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Rock glaciers and related periglacial landforms in the Sierra Nevada, CA, USA; inventory, distribution and climatic relationships

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Abstract

Rock glaciers and related periglacial rock-ice features (RIFs) are abundant yet overlooked landforms in the Sierra Nevada, California, where they occur in diverse forms. We mapped 421 RIFs from field surveys, and grouped these into six classes based on morphology and location. These categories comprise a greater range of frozen-ground features than are commonly described in rock-glacier surveys. Mapped features extended from 2225 to 3932 m (modern, mean 3333 m), occurred mostly on NNW to NNE aspects, and ranged in apparent age from modern to relict (late Pleistocene). Many of the smaller features mapped here are not readily discernible with remote (e.g., air photo) observation; field surveys remain the best approach for their detection. We interpreted the presence of outlet springs, basal lakes, suspended silt in outlet streams, and fringing phreatophytic vegetation, in addition to morphologic indications of current rock movement, as evidence for interstitial ice, either persistent or seasonal. The six classes were distinct in their geographic settings and morphologic conditions, indicating process-level differences. To assess modern climate, we intersected mapped locations with the 30 arcsec PRISM climate model. Discriminant analysis indicated significant differences among the climate means of the classes with the first three canonical vectors describing 94% of the differences among classes. Mean annual air temperatures (MAAT) for modern features ranged from 0.3 to 2.2 °C; mean precipitation ranged from 1346 to 1513 mm. We calculated differences between modern and Pleistocene temperatures in two ways, one based on elevation differences of modern and relict RIFs (662 m) and standard lapse rate, the other using PRISM estimates. For the first, we estimate the difference in MAAT as −3.9 °C (range −2.2–to 7.9 °C); from PRISM, the difference was −3.3 °C (range −1.0 to –6.1 °C). In that persistent snowfields and glaciers are retreating in the Sierra Nevada under warming climates, RIFs will likely become increasingly important in prolonging water storage during the warm season and providing small but distributed water reserves for biodiversity and runoff. Their presence and water contributions would benefit by further hydrologic study.
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1. Introduction

Rock glaciers and related periglacial rock-ice features (RIFs) are widespread landforms in arctic and alpine environments with cold temperatures, low humidities, and abundant shattered rock (White, 1976; Giardino et al., 1987; Giardino and Vitek, 1988). In the regions where they have been studied intensively, rock glaciers cover as much as 5% (Switzerland; Frauenfelder, 2004) to 10% (Chile; Brenning, 2005) of the alpine environment, contain up to 50–80% ice by volume (Barsch, 1996a; Brenning, 2005), and contribute as much as 20% (Switzerland; Haeberli, 1985) to 60% (Colorado; Giardino et al., 1987) of alpine erosion. While ice glaciers have been retreating worldwide and in many mountain ranges are predicted to thaw entirely in the 21st century, water contained in the ice of rock glaciers is protected from thermal changes by insulating rock mantles. As a result, thaw of ice in rock glaciers significantly lags behind ice glaciers, and these landforms appear to be in disequilibrium with climate, especially when climates are changing rapidly (Clark et al., 1994a; Pelto, 2000; Brenning, 2005). For this reason, rock glaciers are likely to become increasingly critical alpine water reservoirs under global-warming conditions (Schrott, 1996), yet this important contribution has not been well recognized.

Compared with typical glaciers (referred to as "ice glaciers" in this paper), rock glaciers remain less well described or studied. Because these features are rock-covered

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and appear superficially similar to moraines, rockfalls, talus or scree slopes, their presence and hydrologic significance have been widely overlooked. In North America, rock glaciers have been little incorporated into studies that estimate regional distribution and extent of stored ice, assess timing and abundance of mountain streamflows, model changes in water yields under warming climates, or define wetland alpine refugia for biodiversity. In many mountain ranges, rock glaciers remain "…landforms whose wide distribution, occurrence, and significance often go unnoticed" (Burger et al., 1999).

Rock-ice features occur in a wide range of forms, shapes, and topographic locations, with many intermediate forms and transitional locations. Because different researchers have grouped diverse forms together under the term rock glacier, or conversely, considered only very specific forms to be rock glaciers, a range of alternative, often conflicting, hypotheses regarding their origins developed. These include glacigenic versus periglacial processes (summarized in Clark et al., 1998; Burger et al., 1999; Whalley and Azizi, 2003), and for the latter, permafrost versus landslide, avalanche, or other periglacial process (summarized in Johnson, 1983; Whalley and Martin, 1992; Whalley and Azizi, 2003). New technologies to investigate internal dynamics (e.g., Berthling et al., 1998; Kääb and Vollmer, 2000; Kääb, 2002; Degenhardt et al., 2003; Janke, 2005) as well as increasing clarity from coring and excavation studies (e.g., Whalley et al., 1994; Clark et al., 1998; Konrad et al., 1999), are casting light on what had seemed to be an intractable internal structural problem. These studies suggest that multiple morphogenic processes occur, and that their expression varies with local conditions, regional climate and history. This has led to increasing acceptance of the equifinality of rock glacier origins, i.e., that different initial conditions and processes can lead to similar external forms (Johnson, 1983; Corte, 1987a, b; Whalley and Azizi, 2003), as well as acceptance that a continuum of landforms can result from similar processes (Giardino and Vitek, 1988; Clark et al., 1994a, 1998; Burger et al., 1999).

The equifinality of rock glacier origins and forms has helped clarify approaches to nomenclature and classification. Many papers have discussed terms and definitions and offered general classifications (summarized in Johnson, 1983; Corte, 1987a; Hamilton and Whalley, 1995; Whalley and Azizi, 2003); the most useful classifications are based on morphology and location rather than assumed origins (Hamilton and Whalley, 1995; Whalley and Azizi, 2003). Several authors distinguish between "rock glaciers", that is, features having steep fronts, steep sides, length greater than width, and existing on a valley floor, and "protalus lobes and protalus ramparts", with similar morphology but occurring on valley walls, in front of talus slopes, and generally wider than long (Martin and Whalley, 1987; Hamilton and Whalley, 1995; Whalley and Azizi, 2003). The diversity of forms and dependence on regional conditions make clear that generalized definitions, important as starting points, are inadequate for regional studies. Rather, site-specific descriptions and classifications have been called for to promote accurate mapping, climatological investigations and process-based studies (Hamilton and Whalley, 1995).

In temperate western North America, local inventories of rock glaciers have been made in several regions, including the Lemhi Range, Idaho (Johnson et al., 2006), Galena Creek, Absaroka Mtns, Wyoming (Potter, 1972), the Colorado Rockies (White, 1971, 1987; Giardino, 1979; Benedict et al., 1986; Vick, 1987; Giardino et al., 1984; Degenhardt et al., 2003; Janke, 2004, 2007), Canadian Rockies (Johnson and Lacasse, 1988; Sloan, 1998), and La Sal Mountains of Utah (Shroder, 1987; Morris, 1987; Parson, 1987; Nicholas and Butler, 1996; Nicholas and Garcia, 1997). In the Sierra Nevada, California, limited information exists on the distribution of rock glaciers, although focused studies on paleoclimate and glacial advances have been conducted for a few large, glacigenic rock glaciers (Clark et al., 1994a; Konrad and Clark, 1998). While many rock glaciers are misleadingly labeled as moraines on topographic maps, a few Pleistocene relict forms are identified as rock glaciers on geologic maps of the Sierra and anecdotal observations suggest that rock glaciers and related RIFs are abundant in cirques and canyons of the Sierra Nevada south of Lake Tahoe. Beyond these, however, the distribution, extent, and significance of rock glaciers, and especially the diverse range of related periglacial features in the Sierra Nevada, are little known.

