaciers in Svalbard and Norway. *Permafrost and Periglacial Processes*, 3: 215–220.

Wahrhaftig, C., and Cox, A., 1959: Rock glaciers in the Alaska Range. *Bulletin of the Geological Society of America*, 70: 383–436.

Wallace, R., 1967: *Type and rates of alpine mass movement, west edge of Boulder County, Colorado Front Range*. Ph.D. thesis. Ohio State University: Columbus.

Whalley, W. B., 1974: Origin of rock glaciers. *Journal of Glaciology*, 13(68): 323–324.

Whalley, W. B., and Martin, H., 1992: Rock glaciers: II models and mechanisms. *Progress in Physical Geography*, 16: 127–186.

White, P., 1979: Rock glacier morphometry, San Juan Mountains, Colorado. *Geological Society of America Bulletin*, 90: 1515–1518; II924–II952.

White, S., 1971: Rock glacier studies in the Colorado Front Range, 1961 to 1968. *Arctic and Alpine Research*, 3: 43–64.

White, S., 1975: Additional data on Arapaho rock glacier in Colorado Front Range, U.S.A. *Journal of Glaciology*, 14(72): 529–530.

White, S., 1976: Rock glaciers and block fields, review and new data. *Quaternary Research*, 6: 77–97.

White, S., 1987: Differential movement across transverse ridges on Arapaho rock glacier, Colorado Front Range, U.S.A. *In* Giardino, J., Shroder, J., and Vitek, J. (eds.), *Rock glaciers*. London: Allen and Unwin, 145–149.

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