Thermal conditions and movement of rock glaciers in the North Cascades, Washington

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Thermal Conditions and Movement of Rock Glaciers in the North Cascades, Washington

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Accepted in Partial Completion
of the Requirements for Degree
Masters of Science

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Master’s Thesis

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Abstract

Rock glaciers are a largely unrecognized phenomenon in the North Cascades. In part this reflects their scarcity there. Additionally, because rock glaciers are widely held to be the product of permafrost conditions, the dearth of literature regarding North Cascade rock glaciers also reflects the notion that active rock glaciers should not exist at all in such temperate mountain ranges. Rock glaciers have been linked to specific air temperature conditions (<-2°C), and, based on that link, are often used as visual indications of mountain permafrost. The North Cascades, a maritime mountain range with high snowfall and relatively warm climate, are a good location to test the permafrost-rock glacier link. Review of aerial photography and satellite imagery, however, reveals at least ten morphologically active rock glaciers and even more that appear inactive. To test the activity and possible link to permafrost conditions, I selected two of the active-looking rock glaciers for movement monitoring and thermal investigation.

Movement monitoring was accomplished by conducting repeat scans with a terrestrial laser scanner; this investigation represents the first attempt to use this technique on rock glaciers in North America. The Craggy Peak rock glacier was shown to be moving downslope at a rate of 5 to 10 cm per year. Movement vectors toward the top of the rock glacier suggested deflation, while vectors toward the toe indicated a slight inflation. Flow toward the top and center of the rock glacier also was faster reflecting the steeper slope while flow toward the toe slowed and vectors radiated out. Movement was not detectable on second rock glacier, Star Peak, due mainly to lack of control points located on and around the scan target. Moreover, lack of a good vantage point at the site limited the scan coverage, inhibiting data processing.
Because the North Cascades are a maritime mountain range with climate conditions thought to be too warm and wet to support rock glaciers, I also deployed miniature temperature data loggers in both rock glaciers to record air temperature at the surface and within the rubble. Three logger strings were deployed with three loggers. Each string contained one surface logger, one logger of intermediate depth and one logger that was between 1.5-2.3 meters deep in the rubble (depending on the string). One year of data has revealed that average ground temperature on the rock glaciers is probably near \(-1 \pm 1^\circ C\) and modeled near-surface air temperature above them is \(0.0 \pm 1.6^\circ C\). Air temperature is marginally to warm to support permafrost, though a more lengthy study period is needed. Thermal exchange during the summer appears to be governed by conductive processes in the form of rain water and solar heating. Moreover, forced convection occurs when wind pumps air into the regolith. During the fall, I document at least one instance where the data loggers capture natural convection when relatively warm air evacuated the regolith. Natural convection occurs when cold air overlays warm air and the subsequent density driven inversion results in warm air escaping into the air and cold air settling into the regolith.
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Chapter 1: Introduction

Rock glaciers are high mountain features thought to be related to permafrost or true glaciers and are generally described as flowing ice that is covered by a mantle of debris. Although true glaciers are sensitive to short-term climate conditions such as summer temperature and winter precipitation, rock glaciers are largely insulated from these seasonal temperature and precipitation variations and respond much more slowly to longer term changes. Therefore, rock glaciers are thought to react to climate more on the decadal scale (Haeberli et al., 2006). As such rock glaciers may be valuable indicators of past climates, as well as continue to provide water sources in semi-arid mountain ranges where true glaciers have since receded due to climate change.

Rock glaciers have been widely studied in many mountain ranges. However, many questions still exist regarding their formation and their relationship with the surrounding climate and environment. Some controversy exists pertaining to the climate and ground thermal conditions required to allow the propagation of rock glaciers. Are they permafrost features or are they glacial features? Moreover, North Cascade rock glaciers have only been given a precursory mention in the literature. The purposes of this study are to establish baseline characteristics of flow and climate conditions at active rock glaciers in the North Cascades and ascertain if climate conditions at these rock glaciers support permafrost. To achieve these goals I followed these steps: 1) regional cataloging and reconnaissance mapping and measurement site identification 2) measure and model ground thermal and climate conditions, 3) ascertain flow rates of the targeted rock glaciers. Each of these steps had specific methodologies and data analyses.

Since the first rigorous investigation by Wahrhaftig and Cox (1959), rock glaciers have been an enigma in the study of alpine environments. Many researchers have attempted to develop a universal taxonomy and mode of genesis for these features as well as define their relationship with current and past climates (e.g., Brazier et al., 1998; Humlum, 1997) yet no consensus exists.
Because they leave easily identifiable remnants, rock glaciers have the potential to be valuable indicators of past climate if the conditions under which they form and exist can be constrained. Over the last several decades, however, speculations regarding rock glacier genesis and conclusions constraining their climate conditions have garnered serious debate among scientists.

Some previous researchers have argued that rock glaciers are definitive indicators of discontinuous permafrost and use them as such when modeling and mapping mountain environments (Barsch, 1977; Barsch, 1996; Haeberli, 1985). The assumption that all rock glaciers are manifestations of mountain permafrost is fueled by the preponderance of rock glaciers in interior mountain ranges that are characterized by continental climate conditions. Indeed, there is significant physical evidence to support the inference that many rock glaciers are essentially creeping permafrost features. However, other evidence suggests that this assumption may not be universally valid. Rock glaciers have been identified in maritime mountain ranges where high precipitation rates and relatively mild winter temperatures abound leading to less abundant permafrost (Brazier et al., 1998; Humlum, 1997, Clark et al., 1994). Humlum (1997) investigated several rock glaciers in Greenland that occur in areas where the Mean Annual Air Temperature (MAAT) appears to be greater than the –2°C Celsius generally believed to be required for rock glacier development (Barsch, 1996). More decisive evidence suggesting that not all rock glaciers are permafrost features was presented by Potter et al (1998) who conclusively show that the Galena Creek rock glacier in the Absaroka Range, Wyoming, contains a core of true glacial ice.

Temperatures within the blocky active layer of rock glaciers in Europe and Asia have been studied and their relationship with surface air and snow cover examined. However, such a study has not been conducted in North America, nor in so purely a maritime mountain range as the North Cascades. We have investigated the climate conditions and near-surface temperature regimes of two morphologically active rock glaciers in the North Cascades, a maritime mountain range (Figure
The purpose of this study is to provide a baseline for future work regarding the climate conditions and thermal regimes at rock glaciers in the North Cascades. Also, Terrestrial Laser Scanning (TLS) techniques were employed on rock glaciers for the first time in North America. From these data, movement rates and velocity fields were quantified and will be presented.

1.1 Definition of Rock Glaciers

The first significant study of rock glaciers was by Cross and Howe (1905) in the Wrangle Mountains, Alaska. Wahrhaftig and Cox (1959) greatly expanded on Cross and Howe’s research and defined three types of rock glaciers in Alaska based on their morphology: Lobate, tongue-shaped, and spatulate rock glaciers. Wahrhaftig and Cox presumed the ice in these rock glaciers to be predominately interstitial, but did not associate this ice with a discrete origin or use the ice origins as a distinguishing characteristic.

In the last forty years, researchers made several attempts to classify rock glaciers based on their geomorphology and origin. Potter (1972) developed the following morphological definition of rock glaciers:

a tongue-like or lobate body usually of angular boulders that resembles a small glacier, generally occurs in high mountainous terrain, and usually has ridges, furrows, and sometimes lobes on its surface, and has a steep front at the angle of repose.

Potter’s definition does not include any origin or process by which rock glaciers could form. In contrast, Barsch (1996) and Haeberli (1985) define rock glaciers specifically as permafrost bodies.
They theorize that rock glaciers form only under conditions conducive to permafrost development and define rock glaciers as such with Barsch (1992) offering the following definition:

Active rock glaciers are lobate or tongue-shaped bodies of perennially frozen unconsolidated material supersaturated with interstitial ice and ice lenses that move downslope or downvalley by creep as a consequence of the deformation of ice contained in them and which are, thus, cohesive flows.

Haeberli (1985) offers a definition that focuses on permafrost:

Active rock glaciers are the visible expression of steady-state creep of ice-supersaturated mountain permafrost bodies in unconsolidated materials. They display the whole spectrum of forms created by cohesive flows.

Such permafrost inclusive definitions do not allow for the possibility of glacigenic mode of genesis and as such may need to be revised.
Chapter 2: Previous Research

2.1 Rock Glacier Origins

Due to their remote locations and coarse surface regolith, rock glaciers are notoriously difficult to investigate, particularly in respect to their internal structure and composition. As a result two different models have been proposed regarding the formation of rock glaciers: a permafrost origin and a glacier ice-cored (glacigenic) origin. Although there are some camps that support only one model, research suggests that both permafrost and glacigenic rock glaciers exist. It is nearly impossible to distinguish between rock glaciers of one origin over another from the surface. Analyzing ice cores remains the most straightforward method for establishing ice origins.

2.1.1 Permafrost Model

Although they had no direct ice exposures to document it, Wahrhaftig and Cox (1959) theorized that ice in rock glaciers in the Alaska Range is primarily interstitial. According to this concept, the ice forms when water from snow melt or rain percolates into a talus and freezes at the permafrost margin forming ice within the rock glacier. The deformation of this ice is essential to the down slope movement of the rock glacier (Wahrhaftig and Cox, 1959; Barsch, 1977). Indeed, Barsch (1996) lists the following as one of the parameters needed for active rock glacier development:

The prospective area for rock glacier development must be part of the discontinuous mountain permafrost belt (temperature control).

Barsch (1977; 1987) and Haeberli (1985) have expanded this concept to encompass all rock glaciers; that is, all rock glaciers require permafrost conditions to develop. The implication of this “permafrost-only” model is that all rock glaciers are manifestations and indicators of mountain
permafrost. A stipulation of the permafrost model, perhaps obviously, is the requirement that the local climate supports the formation of large zones of ice-rich permafrost.

2.1.2 Glacigenic Model

An alternative to the permafrost-only model states that at least some rock glaciers are effectively heavily debris-covered glaciers (e.g., Potter, 1972; Whalley, 1983; Clark et al., 1994). In this model, much of the ice in rock glaciers originates from snow deposition (sedimentary ice) that then gets buried by abundant rockfall in the accumulation zone. Notably, the glacigenic model of formation does not require the stringent temperature or precipitation parameters delineated in the permafrost model. Presumably, rock glaciers could form in a mountain range where true glaciers dominate and borderline permafrost conditions prevail. However, one could argue that because any ice by definition is at or below freezing, all glaciers, including rock glaciers, are frozen ground i.e., permafrost features. But, by convention, true glaciers are typically excluded from this category and because of this arbitrary distinction rock glaciers that contain glacial ice (i.e., dominantly sedimentary ice) should be distinguished from their permafrost counterparts because they contain true glacial origins. The distinction between these models becomes even more important if glacigenic rock glaciers do not require the same conditions to develop as permafrost derived rock glaciers as much could be gleaned from differentiating between the two types.