Rock glaciers have been investigated for their value as archives of historic glacial activity and paleoclimates in similar ways as ice glaciers. By comparing ages and elevations of active (containing glacial ice) and relict (lacking ice) rock glaciers, and interpreting changes in equilibrium line altitudes (ELA or RILA, rock glacier initiation altitude), timing of glaciations and temperature differences have been determined (White, 1981). This has led to clarification of Pleistocene versus Holocene glacial activity and estimates of temperature differences in several regions of the world including the Sierra Nevada (e.g., Clark et al., 1994a; Konrad et al., 1999; Bachrach et al., 2004; Brenning, 2005). Another approach to estimating Pleistocene paleoclimates is based on the assumption that rock glaciers indicate the extent of the permafrost zone, which is assumed to require mean annual air temperatures (MAAT) of -1 to $-2\,^{\circ}\mathrm{C}$ or less to develop, and enables comparison of temperature changes over time (Barsch, 1996b; Frauenfelder and Kääb, 2000; Aoyama, 2005). Pleistocene versus Holocene temperature differences in the alpine zone have also been estimated from chrionomid-based models of lake temperature (Porinchu et al., 2003), as well as other biological proxy estimates such as pollen and packrat-middens.

Few direct studies have been conducted on modern climate relations of rock glaciers, although comparison with ice glaciers has yielded relative information (e.g., Humlum, 1998). Temperature profiles from mini-dataloggers placed at the ground surface of rock glaciers in Japan have been interpreted to suggest that the rock glacier sites are underlain by degrading permafrost (Aoyama, 2005). Brenning (2005) compared rock glacier distribution with regional climate information and inferred that active rock glaciers were not in equilibrium with current climates. Late 20th century changes in air temperature in Colorado were estimated to cause a rise in the lower elevational limit of rock glaciers (Clow et al., 2003). No such studies have been done previously for the Sierra Nevada.

1.1. Goals

We undertook the work here to expand the geographic and climatic knowledge of rock glaciers and related features in the Sierra Nevada and to draw attention to their potential hydrologic significance. We include a wider range of features in our evaluations than has been discussed in rock glacier studies to highlight potential physical and genetic relationships, and to suggest possible hydrologic distribution and significance of little-studied forms. We conducted field-based surveys rather than using remote observations so that we could observe and map landforms that might be undetectable otherwise.

The specific goals of the present study were to compile a geo-referenced database of a representative set of rock glaciers and related periglacial features in the Sierra Nevada; to analyze and distinguish geographic conditions among the diverse forms; and to evaluate modern and paleoclimatic relations of the mapped features.

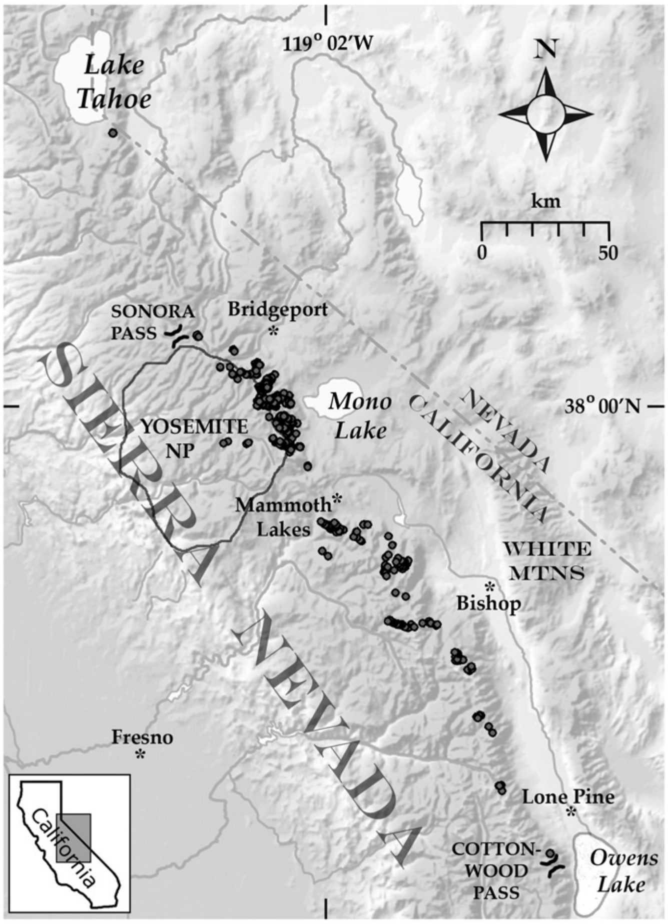

Fig. 1. Map of the study area, Central Sierra Nevada, California, USA. Rock-ice features inventoried were between South Lake Tahoe and Cottonwood Pass with emphasis on the area from Robinson Creek to Rock Creek, and primarily east of the Sierra Crest.

2. Methods

2.1. Mapping and classification

During the field seasons of 2000–2005, we observed and mapped rock glaciers and associated RIFs in the Sierra Nevada from South Lake Tahoe Basin to Cottonwood Pass (Fig. 1), focusing on the region between Robinson Cr., near Bridgeport, CA, and Rock Cr., north of Bishop, CA. We mapped features at locations and elevations where glacial and periglacial processes appear to dominate, and whose form and structure suggested glacial or periglacial origins—e.g., features that have been described as rock glaciers (including debris-covered glaciers); apparently active moraines; protalus lobes and ramparts; creeping scree slopes; solifluction slumps; patterned-ground circles, nets, stripes; and many transitional forms. Ice glaciers and persistent snowfields without associated rock mantling were not included. Each feature was field-mapped visually at coarse resolution on topographic maps and later characterized with digital maps (National Geographic, 2004) for latitude and longitude (center of feature), elevation range from top to base, and local slope aspect. Feature size was described in four ranks (400, 50, 5, 0.5 ha); three shape ranks were scored (wider than long, approximately equal length and width, longer than wide). Where we were able to access the perimeter of the feature, we noted presence or absence of water (ice, springs, lake, audible running water but not surfaced).

For each feature mapped we made preliminary determinations of age. Previous studies (e.g., Ikeda and Matsuoka, 2002) have characterized features as active (embedded ice, active movement of ice and rock), inactive (embedded ice but ablating or stagnant, no movement of landform), or relict/fossil (no ice or movement, only till remains). Because current activity (embedded ice, movement) is difficult to determine and because we specifically sought to identify hydrologic activity rather than glacial dynamics, we use the term "modern", which combines previously used "active" and "inactive" categories. We scored a feature as modern if it was: (1) within the elevation range of local ice glaciers and persistent snowfields; and had (2) oversteepened front and sides relative to the ambient slope; (3) angular rocks with no or little lichen growth; (4) plant cover absent or minimal; (5) appearance of active sorting of clasts, (6) persistent snow or icefield directly above the feature on cirque or valley wall; (7) persistent spring or stream, or presence of phreatophytes (e.g., *Salix*, *Carex*) at the feature's downhill front, or running water audible but not surfaced, and/or (8) presence of suspended silt in outlet streams. For relict features, we made speculative assignments of age, based on appearance, elevation and size compared with known glacial features, such as Holocene, Pleistocene-Recess Peak (Clark et al., 1994a; Clark and Gillespie, 1997) and Pleistocene-Last Glacial Maximum.

Based on observations of ~300 features, we developed a preliminary regional taxonomy. The categories were elaborated from previous classifications (Washburn, 1956; Corte, 1987a; Hamilton and Whalley, 1995) and based on morphological condition and form rather than assumptions about origins, and also on field-visible conditions without reference to subsurface conditions, internal processes or other aspects that require special measurement to determine. We revisited ~20% of the originally mapped features to test the classification, and then continued mapping ~100 additional features, sorting them into the new classification. In this paper we refer to features either as RIFs, or we use the specific group names from our classification. Our survey is not comprehensive for the entire region in that we mapped only canyons we visited by foot. To the extent possible, however, we attempted to map all features in the local areas that we visited.

