THERMAL AND HYDROLOGIC ATTRIBUTES OF ROCK GLACIERS AND RELATED LANDFORMS IN THE SIERRA NEVADA, CA

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Fig. 1 Mt Gibbs Rock Glacier and Kidney Lake

Rock glaciers (Fig 1) and related periglacial landforms (Fig 2), collectively rock-ice-features (RIFs), are common in semi-arid mountain regions such as the Sierra Nevada (Millar et al. 2008), but their cryogenic and hydrologic processes remain little studied. Many features appear to contain embedded ice and/or support high groundwater reserves. Due to rock mantles, RIF ice may lag in response to warming temperatures relative to ice glaciers and winter snowpacks, increasing their importance as hydrologic reserves. We infer thermal and hydrologic RIF characteristics from iButton thermochrons placed in outlet streams and rock matrices. Here we summarize results from iButtons deployed in diverse RIF situations over the past 5 years.

Fig. 2 Boulder-stream RIF in Gibbs Cyn and adjacent wetland

Study Sites

We monitor a set of rock glacier- and boulder stream RIFs of the high central Sierra Nevada (Tbl 1).

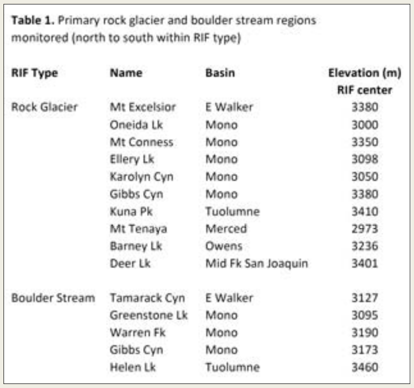

Table 1. Primary rock glacier and boulder stream regions monitored (north to south within RIF type)

RIF Type	Name	Basin	Elevation (m) RIF center
Rock Glacier	Mt Excelsior	E Walker	3380
	Oneida Lk	Mono	3000
	Mt Conness	Mono	3350
	Ellery Lk	Mono	3098
	Karolyn Cyn	Mono	3050
	Gibbs Cyn	Mono	3380
	Kuna Pk	Tuolumne	3410
	Mt Tenaya	Merced	2973
	Barney Lk	Owens	3236
	Deer Lk	Mid Fk San Joaquin	3401
Boulder Stream	Tamarack Cyn	E Walker	3127
	Greenstone Lk	Mono	3095
	Warren Fk	Mono	3190
	Gibbs Cyn	Mono	3173
	Helen Lk	Tuolumne	3460

Goals

- Moniter outlet stream temperatures and infer seasonal persistence of outlet streams
- Monitor summer and winter temperatures of matrices relative to surface air
- Document water bodies and wetlands supported by RIF streams and seepage

Outlet Streams

RIF outlet streams fall into one of two general categories.

1. Outlet streams persist year-round (freeze in winter), suggesting internal ice is present:
    - -- water temp fluctuations are attenuated year-round relative to air temps (Fig 3)
    - -- mean temps of outlet streams are <0°C (annual) and <2°C (summer), and significantly colder than air temps
2. Outlet streams dry by late summer, suggesting internal ice is lacking or transient:
    - -- water temps reflect daily air-temp fluctuations from late-summer thru late fall (Fig 4)
    - -- mean temps of outlet streams are 1-3°C (annual) and 4-8°C (summer)

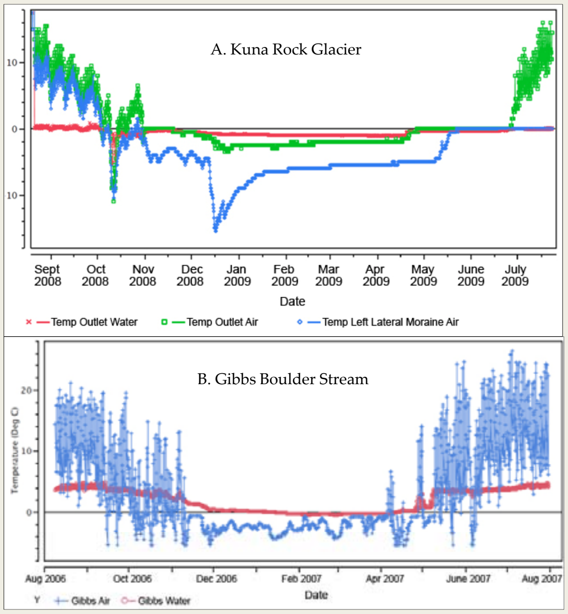

Fig. 3 "Active" rock glacier and boulder stream air and matrix temps

RIF Matrix vs Surface Air Temperatures

Thermochron records of RIF rock matrices (1 m below surface) and surface air temperatures show characteristic patterns:

1. Mean annual temperatures of matrix (-0.1°C) are not significantly different than surface (-0.6°C) for all RIF types regardless of location in the RIF (Tbl 2, Fig 5) as a result of persistent snowpack at these sites

2. Mean summer matrix temps are 1--4° C cooler than surface (6.5°C and 10.2°C, matrix and surface, respectively, $p < 0.001$), and 0--1°C warmer ($p < 0.001$) in winter (Tbl3, Fig 5). The winter pattern is not consistent at all RIF locations.

3. Summer temperature fluctuations in the matrix (Stds, 0.4—1.3°C) are attenuated relative to the surface (Stds, 1.5—4.0°C) (Fig 5)

4. Matrix temps "flatline" near 0°C in late spring/early summer (Figs 4, 5). This appears to result from spring meltwater that refreezes in matrices even when surfaces are dry, as evidenced by field observations (Fig 6) and studies of RIFs in the Swiss Alps (Hoelzle et al. 1999).

5. Matrix temps warm at a much slower rate than surface in summer, showing a significant cubic resistance to warming after temperature thresholds are met (Fig 7). Matrix warming is maximum between surface air temperature ~1°C and 6°C, and becomes asymptotic ~18°C.

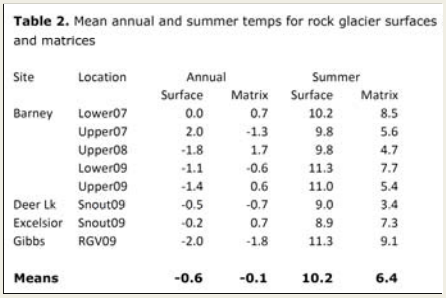

Table 2. Mean annual and summer temps for rock glacier surfaces and matrices

Site	Location	Annual		Summer	
		Surface	Matrix	Surface	Matrix
Barney	Lower07	0.0	0.7	10.2	8.5
	Upper07	2.0	-1.3	9.8	5.6
	Upper08	-1.8	1.7	9.8	4.7
	Lower09	-1.1	-0.6	11.3	7.7
	Upper09	-1.4	0.6	11.0	5.4
Deer Lk	Snout09	-0.5	-0.7	9.0	3.4
Excelsior	Snout09	-0.2	0.7	8.9	7.3
Gibbs	RGV09	-2.0	-1.8	11.3	9.1
Means		**-0.6**	**-0.1**	**10.2**	**6.4**

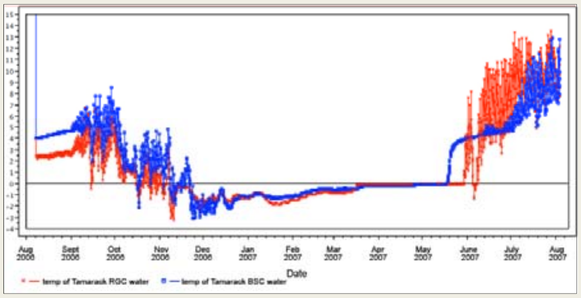

Fig. 4 Outlet streams from "inactive" RIFs

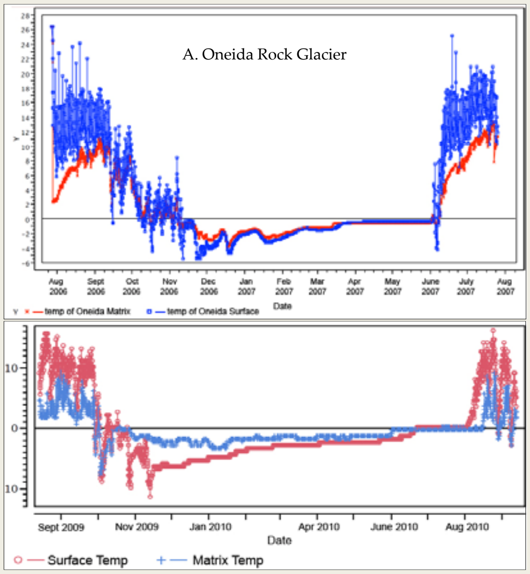

Fig. 5 Surface and matrix air temps at 2 active rock glaciers

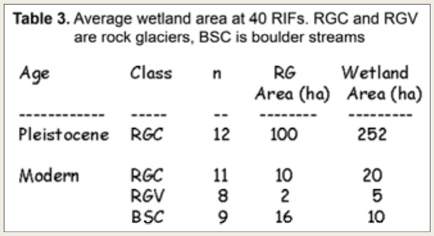

Table 3. Average wetland area at 40 RIFs. RGC and RGV are rock glaciers, BSC is boulder streams