Potter (1972), working on the Galena Creek rock glacier in the Absaroka Range, Wyoming, introduced the concept of a glacier ice-cored rock glacier in contrast to the more widely held interstitial-ice permafrost rock glacier model. In this model, true “sedimentary” glacial ice is buried by steady amounts of rock fall debris from the cirque headwall. Rock glaciers that form in this way can be thought of as essentially heavily debris-covered glaciers, with an accumulation and ablation zone. Partly due to Potters findings, Whalley (1983) argued that permafrost may not be required to form rock glaciers. Humlum (1996) and others have viewed the glacigenic rock glacier as a viable
model, while others (Barsch, 1988, 1996) believe that if flowing ice is primarily sedimentary (glacial) in origin, then it is by definition not a rock glacier. This view introduces a circularity in their reasoning, but emphasizes the strongly held opinion by some that all morphologic rock glaciers are manifestations of permafrost conditions. However, Clark et al (1998) validated the glacigenic hypothesis by extracting demonstrably glacial ice cores from the middle of Galena Creek rock glacier, a glacier that had been previously labeled as permafrost in origin (Barsch, 1989).

### 2.2 Rock Glacier Activity Index

Rock glaciers are generally characterized as being in one of three levels of activity: active, inactive, and relict which refer to the state of ice within the rock glacier (Martin and Whalley, 1993). Active rock glaciers are those that are still flowing, while inactive rock glaciers still contain ice but no longer flow. In extinct or relict rock glaciers, ice is no longer present. The state of ice can be inferred from the surface characteristics of a particular rock glacier. According to Martin and Whalley (1987) the following criteria indicate an active rock glacier:

1. Little or no vegetation growth on the rock glacier surface
2. Rock glacier terminus at or near the angle of repose for the constituent debris

Based on their morphology, inactive rock glaciers are initially difficult to distinguish from active, though the presence of excessive and undisturbed (non-leaning) vegetation may indicate a relatively stable surface. However, downvalley movement of some portion of the rock glacier must be demonstrated in order to indicate activity. Extinct rock glaciers usually exhibit a deflated appearance, implying the loss of ice in the core (Martin and Whalley, 1987).
2.3 Previous Study Areas

Rock glaciers have been studied in many mountainous regions around the world, including the European Alps (Haeberli and Muhll, 1990; Jong and Kwaduk, 1988; Ikeda et al. 2003; Kerschner, 1978), Iceland (Martin and Whalley, 1987), Greenland (Humlum, 1996, 1997, 1998), Alaska Range (Foster and Holmes, 1965; Calkin et al. 1987), Rocky Mountains (Vick 1981, Jackson 1980, Potter 1972, Potter et al. 1998, Johnson et al. 2007), Sierra Nevada (Clark et al. 1994) and the Southern Alps, New Zealand (Brazier et al. 1998). Most of these areas exhibit either continental or arctic climates, while only a few are distinctly maritime. The North Cascades, with their relatively warm winters and heavy snowfall, clearly exhibit a maritime climate. Thompson (1967), the only source that mentions North Cascade rock glaciers, states that there may be several “relict” features east of the Cascade crest and theorizes that the existence of active rock glaciers is unlikely.

2.4 Rock Glaciers and Climate

Researchers have delineated temperature parameters that relate directly to permafrost development and more specifically, rock glacier development (Barsch, 1996, Humlum, 1998). The first of these is mean annual air temperature (MAAT). This is the free air temperature just above the surface of the rock glacier and, according to Barsch (1996), must be less than −2°C to facilitate rock glacier genesis and propagation. A second temperature parameter thought to be important to rock glacier development is the average winter temperature at the base of the snowpack (BTS). Barsch (1996) states that the BTS must also be less than −2 degrees Celsius. However, a more recent study suggests that the BTS must be less than −3 degrees Celsius in order to support rock glaciers (Ikeda et al, 2003).

Humlum (1998) characterized MAATs and mean annual precipitation (MAP) known at a selection of glaciers at the time. He found that the vast majority of rock glaciers occurred below -
6.5° C and 800 mm MAP, though some rock glaciers were located in warmer and wetter maritime climates (in Iceland). Most of the rock glaciers used in Humlum’s study were selected because of their activity levels, their assumed equilibrium with the modern climate, and their proximity to what was thought to be likely rock glacier initiation areas.

2.4.1 Rock Glaciers as Indicators of Permafrost in Models

Many models used to map and predict mountain permafrost operate under the assumption that rock glaciers always indicate this environment. Models such as PERMAMAP (Hoezle, 1994) and PERMAKART (Keller, 1992) rely on several characteristics (Haeberli 1985), used as unequivocal indicators of mountain permafrost. Rock glaciers are one of these. These models have been employed in many places including the Swiss Alps, Norway, and the Front Range of the Rockies (Fraunfelder et al. 1998, Etzelmuller et al, 2001, and Janke 2005). All of these models presume that rock glaciers are indicators of mountain permafrost. Only Janke (2005) acknowledges that rock glaciers may have glacigenic origins but states that even if they contain sedimentary ice, such rock glaciers will still fall under the thermal regimes associated with permafrost. However, by this logic one could use true glaciers as indicators of mountain permafrost as well.

2.4.3 Rock Glacier Response to Climate

Rock glaciers respond slowly to climate change due to the thick insulating debris cover. Several researchers have attempted to assess how increasing air temperature affects flow velocities and dynamics. Kaab et al. (2007) modeled rock glacier response to warming surface temperatures. They established a link between warmer permafrost and increased flow velocity and, after, compiling measured or estimated MAAT and velocities from different rock glaciers they report that warmer air temperatures correspond with faster surface speeds. MAATs that approach 0° C at the
toe of rock glaciers had flows greater than 1.5 m a\(^{-1}\) while lower temperatures lower than -2\(^\circ\) C were generally less than 1 m a\(^{-1}\).

Bondin et al. (2009), monitored climate change and movement on the Laurichard Rock Glacier in the French Alps over a 20 year period. Their results indicate that during the first 15 years of warming, velocity increased and slowed during the last several years as temperatures cooled. On a year to year scale, they found a high correlation between early snow accumulation and greater surface velocity, with the insulating effects of snow keeping the ground warm relative to the air temperature. They speculate that the warmer temperature allowed higher liquid water content at depth, thus accounting for faster flow rates.

Bondin et al. (2009) believed they found active layer thickening at the root, the top, of the rock glacier and a thickening of the ice layer at the toe, implying that there may be ice loss or at least no addition of ice at the top of the rock glacier during warming conditions with greater snowfall. Perhaps more importantly, during one year of their observation period, Bodin et al. (2009) noted that two seasons of high snow fall split by an abnormally warm summer were followed by the rock glacier surface dropping.

2.4.4 Rock Glacier Monitoring

2.4.4.1 Movement Monitoring

Previous studies of rock glacier movement have generally relied on boulder marking and photogrammetry. Through years of monitoring using these methods, rock glaciers have been reported having as little horizontal displacement as 5.9 cm a\(^{-1}\) to as much as 3 m a\(^{-1}\) (White, 1971; Haeberli et al., 1971). More recently methods requiring painstaking instrument placement and high grade GPS gear or total station survey equipment have been implemented. Recently, new technology, ground based LiDAR, has become available that will allow for relatively easy and
accurate assessment of rock glacier movement. Using this new technology, researchers in Europe have found that flow rates for rock glaciers range from 10-20 cm a\(^{-1}\) to 1-2 meters per year depending on ice content and climate (Avian et al., 2008).

Terrestrial Laser Scanning (TLS) or ground-based LiDAR, has been used successfully to detect changes in movement and volume in landslides and rock faces for hazard mapping (Giussani and Scaioni, 2004; Alba et al., 2005). Prokop and Panholzer (2009) found TLS useful for detecting annual movement as small 100 mm using point resolution of 3 cm at 100 meters in landslides. Rock glaciers have not been examined extensively using TLS (Bauer, 2003). Avian et al., (2008) detected vertical displacements of 25-70 cm per year in a rock glacier located in the Alps. Similarly, Bauer (2003) recorded a 1.5 meter a\(^{-1}\) downslope movement as well as 2 meters of upward vertical movement (presumably due to ice manufacture) on another Alps rock glacier.

2.4.4.2 Ground Temperature Monitoring using miniature temperature loggers

In Europe and in sub-arctic areas known to harbor frozen ground, miniature temperature loggers (MTLs) have become a prevalent method of monitoring permafrost, ground thermal regimes, and the basal temperature of the snow pack (BTS). Humlum (1997) first used MTLs to investigate thermal regimes at shallow depth in a rock glacier in Greenland. Burn (1998) used them to investigate permafrost temperatures in the Yukon Territory, Canada. Later, Hoelzle et al. (1999) investigated the usefulness of MTLs in high alpine environments in the Alps. Ishikawa and Hirakawa (2000) used MTLs to record BST measurements and thus map permafrost at high altitudes in Japan. Likewise, MTLs have been used in Norway, Spain, and other areas with discontinuous permafrost to investigate ground-surface temperature interactions (Santos-Gonzalez et al. 2009, Juliussen and Humlum 2008).
2.4.4.3 Ground Thermal Regimes

The temperature variations in the ground at or near the surface are predominately driven by surface temperature. However, the characteristics of the ground are central to the nature of these variations. Course, blocky material has a different temperature profile than that of fine grained soil and bedrock because it responds more readily to temperature change at the surface than fine grained soils that lack large void space (Harris and Pedersen, 1998). Generally the blocky material is noticeably colder than finer sediment because of the higher density cold air sinking into the void spaces displacing and forcing out warmer air. This phenomenon, known as the Balch Effect, is thought to be an important factor in the formation of rock glaciers (Balch, 1990). Harris and Pederson (1998) define the following (including Balch Effect) as possible drivers of temperature variation in the pore space:

1. *The Balch Effect*. Cold air, being more dense then warm air, tends to displace warm air in the pore space.

2. *The chimney effect*. During the winter, cold air enters into pore space through holes in the snow cover. Warmer air, displaced by the cold air, travels upslope eventually escaping through holes in the snow cover. This means that the upper part of a talus slope can often be warmer than the lower part.

3. *Summer time evaporation/sublimation of water/ice in the blocky deposit*. Latent heat is absorbed by the above mentioned processes, lowering temperatures at depth

The cold temperature of blocky material is mitigated by the insulating effect of snow cover (Harris and Pedersen, 1998, Humlum, 1997). As temperature decreases in the fall, precipitation changes to snow, and, as snow cover builds, the ground is cut off from atmosphere cooling. Thus, in areas of low snowfall, cold air is able to permeate deeper into the blockwork, while where snow cover is heavy enough to isolate the ground from the atmosphere (~0.6 according to Hanson and Hoelzle, 2004), the average temperature of the ground is warmer. For this reason, coarse blocky material in some cases can enhance the ability of permafrost to form if snow cover is low.