2.2. Climate modeling

Location data for all mapped RIFs were imported into GIS (Arc Info) as point coverages (latitude/longitude of centers). These groups were intersected with data from the 30 arcsec gridded PRISM climate model (Daly et al., 1994). From that set, we extracted layers for annual, January and July minimum and maximum temperatures, respectively; and annual, January, and July precipitation, respectively, for the period of record, 1970–2000. The PRISM grids were converted to polygons and sequentially intersected with the locations of the RIFs, grouped by the six location classes (see Results, Table 1). To adjust the mean climate values of each 30 arcsec PRISM polygons to the specific elevations of the RIF centers we followed the approach of Hamann and Wang (2005). For this, we used a 90 m digital elevation model (DEM, from PRISM, Daly et al., 1994) clipped to the Sierra Nevada and eastern Sierran ecoregions (Davis et al., 1998), and intersected these with climate data from the PRISM arcsec model, extracting the PRISM climate data with latitude, longitude and elevation. We then regressed response-surface equations of latitude, longitude and elevation of the DEM tiles against the PRISM tiles. Rather than using regression equations of Hamann and Wang (2005), which were based on Canadian locations, we used modified multi-order response-surface equations of the form

$$(\text{latitude} + \text{longitude})^n + \text{elevation} + \text{elevation} \times (\text{latitude} + \text{longitude})^{n-1},$$

where >90% fit was obtained when n, the order of each equation, equaled 6 each for temperature and precipitation data. Terms of the equation that were singular were dropped. As in Hamann and Wang (2005), we took the first derivative for elevation in each equation to estimate lapse rates for climatic data by elevation to adjust temperature and precipitation between the mean elevation of the 30 arcsec PRISM tile to each RIF feature. Surface analysis regressions were done in SAS (SAS, 2004), and first derivatives were computed in Mathematica (Wolfram, 2004).

To determine differences among location classes, we subjected the merged RIF/PRISM-climate data to discriminant analysis. We classified the analysis by location class with the climatic measures as variables, maximizing RIF differences in multivariate climate space. We analyzed

Table 1
Summary of Sierra Nevada rock-ice features by overall group (total), four condition types and six location classes

Group	Condition type	Location class	Class code	Number mapped	Mean elevation (m)	Elevation range (m)	Mean elevation low (m)	Mean elevation high (m)	Active (%)	Active; mean elevation (m)	Active; elevation range (m)	Active; mean elevation low (m)	Active; mean elevation high (m)	Mean size (ha)	Long (%)	Shape equal (%)	Wide (%)
Rock-ice features	All	All		421	3295	2225–3932	3205	3356	75	3333	2673–3932	3253	3385	15	33	41	26
	Rock glacier																
		Cirque	RGC	184	3324	2225–3932	3243	3405	67	3390	2673–3901	3306	3448	20	40	40	20
		Valley wall	RGV	105	3243	2804–3840	3201	3285	69	3292	2941–3840	3205	3337	3	12	27	61
	Boulder stream	Scree slopes	BSC	71	3253	2743–3780	3189	3317	89	3256	2743–3780	3157	3317	4.8	39	54	7
		Stream course	BST	22	3228	2804–3597	3201	3256	100	3228	2804–3597	3201	3256	2.4	91	9	0
	Patterned ground	Alpine flats and slopes	PGA	15	3273	3066–3510	3268	3278	73	3322	3166–3510	3276	3285	1.1	33	47	20
	Mass waste	Alpine slopes	MWA	24	3509	3109–3932	3439	3578	100	3509	3109–3932	3439	3578	15	0	91	9

differences among multivariate climatic means by MANOVA (JMP; SAS, 2004).

We made preliminary assessments of climate differences between modern and Pleistocene conditions using two approaches. First we extracted a subset of RIFs that included groups of modern and Pleistocene-scored features from the same drainages, and calculated the differences between the lower elevations of each feature. For the first method, we multiplied the elevation difference by a standard lapse rate, −6.5 °C/km (Wallace and Hobbs, 2006), which Lundquist and Cayan (2007) verified from 38 weather stations as highly accurate for mean annual temperatures of high elevations in the central Sierra Nevada. For the second method, we calculated modern PRISM climate means for the watershed groups of modern versus Pleistocene RIFs, adjusted by elevation to the selected feature. We used differences in these means to represent differences between modern and Pleistocene conditions, assuming lapse rates have not varied over time. From these PRISM results, we can also estimate local lapse rates directly to compare with the standard rate.

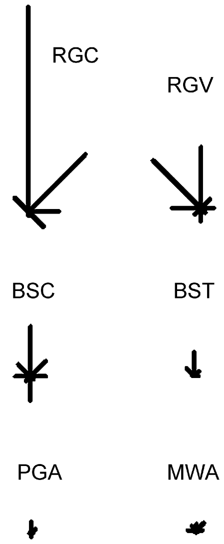

Fig. 2. Slope aspects summarized for six location classes of rock-ice features in the Sierra Nevada. Direction of the wind-rose arms indicates cardinal slope aspects (N up); length of the arms indicates the proportion of features found in that aspect of the total in the Class. Sample numbers vary by location class (see Table 1).

3. Results

3.1. Classification and mapping

We mapped 421 rock-ice features and sorted them into classes relevant to the Sierra Nevada (Table 1; complete data table available at the National Snow and Ice Data Center, ⟨http://nsidc.org/data/ggd652.html⟩, with geo-references, aspect, elevation ranges, form, sizes, and indication of water presence for each RIF, and images for many RIFs). These include four condition types, which distinguish major geomorphic forms, and six location classes, which describe specific locations of RIFs. Mean values for geographic location, size, and shape are given in Table 1; average slope aspects are indicated in Fig. 2.

The overall group of rock-ice features (RIF) is described as follows: (i) distinct high-mountain landforms comprising sorted, angular rock debris; (ii) landforms appear to move collectively by gradual but irregular surface movement and not catastrophic displacement (e.g., avalanche or rockfall); (iii) rock debris reversely sorted (fines low or missing, coarse high); (iv) landform edges typically abrupt (in a few types gradual). Some forms are characterized by over-steepened fronts and/or sides relative to the ambient slope, and the tops of nearly all forms had lower slope angles than the gravity-fall angle of the ambient slope. Features may be modern or relict (defined in methods). Clasts were not freshly abraded or fractured as characterize recent avalanche or rockfall debris; insignificant amounts of embedded material (soil, plant stems, etc.) were entrained in modern RIFs. Occasional steep-sided meltponds occurred in the rock mantle of some forms, revealing massive and stratified underlying ice. In some others, running water could be heard in summer below the surface. Both glacial and periglacial processes appear to be involved in origins, varying by individual feature. Permafrost and/or seasonally frozen ground with freeze-thaw action were likely necessary for the origin of some forms; others appear to derive from ice glaciers; and others yet appear to originate from cumulative snow-, ice-, and rockfall events. Multiple processes appear likely to yield similar forms; conversely, similar processes appear to give rise to different forms depending on environment and microclimate.

The 421 RIFs mapped in the Sierra Nevada extended from 38.8501 °N, at the southern crest of the Lake Tahoe Basin, to 36.4845°N, near Cottonwood Pass, and had a mean elevation of 3295 m (range 2225–3932 m; Table 1). We estimated 75% to be modern features; these had a higher mean elevation (3333 m; range 2673–3932 m) than the overall group. Of the modern features mapped, 52% of those we accessed had at least one indication of persistent water storage. Overall the mean size of the features was 15 ha, with about equal distribution among the three shape categories; primary aspects were northern, although features were mapped in all cardinal directions (Fig. 2). We further describe condition and location classes in the following sections.

