

REGIONAL CONTEXT, INTERNAL STRUCTURE, AND
MICROBIOLOGICAL INVESTIGATION OF THE
LONE PEAK ROCK GLACIER,
BIG SKY, MONTANA

by

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April 2011

DEDICATION

This thesis is dedicated to

Marie Lola Florentine

my paternal grandmother.
She is in memory - as she was in person - a role model
and inspiration for achieving a higher degree
and accomplishing this research.

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ABSTRACT

This thesis is the first to the author's knowledge to conduct a holistic investigation of the physical, chemical and microbial properties of a rock glacier. The Lone Peak Rock Glacier (LPRG) is located in the Madison Range of southwest Montana on Big Sky Resort property. This thesis focuses on three scales of investigation: regional, landform, and micro.

Regional-scale analysis assessed the role of geology and topography as factors in determining rock-glacier distribution in SW Montana above 2000m. Rock glaciers across alpine landscapes in southwest Montana are preferentially distributed according to rock type, with more rock glaciers occurring in intrusive, foliated intrusive and metamorphic catchments relative to the areal proportion of these rock types than in extrusive and sedimentary catchments. This preferential distribution according to catchment geology is likely due to the affect that geology has on topography and provision of talus.

Landform-scale analysis focuses on internal structure, flow dynamics and surface topography of the LPRG. The relationship between surface topography and subsurface structure is explained by passive roof duplex faulting. This finding has implications for rock-glacier flow dynamics and the development of transverse ridges, a common surface feature of rock glaciers studied worldwide.

Micro-scale analysis characterizes microbiological and geochemical properties of rock-glacier ice and evaluates it as a microbial habitat, exploring potential associations between debris content and microbial activity. Amber ice (containing 0.1% debris by weight) appears to be a more suitable microbial environment than debris-poor ice (containing < 0.01% debris). This finding highlights the importance of debris as a potential nutrient and energy source to enhance microbial viability in rock-glacier ice.

CHAPTER ONE

GENERAL INTRODUCTION

This thesis presents the results of the study of a mid-latitude rock glacier - Lone Peak rock glacier (LPRG), located on Big Sky Resort property - in the Madison Range of southwest Montana. The research utilizes an integrated Earth systems approach and focuses on three scales of investigation: regional, landform, and micro. Manuscript one, chapter two includes two scales of analysis. The first is regional-scale analysis examining the distribution of rock glaciers across alpine landscapes in southwest Montana, assessing the role of geology and topography – as factors in determining rock-glacier distribution in SW Montana above 2000m. The second is landform-scale analysis investigating the internal structure, flow dynamics and surface topography of the LPRG. Manuscript two, chapter three, is a micro-scale analysis characterizing the microbiological and geochemical properties of rock-glacier ice and evaluating it as a microbial habitat, exploring potential associations between debris content and microbial activity.

Previous studies of the distribution of rock glaciers in mountainous regions have identified geology, climate and topography as defining parameters for rock-glacier development and thus their spatial distribution (Andre, 1994; Angillieri, 2009; Brazier et al., 1998; Johnson et al., 2007; Morris, 1981). However, the relative importance of these three factors vary by geographic location (Andre, 1994; Brazier et al., 1998; Brenning, 2005; Johnson et al., 2007).

Rock glaciers develop in climates characterized by periglacial conditions (Shaw, 1987). Areas above 2000 m elevation in the mountain ranges studied in southwest

Montana meet these periglacial conditions (semi-arid with mean annual precipitation ranging from 25-183 cm and mean daily minimum temperature ranging from -13 to 1°C). Therefore, the study area is climatically suitable for rock-glacier formation. Thus, formation and distribution of rock glaciers in southwest Montana above 2000 m is likely limited by geology or topography or a combination of these factors (Shaw, 1987).

Rock glaciers ($n=383$) and cirques ($n=462$) were mapped for the Beartooth Plateau, and the Absaroka, Gallatin, and Madison Ranges of southwest Montana using Google EarthTM. Detailed information on the physical parameters for the 383 rock glaciers was also tabulated. The distribution of cirques was used as an approximation for whether or not antecedent topographic conditions were suitable for rock-glacier development. These data were used to address the hypothesis that the distribution of rock glaciers and cirques in southwest Montana above 2000 m was preferential according to rock type.

Internal composition and structure of the LPRG were assessed by geophysical investigations that included seismic and ground penetrating radar (GPR) surveys. Each survey was performed along transverse and longitudinal profiles at the LPRG in order to determine thickness of the unfrozen talus layer, and detect underlying structures beneath the talus/ice boundary. Historic borehole data and observations from excavation of the uppermost, active section of the LPRG helped corroborate geophysical data. The combined dataset was used to evaluate the hypothesis that there was a relationship between the transverse ridges visible at the surface and the internal structure of the LPRG.

Viable microbes have been detected in debris-rich ice from subglacial environments elsewhere (Skidmore et al., 2000; Foght et al., 2004). In such settings debris provides increased nutrients and energy sources for microbes and greater surface area for interstitial water films even at subzero temperatures (e.g. Skidmore et al., 2000; Skidmore et al., 2005; Price, 2007). In contrast, rock-glacier ice has not previously been considered as a microbial habitat. Ice samples were collected at the LPRG after excavation of ~3 m of unconsolidated talus. The ice samples included amber ice, defined as ice containing ~0.1% debris by weight, and clean ice with no measurable debris (< 0.01%). Microbial enumerations included direct cell counts and heterotrophic viability assays on both clean and amber ice samples. Geochemical analysis was also performed on clean and amber ice samples to assess nutrient availability. Together, these data were used to assess rock-glacier ice as a microbial habitat, testing the following hypotheses: 1) A greater number of viable microbes are evident in amber ice relative to clean ice at the LPRG; 2) Concentration of nutrients in amber ice is higher than in the clean ice.

CHAPTER TWO

THE ROLE OF GEOLOGY IN ROCK-GLACIER DISTRIBUTION AND INTERNAL
STRUCTURE: A CASE STUDY FROM SW MONTANAContribution of Authors and Co-Authors

Manuscript in Chapter 2

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Contributions: Dr. Curtis Link was responsible for the seismic refraction survey. His equipment and expertise were used in performing the surveys and processing the raw seismic refraction data.

Co-author: Dr. Colin Shaw

Contributions: Dr. Colin Shaw was also involved in data interpretation, processing LiDAR data using ArcGIS software, and conducting Fourier transform analysis.

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Abstract

Rock glaciers are common geomorphic features of mountain environments. However, studies on both their spatial distribution and internal structure are relatively limited. This study identified 383 rock glaciers in the Beartooth Plateau and the Absaroka, Gallatin, and Madison ranges of southwest Montana. Catchment geology appears to control the distribution of rock glaciers throughout the study area due to its role in creating antecedent topography suitable for rock-glacier development, as well in the production of talus. An analysis of the internal composition and structure on the active portion of the Lone Peak Rock Glacier (LPRG), Madison range, southwest Montana revealed links between internal structure and surface topography that are likely related to debris content in the internal ice layers. Seismic refraction surveys performed along transverse and longitudinal profiles corroborate borehole and excavation data by demonstrating a consistent and distinct transition from unconsolidated (unfrozen) surface debris (2-3 m thick) to a consolidated (frozen) subsurface material. GPR data along similar longitudinal and transverse profiles identified interbedded debris-rich layers which dip upslope toward the rock-glacier headwall along the longitudinal profile, and which show correspondence with transverse ridges at the surface. The presence of fault bounded blocks (i.e. structural horses) detected in the longitudinal GPR data suggests passive roof duplex thrust faulting, in which the roof sequence - unconsolidated (unfrozen) debris – has not been displaced toward the foreland (down glacier), but has been underthrust by the duplex. This study highlights geology as a potentially an important factor in both the distribution of rock glaciers and their flow properties and thus should be analyzed to improve understanding of their geomorphic significance on the landscape and as indicators of (paleo)climatic conditions.

Introduction

Rock glaciers are talus-mantled geomorphic features ubiquitous in mountain environments. They are generally located in continental, dry, winter-cold mountains (Barsch, 1996) but active rock glaciers have been observed worldwide, at a broad range of elevations (Barsch, 1996). Rock glaciers flow due to the inferred presence of internal ice, are bordered by steep margins, and are commonly characterized by transverse ridges. Rock glaciers have been identified as important stores of water in warming climates, and have been shown to be important agents of erosion and mass transport in alpine areas (Millar and Westfall, 2008; Barsch, 1992). However, rock-glacier distribution has typically been documented only in small areas of a few mountain ranges, e.g. the Southern Alps of New Zealand (Brazier et al., 1998), the Andes (Brenning, 2005), the Rocky Mountains (Johnson et al., 2007), and the Sierra Nevada (Millar and Westfall, 2008). Further, a number of these studies have drawn on relatively small sample sizes; 39 rock glaciers (e.g. Brazier et al.), 48 rock glaciers (Johnson et al., 2007).

In contrast to traditional alpine glaciers, which are primarily fed by snow and consist of ice, rock glaciers contain a considerable component of rock debris, which is contributed as talus (Hamilton and Whalley, 1995). They are frequently characterized by transverse ridges on the talus surface (Barsch, 1996), however, no definitive explanation of the formation of transverse ridges exists, though there are multiple working hypotheses as to their genesis (e.g. Degenhardt, 2009; Fukui et al., 2008; Shean and Marchant, 2010; White, 1987). Transverse ridges have been described as the result of exogenic processes -

i.e. thermal alteration (Barsch, 1996), or change in debris input – and/or endogenic processes – i.e. thrust faulting (Arenson et al., 2002; Fukui et al., 2007; White, 1971).

The internal ice body of a rock glacier is typically buried beneath decimeters to meters of rock debris (Elconin and LaChapelle, 1997), making investigation of the internal composition and structure of rock glaciers difficult. The debris-poor ice in the internal core exists as interstitial ice between debris (Haeberli et al., 2006); it may be sedimentary (seasonal snow accumulation, avalanching, rock fall) or periglacial (refreezing of meltwater seeping into pre-existing sediments) (Elconin and Lachapelle, 1997). Thus, the ice within rock-glacier systems is polygenetic and hence the internal composition and structure of rock glaciers are characterized by complexity (Haeberli et al., 2006). Coring and borehole techniques provide single point observations of the internal structure of rock glaciers (Table 3; Haeberli et al., 2006). Geophysical methods, such as ground penetrating radar (GPR) and seismic refraction surveys provide subsurface data that reveal the composition and internal structure of rock glaciers in two dimensions (Berthling et al., 2000; Fukui et al., 2007; Fukui et al., 2008; Hausmann et al., 2007; Isaksen et al., 2000). By combining transverse and longitudinal geophysical profiles some limited three-dimensional information can be inferred (e.g. Fukui et al., 2007). Theoretical analysis suggests that they are the surface expression of thrust faulting but, transverse ridges have not previously been mechanistically correlated to internal structure (Arenson et al., 2002; Barsch, 1996; Kaab and Weber, 2004; Potter, 1972; White, 1971).

Northern Rocky Mountains (NRM)

The Northern Rocky Mountains (NRM) were extensively glaciated during the Pleistocene, as is evidenced by an array of cirques present throughout these ranges. Modern periglacial features are evident in mountain ranges throughout the NRM, including rock glaciers. Rock glaciers have been mapped in some areas of the NRM (e.g. Johnson et al., 2007), but not in southwest Montana. The study area in southwest Montana contains the Beartooth Plateau, Absaroka, Gallatin, and Madison ranges. These ranges are geologically diverse, containing mixed foliated metamorphic-intrusive rocks, extrusive volcanic rocks, fine grained sedimentary rocks and crystalline intrusive rocks. “Absaroka” for this study refers to the western section of the Beartooth mountain range, not the Absarokas in Wyoming. The geologic diversity of these ranges allows an analysis of the importance of catchment geology on rock-glacier distribution in the study area.

Objectives

The study objectives were (i) to map the regional distribution of rock glaciers in a portion of NRM that has not been previously studied and analyze the role of catchment geology on this distribution, and (ii) to investigate potential relationships between rock-glacier surface topography – particularly the characteristic transverse ridges - and internal structure at the Lone Peak rock glacier (LPRG) one of the larger rock glaciers in the wider study area.

Study area description

The NRM are continental and mid-latitude. The four mountain ranges (Beartooth Plateau and the Absaroka, Gallatin, and Madison ranges), in southwest Montana considered in this study are (i) climatically similar, defined by a climatic regime above 2000 m that is appropriate for rock-glacier development (semi-arid with mean annual precipitation ranging from 25-183 cm and mean daily minimum temperature ranging from -13 to 1 °C); (ii) topographically similar, defined by a general north-south orientation and previously glaciated terrain; but (iii) geologically diverse, defined by catchments that include extrusive, foliated intrusive, intrusive, metamorphic and sedimentary rock types (Figure 2.1a and 2.2).