Age	Class	n	RG Area (ha)	Wetland Area (ha)
Pleistocene	RGC	12	100	252
Modern	RGC	11	10	20
	RGV	8	2	5
	BSC	9	16	10

Fig 8. Wetland below Warren Fork boulder stream RIFs

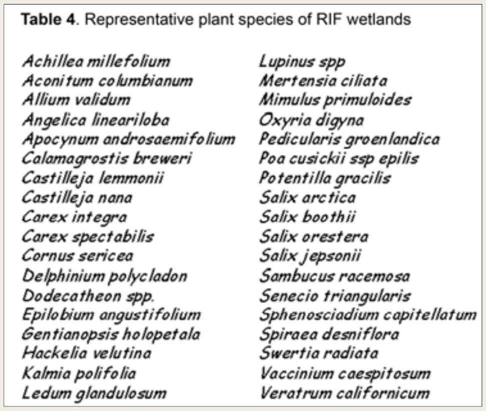

Table 4. Representative plant species of RIF wetlands

Achillea millefolium	*Lupinus spp*
Aconitum columbianum	*Mertensia ciliata*
Allium validum	*Mimulus primuloides*
Angelica lineariloba	*Oxyria digyna*
Apocynum androsaemifolium	*Pedicularis groenlandica*
Calamagrostis breweri	*Poa cusickii ssp epilis*
Castilleja lemmonii	*Potentilla gracilis*
Castilleja nana	*Salix arctica*
Carex integra	*Salix boothii*
Carex spectabilis	*Salix orestera*
Cornus sericea	*Salix jepsonii*
Delphinium polycladon	*Sambucus racemosa*
Dodecatheon spp.	*Senecio triangularis*
Epilobium angustifolium	*Sphenosciadium capitellatum*
Gentianopsis holopetala	*Spiraea desniflora*
Hackelia velutina	*Swertia radiata*
Kalmia polifolia	*Vaccinium caespitosum*
Ledum glandulosum	*Veratrum californicum*

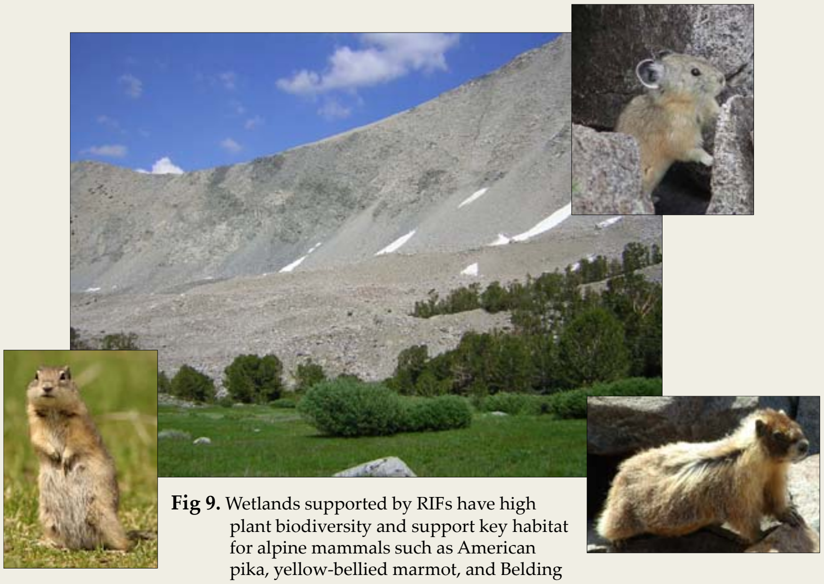

Fig 9. Wetlands supported by RIFs have high plant biodiversity and support key habitat for alpine mammals such as American pika, yellow-bellied marmot, and Belding ground squirrel