Rock glacier and coarse blocky-material thermal regimes have been investigated primarily in the Alps, Spain, and Greenland (Hanson and Hoelzle, 2004; Hoelzle et al., 1999; Santos-Gonzalez et al., 2009; Humlum, 1998). During summer months, these studies generally report a lag of several hours between high and low surface temperatures and those at depth. Winter snow cover attenuates temperature variation and the gradient change from positive to negative following the occurrence of lasting thick snow cover (~0.6 m, according to Hanson and Hoelzle, 2004). As air temperature begins to warm in the spring and snow begins to melt, most researchers reported ground temperature stabilizing for several days to weeks at 0°C. This is usually interpreted as the zero curtain, when the repeated freeze/thaw of water and the subsequent release/absorption of latent heat holds temperatures steady at the freezing point of water.

2.4.4.4 Convection and Conduction

Two basic mechanisms exist for driving temperature at depth: convection and conduction. Convection usually refers to the physical displacement of air due to differing densities as in Balch Ventilation or wind pumping. Conduction is the warming of adjacent air bodies due to the radiative properties. Juliussen and Humlum (2008) believe that conductive mechanisms dominate the summer temperatures, while convective processes are more prevalent in the winter. The respective
density differences of cold air versus warm induce air stratification with warmer air overlaying the
colder air trapped in the pore space. During the winter, the near surface atmosphere temperature
routinely drops below the pore space temperatures creating a density difference. Therefore,
surface air repeatedly sinks into the blockwork, displacing warmer air.
Chapter 3: Study Area

3.1 North Cascades Climate

The North Cascades are generally considered to be a maritime mountain range characterized by mild wet winters and relatively dry summers. The west side of the range is generally wet, receiving around 2-3 meters of precipitation. The east side is significantly drier averaging .9 – 1.5 meters of annual precipitation (NRCS, 2011).

3.2 Rock Glaciers

Rock glaciers are most common in relatively dry climates (Brazier 1998, Thompson 1962, Wahrhaftig and Cox 1959), otherwise the snowfall will overcome the debris flux and create a snow field or normal “clean” glacier. Consistent with this concept, rock glaciers in the North Cascades all are restricted to the ‘dry side’ east side of the range crest in the rain shadow (Figure 1, 2). The termini of most active North Cascade rock glaciers occur at or above 2150 meters asl in mountain cirques while inactive rock glaciers occur down to 1700 meters in cirques and on slopes. In the Northern Hemisphere, north-facing slopes receive less solar radiation than other aspects. Consistent with this, the down-slope direction of inactive rock glaciers have more variation in their aspect while active features occur predominately in northeast facing cirques with aspects ranging from 0° to 70° east. Aspects of relict rock glaciers trend between ~270° and ~40° (Table 1).

Rock glaciers require a consistent talus supply from the headwall to form and flow (Wahrhaftig and Cox, 1959). Evin (1987) attempted to analyze the source areas above rock glaciers to characterize how different lithologies affect development. He found that in the Alps a greater number of rock glaciers occurred in carbonate sedimentary rock units than in igneous and metamorphic units. I was unable to ascertain a clear trend in preferential lithologies regarding North Cascade rock glaciers. Geologic maps of the North Cascades, indicate that rock glaciers do not
appear to preferentially form in one lithology over another (Figure 2). The greatest preponderance of rock glaciers occur in an orthogneiss near the crest of the Sawtooth Mountains east of Lake Chelan.

3.2.1 Craggy Peak Rock Glacier

The Craggy Peak rock glacier is nestled in a deep northerly oriented cirque roughly 50 kilometers east of the mountain crest in a tributary of Eightmile Creek. The geologic unit within which Craggy Peak resides is classified as an andesitic flow (USGS geologic maps). Field observations appear to be congruent with this, as the predominant lithology is andesite. Craggy Peak rock glacier is generally lobate in appearance and exhibits two sections (Figure 3). The west lobe contains the classic ridge and furrow structure associated with such features and is approximately 800 meters long. The east lobe is approximately 650 meters long and has a classic over-steepened front with leaning trees as well as other vegetation on its surface. Grain size ranged from sand and silt at the toe slope to boulders as big as 2-3 meters on the surface. The two lobes are separated by a bedrock bench.

3.2.2 Star Peak Rock Glacier

The Star Peak rock glacier is located on the east side of the Sawtooth-Chelan Range, 3 kilometers east of Lake Chelan, at the head waters of the West Buttermilk Creek drainage. It flows parallel to a long ridge trending to the northeast. Geologic unit in this area as mapped by the USGS is the Oval Peak Orthogneiss. Field inspection of the lithology comprising the main rock glacier surface revealed that the predominant rock type appeared to be a tonalite and exhibited very little if any gneissic banding. The Star Peak rock glacier has several different lobes exhibiting classic ridge and furrow topography. Preliminary inspection of lichen on boulder surfaces indicates that there may be an older less active core with two younger lobes further down-slope (Figure 4). Over-all
length of the feature is approximately 700 meters. Grain size ranged from 0.3 meters to 4 meters on the surface while the toe and sides were much finer.

3.3 Active and Inactive North Cascades Rock Glaciers

To assess the distribution of rock glaciers in the North Cascades, I relied heavily on remote imagery for reconnaissance. I initially identified rock glaciers in the North Cascades using satellite imagery from programs such as Google Earth and Bing.com as well as USGS digital orthographic quarter-quads. I relied on criteria of Martin and Whalley (1987) to distinguish between active and inactive rock glaciers:

1. Little or no vegetation growth on the rock glacier surface
2. Rock glacier terminus at or near the angle of repose for the constituent debris

Additionally, I looked for rock glaciers with ridge and furrow structures and convex upper surfaces. I assumed that any rock glacier that exhibited characteristics corresponding to these guidelines was potentially active and a candidate for more detailed study.

Extinct and inactive rock glaciers can be difficult to distinguish from active rock glaciers using remote imagery because they often display similar characteristics. The most consistent difference is that extinct rock glaciers generally have a ‘deflated,’ concave surface indicating that the ice core has melted away. Since such rock glaciers contain little or no ice and may have developed under significantly different climate conditions, they are not useful indicators of modern climate or extent of modern permafrost. I therefore do not distinguish between relict and inactive rock glaciers and largely ignore them as candidates for monitoring. I focus on active rock in this study because they are those used in models as indicators of permafrost. Inactive rock glacier or relict features could exist in areas that were once permafrost and have since warmed, leaving only deflated remnants.
Chapter 4: Movement Monitoring

4.1 Methods

4.1.1 TLS equipment

The ground based LiDAR unit used in this study is the Optech ILRIS-3D ER laser scanner which is capable of +/- 7 millimeter accuracy at 100 meters and has a 40° by 40° region of interest (ROI) (Figure 5). The ILRIS-3D is capable of detecting returns on natural targets up to 1 km away, but its capabilities are severely limited when objects are extremely wet or snow covered. This unit weighs approximately 16 kilograms not including the customized carrying box and backpack. Both a ruggedized laptop and a handheld PDA were used to control the unit in the field. A digital SLR camera is also attached and calibrated to the scanner. Scan locations were marked using GPS, flagging, cairns, and benchmarks bolted into location directly under the center of the wooden tripod.

4.2.2 Timing

I scanned each rock glacier three different times: in early July 2009, in September 2009, and early September 2010. The goal of these scans was to be able to compare summer movement to winter movement and determine the annual velocity field.

4.2.3 Scanning locations/criteria

Ground based LiDAR is a relatively new advancement in geomorphic research. As such the scanning techniques used here are largely novel and previously untested. Appropriate scan locations had to meet two important criteria: 1) a stable base, and 2) an unobstructed, encompassing view of the target. The first criterion requires a bedrock surface large enough to support the unit’s tripod.
An unobstructed view is necessary to accommodate the line-of-sight requirement for the instrument. The preferred alignment with the target is up the long axis of the rock glacier, high enough to overcome the internal topography of the feature, and parallel to the direction of flow indicated by the morphology. Because of topographic limitations at Star Peak, however, the orientation of the scanner was almost perpendicular to the hypothesized flow direction and only the near side of the rock glacier was scanned. There is no outcrop downslope of the rock glacier that is high enough to view the upper surface of the rock glacier (Figure 4, 6). Craggy Peak, in contrast, provides an ideal situation, in which there is a bedrock wall directly across valley from the rock glacier (Figure 7). Table 2 shows the individual scan details.

4.2.4 TLS Data Processing

I processed and analyzed the TLS data using Optech’s Parser, Matchview, and Innovmetric’s Polyworks v11. The scanner saves files as .pf’s, a point cloud with xyz coordinates, and Parser is needed to export them to formats compatible with the other programs. Matchview is a program through which the process of photo-draping is achieved. In photo-draping, the photographs acquired with the digital SLR are laid over the point cloud, assigning true color to individual points, and also allowing photo-realistic 3-D surface models to be created.

The 40° ROI on the scanner is insufficient to span either rock glacier completely in a single scan. Therefore multiple adjacent and overlapping scans (usually 2-3) were needed. In the IMalign module of Polyworks, these scans are spliced together and treated as a single scan. In this way, holistic scans of one rock glacier in 2009 could be compared to 2010 scans. In the IMInspect module of Polyworks, I used several different techniques to quantify movement of the rock glacier between scans (for a detailed description of these techniques, see Appendix 1). The most useful proved to be drawing vectors between like features on the rock glacier surface in repeat scans. Comparison, or
error, maps generated between holistic scans were useful in determining the quality of the alignment in previous modules (Figure 8).

Once I drew 50 vectors (Figure 9), I divided the surface of the rock glacier into 5 intervals based on a visual inspection of the vector directions and their position on the rock glacier (Figure 9, 10). I also created boxplots to better visualize the variation in the vector components and lengths for each zone (Figure 11). A complete list of the vectors is compiled into Table 3.

4.2 Results

4.2.1 Craggy Peak Rock Glacier

Craggy Peak rock glacier proved to be well suited for laser scanning. The scan location was located at a high vantage point which allowed an encompassing view of the entire rock glacier. The rock glacier itself is surrounded by bedrock outcrops that provide excellent reference points to align composite scans and repeat scans.

Comparisons run on the bedrock features (presumed static) used in the initial alignment calculated an average 0.001 m difference between scan overlays with a standard deviation of 0.028 m. However, any comparisons run along sectors of average vector direction on the rock glacier surface returned a mean of 0.05 m and a standard deviation ranging from 0.15 to 0.17 m (Figure 8).