Lone Peak is located in the Madison Range, and is flanked by radiating rock glaciers on almost all aspects (Figure 2.1a). The Lone Peak rock glacier (LPRG) is the largest of these rock glaciers and is located on the property of Big Sky Resort. It is 1.7 km in length, ~60 –150 m wide and ranges from 2600 – 3109 m in elevation. Its geomorphology was characterized by Goolsby (1972). The surface of the LPRG is characterized by blocky porphyritic andesite with a small percentage of angular siliceous siltstone. Goolsby (1972), divided the LPRG into three segments based on morphologic and stability assessments that are potentially representative of separate episodes of neoglacial activity (Figure 2.1b). The active segment is the uppermost segment, located in the northeast-facing cirque of Lone Peak. This active segment has an average slope of

seven degrees and a 40 degree frontal scarp, is characterized by transverse ridges separated at regular intervals by shallow ($\sim 2\text{-}3$ m) furrows, and moves at ~ 20 cm yr⁻¹ (Goolsby, 1972). The other two segments are less active as indicated by the increased presence of lichen and grasses, and the absence of transverse ridges and steep margins.

Methods

Rock-glacier distribution

Mapping

The distribution of rock glaciers and cirques in southwest Montana were mapped using Google Earth™ and ArcGIS. Features were identified as rock glaciers if they exhibited the following attributes: talus-fed, lobate in shape, bordered by steep margins, and originated above treeline. Rock glaciers below treeline – roughly fewer than one dozen - were not considered. This morphologic definition does not require the landforms identified as rock glaciers to have an *a priori* location (valley-side or within a cirque) (Martin and Whalley, 1987), formation process (permafrost or glacigenic) (Barsch, 1992; Potter, 1972), or internal composition (ice-cored or ice-cemented) (Clark et al., 1998). Features were identified as cirques if they exhibited the following attributes: “hollow, open downstream but bounded upstream by the crest of a steep slope (‘headwall’), which is arcuate in plan around a more gently sloping floor” (Bishop and Shroder, 2004). Morphologic characteristics used to identify rock glaciers and cirques were identified from an aerial perspective of ~ 6 km above ground level using Google Earth™.

The latitude and longitude of rock glaciers and cirques were tabulated, imported to ArcGIS, and then correlated to rock type using a point polygon overlay technique (Figure A.1). The elevations of rock glacier headwall and terminus were recorded, as well as aspect. The minimum elevation of a rock-glacier terminus measured was 2175 m. This elevation represents the rock-glacier threshold, defined as the minimum elevation considered for rock-glacier distribution in this study.

Rock-glacier internal structure

Field-based

A ski tram station was built directly below the terminus of the uppermost segment of the LPRG in 1995, and during tram construction four boreholes were drilled into the rock glacier to depths of 30 m, 35 m, 37 m and 90 m; none reached bedrock (Figure 2.3a). Downslope movement of the tram station has been closely monitored by the ski resort since its construction. Excavations on the rock-glacier surface in August 2009 uncovered ~ 3 m of unconsolidated talus and colluvium overlying an internal ice body (Figure 2.3b). Ice blocks were recovered with a chainsaw as opposed to coring due to the presence of large rocks embedded in the ice at a depth of ~ 20 cm (Figure 2.3b).

Seismic refraction surveys were performed along transverse and longitudinal transects of the rock glacier in the summer of 2009 (Figure 2.3a). Geophones were positioned at 1 m intervals along an 87 m transverse transect and a 197 m longitudinal transect. A sledgehammer seismic source was used at 5 m shot stations, stacking the data

8 times at each location. The data were recorded using a Geometrics Geode recording system with 0.125 m s^{-1} sampling period and 4000 samples per trace. The shot records were processed by picking first arrival times and then analyzed using both refraction tomography and layered solutions with Rayfract® software, Intelligent Resources Inc.

Ground penetrating radar data were collected along transverse and longitudinal transects similar to seismic refraction measurements (Figure 2.3a). A MALA Geoscience Ramac GPR system was used for data acquisition and RadExplorer® software, DECO Geophysical Ltd., was used to process the data. Lower frequency data (25 MHz and 50 MHz) were collected in attempt to detect the contact between rock glacier and bedrock. Data collected for these frequencies reached depths of $\sim 75 \text{ m}$ (50 MHz) and $\sim 100 \text{ m}$ (25 MHz), yet bedrock still was not detected. Therefore, only the results of the 100 MHz data are presented since these data show the internal structure of the rock glacier at the highest resolution. An average radar ice velocity of 0.16 m ns^{-1} was used to convert from time to depth (Isaksen et al., 2000).

LiDAR

LiDAR data for the Lone Peak watershed were downloaded from the National Center for Airborne Laser Mapping website (<http://calm.geo.berkeley.edu/ncalm/ddc.html>). These data were analyzed using ArcGIS software to generate a high resolution topographic map of the uppermost section of the Lone Peak rock glacier (Figure 2.3a, 2.6a, 2.7c). LiDAR data was used to characterize

surface slope of the LPRG and produce high resolution surface topography profiles for analysis.

Results

Rock-glacier distribution

Three hundred eighty three rock glaciers were identified in the study area. Rock glaciers occurred in catchments within sedimentary (n=25), intrusive (n=32), extrusive (n=31), foliated intrusive (n=207), and metamorphic (n=88) rock types (Figure 2.2a). The Gallatin Range, which consists primarily of extrusive igneous and sedimentary rock, supported nine (2% of the total) rock glaciers. The Beartooth Plateau, consisting of foliated intrusive rock, supported 141 (37% of the total) rock glaciers. The Absaroka Range, consisting of a combination of extrusive, foliated intrusive, intrusive, and metamorphic rock types, supported 113 (30% of the total) rock glaciers. The Madison Range of intrusive igneous, metamorphic, and sedimentary rock types had 120 (31% of the total) rock glaciers. Rock glaciers were more abundant in catchments with foliated intrusive, intrusive, and metamorphic rock types relative to those with extrusive igneous and sedimentary rock types (Figure 2.2a). A total of 462 cirques were mapped within the study area and occur in rock types as follows, extrusive (n=67), foliated intrusive (n=220), intrusive (39), metamorphic (n=107), and sedimentary (n=29) (Figure 2.2b). The aspect of 68% of all rock glaciers was between north and east in all mountain ranges

(Figure 2.5a). The elevations of rock glacier head and termini had no statistically discernable trend from east to west (Figure 2.5b).

A Pearson's chi-squared statistical test was used to analyze whether the distribution of rock glaciers and cirques in the study area was in proportion to the areal distribution of rock type in the study area above the rock-glacier threshold (2175 m elevation). There was a significant difference between the expected and actual distribution of both rock glaciers and cirques according to rock type ($p < 0.001$, $df=4$) (Figure A.2). The preferential distribution of rock glaciers according to rock type indicates that catchment geology plays a role in rock-glacier development and distribution, while the preferential distribution of cirques according to rock type suggests that suitable topography for rock-glacier development is a function of bedrock geology.

Rock-glacier internal structure

Transverse ridges at the LPRG are well illustrated when characterized by slope angle (Figure 2.7c). Fourier transform analysis of rock-glacier surface topography suggests a dominant frequency of ~ 8 m for the spacing between ridges. The stratigraphy of the LPRG is also illustrated in Figure 2.3. Borehole data indicate that below the terminus of the active lobe the upper 10 m consisted of unconsolidated, unsorted angular talus and colluvium, similar to the talus at the surface (Figure 2.3d; McCarty, 1995). Beneath the unconsolidated debris alternating layers of ice/rock aggregate were evident from a depth of 10 - 90 meters (McCarty, 1995). Ice rock ratios in this lower section varied between rock-dominated from 10-60 m and to ice-dominated from 60-90 m

(Figure 2.3d). Excavations in the center of the active lobe of the rock glacier revealed ~ 3 m of relatively unsorted angular talus and colluvium underlain by ice (Figure 2.3c). The ice samples recovered were bubble-rich and contained a 10 cm debris band (~0.1% debris) dipping up-ice (Figure 2.3b).

Refraction velocities for the seismic survey transects were relatively consistent along their length with 400 m s^{-1} for the upper layer detected, and 3500 m s^{-1} for the lower layer detected at a depth of 2-3 m. This second velocity of 3500 m s^{-1} is consistent with other observed refraction velocities for ice (Hausmann et al., 2007; Shean and Marchant, 2010). The upper layer is an unfrozen talus layer 2-3 m thick that was also observed at the excavation site (Figure 2.6d). The transverse and longitudinal seismic refraction surveys both demonstrate this same sequence of 2-3 m of unfrozen talus underlain by a frozen layer of ice and debris of unknown thickness, estimated to be > 50 m (Figure 2.6b,c). GPR data on the longitudinal profile of the LPRG show up-slope dipping structures suggesting a layering with the ice-rock unit (Figure 2.6c). These data are interpreted as a sequence of alternating debris-poor and debris-rich layers dipping up-glacier in the longitudinal direction. These alternating layers are evident to a depth of ~10 m in the GPR detected layers (Figure 2.6c). Alternating debris-poor and debris-rich layers were observed present in the ice block sample to a depth of ~ 0.25 m (Figure 2.3b). The transverse GPR profile suggests a synclinal bowl structure (Figure 2.6b) that is similar to the structures observed in transverse sections of Arctic rock glaciers (Fukui et al., 2007; Fukui et al., 2008). These structures also occur in glacial settings with longitudinal flow and transverse compression (Elconin and Lachapelle, 1997). It is unlikely that the LPRG

is experiencing transverse compression at present since it is not topographically connected with the cirque walls on its sides. The LPRG is currently separated from the north cirque wall by a steep gully (Figure 2.1b), however compression in the longitudinal direction is possible; see discussion of the longitudinal GPR data.

Discussion

Rock-glacier distribution

Role of geology

The distribution of rock glaciers was influenced by rock type with foliated intrusive, metamorphic, and intrusive rock types having more rock glaciers than extrusive and sedimentary rock types. The preferential development of rock glaciers on certain lithologies is likely due in part to differences in physical weathering of the rock types. Contribution of blocky debris is important for rock-glacier development, and is presumably controlled by freeze and thaw cycles (Degenhardt, 2009). The talus mantle provides insulation (Stenni et al., 2007), protecting the subsurface from surface temperature fluctuations. Balch ventilation occurs in blocky talus where cold winter air is trapped between talus interstices (Johnson et al., 2007). Blocky talus mantles on rock glaciers keep subsurface temperatures colder than ambient air temperatures both due to insulation and Balch ventilation.

The distribution of cirques that supported rock glaciers versus cirques that did not support rock glaciers is preferential according to rock type. This indicates that rock type affects suitability of topography for rock-glacier formation. Physical and chemical weathering characteristics of different rock types result in topographically diverse landscapes. Terrain and topography play a role in rock-glacier development because steep slopes are necessary for talus production (Hamilton and Whalley, 1995). Cirques provide talus sources and sheltered locations for ice preservation that are conducive to rock-glacier development. Valley-side locations may also exhibit these properties, but they are not easily catalogued as landforms. Hence, the distribution of cirques across the study area was used as an indication of potentially favorable antecedent topographic conditions within each rock type. The number of cirques in extrusive igneous rock type that had rock glaciers was 143% less than the expected based on areal coverage by rock type. Though cirques exist in catchments underlain by extrusive igneous rocks, they tend to not support rock glaciers. The numbers of cirques in foliated intrusive and metamorphic rock type with rock glaciers were 8% and 16% greater than the expected whereas the number of cirques in intrusive and sedimentary rock type with rock glaciers was within 2% of expected. Cirques in these latter rock types support rock glaciers.

Northeasterly rock-glacier aspect

Rock glaciers in southwest Montana generally have a northeasterly aspect with 35% of the total (n=139) oriented directly NE, whereas rock glaciers of the European

Alps generally have a northerly aspect, with 25% of the total (n=205) oriented N (Barsch, 1996). Rock-glacier orientation to the north in the northern hemisphere – Montana and the European Alps – reflects in part the fact that north facing aspects have a greater degree of shading from incoming solar radiation than southerly aspects. Rock-glacier orientation to the northeast suggests an additional control, perhaps delivery of precipitation by westerly winds. Both the mountains of southwest Montana and the Swiss Alps are located at latitudes that are climatically dominated by the westerly winds. However, Montana ranges are generally oriented N/S or NW/SE, perpendicular to the westerly winds delivering precipitation, in contrast to the Alps that generally trend E/W.

The strong northeasterly aspect of rock glaciers in southwest Montana may also be due to antecedent topography, i.e. the preferential availability of cirques. Cirques in southwest Montana tend to have a northeast orientation due to past glacial activity, again due to moisture delivery from westerly winds (Locke, 1990). Cirque orientation is not the only reason for overall northeasterly rock-glacier aspect; 43% of the dataset were rock glaciers not located within cirques. Rock-glacier development is therefore not necessarily linked to past glaciations via cirque topography.

The role of geology on rock-glacier distribution in other mountain ranges

The role of geology on rock-glacier distribution pertains to the provision of talus and antecedent topography. In the Southern Alps, New Zealand and the central Andes, climate and topography were argued as dominant factors defining favorable conditions

for rock-glacier development (Brazier et al., 1998; Brenning, 2005). Brenning (2005) in a study of the central Andes (33-35°S) determined the controlling factors on rock-glacier distribution to be climatic and topographic: rock glaciers were favored in areas around the 0°C isotherm in basins with contributing areas of 0.5 – 1.0 km² that were convergent to concentrate talus. In these studies topography is indicated to be an important factor in rock-glacier distribution as observed in southwest Montana.