3.1.1. Condition type: rock glaciers (RS)

Features are simple or complexly lobed, discrete landforms with abrupt edges, oversteepened fronts and sides, and overflattened tops relative to the ambient slope. Ice was rarely visible except in occasional meltponds where massive, laminated ice bodies underlay a rock debris mantle, or in persistent snow/icefields that adhere to cirque or cliff walls above the primary RIF land form. Features occurred within cirques, extended from cirques into valley floors, or occurred on valley walls, in the midst of scree slopes, in talus cones, or beneath cliffs or avalanche chutes. Adequate quantities of decomposed bedrock or other coarse debris (till, frost-shattered rock) were available above the feature to supply rock mantle/matrix. Potential origins: glacial (rock mantling on clean glaciers) or periglacial (transiently stable and/or seasonally persistent ice interacting with shattered rock masses). Potentially interchangeable from ice glacier to rock glacier and vice versa as climates change. Permafrost (or transiently frozen ground) may be involved in some features. Following the convention of other authors (Clark et al., 1998; Whalley and Azizi, 2003), we use the term rock glacier whether the origin is glacial or periglacial.

We mapped 289 rock glaciers, which ranged from 2225 to 3932 m; 68% were modern (Table 1). Shape and size varied but this category included the largest forms mapped as well as relatively small forms.

3.1.1.1. Location class: cirque rock glaciers (RGC). Features originated in high cirques and were contained either within the cirque (cirque wall or floor) or emanated down-valley as complexly lobed, elongate bodies of rock debris; features also developed from ice-glacier terminal moraines either within or outside the cirque (Fig. 3a). Features often headed with an icefield or snowfield at the cirque wall. Flow paralleled the valley axis, and fronts generally were perpendicular to the axis; arcuate flow lines were common. We mapped 184 RGC features, having mean elevation of 3324 m (active, 3390 m) and mean size of 20 ha; more features were long or equal length-to-width than wide; and 67% were active (Table 1). RGC features were oriented predominantly north, with northeast aspects also common (Fig. 2). Features mapped as modern commonly but not always had either ice fields at their top edges, or lakes or springs and streams directly below the lower edges.

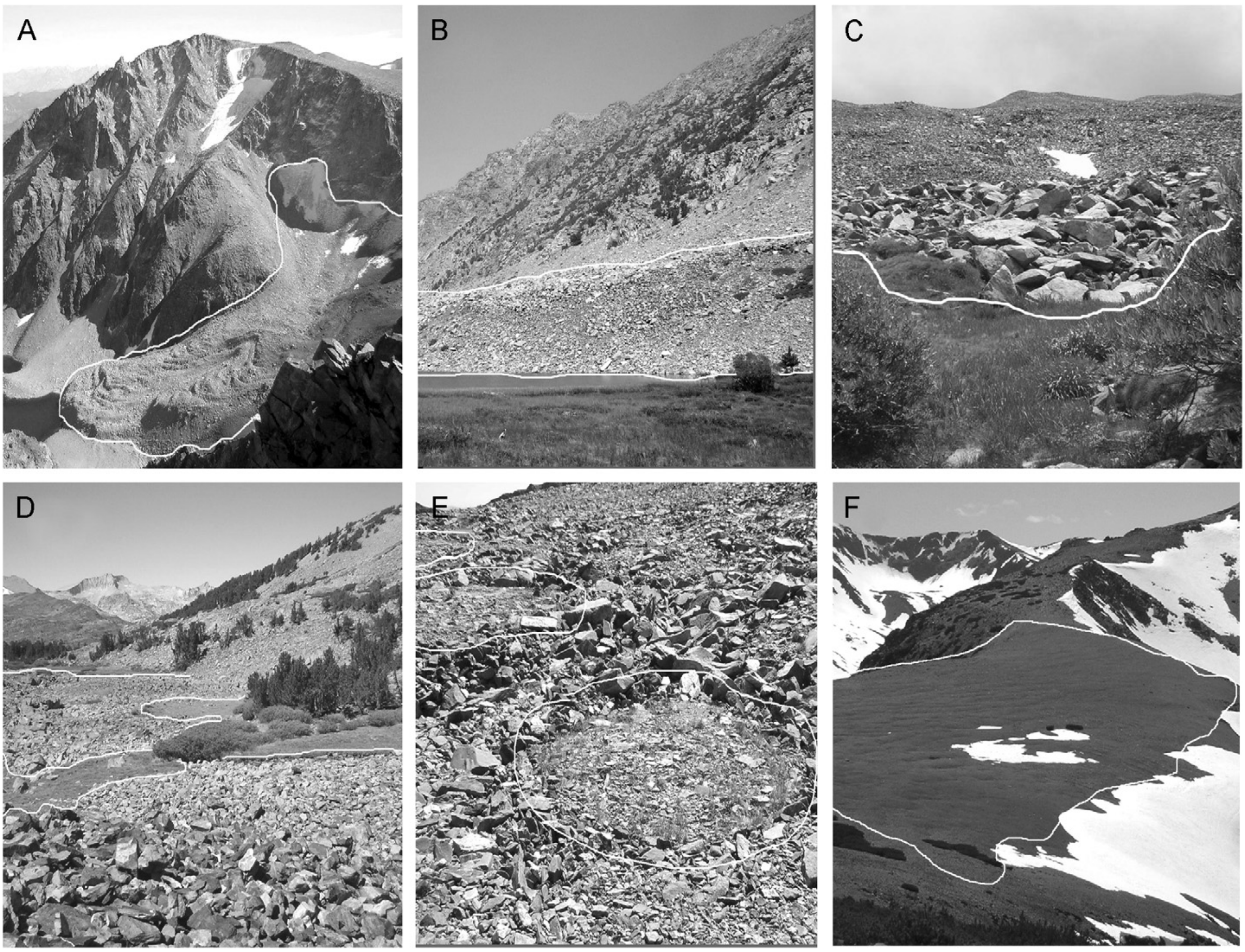

Fig. 3. Rock glaciers and related landforms illustrating the six location classes used to classify features in this study. (A). Cirque rock glacier (RGC) Gibbs Canyon. (B). Valley wall rock glacier (RGV), Lake Canyon (Lundy Canyon). (C). Scree slope boulder stream (BSC), Helen Lk (Kuna Pk). (D). Stream-course boulder stream, Glacier Cyn (Lee Vining Cyn). (E). Patterned ground sorted circles (PGA), Parker Peak (Koip Pass). (F). Mass wasting solifluction slope (MWA), Virginia Cr (Mt. Olsen).

3.1.1.2. Location class: valley wall rock glaciers (RGV). Relatively small features compared with cirque rock glaciers (RGC), which originated on valley walls as short to wide bench-like or wedge-shaped structures, flowed downslope towards the valley bottom, and had fronts that paralleled the valley axis (Fig. 3b). Valley wall features occurred along scree slopes, within talus cones, and below cliffs or avalanche chutes. We mapped 105 RGV features, which had mean elevation of 3243 m (active, 3292 m) and mean size of 3 ha; 61% of the features were wider than long in shape; and 69% were scored as active (Table 1). RGV features occurred on predominately north and northwesterly aspects (Fig. 2). Features mapped as modern commonly but not always had either ice fields at their top, or lakes or springs and streams directly below the lower brim.

3.1.2. Condition class: boulder streams (BS)

Landforms were similar to rock glaciers, dominated by sorted, shattered rock, but lacking oversteepened fronts or sides. Boulder stream front boundaries instead occurred where large sorted boulders (angular, lichen-free, and without recent abrasions) abruptly met deep organic soils supporting mesic "turf" vegetation that appeared to be rolling (carpet-like) over the landform front. The landform appeared to move downslope without turbulence to the rafting rocks. Boulder streams occurred on slopes and valley walls in similar topographic locations as RGV features, and rarely in cirques. Some large features covered entire mountain slopes; very small boulder streams occurred below snowfields on gentle slopes, or along stream-courses in valley bottoms or low-gradient slopes. Abundant sources of decomposed rock and coarse debris (till, frost-shattered rock) occurred above the features and appeared to supply rock mantle/matrix. Running water was often heard below the rocks. Springs, boggy grounds, fringing phreatophytic growth and persistent ponds or lakes were common at boulder stream fronts. Potential origins: periglacial; transiently stable and/or seasonally persistent ice interacting with shattered rock masses. Permafrost processes or repeat freeze-thaw cycles may be involved for sorting and movement and to form the distinctive boundaries at the fronts and sides of these features. Avalanching may contribute snow and ice to these features.