Of the three composite scans created, September 2009 and September 2010 provided the best data sets. Figure 9 shows the distribution of the vectors created in the change analysis. Generally vectors toward the top of the rock glacier exhibited the greatest length (0.06-0.08 m) and had a strong downslope component as well as a component that dipped beneath the rock glacier surface. Toward the toe of the rock glacier, vectors began to display a radial pattern out to the sides of the rock glacier. Here vector length was smaller and varied between 0.03 and 0.07 m. In
this toe section, the vectors adopted a component tilted above the surface of the rock glacier.

Vector length along the rock glacier front was the smallest, varying from 0.03 to 0.045 m. Greatest lengths in the lower lobe of the rock glacier were observed on the left side (Zone 5, Figure 10) averaging 0.08 m, while the right side averaged 0.06 m.

4.2.2 Star Peak Rock Glacier

Data processing for the Star Peak Rock glacier proved to be problematic due in no small part to a general lack of good scan location. Moreover, the bedrock included in the scan is nearly 500 m from the scanner location, on the far side of the rock glacier (Figure 6b). There was thus little control for aligning on the near side of the rock glacier. Scanner accuracy was also insufficient at 500 meters to establish precise control points on the bedrock wall, in turn preventing the construction of accurate composite change-detection scans. Scans were taken from a position nearly perpendicular to the inferred flow direction and at an elevation that did not allow for complete coverage of the rock glacier (Figure 6) leaving large holes in the data set. As such scans taken from Star Peak proved to be difficult to align and process primarily due the relatively poor location of the scan site perpendicular to the movement of the rock glacier. Combined with the apparent slow velocity of the rock glacier and the dearth of good bedrock control points on the near side, this combination of factors prevented any significant change detection at this site.

4.3 Discussion

Measurements appear to be reasonably conclusive for Craggy Peak. Bedrock crops out on three sides of the rock glacier and an ideal scanner vantage point produced enough control to constrain scan overlays and generate accurate change detection. From these compared overlays, preliminary data suggests that portions of the surface on the steepest slope have moved the most while radial spreading at a slower rate has occurred near the toe (Figures 9,10). The upper portion
of the rock glacier has the steepest slope and it follows that this would be the zone of greatest
displacement because here the basal shear stress would be the greatest. The below-surface
component (downward directed) of the vectors in sector 1 suggest that there may be thinning
through this zone. It is unclear whether this is due to melting ice or ‘stretching’. The lower portion
exhibits the radial spreading one might expect from this type of flow. Moreover, the slight upward
component (above surface) of the vectors indicates thickening, which would be expected if the
material from higher was piling here. These results are impressive considering the scanning distance,
250 to 400 meters. However, analysis of the boxplots indicates that there is a large amount of
variation in the components of the vectors even within zones (Figure 11). Whether the variation is
real or if it is due to errors in vector selection is unclear at this point.

The original technique used in this project compared points from one scan to the next
nearest point on the next scan using the Comparison tool in IMSurvey. However, because of near
random nature of the point coverages, it was impossible for this automated process to track the
specific changes along the surface of the rock glacier. Instead, the program compared reference
points on the older scan to only the closest point on the overlaying scan. Therefore, it was
impossible to accurately report horizontal and vertical components of movement. The original aim
of this aspect of the project was to ascertain if the selected rock glaciers were as active as their
morphology indicates. These early measurements strongly suggest that at least a small amount,
0.03 to 0.09 m, of movement is taking place, indicating that the Craggy Peak rock glacier is
marginally active. These numbers possibly could be constrained much more rigorously by using
scanning techniques outlined in Appendix A Section 3.
Chapter 5: Temperature

5.1 Methods

5.1.1 Temperature Loggers

In order to quantify temperature conditions at North Cascades rock glaciers, I installed temperature data loggers in three locations along the length of two active rock glaciers. At each location I placed three equally-spaced loggers along a line reaching from the surface to approximately 2-3 meters below the surface of the rock glacier (Figure 3, 4, 7); the total depth at each site depended on how deep I could reasonable place the sensor string through gaps in the rubble. The sensors were labeled numerically for their position on the rock glacier and alphabetically for their position beneath the surface. For example, the logger string at the point closest to the toe of the rock glacier would be String 1, with logger 1a set at the surface, logger 1b being intermediate in depth, and logger 1c being the deepest (Table 5). The loggers I employed are model DS1921G Thermochron ibuttons. These instruments have an effective range of –30 to 70 degrees Celsius, measure in 0.5 degree increments, and have nominal accuracy of ±1˚C (Thermochron ibutton). Each ibutton stores up to 2100 data points, which is enough to record six data points per day for approximately a year. Because of the time between opportunities to download data from the ibuttons, I recorded summer temperatures on an hourly basis and winter temperatures in four-hour increments.

These ibuttons are only water resistant and needed to be protected from moisture to insure they remain operational. I used latex condoms and ziplock bags to protect each logger from the elements while still recording accurate temperatures. To mitigate the potential for temperature being affected by direct solar radiation, I placed each surface logger in the shadow of large nearby rocks on the north-facing side whenever possible. I secured them to nylon lines at equal intervals.
and lowered them between rock crevices to depths of up to 3 meters, but averaging 2 meters.

Three logger strings at varying elevation on the rock glacier allows longitudinal profiles to be constructed on the rock glacier surface. Also, three loggers on each string allows a ground temperature profile to be constructed and projected to depth to establish the mean annual ground temperature as well as to predict the depth of permanently frozen ground (if any). Best-fit lines used to construct these profiles were either linear or second-order polynomial regressions and selected based on visual inspection of the data and how closely the project line mimicked expected ground temperature profiles.

5.1.2 Modeled Temperature Conditions

Understanding how near-surface air temperature compares with temperatures at the rock glacier surfaces and in the pore spaces is an important part of this study. Unfortunately, winter 2010 air temperature was not recorded on site because the sensor placed above the projected snow level failed once temperatures dropped in late October 2009. To replace these missing data, I constructed models of the air temperature using daily averages from nearby SNOTEL sites as proxies (NRCC, 2010). Five different SNOTEL sites: Rainy Pass, Harts Pass, Lyman Lake, Stehekin, and Pope Ridge, were selected mainly due to their proximity to the study area. Therefore, I instead generated air temperature values by implementing linear regression models. I analyzed temperature data I collected at the surface of the rock glaciers from ibuttons from July to mid-October 2009, and correlated them with temperature measurements at nearby SNOTEL sites (Figure 1). From the SNOTEL data with the highest correlation, I constructed linear lapse-rate relationships with rock glacier surface measurements. Using these summer and fall relationships, I predicted winter air temperature
The linear regression models were validated by using a technique called backcasting. When backcasting, a portion of the measured data (validation period) is used to predict another portion of measured data (calibration period). The prediction skill of the model can then be quantified by using model validation parameters such as Reduction of Error (RE) and Coefficient of Efficency (CE) as well as the squared correlation ($r^2$) (National Research Council, 2006). I created models from multiple SNOTEL datasets, using summer 2009 and 2010 temperature data from as both the validation and calibration periods to ascertain the most skilled model.

The most important periods in model reconstructions to accurately predict are the fall (October through November) and the spring (April and May). These periods mark the transition of summer dominated air movement to winter and vice versa. Moreover, the end of the fall period marks the time period in which snow begins to fall. This is important because snow forms a barrier between the pore space and the atmosphere. Therefore, if the model recreates these periods accurately, than a case can be made that the winter reconstruction was also representative.

5.1.3 Convection vs. Conduction

Distinguishing between convective or conductive modes of thermal transfer at depth is a non-trivial process but important in understanding thermal regimes in regolith. The Rayleigh number is sometimes used in fluid mechanics to determine if natural convection is occurring (Goering, 2002). This number ($Ra$) can be calculated using the following equation:

$$Ra = \frac{C\beta gKH\Delta T}{\nu k}$$

Eq 1

Where $C$, $\beta$, $\nu$ are, respectively, the volumetric heat capacity, expansion coefficient, and kinematic viscosity of the pore fluid (air in this case), $g$ is the gravitational acceleration due to
gravity, \( K \) is the intrinsic permeability of the material, \( H \) is the layer height, \( \Delta T \) is the temperature difference between the top and bottom of the layer, and \( k \) is the thermal conductivity of the material (Goering, 2002). Generally speaking, in modeled situations where the layer in question is bounded above and below by impermeable material and when the Rayleigh number exceeds 40, the layer will experience natural convection (Goering, 2002). However, in situations where the top of the porous medium is left open, convection can occur at lower values, near 27 according to Serkitjis and Hagentoft (1998). Therefore, during winter months when snow cover exceeds a depth of 0.6 m, Rayleigh number values of 40 or more indicate potential convection. However, during the fall while the blockwork is open to the atmosphere, convection may be occurring at lower values. These threshold values of convection reflect only density inversions induced by temperature differences between two layers; it does not consider convection induced by air movement outside the layers under consideration.

In this study, I adopt the values of Juliessen and Humlum (2008) for the constants in the Rayleigh equation above. In their work, the thermal conductivity and permeability are the values with greatest uncertainty. These parameters are based on rough estimates of the porosity of the blockwork and underestimate the intrinsic permeability of the material. Likely, the magnitude of the resulting Rayleigh number is not exact. However, the potential range of variation in intrinsic permeability is small enough that it does not greatly affect the resulting Rayleigh number. A more important factor in the Rayleigh equation is temperature gradient.

When looking for places in the temperature record that may record natural convection, I used two criteria: 1) a Rayleigh number that approached or exceeded 27 in the fall and 40 in the winter, and 2) warming of air in the matrix while the surface temperatures were cold. I identified these areas by plotting the slope of the temperature for each logger with the Rayleigh number and
temperature gradient. Periods where the surface temperature decreased and matrix air did not respond or actually warmed are areas of potential convection. The assumption here is that surface temperature is being driven by atmospheric air temperature and if matrix air warms as the surface cools, then the only source of heating is from air trapped in the rubble. That warm air in matrix therefore may be moving upwards and being sensed by the lower temperature logger.

5.1.4 PRISM Data

To gain some understanding of how the climate of year 2009-2010 compared to the general climate of the area over the past 100 years (i.e., how representative it was), I compared data from the SNOTEL and studied sites to data generated using Parameter-elevation Regressions on Independent Slopes Model (PRISM). PRISM is a climate mapping system created by Dr. Christopher Daly that produces precipitation and temperature coverages based on point data (PRISM, 2010). PRISM generates monthly high temperature, monthly low temperature, and monthly precipitation. These data are generated from models constructed using, in part, measured weather data and are projected over the United States at a 4 km by 4 km grid resolution and projects back in time to 1895.

I treat PRISM precipitation values between the months of October and April as snow-water equivalent (SWE) because at SNOTEL locations approaching the elevations of the rock glaciers, almost all of the precipitation falls as snow during those months. I compared and correlated recent SNOTEL data to the PRISM data to test the validity of the modeled data.