In the Lemhi range of northern Idaho Johnson et al. (2007) argued that rock-glacier development and distribution were determined by lithology and insolation as a function of topographic shading. Lithology controlled Balch ventilation and surface-water availability (Johnson et al., 2007). Surface-water availability was variable due to differences in the hydrology of karsted topography associated with carbonate rock types versus non-karsted topography associated with metasedimentary and quartzite rock types (Johnson et al., 2007). We did not analyze the hydrologic impacts of rock type but there are some similarities to our findings, that lithology had an important control on rock-glacier distribution due to its affect on talus production, and perhaps the process of Balch ventilation.

Rock-glacier internal structure

Stratigraphy

The stratigraphy of the internal ice mass of a rock glacier can vary significantly between parts of the rock glacier (Elconin and Lachapelle, 1997). Ice coring with a

mechanical diamond-bit drill at the Foscagno rock glacier in the Italian Central Alps recovered a core with the following stratigraphy: unconsolidated debris (0-2.5 m), partially frozen ice and rock (2.5-4 m), massive ice (4-7.65 m), and frozen debris with lenses of segregated ice (7.65-14.5 m) (Guglielmin et al., 2004). Ice coring with a hand-powered Sipre-corer at the Galena Creek rock glacier in the Absaroka Range of Wyoming recovered a 9.5 m core consisting entirely of clean, bubble-rich ice with silty debris layers spaced roughly at 20 cm intervals throughout the 9.5 m core (Steig et al., 1998). The stratigraphy of the LPRG demonstrates ice types similar to those described in both studies. At the excavation site at the LPRG unconsolidated talus overlies a short interval (0.25 m) of bubble-rich ice with silty debris layers that is underlain by a mixed ice and rock layer.

Structure

The GPR data for the LPRG (Figure 2.6), has some similarities to GPR studies on a rock glacier on James Ross Island, Antarctic Peninsula that revealed up-slope dipping debris bands in the longitudinal survey, and synclinal structures inclined toward the center part of the rock glacier in the transverse survey (Fukui et al., 2007; Fukui et al., 2008). Similarly a GPR study on rock glaciers on Prins Karls Forland, Svalbard, revealed up-slope dipping debris bands in the longitudinal survey (Berthling et al., 2000). GPR findings were combined with velocity measurements on two rock glaciers in Svalbard to describe composition, flow and development of the landform (Isaksen et al., 2000).

Isaksen et al. (2000) estimate an approximate age of the rock glaciers at 4000 years, based on velocity data ($0.08 - 0.10 \text{ cm yr}^{-1}$) and note highest velocities toward the headwalls, with decreasing velocities toward the termini. Velocity measurements were collected via monitoring the rock-glacier surface from 1994-1997. Up-slope dipping layers in the frontal part of the rock glaciers were detected, and were interpreted to be alternating layers of frozen sediments and buried rockslide debris (Isaksen et al., 2000). Similar structures were detected at the LPRG. The structure of frozen substrate at the LPRG is of up-slope dipping layers on a centimeter- to meter- scale and structural horses (or fault bounded blocks) on the meter-scale (Figure 2.7).

Surface topography and deformation of the LPRG

The active upper lobe of the rock glacier is $\sim 310 \text{ m}$ in length. There is a dominant wavelength of 8 m from ridge to ridge on this active segment and an average annual velocity of $\sim 0.16 \text{ m yr}^{-1}$ (average velocity $\sim 0.15 \text{ m yr}^{-1}$ for 1972-1974 near the tram station, and $\sim 0.17 \text{ m yr}^{-1}$ from 1990-1995 just above the tram station). Assuming the current rock glacier velocity (0.16 m yr^{-1}) has been constant in the recent past suggests that the upper lobe is approximately 1900 years old. This age estimate is comparable to rock glacier ages in the region, such as at Galena Creek in the Absaroka Range, Wyoming (^{14}C ages of 2250 ± 35 and $2040 \pm 35 \text{ yrs BP}$), and further south in the Madison Range (Konrad and Clark, 1998; Shaw, 1987).

Multiple working hypotheses have been proposed to explain the formation of transverse ridges in rock glaciers. These include internal factors such as the dynamic evolution of transverse ridges in response to compressive flow (Potter, 1972; Wahrhaftig and Cox, 1959; White, 1987), and hypotheses relating transverse ridges to overthrusting and “bulging” (Kaab and Weber, 2004) and external processes such as an increase in debris input (Barsch, 1996). At the LPRG, the up-slope dipping structures observed in the longitudinal GPR profile data reveal structural “horses”, or fault bounded blocks (Root, 1990). We propose that these structural “horses” are associated with passive roof duplex faulting. Duplex faulting occurs where there are two decollement layers, i.e. where thrust-faulted material is sandwiched by non-thrusting layers. Passive roof duplex faulting is characterized by duplex faulting where the roof sequence has not been distally displaced (toward the toe), i.e. where the roof sequence is passive. The talus mantle at the LPRG is analogous to a passive roof that has been underthrust by the duplex faulting of ice and debris layers beneath it (Figure 2.7). Thirteen structural horses were identified in the longitudinal GPR survey (Figure 2.7) and appear to be related to thirteen prominent (1-2 m relief) ridges that are perpendicular to the GPR survey transect (Figure 2.7). Thus, the transverse ridges characterizing the surface topography at the LPRG appear to be the surface expression of passive roof duplex faulting.

Detachment surfaces are the planes of failure along which duplex faulting occur. and result from a mechanical contrast between materials (Brocher et al., 2004). Experiments suggest that frozen debris in glacial systems is weaker than clean ice at near-zero temperatures (Lawson, 1996). We hypothesize that englacial debris layers at depth

(30 - 90 m) and near the surface are weaker than clean ice, and so provide detachment surfaces that accommodate compression via passive roof duplex faulting. Analogue experiments that model rock-glacier deformation using Xanthan gum, sand and gravel, have shown that transverse ridges are more likely to develop when heterogeneous materials are present (Kaab and Weber, 2004). Our results support this finding and furthermore suggest that heterogeneous materials are necessary for the development of transverse ridges.

It has previously been suggested that transverse ridges are the product of thrusting, which is caused by compressive flow in rock glaciers (Degenhardt, 2009; Fukui et al., 2008; Shean and Marchant, 2010; White, 1987). Thrusting however has not been invoked to explain either a direct connection between individual transverse ridges to subsurface structures or a specific structural regime. Our passive roof duplex faulting interpretation of GPR data at the LPRG is consistent with findings from previous studies on the internal composition and structure of rock glaciers. Compression likely characterizes the structural setting of our longitudinal GPR survey. We hypothesize that the LPRG is experiencing proximal extension (toward the rock-glacier headwall) and distal shortening (toward the rock-glacier terminus), as is demonstrated in other gravity-driven deformation systems such as in fold belts on passive tectonic margins (Butler and Paton, 2010; Rowan et al., 2004). Deformation is partitioned within deepwater fold and thrust belts in unlithified sediment via localized thrusting, ductile deformation, and lateral compaction. Similarly diversified mechanistic explanations for rock-glacier deformation

are likely; rock glaciers are gravity-driven deformation systems, and are furthermore rheologically complex due to compositional heterogeneity (debris and ice).

This study of the LPRG explored deformation via localized thrusting but future studies could consider potential ductile deformation and lateral compaction components also. Further investigations could include: a) velocity measurements and strain analysis to investigate the existence of a zone of extension near the rock-glacier headwall and a zone of compression near the toe of the active lobe; b) more extensive GPR work to determine subsurface structures toward the headwall and the sub-surface extent of up-slope dipping structures; and c) additional coring to bedrock.

Summary

Geology is a key factor in the development and distribution of rock glaciers in southwest Montana above an elevation of 2175 m, approximately coincidental with the 0°C isotherm. Rock glaciers in our study area were preferentially distributed in catchments with metamorphic, intrusive, and foliated intrusive rock types relative to those with extrusive igneous and sedimentary rock types. Catchment geology determined antecedent topography with regard to the presence of cirques, and presumably talus production, which affect rock-glacier development and hence distribution. Rock-glacier orientation to the northeast suggests that the topographic affects on insolation and the delivery of precipitation affect rock-glacier distribution, and that rock-glacier distribution is somewhat, though not entirely, affected by previous glaciation.

Rock glaciers have variable internal composition and structure; they cannot be oversimplified. Our study indicates that transverse ridges, a common geomorphic feature used to identify active rock glaciers, could be the result of passive roof duplex faulting. Passive roof duplex faulting is a type of thrust faulting that commonly is observed in gravity-driven deformation systems. This interpretation is consistent with data presented on the composition and structure of the internal ice body at the LPRG. Additional work at other rock glaciers would be required relating surface topography to internal structure to determine how widespread similar endogenic, deformational processes are. This study highlights geology can be an important factor in both the distribution of rock glaciers and their flow properties and thus should be analyzed in future studies to improve understanding of their geomorphic significance on the landscape and as indicators of (paleo)climatic conditions.

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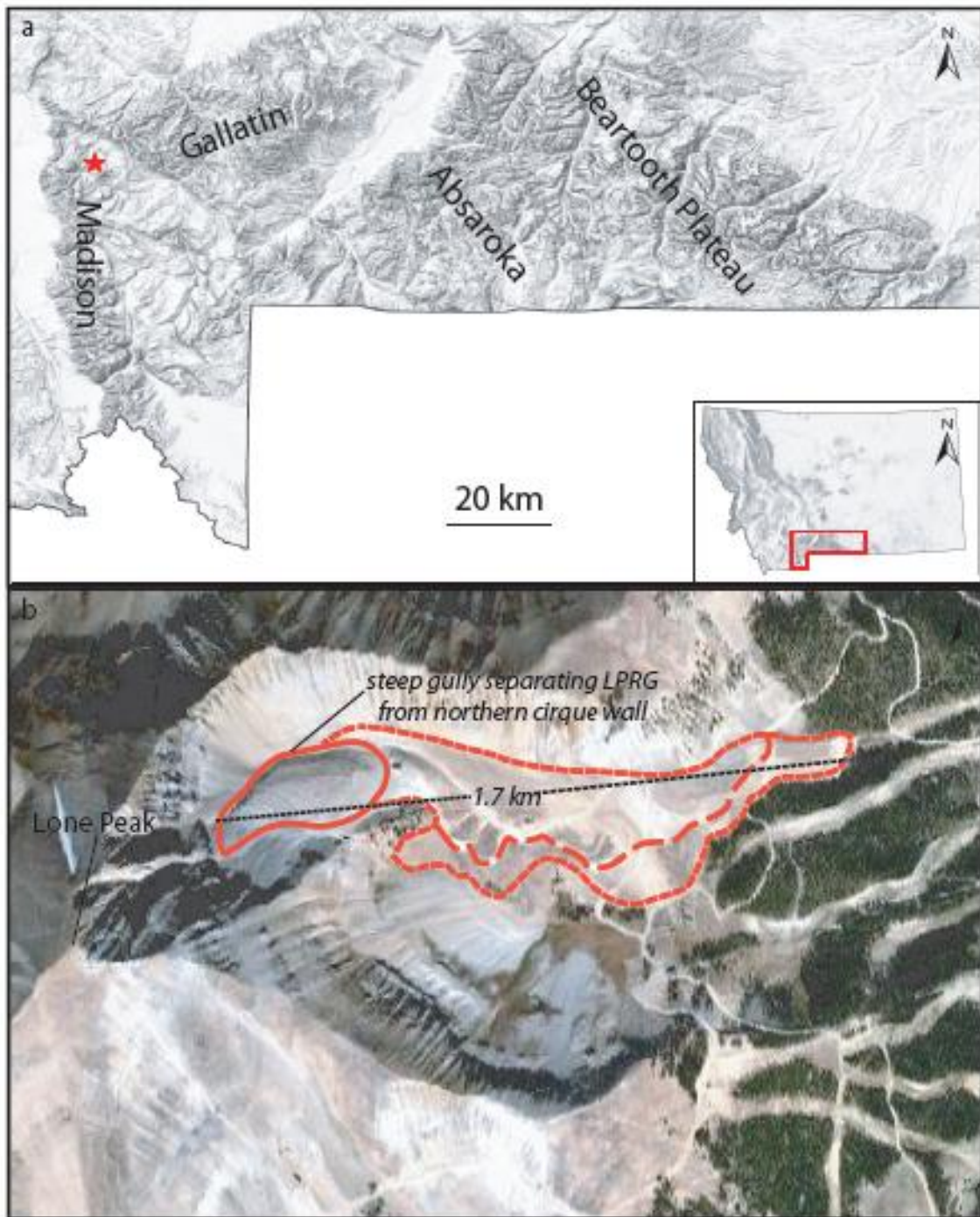


Figure 2.1 (a) Study area in southwest Montana; star illustrates the location of the Lone Peak rock glacier (LPRG). (b) The LPRG, with different segments outlined; uppermost, active segment which is the subject of this study outlined by solid red line.