We mapped 93 boulder streams, which ranged from 2743 to 3780 m; 94% were active (Table 1). This category comprised relatively smaller forms (often less than 5 ha) with more diverse shapes than rock glaciers. Aspects included all cardinal directions, with south as well as north common. Some features (especially stream course features) had very low relief. We divided boulder stream into two location classes.

3.1.2.1. Location class: scree slopes (BSC). These landforms occurred on valley walls and other slopes of steep to low gradient (Fig. 3c). Features ranged from large (entire slopes) to small (below persistent snowfields). While running water was often heard below the surface, it was diffuse across the feature, not concentrated as in a stream course. We mapped 71 BSC features, which had a mean elevation of 3253 m (active, 3245 m), and mean size of 4.8 ha (Table 1). Most BSC features were longer than wide or had about equal width and length. Boulder stream types were in similar locations as the rock glaciers, although they were lower in elevation and occurred on a wider range of aspects (Fig. 2). Water is often heard below modern features, and springs and outlet streams are common but not always present.

3.1.2.2. Location class: stream courses (BST). Boulder streams that followed stream courses, either on slopes or in valley bottoms; slopes varied from moderate to very low gradient (Fig. 3d). We mapped 22 BST features, which had a mean elevation of 3228 m (100% mapped were active), and mean size of 2.4 ha (Table 1). Most BST features were elongate and narrow. Running water was often heard below the surface as a concentrated stream; the stream itself often surfaced and submerged many times.

3.1.3. Condition class: patterned ground (PG) and location class (PGA)

These landforms were similar to boulder streams but associated with standing water or saturated soils, rather than running water, and usually small to very small in size. Features were distinctly bounded, with sorted rock (angular, no lichens or soil) abruptly meeting weathered soil surfaces (Fig. 3e). Some patterned ground features had weathered soil within the boundaries. Features occurred on very high, exposed, often windswept, snow-free plateaus, benches and slopes; some features bounded alpine lake margins at locations that may be submerged during spring melt. Many forms of patterned ground (nets, stripes, sorted circles) have been described elsewhere (Washburn, 1956). A feature was considered modern when it had abrupt boundaries, and rocks were angular with no lichen growth. Potential origins: Periglacial (permafrost and/or seasonally frozen ground processes, e.g., freeze-thaw, convection, contraction).

We mapped 15 PG features; the mean elevation was 3273 m, 73% were mapped as active. PG features were the smallest in size of all categories, averaging 1.1 ha. Shapes were mostly equally wide as long, although irregular length and width features also occurred. Many occurred on flat benches and lake margins, although northerly slopes were favored (Fig. 2). Only features located at lake margins regularly had water associated with them.

3.1.4. Condition class: mass wasting (MW) and location class (MWA)

These landforms occupied high, exposed and relatively low gradient alpine slopes and comprised complex slumps and hummocks that appear to creep downslope (Fig. 3f). Individual hummocks often have oversteepened fronts relative to the general slope, resembling diminutive rock glaciers (RG) fronts. Soil is often developed on these features, unlike rock glaciers or boulder streams. In themselves, these features do not appear to be reservoirs of large ice masses or rock-ice matrices; however, because they cover large areas and may be associated with permafrost or seasonally frozen ground, their hydrologic significance may be important. These are large features, and occur at the highest mean elevations of all categories mapped. Potential origins: periglacial, with downslope movement of saturated soils interacting with permafrost, transiently frozen ground, or slick bedrock. The only forms mapped appeared to be of solifluction origin.

We mapped 24 MWA features, averaging 3509 m elevation, 100% active, with mean size 15 ha; almost all were about as wide as long, and orientations were diverse (Fig. 2). Water is not associated with these features, at least not obviously during the warm seasons.

3.2. Climate

Discriminant analysis of PRISM climate data indicated significant differences among the RIF condition types and location classes: rock glacier (RCG, RGV) and boulder stream (BSC, BST) means were significantly different ($p<0.0001$), as were classes RGC and RGV ($p<0.0001$), and classes RGC and MWA ($p<0.0001$). The first three canonical vectors (CV) described 94% of the differences among six classes (50%, 33%, and 11%, respectively; R^2's were 22%, 16% and 6%, respectively); the first two were significant at $p<0.001$. Correlations of the CVs to the climate data indicated strong associations (correlations $>|0.5|$): CV1 with greater July precipitation, CV2 with greater precipitation and lower temperatures except for July precipitation and January maximum temperature, and CV3 with annual, January, and July maximum temperatures, and annual and January minimum temperatures (Table 2). Five of the six location classes separated distinctly in the plot of canonical scores from the discriminant analysis (Fig. 4), which indicates the mean and its 95% confidence limit for each class. The largest

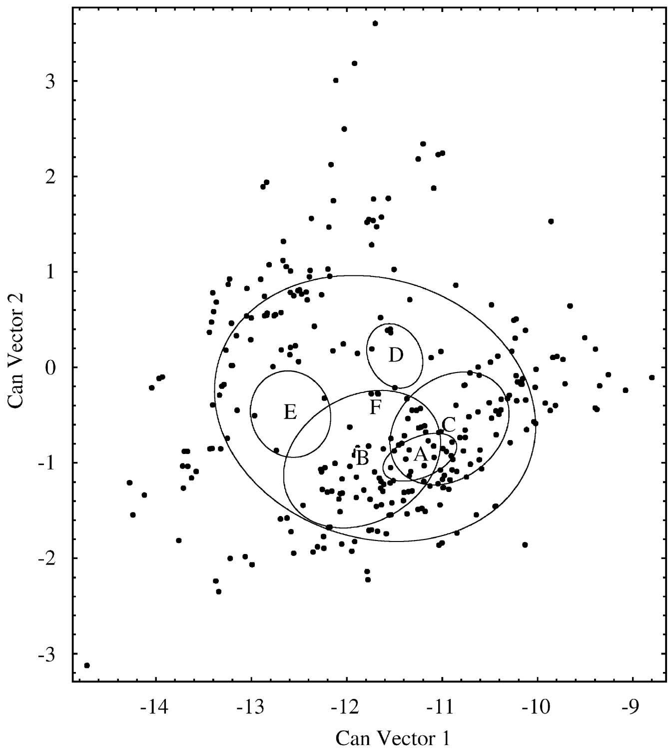

Fig. 4. Canonical vector plot for the first two canonical vectors (Can Vector) from discriminant analysis of 6 rock-ice feature location classes and 10 PRISM climate variables. Labels indicate the mean of the distribution for each location class (A = BSC; B = BST; C = MWA; D = RGC; E = RGV; F (largest ellipse) = PGA); ellipses are the 95% confidence limits for each mean, axes are canonical scores. Can Vector 1 is most strongly correlated with July precipitation; Can Vector 2 is correlated with all but July precipitation and January maximum temperature, and Can Vector 3 is correlated with annual, January, and July maximum temperature, and annual and January minimum temperature. See Table 1 for location class codes.