Because I did not have a means of measuring snow accumulation at the rock glacier sites, I had to rely on comparisons to conditions at nearby (~10 km) high-altitude SNOTEL sites. To estimate snow depths at the rock glacier sites I compared snow densities at the SNOTEL sites and applied these to PRISM estimates of precipitation at the rock glaciers. This process enabled me to make approximate estimates of snow water equivalent. I then used an average snow density
recorded at SNOTEL sites to gain an approximate snow depth. Snow depth is important when characterizing ground temperature because of its insulating affect. Sufficient snow cover can keep air temperature from interacting thus changing the way heating and cooling act at depth.

5.2 Results

5.2.1 Climate

5.2.1.1 Cascades Weather 2010 Water Year

The water year of 2010 was dry relative to the 30 year average of SNOTEL measurements in the region. Most stations on the east side of the North Cascades recorded snowpack that was between 60 to 85% of average (SNOTEL). For example, Hart’s Pass recorded 995 mm SWE, 83% of its 1200 mm average (since 1979). Although less snow was received in the 2010 water year, the timing of snow fall and snow melting was congruent with previous years.

Temperatures for the 2009 water year appear to have been slightly cooler than average. The 20 year average at Hart’s Pass is 0.38° C (Hart’s Pass data was only complete to 20 years), while the 2010 average was -0.33° C (NRCS, 2010). Winter temperatures were only 0.4° C cooler whereas summer was 0.8° C warmer. Similar trends are recorded by other SNOTEL stations.

5.2.1.2 Climate (Modeled)

All models were statistically significant (p-values <0.01) and exhibited reasonable skill in reconstructing summer conditions (RE and CE greater than 0.5 in most cases). However, at Craggy Peak, 2010 summer models generated winter temperatures that were consistently too warm. Furthermore, in the vital portion of the reconstruction, that is fall of 2009, 2010 models over predicted temperatures by 2.3 °C. Of the 2009 modeled temperatures, Rainy Pass proved to be the best predictor with a RE value of 0.878, a CE of 0.876, an r² of 0.881, and a standard error of ± 1.6° C (Figure 12). Data generated from the 2009 Rainy Pass model is therefore used as the primary air
temperature for the Craggy Peak rock glacier. By extending the model to September 30th 2010, I calculated the average annual air temperature to be -0.05± 1.58° C for the 2009 water year.

Star Peak models produced high RE and CE values as well as correlations through the important fall period. However, 2009 models generally under-predicted temperatures during the summer of 2010. Of the 2010 models, Rainy Pass data again provided the best fitting model as the 2010 data best reconstructed Star Peak summer 2009 data with a RE value of 0.943, a CE of 0.937, an $r^2$ of 0.952 and a standard error of ± 1.0° C (Figure 12). Therefore, this model was used as the primary air temperature at Star Peak. By extending the model to September 30th 2010, I calculated the average annual air temperature to be 0.3± 1.0° C for the 2009 water year.

For ease of reference I divided the temperature data into seasons based on their temperature characteristics: Summer 2009 is June 30 2009 (July 7th for Craggy Peak) through Nov 1 when air temperature is dominantly positive. I defined Winter 2010 as Nov 1 through May 24 2010 when air temperature is dominantly negative. Summer 2010 is after May 24.

Average yearly air temperature at Craggy Peak, computed from October 1st 2009 to September 30th 2010 is -0.05 °C. The mean temperate of Summer 2009 was 8.1 °C varying from -7 (in October) to 21.04 °C. Winter 2010 temperatures averaged -5.0 °C and varied between -24.5 to 17.9° C while Summer 2010 averaged 8.4° C varying from -0.6 to 17.9° C.

5.2.1.3 Prism

Hart’s Pass data compare relatively well to PRISM, with an $r^2$ value of 0.7973 and averaged within 15 mm SWE of each other. Much of this variation can be attributed to the fact that SNOTEL data are point measurements and PRISM data are projected over a 16 km$^2$ grid cells.

Craggy Peak temperature minima and maxima increased 0.0061 and 0.005° C/year since
1895, while winter precipitation increased ~1.15 mm/year (Figure 13). Average winter precipitation (treated as SWE) is 655 mm per year since 1895 but this has increased to 705 mm in the last 30 years. Craggy Peak received only 540 mm SWE during the winter of 2010, 77% of the 30 year average. Average annual high temperature since 1895 is 6.6° C, compared to 6.8° C averaged over the last 30 years. The 2010 water year average high temperature was 6.33° C. Average yearly low temperature exhibit a similar trend of a warmer 30 year average and a cool 2010.

According to PRISM, Craggy Peak receives ~400 mm less SWE than the closest SNOTEL site, Hart’s Pass (Table 5). Using an average snow density of 32% calculated from Hart’s Pass data, this could translate to as much as 1.3 fewer meters of snow depth. Regardless, according to PRISM data, by the end of November 2010, there had been 210 mm SWE at Craggy Peak which could be as much as 0.667 meters of snow based on the snow density at Hart’s Pass over the same period.

**Star Peak**

High and low temperatures increased ~0.02° C/year since 1895, while winter precipitation increased ~3.65 mm/year (Figure 14). Average winter precipitation is 1217 mm and in the last 30 years this has increased to 1386 mm. Star Peak received 941 mm during the winter of 2010; 69% of the 30 year average. Average yearly high temperature since 1895 is 5.3° C while over the last 30 years it has been 6.2° C. The 2010 water year average high was 5.4° C. Average yearly lows exhibit a similar trend of a warmer 30 year average and a cool 2010.

**5.2.2 Thermal Conditions**

Star Peak and Craggy Peak exhibit similar thermal characteristics. Summer conditions are characterized by large diurnal fluctuation at the surface, lagging attenuated temperatures at depth, and a positive temperature gradient (i.e., cooling with depth). The coldest days corresponded to precipitation events (Figure 15), while shading appeared to be a major controlling factor with daily
high temperatures. Winter temperatures are stable and exhibit a negative temperature gradient (i.e., warming with depth). Daily mean air temperature (DMAT) is the temperature modeled from SNOTEL data and, daily surface temperature (DST) is the surface logger temperature. Although the nominal uncertainty for the iButtons is ±1° C, actual relative variability appears to be substantially less in most cases; however, because the iButtons were not calibrated, the absolute uncertainty is propagated through my gradient calculations and model results.

5.2.2.1 Craggy Peak

General Observations

For ease of reference, annual ibutton temperature data are divided into five temporal intervals that exhibit similar characteristics between logger strings (Figure 16-21). At Craggy Peak, Interval 1 encompasses the period between June 30th and September 30th. Interval 2 is October 1st through November 30th, while Interval 3 is December 1st through mid-April. Interval 4 is mid-April through mid to late-June, and Interval 5 is late June to Aug 10th.

Interval 1

Surface Temperature

Interval 1 is characterized by large diurnal temperature variations as well as large variations in daily average temperature and positive temperature gradients (Figure 22-24). The hourly data indicate that peak surface temperatures (daily highs) occur at 1 or 2 o’clock in the afternoon. Daily lows occur between 7 and 9 in the morning.

Deep Temperature

When compared to surface measurements, high and low temperature at depth were attenuated, having a smaller range and being 2-7 degrees colder, and generally lagged by 1-3 hours. During this period, r-squared values with SNOTEL air temperature averaged 0.74.
Interval 2

Interval 2 comprises a period in which temperatures begin to switch from positive to negative, after summer heating but before major snowfall. Surface temperatures at this time varied from -9±1 °C (the coldest temperature recorded in any interval) to 12±1 °C with a mean of 6.7±1 °C (Figure 22-24). The relationship between surface and sub-surface temperatures becomes more blurred through this time period. Except for several instances, Interval 1 temperature gradients were positive, that is, temperature cooled with depth. However, in Interval 2, as surface temperatures cooled, gradients began to switch from positive to negative, i.e., temperatures at depth were warmer than at the surface. Usually this switch occurred on cooler days whenever air temperature approached or dropped below 0 °C. Warmer days returned to positive gradients. Of note, during the first few weeks of October, temperatures at the deepest logger of String 1 (1c at 2.3 m) rose to several degrees above freezing and remained that way for several days at a time. None of the other data in that string, DMAT, or daily high temperatures approach these values, making it a singular anomaly in the Craggy Peak data. Correlation between air temperature and deep ibuttons remains high at 0.75. Correlation at depth is significant as well at 0.57.

Interval 3

Surface Temperature

Interval 3 coincided with burial by a thick winter snowpack at the rock glacier, and is characterized by relatively stable temperatures and a largely negative gradient (warmer at depth). Daily mean air temperature averaged -6.6 °C and never warmed above 0 °C during this time period and some of the colder days approached -20° C. In contrast, loggers positioned at the surface of the rubble record an average temperature of -3.4±1° C, while only varying between -5 and -2 °C.

Temperatures at Depth

Sub-surface temperature averaged -2.2 ±1.5°C. Gradients were consistently negative on
all strings, averaging -0.6 °C/m. However, instrument error (± 0.9 to 1.2°C/m) overlapped into positive temperatures. R-values between surface loggers and air temperature remains weak but significant at 0.39, while correlation with deep loggers is similar but inverse at -0.4.

**Interval 4**

Interval 4 began shortly after the first few days of positive mean air temperature when the loggers warm to a new temperature plateau (inferred to be the Zero Curtain). During this period, DMAT is 2.3 °C and ranged between -5 °C and 10 °C. Rubble surface sensors record an average temperature of 0±1° C with an average daily range of 11 °C. Sub-surface temperatures averaged -0.2±2.8 °C (Figure 22-24). In strings 1 and 3, the first occurrence of positive DMAT coincides with a switch from a negative to positive gradient. Ground temperature warms by 1.5° to 2.0° C, but rubble surface temperatures warmed more quickly and surpass temperature at depth. The rest of Interval 4 is characterized by a gradient oscillating between positive and negative. String 2 shows a different trend. The surface sensor measured warming of 3.5° to -0.5° and the deep sensor warmed 2.5° to 0.5° C, as the dominant gradient changed from a stable -0.65 °C/m to an equally stable -0.43°C/m. This period also marks the lowest r-value between loggers and air temperature. Upper loggers correlate at 0.29 and deeper loggers -0.05.

**Interval 5**

Interval 5 begins when all sensors (those at the surface and depth) begin to covary with the air temperature on a daily basis. However, DMAT does not appear to match well with temperatures at sensor sites 3 and therefore String 3 will be described separately. String 1 daily surface averages 11.6±1 ° and varies from 3.8 to 17.3 °C while String 2 reports a mean of 10.6±1°C and range from 2.5°C to 14.25°C. At depth String 1 averaged 5.8±1°C, ranging from 0.5°C to 10.2°C and String 2 averaged 4.9±1°C and varied from .58 ºC to 8°C. String 3 was significantly colder, averaging 3.2±1°C.
at the surface and varying from -3.4°C to 13.5°C. At depth, String 3 recorded a mean of 1±1°C and ranges from -3.4°C to 7.8°C. These temperatures indicate that String 3 was most likely still under snow for a portion of this time period. Gradients at this juncture are wholly positive averaging 2.63 °C/m, greater than the ±1.2°C/m instrument error, while being as high as 7.5 °C/m. Correlations return to significant: 0.78 for upper loggers and 0.41 for deeper loggers.