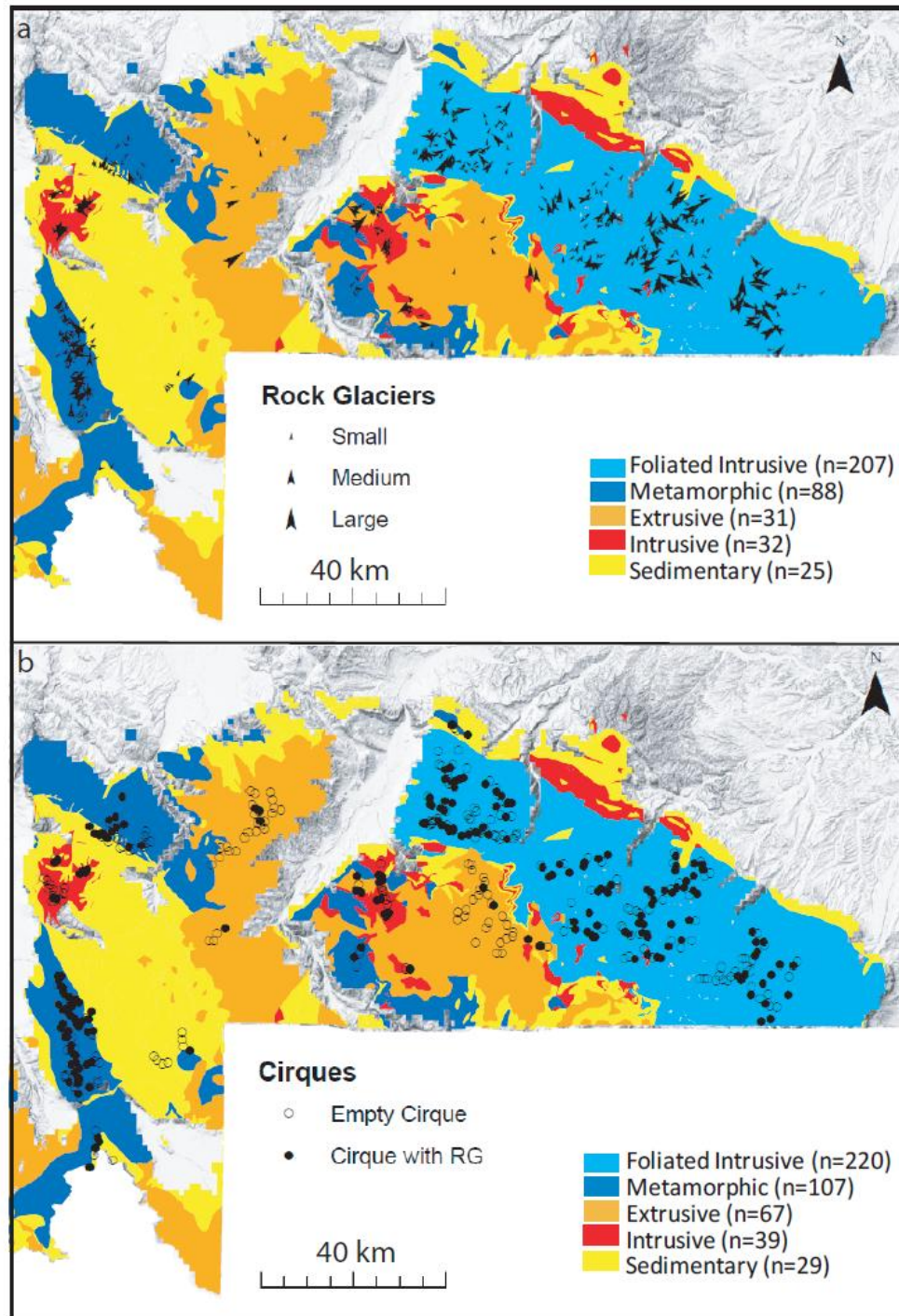


Figure 2.2 Map demonstrating the distribution of rock glaciers and cirques according to rock type. (a) Rock glaciers classified by black triangles, rotated according to aspect and size. (b) Cirques classified by presence or absence of rock glacier.

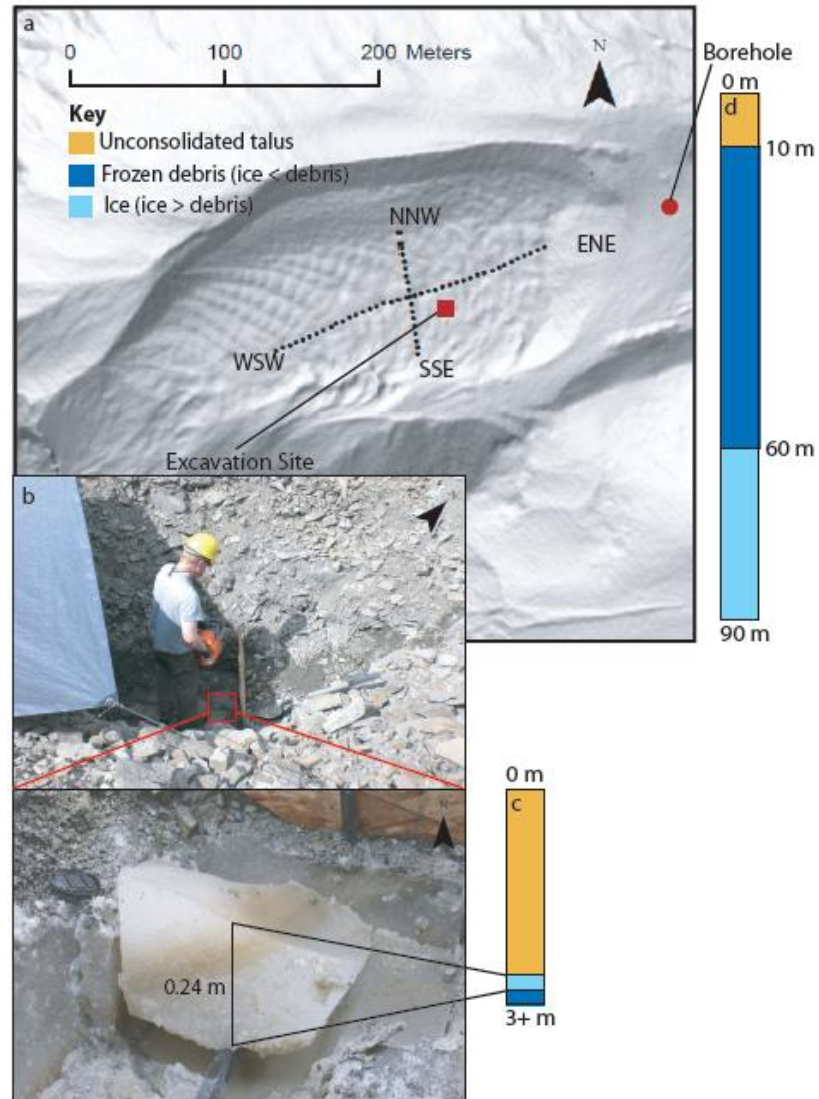


Figure 2.3 (a) LiDAR image of the LPRG. Longitudinal and transverse transect lines surveyed using seismic and GPR techniques are displayed with dashed black lines. Red circle indicates the approximate location of 1995 boreholes, and red square indicates location of excavation and ice sampling in 2009. (b) Top panel is a photograph of excavation site; field worker is standing on frozen substrate and surrounded by unconsolidated talus, which makes up the walls of the pit. Bottom panel is ice sample with up-dipping cm-scale debris layers. (c) Stratigraphy at the excavation site. (d) Stratigraphy at the tram construction site. Note difference in scale between stratigraphic columns.

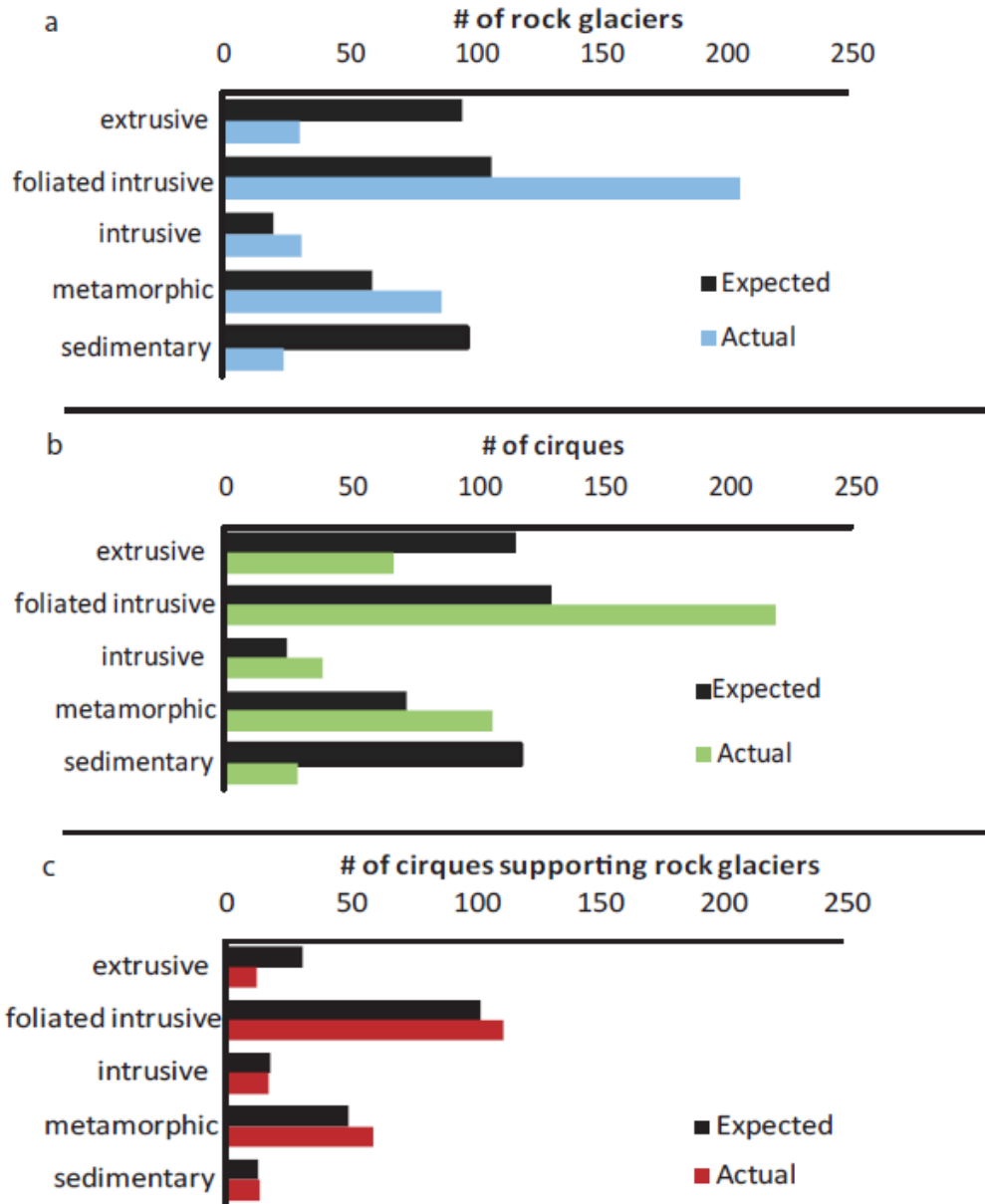


Figure 2.4 Actual and expected distribution of rock glaciers and cirques in study area (a) Number of rock glaciers according to rock type (b) number of cirques according to rock type, and (c) number of cirques with rock glaciers. Expected values for (a) and (b) were calculated using the areal proportion of each rock type. Expected values for (c) were calculated using the proportion of cirques within each rock type to total number of cirques for the study area.

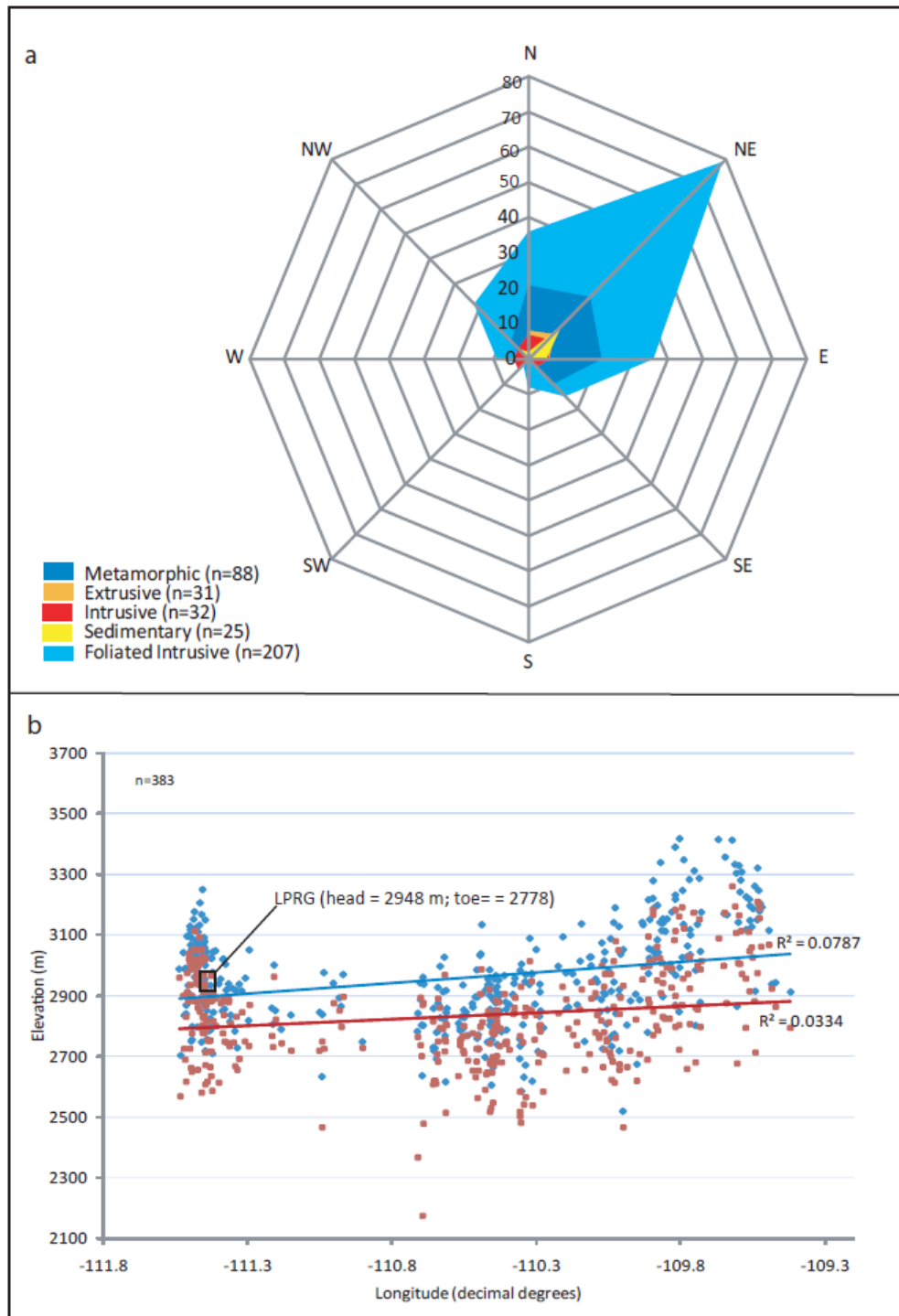


Figure 2.5 (a) Rock-glacier aspect is predominantly to the northeast. (b) Rock-glacier head and terminus elevation. Red data points are terminus elevation, blue data points are head elevation.