Table 2
Correlations of scores of the first three canonical vectors (CV) from the discriminate analysis among feature classes with the nine climate variables from the adjusted PRISM climate model

	Annual precip	January precip	July precip	Annual T_{max}	January T_{max}	July T_{max}	Annual T_{min}	January T_{min}	July T_{min}
Annual precip	1.000								
January precip	0.928	1.000							
July precip	−0.117	−0.177	1.000						
Annual T_{max}	−0.422	−0.336	−0.103	1.000					
January T_{max}	−0.384	−0.287	−0.138	0.971	1.000				
July T_{max}	−0.484	−0.425	−0.018	0.966	0.888	1.000			
Annual T_{min}	−0.491	−0.435	0.175	0.750	0.757	0.736	1.000		
January T_{min}	−0.526	−0.481	0.044	0.875	0.857	0.858	0.927	1.000	
July T_{min}	−0.469	−0.420	0.136	0.667	0.681	0.651	0.980	0.872	1.000
CV 1	0.204	0.189	0.814	−0.490	−0.488	−0.436	−0.239	−0.318	−0.265
CV 2	0.615	0.619	−0.495	−0.517	−0.388	−0.650	−0.643	−0.581	−0.570
CV 3	−0.087	0.043	0.047	0.662	0.707	0.559	0.526	0.671	0.490

scatter of points was for class PGA, which contained the variability of the other classes.

Mean climate values derived from the elevation-adjusted PRISM climate model and grouped by the six location classes are shown in Table 3, which includes only modern RIFs ($n = 310$). Based on mean annual air temperature, the coldest class of RIFs was MWA, at 0.3 °C. The rock glacier classes, RGC and RGV, were in warmer environments, 0.9 and 1.9 °C, respectively, and the PGA class intermediate, at 1.2 °C. The boulder stream classes, BSC and BST, had the higher means, 1.9 and 2.2 °C, respectively. This order among the classes was generally

Table 3
Summary of 10 mean climate values for six rock-glacier location classes derived from the 30 arcsec PRISM model

Location class[a]	N	Annual temp. (°C)	Annual T_{min} (°C)	January T_{min} (°C)	July T_{min} (°C)	Annual T_{max} (°C)	January T_{max} (°C)	July T_{max} (°C)	Annual precip (mm)	January precip (mm)	July precip (mm)
RGC	124	0.9	−4.7	−11.6	4.8	6.5	−0.5	16.1	1492	218	19
RGV	68	1.9	−4.0	−10.9	5.4	7.8	0.5	17.7	1359	186	15
BSC	63	1.9	−3.8	−10.8	5.5	7.5	0.1	17.6	1346	184	24
BST	21	2.2	−3.8	−10.7	5.6	8.1	0.6	18.2	1402	198	21
PGA	9	1.2	−4.5	−11.6	4.8	6.9	−0.3	16.8	1513	221	20
MWA	22	0.3	−4.9	−12.1	4.6	5.5	−1.6	15.4	1427	196	24

Only features mapped as modern are included; PRISM values are adjusted to the mapped mean elevation of each feature.
[a]See Table 1 for location class codes.

Table 4
Differences in temperature estimated for Holocene versus Pleistocene climates based on lower elevations of relict Pleistocene (P) and modern Holocene (H) rock glaciers grouped by watersheds from north to south

Watershed groups	Age	N	Mean elevation (low)	Mean elevation difference H – P (m)	Standard lapse difference in T_{ann} P – H (°C)	PRISM-estimated difference in temperature P – H (°C)						
						T_{ann}	T_{max}	Jan. T_{max}	July T_{max}	T_{min}	Jan. T_{min}	July T_{min}
Robinson Cr, Tamarack Cyn	P[a]	1	2747									
	H	2	3198	451	−2.9	−1.0	−6.6	−3.6	−5.1	0.4	−1.1	−0.3
Green Cr, Mt. Dunderberg	P	1	2682									
	H	1	3414	732	−4.8	−1.9	−4.9	−3.8	−5.9	−0.4	−1.9	−1.3
Mt Warren/Lundy Cyn	P[a]	3	2702									
	H	2	3280	578	−3.8	−1.5	−5.6	−4.4	−12.4	−1.6	−2.0	−1.0
Lower Lee Vining Cyn, Dana Cliffs	P[a]	6	2682									
	H	5	3406	724	−4.7	−2.9	−4.7	−3.7	−5.5	−1.0	−1.3	−0.8
Gibbs Cyn	P	2	2545									
	H	1	3170	625	−4.1	−2.3	−4.6	−3.7	−5.2	−0.5	−1.4	−0.1
Bloody Cyn	P[a]	2	2820									
	H	4	3437	617	−4.0	−2.4	−4.0	−3.2	−4.6	−1.5	−1.6	−0.1
Parker Cyn	P	2	2881									
	H	2	3589	708	−4.6	−2.5	−5.7	−4.7	−6.2	−2.4	−3.1	−0.7
Hilton Cr	P	1	2225									
	H	1	3442	1217	−7.9	−3.7	−9.2	−8.3	−9.4	−4.8	−4.8	−2.0
E Fk Rock Cr, Francis Cyn	P[a]	1	3292									
	H	3	3627	335	−2.2	−6.1	−3.5	−3.7	−3.1	−2.1	−1.9	−4.1
N Fk Bishop Cr	P[a]	1	2825									
	H	1	3292	467	−3.0	−2.4	−1.4	−1.3	−1.1	−0.3	−0.2	−1.6
Cottonwood Cr	P	1	3168									
Center Basin	H	1	3701	533	−3.5	−2.0	−2.5	−2.7	−2.8	−0.1	−0.1	−1.1
Average (all groups)				630	−4.1	−3.3	−4.9	−4.2	−5.4	−1.6	−2.0	−1.2

Only cirque rock glaciers (RGC) are included. Mean annual air temperature (T_{ann}) differences are calculated using standard lapse rate (−6.5 °C/km) and PRISM model. Differences are also estimated by PRISM for annual maximum and minimum temperatures (T_{max}, T_{min}, respectively) and for January and July maximum and minimum temperatures (Jan T_{max}, July T_{max}, Jan T_{min}, July T_{min}, respectively). In the Cottonwood/Center Basin group, features are not within a watershed and the closest available pair is used.
[a]Lower elevation truncated by mainstem valley-glacier or other topographic barrier to climatic minimum elevation.

similar for the other temperature variables. Mean annual precipitation of the location classes ranged from 1346 mm (BSC) to 1513 mm (PGA) (Table 3). As expected, the primary precipitation falls in winter, but a significant amount also occurs during summer at these elevations.

Based on differences in base (low) elevations of grouped modern versus relict RIFs, we calculated temperature differences between modern and Pleistocene last glacial maximum (LGM) climates (Table 4). Using the standard lapse rate (−6.5 °C/km) and the mean elevation difference among the RIFs grouped by watersheds (630 m), Pleistocene MAAT on average was 4.1 °C colder than present (range, 2.2–7.9 °C). Considering only watersheds with Pleistocene features where the low elevations were not truncated by mainstem glaciers, hanging valleys or other topographic barriers (see Table 4), the temperature difference was −4.4 °C. Using the PRISM model (and its inherent lapse rates) to directly infer modern temperature differences between the elevations of the modern and relict RIFs, the calculated difference between modern and Pleistocene MAAT was slightly less, −3.3 °C (Table 4). Differences in maximum temperatures were greater than in minimum temperatures, especially in summer. Differences in means for all climate variables were significantly different between Holocene and Pleistocene ($p<0.0001$). Lapse rates from the PRISM model varied from −2.8 to −8.8 °C/km.

4. Discussion

4.1. Mapping and distribution

The Sierra Nevada lies within a warm Mediterranean and semi-arid climate zone where decomposed rock is abundant, especially along metamorphic exposures of the eastern escarpment. Modern ice glaciers are small and few in number, persistent snowfields are similarly small and scattered. In this study we mapped and described geographic relations of 421 rock glaciers and evaluated features using a classification of six primary categories. While rock glaciers and related RIFs are common in the Sierra, they tend to be smaller in nature, and occupy more diverse environments than is the case for mountain ranges that receive greater precipitation and are located in cool, humid climates.