**Temperature Profile**

Winter mean temperature at each logger was taken to be Interval 3, while summer mean is Interval 5 (selected over Interval 1 for completeness of data). String 1 summer and winter profiles intersect at 4.3±0.5 meters deep, String 2 intersects at 7±1 meters, and String 3 at 4.1±0.5 meters (Figure 25). Summer temperature reaches 0°C at 5.8±1 meters below the surface at String 2 and 4±0.3 and 3.1±0.5 meters at strings 1 and 3 respectively. The intersection of summer and winter profiles hovers near -1.0 °C and this is likely near the average ground temperature.

**5.2.2.2 Star Peak**

**General Observations**

Temperatures at Star Peak loggers did not vary greatly with depth during the winter months (Interval 3 and parts of 2 and 4). Loggers that recorded surface temperatures during the summer were within 1 degree of, the instrument error, of loggers deeper in the rubble (Figures 19-21). As such, temperature gradients were equally low and error overlap makes any interpretation ambiguous at best.

**Interval 1**

During this time interval, surface temperature correlates well with air temperature. Surface temperature highs occur between 1:00 and 4:00 PM, whereas lows occur between 4 and 7 am. Average daily surface temperatures (DST) range from -2.7±1 °C at the end of the summer to
19.1±1.02 °C at the beginning of August. DMAT averaged 11.7± 1.02 °C and while measured DST averaged 12.1±1 °C (Fig. 12, 13), String 3 is nearly 4° C warmer than Strings 1 and 2 (12° C vs ~8° C).

**Interval 2**

Temperatures fall steadily through Interval 2, DMAT is -3.1± 1.0 °C varying from 4.1 °C to -9.6 °C, and DST averaged -3.5± 1 and varied from 3.6 to -10.8 °C. Sub-surface temperatures averaged -3.6± 1 °C ranging from -9.8 to 1.7 °C. The temperature gradient oscillated between negative and positive during this interval. Negative gradients usually occurred when DST approached 0 °C, while positive gradients occurred when DST warmed. However, at Star Peak sites, the gradient between loggers was usually well within the instrument error and often overlapped into positive and negative values (Figures

**Interval 3**

Temperatures in Interval 3 exhibit little variation and a poor correlation between DST and DMAT. DST ranges from -4.5 to -1.0 °C and averages -3.0 °C. Temperature gradients for this period are generally negative. In Strings 1 and 2, the gradient is relatively small, -0.3 to –0.6 °C/m, well within the ± 1 to 1.3°C/m from instrument error. In String 2, the gradient between the 2b and 2c sensors never become negative. In String 1, the gradient is more strongly negative between the same two sensors. String 3 averages nearly 0±1 °C/m for the duration of this period. The strongest gradient is between 3b and 3c and averages 0.1 °C/m.

**Interval 4**

On April 15th, DMAT became positive for the first time since October and remained so for about 7 days before dropping below 0°C again. The response in the in-situ sensors was muted and absent entirely. In String 1, temperatures increased from –1.5 to –0.5°C 5 days after the DMAT increase. In String 2 and 3, there was a steady, gradual warming until the end of the second
stronger warming period 20 days later during which they both increased –2.5 to –0.5 °C. Midway through Interval 4, in the first week of June, temperatures at all loggers rose to 0±1 °C. Shallow loggers held this temperature to late June/early July after which they began to reflect DMAT. Deeper loggers (b and c) maintained steady temperatures at 0 °C until the second week of July. There was no gradient at String 1 throughout Interval 4. Strings 2 and 3 exhibited generally positive gradients as shallow sensors warmed faster than those at depth.

**Interval 5**

In Interval 5, all sensors establish large positive gradients with DST mirroring DMAT as subsurface temperature were attenuated. DST averages 10.6±1 °C at String 1 and varies from 0°C to 17°C. String 2 is nearly the same, but String 3 averages 6.3±1 °C and ranges -2.5°C to 18.7°C. At depth Strings 1, 2, and 3 average 5.4±1°C, 7.3±1°C, and 3.1±1°C respectively, while ranging from -2.5°C to 14.4°C. DMAT is 11.9±1.02 °C.

**Temperature Profile**

The temperature profile for each logger string at Star Peak projected at depth (Figure 25). Winter mean temperature at each logger was taken to be Interval 3, while summer mean is Interval 5. Thermal profiles calculated Star Peak indicate that the average ground temperature (the intersection between the winter and summer profiles at depth) varies widely from the lower logger location to the upper (Figure 25). String 1 recorded an average ground temperature of 0.5±1° C, whereas strings 2 and 3 produced -1.0±1° C and -4.5±1° C respectively. Summer temperature profiles at strings 2 and 3 also indicate that the depth of the 0° C isotherm is near 5±1 meters deep.

**5.2.3 Convection and Conduction**

Computation of the Rayleigh number revealed several instances where natural convection may have occurred (Figures 27-32). The largest uncertainty in these measurements is in regard to
the snow cover at these points. If the blockwork is open to the atmosphere, then the critical Rayleigh number for natural convection is near 27 while if snow is covering the area then 40 is the critical value for convection (Serkitjis and Hagentoft, 1998; Goering, 2002). Through the months of October and November, the Rayleigh number approaches 40 but rarely reaches it. Much more often 27 is reached and exceeded during the fall in instances where there is a strong negative temp gradient (Figures 27-32). CpS1 recorded the most likely occurrence for convection between October 9th to November 3rd where the Rayleigh number approaches critical values and the behavior of the temperature strings is congruent with what might expect (Figure 33). When accounting for instrument measurement error in the gradient calculation, the lower boundary of the error envelope rarely approaches the critical value, while the upper boundary often exceeds it.

5.3 Discussion

Analysis of the logger data revealed several potential mechanisms through which ground temperature interacts with air temperature. It bears noting that instrument error, especially at Star Peak where logger records along strings are within a degree or less of each other, makes any interpretations less conclusive. However, instances at Craggy Peak especially have a large enough temperature spread between loggers to fall outside of the nominal instrument error and potentially indicate where some different processes, such as wind pumping, natural convection or other mechanisms come into play.

5.3.1 Temperature Conditions
5.3.1.1 Summer Regimes

Summer thermal regimes behaved predictably with ground temperatures lagging surface temperatures and reflecting progressive attenuation with depth. Slightly more time is required for air in the pore space to respond to surface warming. When temperature gradients are positive,
Conduction is the primary way that air at depth warms (barring wind pumping). These conductive processes sometimes take several hours (see Figure 26) to transfer heat to depth. Lag from conductive warming is governed primarily by the grain size of the rubble in the matrix and temperature gradient between surface and depth. Smaller grain sizes form an insulating blanket impeding energy transfer through the greater portion of rocks. The temperature gradient, that is the difference in temperature between the surface and in the pore space, controls how quickly temperature will change at depth via the transfer of energy.

A second way heat is transferred during the summer is through forced convection, i.e. wind pumping. This is the lateral movement of air into the pore space via the wind. In this study this phenomenon was hard to constrain. However, one could infer where wind pumping occurs based on low lag, and low gradient in the temperature measurements. Throughout the summer, ground temperature will warm following the warming of the diurnal temperature cycle. However, surface temperature rarely reaches the lows of the ground temperature (Figure 24), implying that any cooling in the rock matrix during the summer months must be driven by either convective or conductive processes from colder air deeper in the rubble. In this way, any ice or residual cold air from the winter deep in the matrix mitigates the effects of summer warming.

Daily average summer temperature at the surface was nearly always warmer than daily average temperature at depth and well outside of the error envelopes. The resulting positive thermal gradient is maintained in part because the density differences between the cool ground air and the warmer surface air establishes a stable gradient that resists convective air movement. This stable density gradient disappears when the surface temperatures dropped to below 5°C. While some of these temperature inversions could be attributed to instrument error (instrument error envelopes often overlap during these events), universal inversions occurrence through all logger...
strings suggests that reversing gradient is probably an actual event. I attribute this phenomenon to the temporal nature of these temperature drops as they only occurred briefly and temperature warmed quickly thereafter. Thus ground temperature did not have time to equilibrate with the drop in surface temperature resulting in a temporary gradient inversion. These sudden drops in surface temperature are probably related to cooling from precipitation events where surface temperature drops suddenly with the onslaught of rain. Incremental precipitation from nearby SNOTEL sites confirms that precipitation corresponds with many of the temperature drops (Figure 15). It bears notice that at many of these points the Rayleigh number approaches and exceeds 27 and in some cases 40, indicating that natural convection may have occurred (Figures 27-32). However, instrument error, inexact calculations, and other unknowns (such as wind pumping) may be creating these signals.

5.3.1.2 Fall Regimes (Interval 2)

The key periods of ground/surface temperature interaction are during the months of October and November (Interval 2), when temperatures are dropping but before major snow accumulation, and during the months of May and June when snow is melting allowing warming of air in the rock matrix. Repeated shifts between positive and negative temperature gradients mark this transition as air density differences cause natural convection. During the summer, less dense warm air rests on top of cold air creating a stable stratification, where heat transfer occurs through conduction. In the fall, when surface temperatures become colder, the now relatively warm ground air is expelled through natural convection. The expulsion of warm air and its replacement with colder air is an important part in what governs ground temperature mainly because convection is a more efficient means of heat transfer then conduction and, for the winter, controls the minimum ground temperature as well as the minimum BTS.
The potential for ground cooling increases the longer the air in the rock matrix is exposed to the surface air. However, early, heavy snowfall can inhibit ground cooling by inhibiting the forced convection in the regolith. The North Cascades differ from most other maritime mountains that support rock glaciers (e.g., Norway (Juliussen and Humlum (2008), maritime Greenland Humlum (1997), and the Swiss Alps (Hanson and Hoelzle, 2004)) in that the interval during which open blockwork is exposed to cold winter air is several weeks shorter. These slightly dryer climates locations develop colder ground temperature mainly because they lack the thick insulating blanket of snow which results. In the North Cascades, abundant and early snow accumulation in the fall tends to inhibit air exchange with the atmosphere resulting in warmer ground temperatures throughout the winter.

**Evidence for Natural Convection**

In October, deep temperature at Cp1c and Cp2c sometimes warm to near or above 0° C over 3 to 5 days (Figure 33). At the same time, Cp1a and Cp2a continue to vary greatly and are generally much colder than Cp1c and Cp2c, with negative gradients (Figures 27-28). This begs the question: What is causing the warming at the deeper loggers as there is no warm air input from above? Moreover, at precisely the same time when the surface loggers (1a and 2a) are cooling, the matrix loggers are warming. Slight attenuation and warmer temperatures (still well below freezing) at Cp1a suggest that some amount of snow has covered that location, while higher on the rock glacier, Cp2a and Cp3 appear to still correspond freely with the atmosphere (Figure 16-17, Table 6).