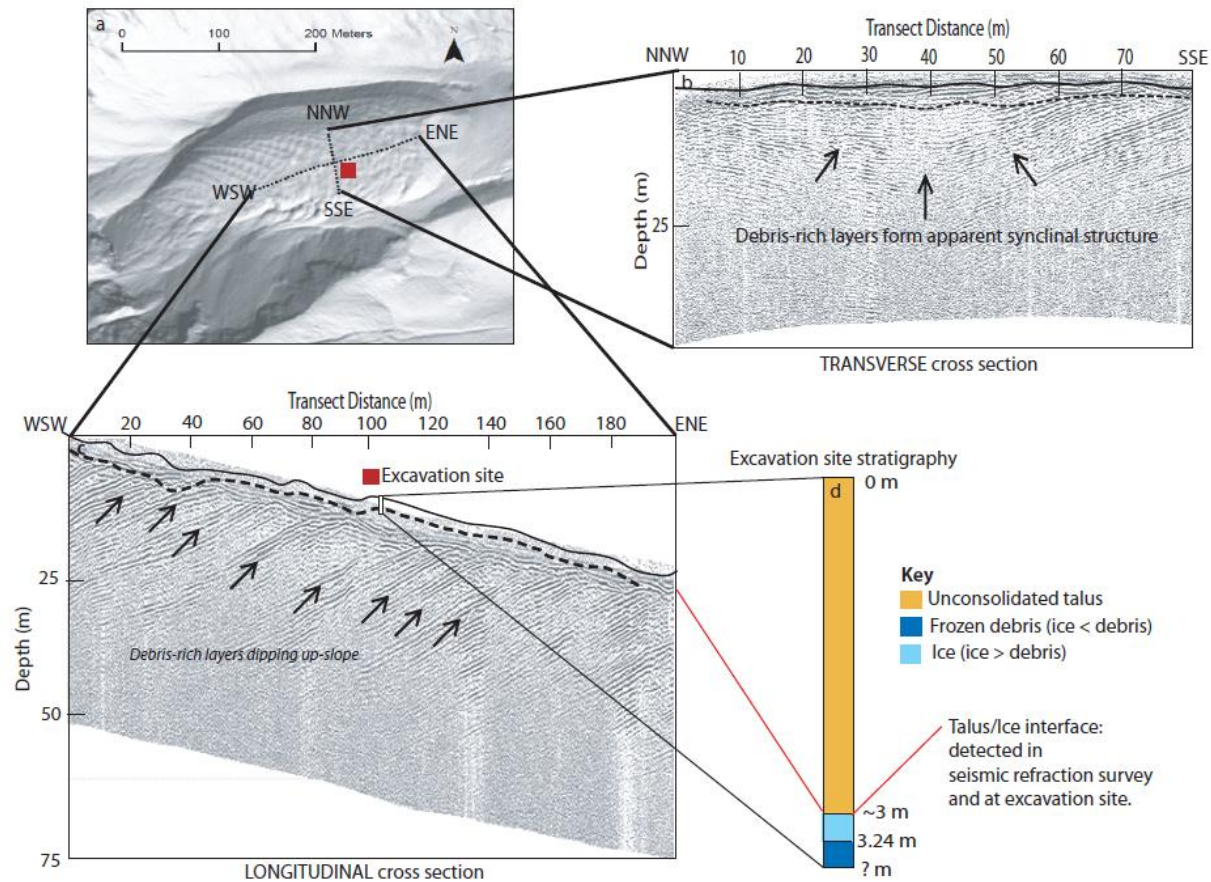


Figure 2.6 (a) LiDAR image of the LPRG. Longitudinal and transverse transect lines surveyed using seismic and GPR techniques are displayed with dashed black lines. Red square indicates location of excavation and ice sampling in 2009. (b) Transverse survey results. (c) Longitudinal survey results. Seismic refraction results (solid line indicates ground surface, dashed line indicates frozen substrate) overlays 100 MHz GPR data in both (b) and (c). (d) Excavation site stratigraphy.

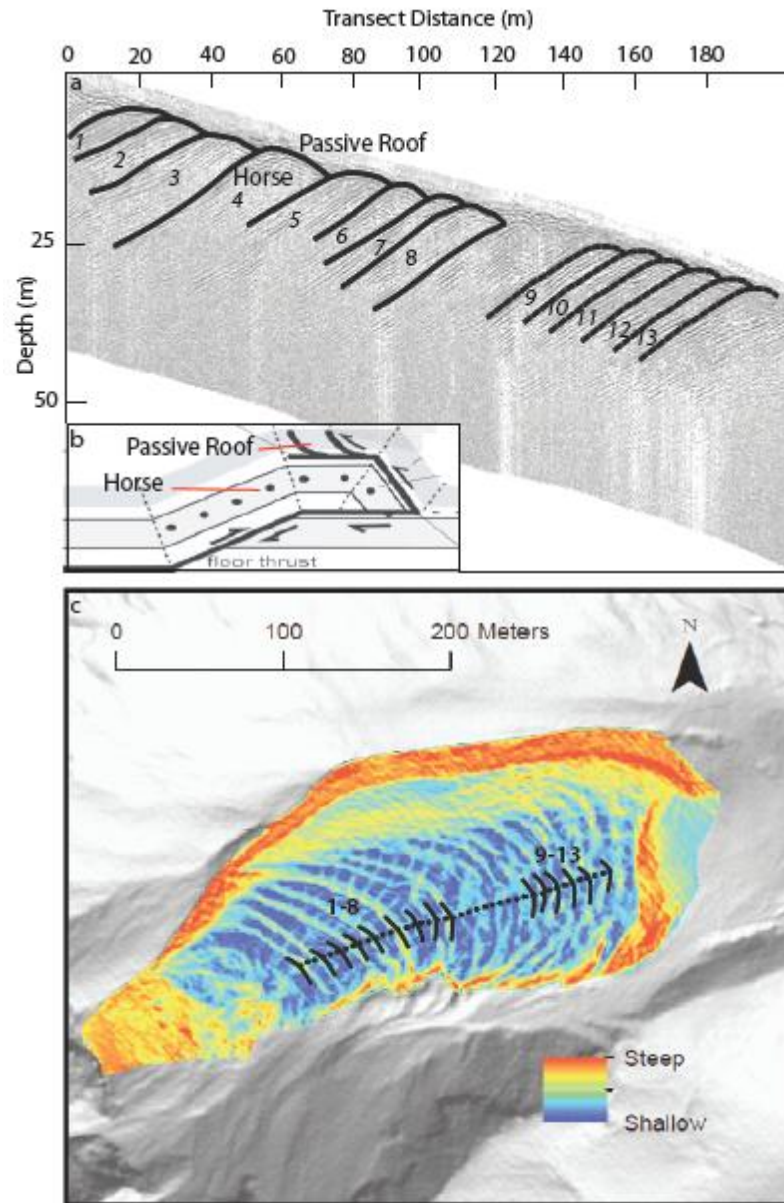


Figure 2.7 Passive roof duplex faulting at the LPRG. (a) Thirteen structural horses are detected in the longitudinal GPR profile data. (b) schematic diagram of structural “horses” in a passive roof duplex (Brocher et al., 2004) (c) LiDAR image of the LPRG with slope angle illustrated. Thirteen transverse ridges correspond to the structural horses detected in the LPRG subsurface along the longitudinal profile. The maximum angle (steep) is $\sim 84^\circ$ and the minimum angle (shallow) is $\sim 0^\circ$.

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CHAPTER THREE

ROCK-GLACIER ICE AS A MICROBIAL HABITAT

Contribution of Authors and Co-Authors

Manuscript in Chapter 3

Author: Caitlyn E. Florentine

Contributions: Caitlyn Florentine was responsible for sample collection and processing, data analysis, and was the primary author.

Co-author: Dr. Mark Skidmore,

Contributions: Dr. Skidmore aided in the experimental design and microbiological and chemical analysis.

Co-author: Scott Montross

Contributions: Scott provided input on methods for ice cutting, sampling and geochemical/microbiological analysis.

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Abstract

Debris-laden basal ice in subglacial systems has been shown to be a more amenable microbial habitat than debris-poor ice. The rock debris serves as a potential carbon, energy and nutrient source and the particles provide greater surface area for trapping water films within the ice even at sub-freezing temperatures. Rock-glacier ice has not previously been considered as a microbial habitat. However, the similarity of the debris laden “amber” ice of the rock glacier to that of basal ice from glaciers suggests that it too may be a preferential icy microbial habitat. Approximately 3 m of surface talus was excavated at the Lone Peak rock glacier (LPRG), southwest Montana, in August 2009 to expose a ~25 cm thick layer of clean ($< 0.01\%$ debris) and amber (0.1% debris) rock-glacier ice. This ice was sampled for isotopic, microbiological, and geochemical analysis. Direct cell counts on melted ice samples showed a similar order of magnitude in total cell counts in the clean and amber ice from ~ 2 to 5×10^4 total cells mL^{-1} . A greater proportion of cells in the amber ice stained “live” relative to the clean ice. Inoculation experiments using ice melt were undertaken to assess culturable aerobic heterotrophs via plate counts and microaerophilic heterotrophs via most probable number (MPN) estimations. Culturable heterotrophs in amber ice (1.1×10^3 cells mL^{-1} , 5.3×10^2 colony forming units (CFU) mL^{-1}) were at least one order of magnitude greater for amber ice than for clean ice (1.2×10^1 cells mL^{-1} , 1.3×10^1 CFU mL^{-1}), which is consistent with the cell count data. Amber and clean ice samples were analyzed every 2 cm across the 24 cm ice block for solute concentration. The peak concentrations of a key nutrient species, nitrogen (total dissolved nitrogen, nitrate, and ammonium) fall within the amber ice band. The data support the hypotheses that viable microbes increase in concentration with debris in the rock-glacier ice as in other glacial settings and that enhanced nutrient availability is related to the presence of debris. These findings are significant as rock glaciers are ubiquitous features in mountainous environments on most continents on Earth and may serve as terrestrial analogues for similar features in equatorial mountainous regions on Mars. The internal ice in such Martian features would be good targets for investigating extant or extinct microbial life.

Introduction

Rock glaciers are ubiquitous geomorphic features in alpine environments, recognizable by a talus mantle, steep-toe, and lobate shape (Barsch, 1996). No investigation has been made on the microbial component of rock-glacier ice. Investigations have been undertaken to understand the geomorphic distribution of rock glaciers and their physical nature in terms of deformation mechanics and hydrologic significance (e.g. Barsch, 1996; Brenning, 2005; Elconin and LaChapelle, 1997; Fukui et al., 2007; Fukui et al., 2008; Haeberli et al., 2006; Johnson et al., 2007; Konrad et al., 1999). Two studies have documented the isotopic composition of rock-glacier ice from shallow ice cores (Steig, 1998; Stenni, 2007), however, only one study to the authors' knowledge has examined the aqueous geochemistry in a rock-glacier system (Williams et al., 2006). Williams et al., (2006) measured solute concentrations in waters draining the debris-rich talus at the terminus of rock glaciers in the Colorado Front Range and noted elevated nitrate concentrations late in the melt season (October) that they suggest may have a microbial source, though no microbiological analyses were conducted. To the best of the authors' knowledge no study has reported on the microbial component of rock-glacier ice.