Our initial intent had been to limit the inventory to forms traditionally considered to be rock glaciers and protalus ramparts. We found, however, that these terms were inadequate to describe the diversity of features in the Sierra Nevada. For example, for features previously considered as "rock glaciers" (e.g., Wahrhaftig and Cox, 1959; Hamilton and Whalley, 1995) we found that distinctions of "valley floor" (also called "tongue-shaped") versus "valley wall" (also called "protalus ramparts" or protalus lobes") did not describe the forms and shapes that occurred within Sierran cirques or that extended down-valley. Other forms found in the Sierra did not fit generalized classifications at all, such as features that develop from ice-glacier terminal moraines (e.g., Clark et al., 1994a, b; Corte, 1999; Whalley and Azizi, 2003), or from pocket or niche glacier locations, which are relatively common in the Sierra Nevada.

In addition to rock glaciers, we included other RIFs not usually considered within a rock glacier context. Landforms that we classed as boulder streams have been little discussed in the literature as discrete rock-ice features. Features with similar characteristics have occasionally been described as block fields (especially when associated with patterned ground processes; Harris et al., 1995; Ballantyne, 1998), although the boulder streams we describe bear little resemblance to the processes or forms of typical block fields. It is likely also that previous studies of water-bearing talus fields have included landforms that we describe as boulder streams (e.g., Johnson, 1983; Clow et al., 2003). Compared with rock glaciers, modern boulder streams in the Sierra regularly have as much or more apparent water associated with them. Running water below the surface is obvious and widespread; outlet springs, streams and ponds are common, large, and persistent; and phreatophytes commonly fringe their bases. Freeze-thaw cycles of water-saturated matrices (soil or rock) in adjacent and subsurface soils of the BSC features may contribute to the sorted rocks and the characteristic pattern of the landform diving under or pushing forward dense, humic soils at the lower edges. The nature of their water storage and potential movement—whether ice-matrix derived from avalanche, frozen-ground processes derived from discontinuous permafrost, or other (Mackay, 1983; Williams, 1983) is unknown.

Patterned ground and related permafrost features are common in arid, cold climates of the world (Washburn, 1980; Ballantyne, 2002). In the Sierra Nevada, when mentioned at all, they have been described as relict features, because permafrost has generally not been assumed to exist in the range. Intensive research in the adjacent White Mountains of California, however, has demonstrated the presence of discontinuous modern patterned ground features and processes at 3800 m; above 4150 m modern patterned ground processes become the dominant landscape phenomena (Wilkerson, 1994, 1995). Freeze-thaw cycles throughout the year are common in some parts of the White Mountains, with over 220 cycles per year observed (LaMarche, 1968). Wilkerson (1994, 1995) defined abundant modern sorted circles, nets, and stripes, and studied the movement and soil processes of frost boils and other permafrost features. While he assessed the larger features in the White Mountains to be relict, the presence of active permafrost processes there suggests that similar conditions may exist in the Sierra Nevada.

Patterned ground landforms are especially likely to occur on exposed plateaus and ridge tops where water collects, yet wind sweeps snow free, maintaining exposure of the ground surface to freezing air (Gleason et al., 1986; Nelson et al., 1988; Kessler and Werner, 2003). The morphology and occurrence of features on very high, rocky, and windswept locations at the extreme eastern (dry) edge of the Sierran escarpment corroborate this. Other features occurred near lake margins where soil water tables are high yet exposed, and related boulder stream features may also be found along stream margins. These environments have been noted as favorable for patterned ground formation in other regions (Mackay, 1980; Hallet et al., 1988; Hallet, 1990). Many of the features we mapped appeared to be active (criteria of Wilkerson, 1994) and potentially follow from the mechanics suggested by Kessler and Werner (2003), with form depending on initial slope, aspect, and edaphic conditions.

Features we mapped as mass-waste solifluction (MWA) have been observed in the Sierra Nevada, but not studied as intensively as in the White Mountains (Jones, 1993; Wilkerson, 1994). Solifluction is a well-known periglacial process associated with high water-content soils (Matsuoka, 2001; Ballantyne, 2002), and its role in transformation into patterned ground including nets and stripes has been studied (Washburn, 1956; Gleason et al., 1986; Kessler and Werner, 2003). These features are thought to indicate the presence of seasonally or permanently saturated frozen ground sliding over ice or slick bedrock. While the former seems unlikely in the Sierra Nevada, no studies have been conducted to investigate the subsurface hydrologic conditions of these abundant slowly creeping alpine landforms.

The geographic partitioning of our location classes indicates their distinct environments and independently corroborates the distinctions among our mapped classes. While other studies on rock glaciers and related features indicate that northerly orientations and elevations within the permafrost zone are common (e.g., Wahrhaftig and Cox, 1959; Corte and Espizua, 1981; Burger et al., 1999; Brenning, 2005), Johnson (1983) found no preferred orientations within valleys and that these features occupied diverse locations and elevations. The highest features in our classification were the mass wasting solifluction fields (MWA), followed by cirque rock glacier (RGC). The RGC class also had the narrowest range of northerly orientations, while other categories were more diverse, with features in the MWA class oriented in all main directions. Johnson et al. (2006) found that elevations above 2600 m, north-facing aspect (300–360°), and less than 2300 h of direct sunlight per year were necessary conditions for existence of modern rock glaciers. While our mapping emphasized the east side of the Sierra Nevada crest, both relict and modern RIFs appear more dominant on the east than on the west side. Further, large, relict Pleistocene features are most common in the easternmost canyons of the east slope. That is, those canyons whose heads are farthest east of the crest are more likely to contain Pleistocene RIFs than canyons that head nearer the crest. As there is no systematic difference in rock type along this gradient, the difference likely reflects a lower ice-to-rock volume in the increasing rainshadow of the eastern escarpment.

In this paper, we described and mapped a diverse group of rock-ice features for purposes of highlighting potential water reserves in previously overlooked landforms. We recognize, however, that these types are likely to be heterogeneous in origin, and that interchange among states is limited to certain features. From previous studies and our field observations, we hypothesize that the categories described in this paper as rock glacier (types RGC and RGV) and scree-slope boulder streams (BSC) are potentially interchangeable endmembers, as climatic and rock-debris conditions change. Further, typical ice glaciers appear likely to interchange with rock glaciers of RGC type. A different set of ground freeze-thaw processes appears to dynamically link patterned ground (PG), solifluction slopes (MWA) and streamside boulder streams (BST) types. Many intermediate and potentially transitional forms exist that suggest these patterns of transition are possible as climates and conditions change.

Because our mapping is derived from field observations, based mostly on horizontal or angled views of features rather than aerial, inaccuracies of size and shape may exist in the inventory. We confirmed the locations and extents of a subset of features by air photos. Air photos, however, allowed detection only of the larger rock glaciers, and most of the smaller features could not be discerned. The categories most likely to be mapped by air or other remote methods are RGC. Some of the larger valley wall rock glaciers (RGV) may be detectable as well, especially with oblique projections, or where shadows allow perspective on valley walls. Remote observation does not, however, discriminate most of the other categories. Ground-mapping remains the best approach for their inventory.