Water Bodies and Wetlands Supported by RIF Water Reserves

1. Many high-elevation rock glaciers support persistent lakes below their snouts (Fig 1) whereas other rock glaciers and especially non-rock-glacier RIFs support wetlands (Figs 2, 8, 9)

2. Of 40 RIFs measured, wetlands were larger in extent than the area of the RIF (Tbl 3), about twice the size of adjacent rock glaciers

3. Wetlands in front of RIFs support Alpine Wetland, Subalpine Meadow, and Subalpine Wetland Shrub (Sawyer & Keeler-Wolf 1995) plant communities with high species biodiversity (Tbl 4, Millar et al, in prep); these are key habitat for alpine mammals (Millar & Westfall 2010) (Fig 9)

4. Karst ponds (sink holes) on rock-glacier surfaces reveal stratified ice (to ~10m depth) on uphill and downhill walls (Fig 10), suggesting glaciogenic origin of some RIFs

Active vs Inactive RIFs

Based on patterns above, we propose that **active RIFs** have persistent, near-freezing, water in outlet streams; annual mean matrix temps below freezing and fluctuations attenuated relative to surface; matrices resist warming; and support floristically diverse wetland communities or water bodies at their forefront. **Inactive RIFs** have outlet streams with mean annual water temps considerably above freezing and often dry by autumn; maintain internal thermal properties similar to active RIFs; and usually have dry meadow or shrub communities adjacent to their snouts.

Intensive study of groundwater and/or permafrost processes of RIF landforms will be important for understanding hydrologic contributions as temperatures increase in the future and other sources of water in these semi-arid mountains disappear.

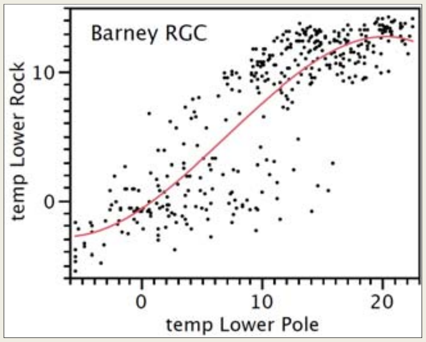

Fig. 7 Resistance of matrix to summer warming

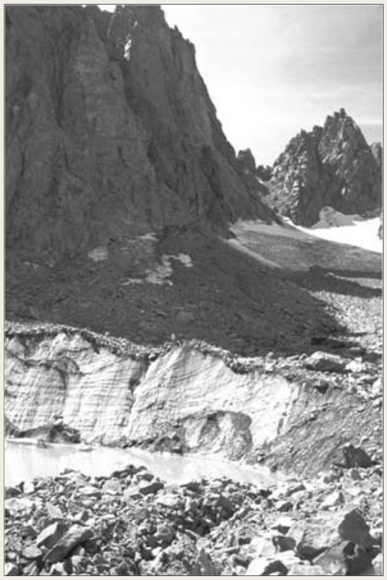

Fig. 10 Karst pond on South Fork Rock Glacier, revealing embedded and stratified ice

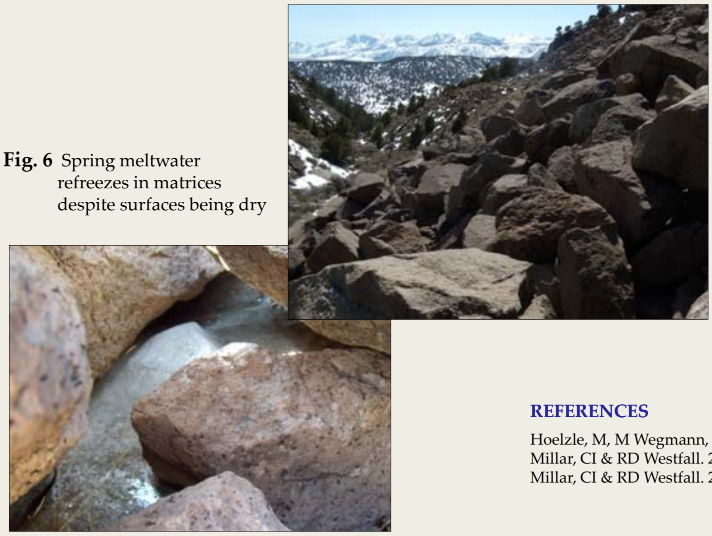

Fig. 6 Spring meltwater refreezes in matrices despite surfaces being dry

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