Florentine et al. (in preparation – Chapter three of this thesis) demonstrated alternating bands of debris poor and amber ice (with increased debris content) in samples of the internal ice at the Lone Peak rock glacier (LPRG), southwest Montana. Research in other glacial systems suggests that debris-rich basal ice provides a microbial habitat with higher cell numbers and a greater number of viable cells than in glacier ice (Sharp et al., 1999; Skidmore et al., 2000; Miteva et al., 2009). The debris in the ice enhances nutrients

and potential chemical energy sources, which supports the microbial community (e.g. Davila et al., 2010). This study investigated the geochemical and microbial characteristics of the ice from the Lone Peak rock glacier (LPRG) to assess whether, as in glacial systems, amber ice (debris-rich) provides a more favorable microbial habitat than debris-poor ice.

Rock glaciers exist at the Arctic Circle (Andre, 1994; Degenhardt, 2009; Isaksen et al., 2000; Woodward et al., 2003), in Antarctica (Shean and Marchant, 2010), and at lower latitude alpine settings including the Andes of South America, the Rockies of North America, and the Alps of Europe (Brenning, 2005; Haeberli et al., 1979; Potter, 1972; Stenni et al., 2007). Rock glaciers are ubiquitous terrestrial features in mountainous environments and thus represent significant potential microbial habitat, previously unconsidered in these environments.

Site Description

Lone Peak is located on Big Sky Resort property in the Madison Range of southwest Montana (Figure 3.1). A well developed rock glacier that is ~1 km in length occupies the northeastern cirque of Lone Peak (Figure 3.1a). Lone Peak is a laccolith intrusion emplaced approximately 60 Ma (Bolm, 1969). The headwall of Lone Peak's northeast cirque is characterized by porphyritic andesite intruded between layers of Cretaceous silicious shales (Figure 3.1a). The surface of the rock glacier is blanketed by talus weathered from the cirque headwall composed of porphyritic andesite and silicious shale (Figure 3.1b).

Methods

Sample Collection

Snow

Snow samples were collected in April of 2008. A 280 cm deep snow pit was dug from the snow surface to the ground layer of talus. Thirteen snow samples were taken at 20 cm intervals. The samples were then transported in coolers directly to refrigerators at MSU lab facilities.

The melted samples were filtered through a 0.2 micron filter into 25 mL plastic vials that had been rinsed three times with 3-4 mL of filtered water. These plastic bottles were labeled, sealed with parafilm, and stored with no head space in a refrigerator until they were analyzed for $\delta^{18}\text{O}$ and δD 24 hours later.

Talus

The talus layer was ~3 m deep as revealed through excavation using a Bobcat mini-excavator. Talus tends to be ~10-50 cm in diameter at the surface. Fine material – produced by the *in situ* weathering of the more fissile shale talus – was encountered beneath the surface of boulder-sized talus, and continued to be present down through the talus profile (~3 m) (Figure 3.1c). Excavation of the talus to a depth of ~3 m depth below the surface exposed a continuous ice surface that was sampled for microbiological and geochemical analysis (Figure 3.1d).

Ice

A hand-powered Sipre ice corer was ineffective for ice sampling due to the presence of a rock and ice layer encountered ~ 25 cm below the ice surface. The rock in this impenetrable layer was similar in character and size to the talus found at the surface. Therefore, samples of the ice in ~25 cm square blocks were taken using a chainsaw. The ice sample collected was ~25 cm square block that included clean, bubble-rich ice interrupted by an amber ice band (Figure 3.1d). “Clean ice” is ice with no visible debris present, and “amber ice” is amber in color due to very fine grained debris present (Mager et al., 2009). These blocks were stored frozen on dry ice in insulated containers and taken directly back to lab facilities at Montana State University and stored at -30°C.

Sub-sampling from the ice block was performed in the MSU Cold Lab Facility in a room kept at -30°C, using a band-saw. Dirty exterior material was removed by cutting ~1 cm from every dimension of the block to expose fresh surfaces. Sub-sampling cuts were made with respect to the amber ice band present in the block (Figure 3.1d). Samples taken at 2 cm intervals were cut along a profile perpendicular to the amber and clean ice boundaries, from 2-24 cm for geochemical analysis (Figure 3.1d). Zero indicates the contact between the ice surface and unfrozen talus. The sample from 0-2 cm did not yield enough volume for chemical analysis. Samples for microbial and physical analysis were taken from the amber ice band (8-16 cm) and the bottom clean ice band (18-24 cm) (Figure 3.1d). The top clean ice band yielded small volume samples due to the somewhat triangular/prismatic shape of the block sample, and were therefore not used for analysis.

Sample Analysis

Physical

Three clean and three amber ice samples (~200 g) were rinsed with milli-Q water to remove contaminant debris, and then mass was recorded. The samples were melted at room temperature overnight. The masses of six 0.2 μm filters were recorded. Melted ice samples were then individually filtered through 0.1 μm filters following the procedures of Montross (2007). Filters with filtered debris were then dried overnight in an oven set to 100°C, then the mass was recorded. The mass of debris was determined by subtracting the original mass of the filter from the mass of the filter with debris. The mass of debris was then considered as a percentage of the mass of frozen sample.

Melted amber ice samples (~600 mL) were centrifuged and the supernatant extracted. The debris was dried at 100°C for 5 hours and was then pulverized into a fine powder using a mortar and pestle. Andesite and shale samples collected from the surface of the LPRG near the excavation site were cut using a rock saw, to remove weathered surfaces, crushed using a rock crusher, and then ground into a powder using a mortar and pestle. The mineralogical composition of the powders from the ice-debris and rock samples was analyzed using X-Ray Diffraction (XRD) in the Image and Chemical Analysis Laboratory (ICAL) at MSU. Data were processed using DMSNT software, and the database of standards referenced was ICDD PDF2. Minerals were identified as peaks of intensity in the diffracted x-ray measured. Minerals were identified as peaks above background intensity.

Chemistry

Tritium concentrations were analyzed on two samples from the ice block; one from the amber ice, one from the clean ice (Figure 3.1d) at Isotech Laboratories Incorporated. Eleven ice sub-samples were taken at 2 cm intervals along the block-ice sample and were analyzed for their isotopic and geochemical composition. Samples were melted at room temperature overnight, then filtered through a 0.45 μm membrane filter. Melted, filtered samples were stored in 20 mL plastic scintillation vials for ion and nutrient analyses, 20 mL glass vials with no headspace for isotopic analysis and 40 mL furnace glass vials for TDC/DOC/TDN analysis. All filtered samples were stored at 4°C. Aqueous geochemical analysis was performed in the Department of Land Resources and Environmental Sciences Watershed Hydrology Lab facilities at MSU. Major cations and additional anions were determined using a Metrohm Peak ion chromatograph (IC) (Montross, 2007). The concentrations of nitrite-nitrogen ($\text{NO}_2\text{-N}$), nitrate-nitrogen ($\text{NO}_3\text{-N}$), ammonium-nitrogen ($\text{NH}_4\text{-N}$), and phosphate-phosphorous ($\text{PO}_4\text{-P}$) were determined colorimetrically using a SEAL QuAAtro segmented flow autoanalyzer (SEAL) according to the manufacturer's specifications. Isotopic concentrations ($\delta^{18}\text{O}$ and δD) were determined using a Los-Gatos Research liquid-water isotope analyzer according to manufacturer's specifications. Concentrations of total dissolved carbon (TDC), dissolved organic carbon (DOC), and total dissolved nitrogen (TDN) were measured by oxidative combustion at 720°C on a Shimadzu TOC- V_{csh} carbon analyzer attached to a TMN-1 total nitrogen measuring unit. Dissolved inorganic carbon (DIC) was determined as the difference between TDC and DOC.

Microbiology

Clean and amber ice samples were rinsed with 70% ethanol and then rinsed with 0.2 μm filter sterilized water. The samples were handled with sterilized tongs and allowed to melt in sterilized plastic beakers. Samples were allowed to melt for 22 hours in a refrigerator at 4°C. Aliquots of these melted samples were used for growth experiments and cell counting.

Cell counts were performed via epifluorescence microscopy and the Live/Dead BacLight Bacterial Viability Kit (Molecular Probes, Inc) stain. Filtration and slide preparation of the clean ice, amber ice, and a blank were performed simultaneously. Blank slides were prepared with all reagents and 0.2 μm filter sterilized water that was used for ice sample rinses. Filtration and slide preparation were performed on 10 mL duplicate samples of clean and amber ice following the methods of Montross (2007). Cells on the filters were viewed using a Nikon Optiphot epifluorescent microscope, equipped with a DM510 filter cube (Nikon), at a final magnification of 1000X. The total number of cells in each field of view (one field of view at 1000 x = 16,741 μm^2) were counted and for each 10 mL sample a total of 30 fields were viewed. The average number of cells in each sample was calculated by multiplying the average number of cells in the 30 fields viewed by the total number of fields of view per filter. The total number of fields of view per filter (12,010) was calculated by dividing the total area of the circular 16 mm-diameter filter ($A=\pi*(8\text{mm})^2$ or $2.0 \times 10^8 \mu\text{m}^2$) by the area viewed in each field of view (16,741 μm^2). This method was adopted from Porter and Feig (1980), Kirchman et al., (1982), and Montross, (2007).

Aliquots of the melted clean and amber ice samples were used to determine aerobic heterotrophic growth. Serial dilutions (10^0 , 10^{-1} , 10^{-2} , 10^{-3} , 10^{-4} , 10^{-5}) of the samples were made using a sterile phosphate buffered saline solution (PBS), and mixed by vortexing. Triplicate R2A plates (Difco) (Foght et al., 2004) were inoculated with 200 μ L of each dilution and incubated aerobically at 4°C in the dark for 6 weeks. Heterotrophic colony-forming units (CFU) were determined on a weekly basis. Blanks were prepared using filtered water used to rinse ice samples prior to melt and also without inoculum but open in the HEPA filtered hood during inoculation procedures. Neither set of blanks resulted in any growth after the 6 week incubation period.

Five-tube most probable number (MPN) estimations were performed according to the methods of Oblinger and Koburger (1975) in 18 x 150 mm test tubes containing 10 mL of semisolid R2A agar media to assess for heterotrophic growth under microaerophilic conditions (Foght et al., 2004) and 200 μ L of inoculum from the serial dilution described above. These test tubes were also incubated at 4°C for 6 weeks. Growth was scored on the presence of bands of turbidity beneath the agar surface. Blanks were also prepared and did not evidence growth.

Results

Physical

The mineral assemblage of a shale rock sample, as determined by XRD analysis, matched the mineral assemblage of the debris from an amber ice sample. The mineral components common to both the shale and amber ice debris samples included: quartz, plagioclase feldspar, pyroxene, illite/muscovite/biotite, and kaolinite/smectite/chlorite.

The mineral assemblage of andesite included two mineral components that were not in the amber ice debris sample: amphibole and hematite (Table).

Isotopic composition of snow and ice

Tritium concentrations for the amber and clean ice samples were below one tritium unit (1 TU). The δD and $\delta^{18}O$ values of ice and snow were compared to the global meteoric water line (GMWL) (Kendall and McDonnell, 1998). The GMWL is $\delta D = 8 \times \delta^{18}O + 10$ (Kendall and McDonnell, 1998). When plotted together, the isotopic data for snow and ice from the LPRG lie along a trend line that may be representative of the local meteoric water line (LMWL) ($\delta D = 7.1 \times \delta^{18}O - 7.2$) (Figure 3.2).

Microbial enumerations

The abundance of live and dead cells counted in the LPRG ice differs between amber and clean ice samples. Total cell counts for clean ice samples (n=2) were 4.8×10^4 ($\pm 0.5 \times 10^4$) cells mL⁻¹ compared to 1.7×10^4 ($\pm 0.08 \times 10^4$) cells mL⁻¹ for amber ice samples (n=2). Approximately 80% of cells in the amber ice stained “live”, and ~20% stained “dead”. This compared to ~30 % staining “live” and ~70 % dead in the clean ice samples. (Table 3.1).

Aerobic heterotrophs were enumerated on R2A agar inoculated with melt from amber and clean ice samples. A greater number of colony-forming units (CFU) were detected on R2A agar inoculated with amber-ice samples (5.3×10^2 CFU mL⁻¹) than with clean-ice samples (1.3×10^1 CFU mL⁻¹) (Table 3.1). The viable aerobic heterotrophs as

documented via CFU represented 3.8% of the live cell count values in amber ice, and 0.1% in the clean ice (Table 3.1).

Microaerophilic heterotrophs were enumerated in semisolid R2A agar with both amber and clean ice samples. A greater number of viable cells were observed on media inoculated with amber ice (1.1×10^3 cells mL⁻¹) than with clean ice (1.2×10^1 cells mL⁻¹). The microaerophilic heterotrophs represented 7.9% of the live-cell counts in amber ice and 0.1% in the clean ice (Table 3.1). Viable heterotrophs grew using aerobic and microaerophilic media for both clean- and amber-ice samples, with a greater number of viable heterotrophs grown on media with amber ice inoculum than with clean ice inoculum.

Geochemistry

The ionic concentration of sodium and chloride covaried with depth in the ice sample profile ($r^2=0.88$). The ionic concentration of calcium and bicarbonate also covary with depth ($r^2=0.99$). Nitrogen species (total nitrogen, nitrate, and ammonium) covary with depth as well ($r^2 > 0.8$). Maximum concentrations of each geochemical species occur in the amber-ice band (8-16 cm) with the exception of calcium, bicarbonate, and DOC. Covariance was determined by multiple regression analysis (Figure B.2). Other high r^2 values include the covariance between calcium and fluoride ($r^2=0.92$), and magnesium and nitrogen species ($r^2 \geq 0.84$).