Cp1c plateaus at 3° C, a greater interval than can be accounted for by instrument error, for three days and 1.5° C several days later following a drop in temperature down to -2° C (Figure 33). Over the same period Cp1a records temperatures of at least 2° cooler, and the temperature gradient between the two surface and matrix loggers is great enough to induce natural convection.
(as indicated by the calculated Rayleigh Numbers). I hypothesize that these warm periods (Figure 33) are caused by the convective release of deep warm air. The implication here is that these repeated warmer plateaus deplete the warm ground air directly below the logger string. Summer ground temperature profiles suggest that the 3°C isotherm exists near 3 meters below the surface (Figure 25). Since Cp1c is only 0.9 meters higher than 3°C isotherm and the duration of the 3°C plateau is several days, the implication is that air is moving laterally to this location. These lines of evidence suggest that String 1 is located on a “chimney”. Though, convection must be an important means of energy transfer through the Fall and no clear evidence for it exists at the other strings, the implications are that chimneys are localized features that may occur in discrete intervals while the diffusion of cold air into the matrix via conduction is probably widespread.

5.3.1.3 Winter Regime (Interval 3)

Hanson and Hoezle (2002) used the dynamic relationship between ground and surface temperatures to investigate the effect of snow cover on ground temperatures. Based on instrumentation in a rock glacier in the Swiss Alps, these workers concluded that once snow cover reached 0.6 m thick, air and ground temperature became largely decoupled. Despite indications from PRISM and SNOTEL data that snow depths were thicker than 0.6 m at measurement sites by the end of November (>1.6 m at Star Pk; 0.67 m at Craggy Peak), BTS and modeled air temperatures continued to exhibit a statistically significant correlation at several logger strings (Craggy Peak’s String 1: 0.71 and Star Peak’s String’s 1 and 3: 0.66 and 0.59 respectively, Table 6). There may be several different reasons for these high correlations. At SPst3, note that the temperature gradient over the same period (November-April) at these logger strings is also low, meaning that there is little difference between the BTS and deep temperatures (Figure 21). The high correlation and lack of temperature gradient implies that cold above-snow air continues to interact with the air in the regolith despite the insulating effect of the snow cover (Table 6). However, early season snow in the
North Cascades is relatively dense and compactable, it is unlikely that the cold air moves through the pores in the snowpack itself. If air temperature is still effecting ground temperature, it is likely through breaks in the snow cover, probably adjacent to large boulders that act as conduits for air travel (the Chimney Affect, (Harris and Pedersen, 1998)). A photograph taken from the air in January of 2010 supports this hypothesis as it reveals numerous boulders still uncovered with likely gaps along their edges (Figure 31). Additionally, all three thermistor sites on Star Peak rock glacier are located on local ridges where it appears that early-season snow cover is thinner, evidenced by the smaller boulders visible at these locations in the winter photograph (Figure 31).

A second hypothesis is based on Hoelzle et al. (1999) observation that during the winter cold air tends to pool in furrows adjacent to ridges on the rock glacier surface. They theorized that the cold air in these furrows could migrate laterally into the ridges through gaps in the snow cover. This could explain the lack of a temperature variation between the upper and lower loggers as air moves into the matrix and creates a stable temperature between loggers.

However, perhaps the best explanation considering visual and quantitative inspection of the data may be that the correlation between matrix and atmospheric air is coincidental. While the correlation is significant, variation in the matrix air temperature is seldom more than 0.5 to 1 °C, indicating that it is unlikely that air temperature is greatly affecting regolith temperature. Low gradient between loggers as is the case at Star Peak’s String 3 may indicate that snow had sifted down into the matrix encasing the logger string in its entirety, thus creating a relatively stable temperature setting. Furthermore, these small differences, although possibly real, are within the nominal uncertainty of the instruments and so their significance cannot be confirmed.
Zero Curtain

Interval 4 is dominated by the well-studied zero curtain (Outcalt et al. 1990). During this period, the repeated freeze-thawing of water in and at the base of the snowpack releases and absorbs latent heat causing temperatures to stabilize at 0°C. These periods generally occur when surface air temperatures routinely reach above freezing (see Interval 4 in Figures 16-21).

5.3.2 Thermal Exchange Characteristics

I generated summer and winter thermal profiles, i.e. how temperature changes with depth, by projecting the average temperature at each logger to depth (Figure 25). It should be noted that uncertainty is great regarding these thermal profile constructions. In order to gain an accurate representation, temperatures at depth must be primarily driven by conduction. However, during the summer months, the rubble pore space is more open to wind and solar driven temperature variation that could skew temperature average. Moreover, lack of control at depth (i.e., below the deepest logger) makes any projection guess work at best.

Craggy Peak strings are situated at sites that are at similar elevation to the surrounding surface and are less exposed to horizontal air movement. Based on visual comparison of data, CpS1 and CpS3 appear to have been skewed most by interaction with the atmosphere during both summer and winter months, while the more attenuated deep loggers of CpS2 indicate that air exchange with the atmosphere may be less of a factor (Figures 25, 16-18). During the summer and winter months, CpS2c varies the least of all the deep loggers, probably indicating the rubble layer here is the most effective at filtering out convective driven temperature variations. Therefore, CpS2 has the most potential for estimating the mean annual ground temperature; which is, according to these projections, -1.0±1 °C. This temperature can also be taken as the maximum long term surface temperature mean as generally, average surface temperature is often slightly colder than ground
temperature (CITE). A second piece of information that can be gleaned from projecting the temperature at depth is the thickness of the active layer. Using the summer temperature gradient one can infer the depth at which the 0° isotherm occurs and therefore, by definition, where the ground is frozen. All of these projections are based on the assumption that the temperatures at depth are stable and changes are driven by conduction. However, based on the temperature correlation with the atmosphere, a convection driven temperature gradient is more likely indicating that 3 to 5.7 meters are minimum depths.

Humlum (1998) theorized that stable temperatures at depth may reflect a minimum temperature for any ice body below. Any warming of deep loggers must be attributed the average temperature of ice within the blocky material whenever the temperature gradient is negative. A negative temperature gradient precludes the possibility of warming from the surface. Moreover, there is no other mechanism for transporting warmer air into the pore space, barring wind pumping. Analysis of the Rayleigh number indicates that air mixing via natural convection may occur in the Fall. However, whether the temperature shift is due to natural or forced convection is not clear as wind pumping could presumably generate the same affect. When snow cover reaches a certain point, the data indicates that natural convection is unlikely, and therefore temperature change must be driven by conduction. Thus, due to the negative nature of the winter temperature gradient, perhaps we can infer that the deepest loggers record the minimum of ice temperature and the average annual temperature of the ground.
Chapter 6: Conclusions

Review of aerial photography revealed at least ten morphologically active rock glaciers and equivalent numbers of inactive rock glaciers. Likely there are more relict features that are difficult to distinguish from glacier landforms. Most rock glaciers are located on the east side of the main divide in north facing cirques or cliffsides.

Repeat TLS scans of two of these rock glaciers produced somewhat mixed results regarding their activity. Refinements in the scanning technique are required in order to more conclusively constrain movement. However, preliminary results indicated that Craggy Peak may be moving rates of up to 5 to 10 cm/yr. No significant movement was detected at Star Peak rock glacier because of poor scanning geometries. However, at least part of the rock glacier appears to be active due to fresher surface. Movement analysis techniques require refinement as well as more rigorous statistical analysis of the results (see Appendix A). Ideally, more than 100 vectors would be chosen, potentially from targets set on the rock glacier, and then analyzed to ascertain statistical significance.

Craggy and Star Peak rock glaciers exhibit mean annual air temperatures of $-0.1 \pm 1.6^\circ$ C and $0.3 \pm 1.02^\circ$ C respectively (Figure 12), whereas average ground temperature is projected to be near $-1.0$ to $0^\circ$ C (Figure 25) at the toe of the rock glaciers. Ground temperature at the top of the rock glaciers cool to $2.1$ to $-4.5^\circ$ C near the top. These data indicate that the climatic conditions at the studied rock glaciers is slightly warmer than traditional interpretations of rock glaciers conditions (<-$2$ C) warrant. However, the period of this study encompass only one year of data and a longer term record must be established in order to conclusively constrain long-term temperature conditions. Convective air circulation after snow fall at Craggy Peak is unlikely at two of the three logger sites.
given the low Rayleigh numbers. This result implies that temperature change at depth is likely driven by average ground or ice temperature in the winter. However, string 1 at Craggy Peak appears to record several instances during the fall during which a temperature inversion occurs, possibly reflecting convective flow. Conceptually, such convection would occur as the ground acclimates to colder air temperatures. Relatively warm air travels through the regolith laterally to evacuate at discrete locations of upward flow, or “pipes”, at the surface of the rock glacier (Figure 35). This process occurs as colder air sinks to depth over most of the rock glacier replacing the evacuated cool interstitial air. Once ~1 meter of snow falls, these “pipes” are sealed, convection largely stops and ground temperature equilibrates through conduction to its long term average. A more complete coverage of data loggers over the rock glacier surface would be needed to fully test this hypothesis.

At Star Peak, it seems likely that many of the loggers were not recording the free air beneath the snowpack, but were instead incased in snow that filtered into the regolith. Thus, it is difficult to track convection or to model winter thermal regimes. However, the instrumental uncertainty means that it is possible some signals were missed. Summer ground temperature at both rock glaciers is a product of both conductive and forced convective heat transfer where stratification of air layers warms the ground through conduction and wind pumping forces air exchange via convection.

These preliminary results for ground temperature and air temperature suggest that Craggy Peak and Star Peak exist in conditions warmer than those delineated by Barsch (1996). Results at Craggy Peak are especially significant because of the LiDAR results indicate that the rock glacier is active and thus still in balance with the local climate. Based on temperature data collected in this study, Craggy Peak is at the warmer limit of the discontinuous permafrost interval and, at -0.1 ± 1.6°
C, is warmer than the -2° C reported by Barsch (1996). While more a temporally extensive record should be established at Craggy Peak before these conclusions can be confirmed, these results suggest that the practice of using rock glaciers as indicators of extensive mountain permafrost should be re-evaluated.