4.2. Climatic relationships

Our estimates of modern climate means from the PRISM model are the first assessments for rock glaciers or related RIFs in temperate western North America. Modern climate relations for rock glaciers in other regions have been inferred from low-elevation weather stations (Humlum, 1998), based on assumptions of limiting climate requirements for permafrost (Frauenfelder, 2004; Aoyama, 2005), or estimated from mini-dataloggers installed in the local environment of a few specific features (Humlum, 1998; Krainer and Mostler, 2002; Aoyama, 2005). The PRISM model we used to estimate current climate conditions combines information from standard weather stations, with additional relevant local information to output geographically seamless climate data for 30 arcsec polygons (Daly et al., 1994). Using digital elevation models (DEMs) and local lapse rates from PRISM to adjust the polygon means for individual RIF sites, our resolution for estimating climate means is approximately 400 m. Despite this resolution, our calculations may systematically underestimate local conditions of the RIFs. Although PRISM estimates elevation-related climate well, it does not incorporate local topographic conditions or aspect. Thus, reduced solar insolation, inversion effects, and north-facing aspects and confined walls of many of the RIF cirque and related locations would not be well incorporated in the PRISM estimations.

Considerable attention has been paid to MAAT required to support active rock glaciers and patterned ground processes, with the assumption by some researchers that permafrost necessarily underlies all features. Soil temperatures must persist below 0 °C for at least 2 years to enable permafrost development; to support this MAAT must generally be below −2 °C for continuous permafrost and below 5 °C for discontinuous permafrost. In the Sierra Nevada, permafrost has not been assumed to exist. Clark et al. (1994a), however, found late summer temperatures slightly above 0 °C from a silty sandy matrix in a 1 m pit in the terminus of a Sierran rock glacier, and silt-laden water at ~0 °C from a spring on the front. We have also found rock glacier outlet streams to average 0–1 °C throughout summer and autumn and to contain high amounts of suspended silt (unpublished study). While none of our estimates from PRISM for MAAT of the location classes was as low as −2 °C, they fell within the range for discontinuous permafrost (0.3–2.2 °C). Our PRISM estimates compare with Brenning's, (2005) value of 0.5 °C MAAT of the main rock glacier zone of the Chilean Andes and discontinuous sites of active rock glaciers having MAAT of 4 °C; comparable values were found in other Andean studies (Trombotto et al., 1997). Similarly, in the Italian Alps, the mean elevation of the fronts of active rock glaciers was significantly lower than the −2 °C isotherm, suggesting that either this temperature is not indicative of climate requirements for rock glacier formation or that the features studied were not in equilibrium with current climate (Baroni et al., 2003).

In the White Mountains, adjacent to the Sierra Nevada, permafrost has been documented by the presence of active patterned-ground processes (Wilkerson, 1994, 1995). At 3801 m in the White Mountains, where these features exist, MAAT is −1.7 °C with 455.6 mm mean annual precipitation (Powell and Klieforth, 1991). At Niwot Ridge, Colorado, where active permafrost has been documented, MAAT is −3.9 °C at 3750 m, with 1020.8 mm precipitation (Ives, 1973).

Other direct measurements elsewhere indicated colder conditions related to rock glaciers, most of which have been interpreted to indicate permafrost. For instance, dataloggers placed at the base of the snow cover at an Austrian rock glacier recorded cool-season temperatures (November–May) between 0 and −10 °C, whereas adjacent loggers on permafrost-free areas did not record temperatures colder than 0 °C (Krainer and Mostler, 2002). Similarly, in the Japanese Alps, dataloggers recorded mean annual temperature at the base of the snow cover near rock glaciers less than −2 °C, despite having mean annual temperature at ground surface above 0 °C (Aoyama, 2005). In Spitsbergen, temperature measurements on and within a single rock glacier indicate mean annual ground temperatures less than 0 °C (Humlum, 1998), with suggestions of a shallow permafrost depth. In a New Zealand inventory of rock glaciers, active forms were located within the climatic boundaries where the mean annual isotherm was −2 °C or less for air temperature (Brazier et al., 1998). Late 20th century changes in air temperature in Colorado between 1.1 and 1.4 °C were estimated to cause an increase in the lower elevational limit of rock glaciers (estimated from permafrost indicators) by 150–190 m (Clow et al., 2003).

Our two estimates of differences between modern and Pleistocene MAAT (−4.1, −3.3 °C) are similar to other estimates from rock glaciers, ice glaciers and other proxies. Rather than using ELA or RILA to estimate climates, however, which are difficult or impossible with relict features, we estimated the difference in elevations of the base of modern versus relict rock glaciers (mean 630 m). Differences in the elevations of relict and modern features among watersheds yielded a range of estimates for the difference in climate depending on watershed. Similar variance in ELA levels of Recess Peak (late Pleistocene) advances in the Sierra Nevada was documented by Clark et al. (1994a), central Mexico (White, 1981), and in Japan (Aoyama, 2005) where local topographic control of climate was implicated. Our estimates may be biased by misassignment of age, both of relict features as being LGM, and modern features as being active, and also by the fact that lower elevations for some of the Pleistocene features have been truncated by hanging canyons and mainstem glaciers, and thus do not reflect a climatic low elevation. Nonetheless, both methods we used gave similar results. In other regions, estimates of late Holocene versus late Pleistocene temperatures from rock glaciers ranged from −2 °C (Swiss Alps, Barsch, 1996b; Frauenfelder and Kääb, 2000; Japan, Aoyama, 2005) to −5.5 °C (Chilean Andes; Brenning, 2005) and −6 °C (central Mexico; White, 1981). In the case of the Japanese Alps, the mean difference between minimum elevations of active and relict rock glaciers (310 m) was about half of what we estimated for the Sierra Nevada, and accounted for their temperature estimate (1.9 °C) being about half of ours.

Other alpine and regional montane proxies also give similar Pleistocene–Holocene temperature differences or comparable elevation–displacement ranges to our RIF analyses, although the time ranges in some cases differ from ours. Porinchu et al. (2003) used chrionomid-based lake temperatures to model a 4.7 °C difference between late glacial (post-LGM) and early Holocene climates from a subalpine Sierra Nevada lake in the center of our mapping region. Thompson (1990) summarized isotopic data from the Great Basin to calculate 4.1 °C difference between LGM and the present (Thompson, 1990). In the Sierra Nevada and in the Great Basin, elevational displacement of upper treeline from LGM to the present has been estimated as 580 m for bristlecone pine (*Pinus longaeva*; Thompson, 1988), 600 m for junipers (*Juniperus* spp.; Jennings and Elliott-Fisk, 1993), and 600 m for white fir (*Abies concolor*; Anderson and Smith, 1994), which are surprisingly similar to our rock-glacier estimated mean displacement of 630 m.

5. Conclusions

In this study we field-mapped 421 rock glaciers and related rock-ice features in the central and southern Sierra Nevada, California. We grouped the features into six morphological and location classes that were adapted from conventional nomenclature to fit Sierran conditions and landforms. The six classes separate significantly in geographic condition, size, and shape and climate. Our inventory includes a wider range of features than commonly included in rock glacier studies. In so doing, we draw attention to potentially significant yet overlooked hydrologic conditions of these landforms in semi-arid ranges, such as the Sierra Nevada under warming climates. These include contributions to groundwater storage and to providing wetlands important for alpine biodiversity within otherwise xeric and rockbound environments. Even in RIFs that may lack permanent or glacial ice, rock mantling of these features appears to prolong water storage and runoff through the warm season. These hydrologic roles may become increasingly important in the future, as surface snow- and ice fields melt earlier under rising temperatures.

Using the PRISM climate model, we estimated current temperature and precipitation means for the six location classes. MAAT of 0.3–2.2 °C corroborate the assumption that these features may retain ice in the Sierra Nevada. It also suggests that discontinuous permafrost may exist in some cirques, narrow canyons and exposed plateaus, as it does in the adjacent White Mountains. The PRISM model may over-estimate temperature relative to local topographic conditions of cirques and narrow, steep canyons; it is possible that active RIFs are in disequilibrium with warming conditions of the 20th and 21st centuries, as is suggested elsewhere. Based on mean differences in minimum elevations of modern versus relict RGC, we estimate Pleistocene climates to have been 3.3–4.1 °C colder than current (Holocene) conditions.

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