Geochemical data are presented in Figure 3.2. Error in sample replicates was below ~ 15% with the exception of Mg^{2+} and F^{-} replicate measurements at the 18 cm depth interval (error < 35%). Charge balance error was ~13% on average through the depth profile. Li^{+} , K^{+} , and NO_2^{-} concentrations were below detection limits (< 0.005 mg L^{-1} , < 0.005 mg L^{-1} and < 0.1 $\mu\text{g L}^{-1}$ respectively) and not presented.

Discussion

Physical

The physical nature of the clean and amber ice is defined by the presence and absence of debris. The concentration of debris in amber and clean ice samples is 0.1% and <0.01% respectively. XRD analysis suggests that the mineralogical composition of the debris in the LPRG may be related to the shale rock found within the catchment; however, a greater sample size of ice and surface rock samples (shale, andesite) is needed to adequately relate amber-ice debris composition to that of the surface rock.

The samples (amber and clean) processed for tritium were from the bottom of the ice block, and were not in contact with the overlaying unconsolidated debris. $\text{TU} < 1$ indicates that the ice sampled for tritium concentration was formed by waters that came from an atmospheric source prior to nuclear fallout of the 1950s. Wet sediment observed at the ice sampling excavation site and annual disappearance of snow from the surface of the LPRG suggest that snowmelt could be interacting with ice below the upper ~ 3 m of unconsolidated debris. An additional ice sample from the top of the block should be analyzed for tritium concentration to assess whether more recent snowmelt (i.e from the past 50 years) is interacting with the surface layer of internal ice at the LPRG.

Microbiology

Direct cell counts and inoculation experiments both indicate a greater proportion and number of viable microbial cells from melted amber ice at the LPRG relative to the clean ice aerobic. Microaerophilic culturing results consistently showed at least an order of magnitude more viable cells in the amber ice samples relative to the clean ice samples. The low proportion of viable cells in the clean ice suggest that cells staining “live” by microscopy may be viable but not culturable.

Geochemistry

Debris content is the defining physical characteristic of the LPRG ice, and changes with depth across clean (<0.01%) and amber (0.1%) ice bands. Nutrient species nitrogen, nitrate, and ammonium covary with depth suggesting that solute concentration varies with debris content. Nutrient availability may be associated with the presence of debris because peak concentrations of nitrogen, nitrate, ammonium and phosphate occur within the amber-ice band. Nutrient concentrations – like microbial activity - seem to be associated with the presence or absence of debris within the LPRG ice.

A high r-squared value describing covariance of calcium and fluorine potentially suggests apatite ($\text{Ca}_5(\text{PO}_4)_3(\text{F}, \text{Cl}, \text{OH})$) as a source lithology for debris in amber ice samples. The covariance of magnesium with nitrogen species ($r^2 \geq 0.84$) is also notable, and may relate to a potential lithological source, though it likely relates back to the variation of solute concentration and nutrient availability with debris content.

To the author’s knowledge there are no other published studies on the microbial content and/or microbial viability in rock-glacier ice. However, the findings of this study

are consistent with investigations in other subglacial systems, where there is a positive association between microbial cells, microbial viability and abundance of debris in basal ice (e.g. Sharp et al., 1999, Skidmore et al., 2000; Miteva, 2009).

Summary

No previous investigation has holistically characterized rock-glacier ice as a microbial habitat based on its physical, microbial, and geochemical properties. Rock-glacier ice is physically characterized by the presence or absence of debris. Findings from this study show that cellular biomass within rock-glacier ice was associated with debris with 1) a greater proportion of live cells in amber ice than clean ice as determined by direct cell counts and 2) a greater number of viable heterotrophs in amber ice than clean ice as assessed via aerobic and microaerophilic culturing techniques. Nutrient concentrations, especially nitrogen species and phosphorous, were elevated in the amber ice and consistent with enhanced microbial activity.

This study indicates that rock-glacier ice serves as a viable microbial habitat. This finding has implications for microbial habitat in mountain systems worldwide given the widespread distribution of rock glaciers (Barsch, 1996) and the search for extraterrestrial life in similar environments on Mars, where rock-glacier-like features have been identified at low latitudes 5°S (Mahaney et al., 2007; Whalley and Fethi, 2003). These equatorial latitudes are warmer than polar locations and thus potentially favorable for long term (rover) missions to Mars as demonstrated by Spirit (14°S) and Opportunity (2°S).

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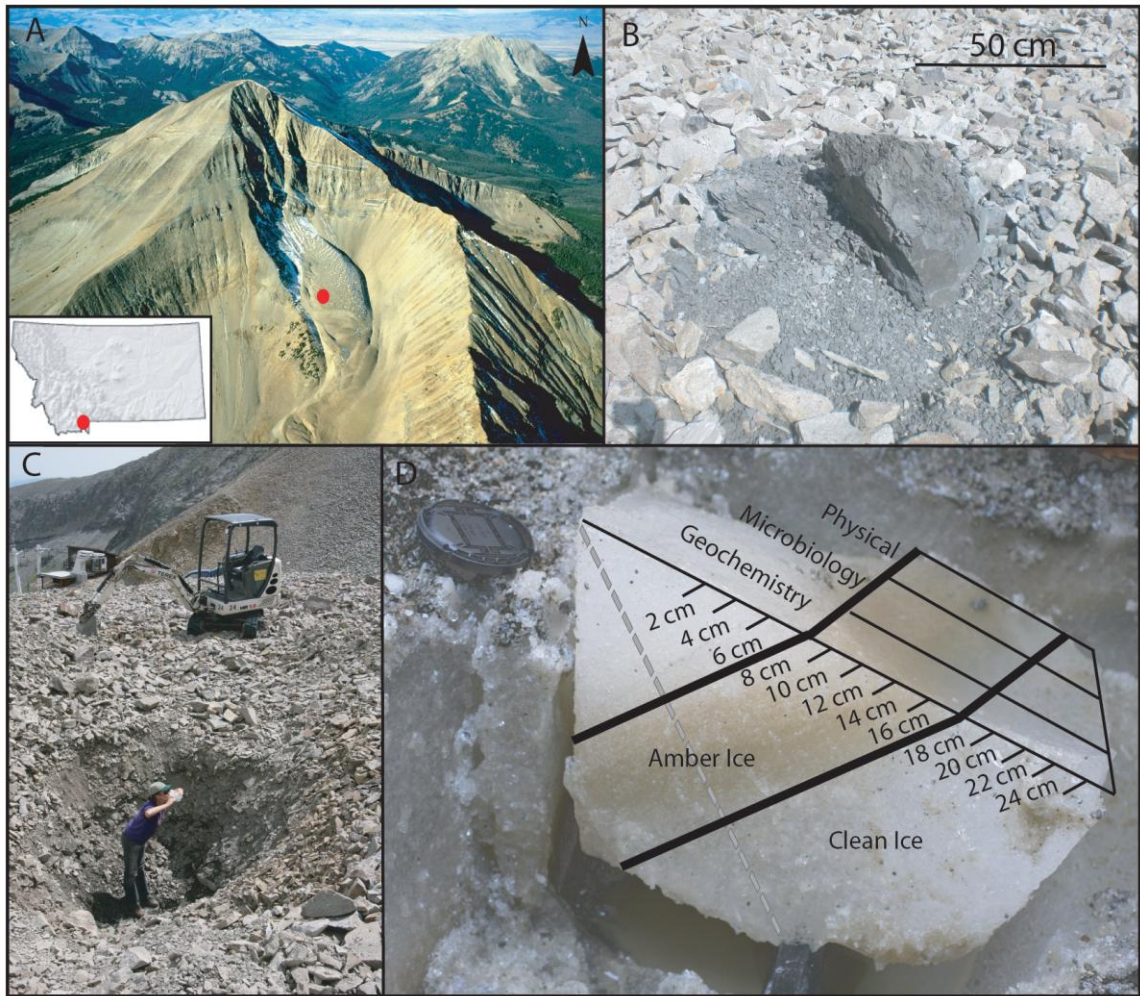


Figure 3.1 Study site and excavations at the Lone Peak rock glacier (LPRG) in the Madison Range, MT. (a) The LPRG with ice sampling location noted in red (photograph by Dave Lageson, 1980s). Inset shows study site near Big Sky, MT indicated by red dot. (b) Weathered shale rock on the LPRG surface. (c) Ice sampling excavation pit. (d) Ice sample with subsamples used for duplicate analyses delineated (photograph by Tim Brox). Amber and clean ice delineated with thick black lines. Samples used for geochemistry, microbiology, and physical analysis delineated by thin black lines.

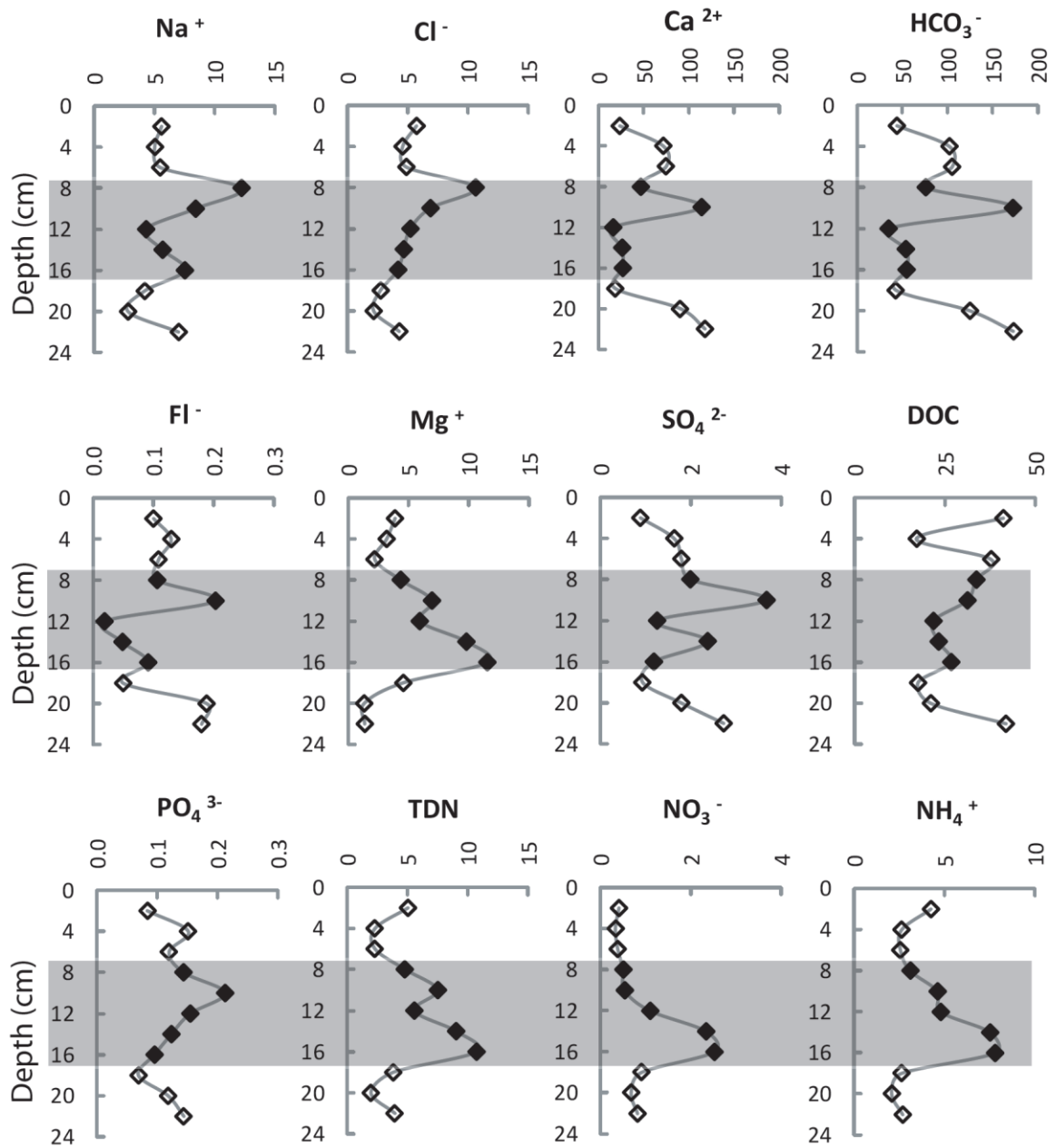


Figure 3.2 Geochemical data (μmol L⁻¹) from the LPRG. Open symbols are clean ice samples, closed symbols are amber ice samples. Amber ice interval (8-16 cm) highlighted by gray bar. See text for details; see Figure B.2 for covariance statistics. Dissolved organic carbon is abbreviated as DOC; total dissolved nitrogen is abbreviated as TDN.

Table 3.1 Microbial biomass and viability including total direct counts, colony forming units (CFU), or most probably number (MPN) (data reported per mL melted sample). Cultures were incubated at 4°C for six weeks.

	Direct Cell Counts*					Aerobic Heterotrophs**		Microaerophilic Heterotrophs***	
	Live		Dead		Total	MPN		Plates	
	<i>cells mL⁻¹</i>	<i>% of Total</i>	<i>cells mL⁻¹</i>	<i>% of Total</i>	<i>cells mL⁻¹</i>	<i>CFU mL⁻¹</i>	<i>Live (%)^β</i>	<i>cells mL⁻¹</i>	<i>Live (%)^β</i>
Amber Ice	1.4 × 10 ⁴ (0.07)	82	3.0 × 10 ³ (0.2)	18	1.7 × 10 ⁴ (0.08)	5.3 × 10 ² (2.0)	3.8	1.1 × 10 ³	7.9
Clean Ice	1.4 × 10 ⁴ (0.2)	29	3.4 × 10 ⁴ (0.3)	71	4.8 × 10 ⁴ (0.5)	1.3 × 10 ¹ (0.5)	0.1	1.2 × 10 ¹	0.1

*Mean number of cells (+/- 1 standard deviation): amber n=2; clean n=2

**Mean CFU (+/- 1 standard deviation): amber n=3; clean n=3

***MPN; n=5 (following Oblinger and Koburger, 1975)

^β Percent of live cells derived from direct cell counts.

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CHAPTER FOUR

GENERAL CONCLUSION

This thesis presented findings on the Lone Peak rock glacier (LPRG) on three distinct scales: regional, landform, and micro- as described in chapters two and three. Climatic conditions above 2000 m in the study area are suitable for rock-glacier development (semi-arid with mean annual precipitation ranging from 25-183 cm and mean daily minimum temperature ranging from -13 to 1 °C). My analysis has demonstrated that rock-glacier distribution in southwest Montana is preferential according to geology, with a significant difference in the number of rock glaciers in catchments with metamorphic, intrusive, and foliated intrusive rock types relative to the areal coverage of those rock types when compared to those with extrusive igneous and sedimentary rock types ($p < 0.001$). Cirques were defined as “hollow, open downstream but bounded upstream by the crest of a steep slope (‘headwall’), which is arcuate in plan around a more gently sloping floor” (Bishop and Shroder, 2004). Cirques were used as indicators of suitable topographic conditions for rock-glacier development. The distribution of cirques was preferential according to rock type ($p < 0.001$) indicating that rock type affects topography. The distribution of cirques that support rock glaciers was preferential according to rock type ($p < 0.01$), even when the relative availability of cirques within each rock type was accounted for. These findings cumulatively suggest that rock glaciers are distributed across southwest Montana according to rock type due to the affect that geology has on antecedent topography and additional geologic affects, likely talus production.

The relationship between internal ice properties and surface topography of the LPRG were analyzed using borehole, excavation, LiDAR, and geophysical data. These data show that the active lobe at the LPRG has the following stratigraphy. Approximately 3 m of unconsolidated talus overlies an internal ice body that has ice layers with alternating geophysical properties in the upper ~ 10m, interpreted to be the result of variable amounts of debris in discrete layers in the ice. At a single excavation site the upper ~ 0.25 m of the internal ice body contained debris poor ice with an “amber” ice band, overlying a frozen layer of debris and ice to an unknown depth. These two sets of observations are consistent. Up-glacier dipping layers detected via GPR interpreted to represent alternating debris-rich and debris-poor ice layers appear to demonstrate duplex thrust faulting, complete with structural horses. Correlation of these structural horses with individual transverse ridges suggests that each duplex fault is directly related to a transverse ridge on the rock-glacier surface. Thus my data suggests that passive-roof duplex faulting of the internal ice layer and overlying talus as a result of compressive flow in the active segment of the LPRG may explain the development of transverse ridges. Multiple working hypotheses pertaining to the genesis of transverse ridges have been presented by previous researchers (Arenson et al., 2002; Barsch, 1996; Kaab and Weber, 2004; Potter, 1972; White, 1971). The work in this thesis supports the hypothesis that transverse ridges are the result of internal processes in a rock glacier, such as the deformation of buried layers (Kaab and Weber, 2004).

Rock glacier ice has not previously been considered as a microbial habitat. Ice from the LPRG consisted of amber ice, with visible debris and 0.1% debris by weight, and clean ice with no visible debris and <0.01% debris by weight. Direct cell counts

showed more live than dead cells present in amber ice samples, whereas clean ice showed fewer live than dead cells. Heterotrophic viability assays also showed more viable cells associated with amber ice than clean ice. Geochemical data indicate higher concentrations of nutrient species in amber ice samples, which is consistent with a greater proportion of viable microbial cells in the amber ice.

Rock glaciers are ubiquitous terrestrial features in mountainous regions, over a wide latitudinal and altitudinal range (Barsch, 1996). They are significant agents of geomorphic activity and mass transport in these mountain systems (Degenhardt, 2009) and have been suggested as possible archives of paleoclimate data (e.g. Konrad et al., 1999). My thesis demonstrates their potential as significant microbial habitat also. My exploratory study at the LPRG and in SW Montana has improved our understanding of the role of geology in rock-glacier distribution, internal ice rheology and as microbial substrate within the ice. Given the widespread distribution of rock glaciers worldwide, future research to expand our understanding of the critical role geology has in these landforms is warranted. Further, a better understanding of rock glaciers would provide a basis for considering analogous extraterrestrial landforms. Features that are geomorphically similar to Earth's rock glaciers have been identified in the equatorial regions on Mars, i.e. those that are easily accessible via lander and rover missions (Mahaney et al., 2007; Whalley and Fethi, 2003). NASA's Mars exploration strategy in the search for extant and extinct life is one of "follow the water" (Hubbard et al., 2002). At present all known water close to or at the surface of Mars is in the form of ice (Davila et al., 2010). Therefore, if the rock-glacier landforms on Mars have similar internal ice to their terrestrial counterparts they provide definitive targets where ice is relatively near the

planet's surface for future exploration. Improved understanding of rock glaciers is warranted, both due to the landforms' ubiquity on planet Earth and potential as an extraterrestrial analogue.

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APPENDICES

APPENDIX A:

GIS METADATA AND STATISTICAL CALCULATIONS

Figure A.1. Data dictionary for geologic data used in ArcGIS for classification of rock type across the study area. Sedimentary and sedimentary carbonate facies were grouped into “sedimentary.” Volcanic and volcanoclastic were grouped as “extrusive.” Foliated intrusive, intrusive and metamorphic rock types were classified as is.

Data set;	Geology (general geology of Montana)
Source;	National Resource Information System, Montana Geographic Information Clearinghouse
Date/publisher;	1955/U.S. Geological Survey
Scale/resolution;	1:500,000, meter
Projected coordinate system;	NAD_1983_Lambert_Conformal_Conic
Projection;	Lambert Conformal Conic
Attribute fields of interest;	ROCK_TYPE (sedimentary, sedimentary carbonate facies, volcanic, volcanoclastic, extrusive, foliated intrusive, intrusive, metamorphic)
Description;	Vector dataset used to identify the geologic rock type at rock glacier locations. Shapefile.

Figure A.2 Calculation of expected values for Pearson's Chi Squared statistical tests. "A" relates to the distribution of rock glaciers, "B" relates to the distribution of cirques, and "C" relates to the distribution of cirques that support rock glaciers.

A	Area	Expected Frequency	Expected no. rock glaciers	Actual no. rock glaciers
B	Area		Expected no. cirques	Actual no. cirques
C	Cirques		Expected no. cirques supporting rock glaciers	Actual no. cirques supporting rock glaciers
Extrusive	e	e/T	$e/T \cdot A$	E
Foliated Intrusive	f	f/T	$f/T \cdot A$	F
Intrusive	i	i/T	$i/T \cdot A$	I
Metamorphic	m	m/T	$m/T \cdot A$	M
Sedimentary	s	s/T	$s/T \cdot A$	S
Total=T = e + f + i + m + s			Actual = A= E + F + I + M + S	

APPENDIX B:

SUPPLEMENTARY CHEMICAL DATA AND STATISTICS

Table B.1 XRD analysis of debris from amber ice sample and surface rock samples of shale and andesite from the LPRG. Check marks (“√”) indicate mineral is present, “x” indicates that mineral is not present.

Mineral	Amber Ice Debris	Shale	Andesite
	(n=1)	(n=1)	(n=1)
Quartz	√	√	√
Plagioclase feldspar	√	√	√
Pyroxene	√	√	√
Illite/Muscovite/Biotite	√	√	√
Kaolinite/Smectite/Chlorite	√	√	x
Amphibole	x	x	√
Hematite	x	x	√

Figure B.1 Isotopic data for snow samples collected at the surface of the LPRG and ice samples collected beneath ~3 m of unfrozen talus at the LPRG. Data are shown with linear trend lines for snow and ice separately. Both snow and ice data (n=24) plot cumulatively on a linear trend line of $y = 7.1191x - 7.2378$; $R^2 = 0.9626$.

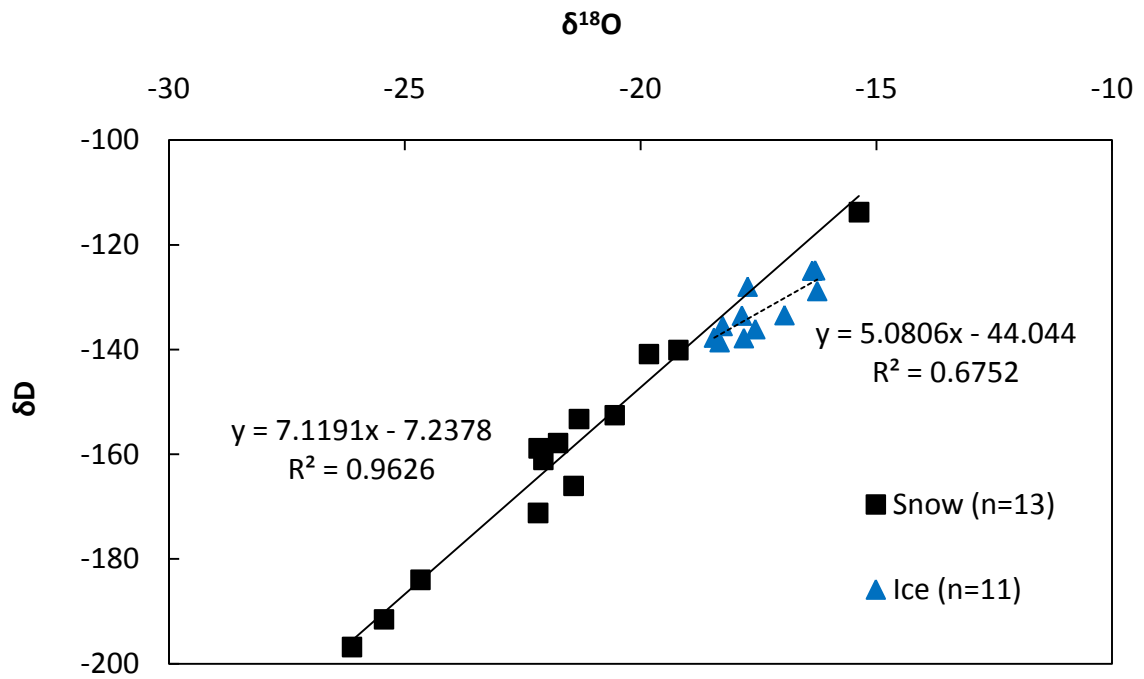


Figure B. 2

Correlation matrix for geochemical species, showing the coefficients of determination (r^2 value). The result of multiple regression analysis, performed using R-software (version 2.10.1). Code as follows:

```
> dataset=read.csv(file.choose(),header=T)
```

```
> names(dataset)
```

```
> round(cor(dataset),2)
```

	Na ⁺	Ca ²⁺	Mg ²⁺	FI ⁻	Cl ⁻	SO ₄ ²⁻	HCO ₃ ⁻	DOC	TN	NO ₃ ⁻	PO ₄ ³⁻	NH ₄ ⁺
Na ⁺	1	0.12	0.23	0.17	0.88	0.4	0.17	0.46	0.35	-0.01	0.32	0.16
Ca ²⁺	0.12	1	-0.49	0.92	-0.01	0.76	0.99	0.33	-0.35	-0.45	0.59	-0.46
Mg ²⁺	0.23	-0.49	1	-0.44	0.1	0.01	-0.42	-0.25	0.95	0.84	0.01	0.95
FI ⁻	0.17	0.92	-0.44	1	0.02	0.63	0.91	0.34	-0.28	-0.44	0.44	-0.42
Cl ⁻	0.88	-0.01	0.1	0.02	1	0.29	0.01	0.41	0.18	-0.24	0.41	0.05
SO ₄ ²⁻	0.4	0.76	0.01	0.63	0.29	1	0.81	0.27	0.15	-0.09	0.78	0.02
HCO ₃ ⁻	0.17	0.99	-0.42	0.91	0.01	0.81	1	0.34	-0.26	-0.39	0.61	-0.4
DOC	0.46	0.33	-0.25	0.34	0.41	0.27	0.34	1	-0.01	-0.27	0.02	-0.09
TN	0.35	-0.35	0.95	-0.28	0.18	0.15	-0.26	-0.01	1	0.82	0.06	0.95
NO ₃ ⁻	-0.01	-0.45	0.84	-0.44	-0.24	-0.09	-0.39	-0.27	0.82	1	-0.24	0.87
PO ₄ ³⁻	0.32	0.59	0.01	0.44	0.41	0.78	0.61	0.02	0.06	-0.24	1	-0.02
NH ₄ ⁺	0.16	-0.46	0.95	-0.42	0.05	0.02	-0.4	-0.09	0.95	0.87	-0.02	1