Future studies at these sites should continue to record thermal regimes and climate conditions at these rock glaciers. More logger strings would help identify areas of natural convection as well as help constrain ground temperatures. Installation of a weather station would help link temperature events recorded in the regolith to atmospheric processes. Continued use of the TLS, perhaps augmented with total station and GPS methods, would help more rigorously constrain movement at Craggy Peak.
Figure 1. Study area, including location of select rock glaciers and SNOTEL sites. Blue triangles indicate potentially active rock glaciers based on their morphology, black triangles indicate inactive or relict rock glaciers. Red triangles indicate rock glaciers investigated in this study. SNOTEL sites used in this study indicated by yellow circles.
Figure 2. Map showing major geologic units (Bedrock and surficial units) near study sites. See Table 1 for unit descriptions. Red diamonds are instrumented rock glaciers, blue triangles are active rock glaciers, black triangles are inactive rock glaciers.
Figure 3. Two views of Craggy Peak rock glacier, indicating two main lobes. A is an aerial photograph taken in July 2009 (Google Earth). B is a LIDAR image of the rock glacier collected in September of 2009 during this study. 5 meter contours (light blue lines) have been constructed based on the LIDAR data using Polyworks (v11). Sensor string locations are denoted by red dots.
Figure 4. Star Peak rock glacier. (A) is a contour map constructed from LIDAR. Contours are at 5 meter intervals and red dots are string location. (B) is a Google Earth satellite photograph of the same rock glacier. Note the two separate lobes indicated by the dashed lines. The Southern lobe is likely younger based on the lichen development.
Figure 5. The Optech ILRIS 3-D terrestrial laser scanner.
Figure 6. Star Peak processed LIDAR image (A) and a photograph from the scan site (B). The blue rectangle indicates bedrock used as a stable reference surface when attempting a change detection diagram. The LIDAR image has been rotated toward the viewer slightly. Black lines indicate the same furrow features on each location and the black ovals are also the same locations.
Figure 7. Location of temperature loggers as indicated by the red arrows at Craggy Peak (A) and Star Peak (B).
Figure 8. Change analysis of bedrock reference surfaces using “Shortest” method. Distance is the mean distance from the scanner to that target. Number of points is the number of returns from the indicated zone. Mean is the average distance between like points in each scan. The smaller the mean the better the two scans overlay. Points within x-Standard deviation is the percentage of points within the indicated standard deviation. Units are in meters. Bedrock less than 600 meters from the scanner location exhibits mean change of ~3 mm with a standard deviation of ~2.5 cm.
Figure 9. Vectors drawn on the surface of the Craggy Peak rock glacier between the same features in subsequent LIDAR scans. Cone points indicate the direction of movement and different colored areas are zones that have similar directions.
Figure 10. Movement analysis results for Craggy Peak rock glacier. Arrows represent average movement directions for each zone.
Figure 11. Box plots of the distribution of the vectors. Table 3 is the data in full. Box plots are a visualization of descriptive statistics where the upper bracket represents the maximum value, the lower bracket is the minimum value, the top of the ‘box’ is the 3\textsuperscript{rd} quartile, the bottom of the ‘box’ is the 1\textsuperscript{st} quartile, and the middle bar the median. Any dots outside the bracket are outliers.
Figure 12. Modeled air temperature data between June 30th 2009 and September 20th 2010. Solid black lines are temperatures modeled using a linear regression between surface temperature measured at the rock glacier sites and air temperature recorded at nearby SNOTEL. The red lines are measured surface temperature. Dotted lines represent the model’s standard error: +/- 1.58 C for Craggy Peak and +/- 1.02 C for Star Peak). Prediction skill between Craggy Peak and the Rainy Pass SNOTEL site is generally good with an RE and Ce of 0.878 and 0.876 respectively. The same values between Star Peak and the Rainy Pass SNOTEL site are marginally better: an RE of 0.943 and CE of 0.937.
Figure 13. PRISM climate data for the Craggy Peak area. The average precipitation is the average in the winter for a given year. Temperature data is the yearly average high or low.
Figure 14. PRISM climate data for the Star Peak area. The average precipitation is the average in the winter for a given year. Temperature data is the yearly average high or low.
Figure 15. Surface temperature as recorded by ibuttons at each investigated rock glacier and precipitation events recorded at Hart’s Pass SNOTEL site. During summer months, nearly all large drops in temperature correspond to a precipitation event. A small intermittent lag between temperature and precipitation may reflect the SNOTEL site’s position west (upwind) of the rock glaciers (see Figure 1).
Figure 16. Craggy Peak Logger string 1 (CpS1) for June 30, 2009 – Aug. 10, 2010. Data plotted is daily average. Sensor 1a (red) is at the rubble surface whereas 1c (blue) is 2.3m deep in the regolith. Snow depth data are from two SNOTEL sites, Hart’s Pass (blue) and Lyman Lake (black).
Figure 17. Craggy Peak Logger string 2 (CpS2) for June 30, 2009 – Aug. 10, 2010. Data plotted is daily average. 2a (red) is at the rubble surface while 2c (blue) is 2.3m deep in the regolith. Snow depth data is taken from two SNOTEL sites, Hart’s Pass (blue) and Lyman Lake (black).
Figure 18. Craggy Peak Logger string 3 (CpS3) for June 30, 2009 – Aug. 10, 2010. Data plotted is daily average. 3a (red) is at the rubble surface while 3c (blue) is 1.7m deep in the regolith. Snow depth data is taken from two SNOTEL sites, Hart’s Pass (blue) and Lyman Lake (black).
Figure 19. Star Peak Logger string 1 for June 30, 2009 – Sep 8, 2010. Data plotted is daily average. 2a (red) is at the rubble surface while 2c (blue) is 1.5m deep in the regolith. Snow depth data is taken from two SNOTEL sites, Hart’s Pass (blue) and Lyman Lake (black).
Figure 20 Star Peak Logger string 2 for June 30, 2009 – Sep 8, 2010 with . Data plotted is daily average. 2a (red) is at the rubble surface while 2c (blue) is 1.5m deep in the regolith. Snow depth data is taken from two SNOTEL sites, Hart’s Pass (blue) and Lyman Lake (black)
**Figure 21.** Star Peak Logger string 3 (CpS3) for June 30, 2009 – Sep 8, 2010. Data plotted is daily average. 3a (red) is at the rubble surface while 3c (blue) is 2.1m deep in the regolith. Snow depth data is taken from two SNOTEL sites, Hart’s Pass (blue) and Lyman Lake (black).
Figure 22. Box plots of Craggy Peak thermistor strings 1 and 2. Columns are ordered with the shallowest logger in the string toward the top with each subsequent logger below it. Box plots are a visualization of descriptive statistics where the upper bracket represents the maximum value, the lower bracket is the minimum value, the top of the ‘box’ is the 3rd quartile, the bottom of the ‘box’ is the 1st quartile, and the middle bar the median. Any dots outside the bracket are outliers. The temperature zones are time intervals where temperature fluctuations and magnitudes are similar (See figures 16-17).
Figure 23. Box plots of Craggy Peak thermistor string 3 and Star peak string 1. Columns are ordered with the shallowest logger in the string toward the top with each subsequent logger below it. Box plots are a visualization of descriptive statistics where the upper bracket represents the maximum value, the lower bracket is the minimum value, the top of the 'box' is the 3rd quartile, the bottom of the 'box' is the 1st quartile, and the middle bar the median. Any dots outside the bracket are outliers. The temperature zones are time intervals where temperature fluctuations and magnitudes are similar (See figures 17-18).
Figure 24. Box plots Star Peak strings 2 and 3. Columns are ordered with the shallowest logger in the string toward the top with each subsequent logger below it. Box plots are a visualization of descriptive statistics where the upper bracket represents the maximum value, the lower bracket is the minimum value, the top of the ‘box’ is the 3rd quartile, the bottom of the ‘box’ is the 1st quartile, and the middle bar the median. Any dots outside the bracket are outliers. The temperature zones are time intervals where temperature fluctuations and magnitudes are similar (See figures 19-21).
Figure 25. Best-fit thermal profile regressions for stations 1-3 on each rock glacier (Star Peak on left, Craggy Peak on right). The x-axis is temperature in degrees Celsius and the y-axis is meters below the surface. Red arrows indicate projected intersection of summer and winter profiles at depth, which indicates the average ground temperature; blue arrows indicate the projected depth of the summer 0°C isotherm.
Figure 26. Summer temperature data from Star Peak String 3. Data is recorded in one hour increments; x-axis is the numerical day beginning on June 29, 2009. Note that temperatures at the deepest thermistor (blue line), peak slightly (2-4 hours) after the surface temperature (red line).
Figure 27. Hourly data from Craggy Peak String 1. (A) is logger 1a plotted with 1b and the Raleigh number for that interval. (B) is the data for 1b vs 1c. Dashed line is the Rayleigh threshold for convection (40). X-axis is the numeric day.
Figure 28. Hourly data from Craggy Peak String 2. (A) is logger 1a plotted with 1b and the Raleigh number for that interval. (B) is the data for 1b vs 1c. Dashed line is the Rayleigh threshold for convection (40). X-axis is the numeric day.
Figure 29. Hourly data from Craggy Peak String 3. (A) is logger 1a plotted with 1b and the Raleigh number for that interval. (B) is the data for 1b vs 1c. Dashed line is the Rayleigh threshold for convection (40). X-axis is the numeric day.
Figure 30. Hourly data from Star Peak String 1. (A) is logger 1a plotted with 1b and the Raleigh number for that interval. (B) is the data for 1b vs 1c. Dashed line is the Rayleigh threshold for convection (40). X-axis is the numeric day.
Figure 31. Hourly data from Star Peak String 2. (A) is logger 1a plotted with 1b and the Raleigh number for that interval. (B) is the data for 1b vs 1c. Dashed line is the Rayleigh threshold for convection (40). X-axis is the numeric day.
Figure 32. Hourly data from Star Peak String 3. (A) is logger 1a plotted with 1b and the Raleigh number for that interval. (B) is the data for 1b vs 1c. Dashed line is the Rayleigh threshold for convection (40). X-axis is the numeric day.
Figure 33. Craggy Peak String 1 plotted over the fall and early winter of 2009. Data is in 4-hour increments. Periods of possible warm-air driven convection indicated by circles.
Figure 34. A photograph of Star Peak taken in late January 2010 (courtesy of John Scurlock). Arrows indicate the approximate locations of the logger strings. Notice that many larger boulders are not completely incased in snow.

Figure 35. Cartoon representation of how natural convection may occur following light snowfall during the Fall.
### 8.0 Tables

<table>
<thead>
<tr>
<th>Unit</th>
<th>General Composition</th>
<th>Active</th>
<th>Inactive</th>
</tr>
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<tbody>
<tr>
<td>Golden Horn batholith</td>
<td>granite</td>
<td>Silver Star</td>
<td>-</td>
</tr>
<tr>
<td>Monument Peak stock</td>
<td>granite, continental sedimentary</td>
<td>Monument Pk1</td>
<td>Monument Pk2</td>
</tr>
<tr>
<td>Winthrop Sandstone</td>
<td>rocks</td>
<td>-</td>
<td>Oceola Pk2</td>
</tr>
<tr>
<td>Virginian Ridge Formation</td>
<td>marine sedimentary rocks</td>
<td>-</td>
<td>Oceola Pk1</td>
</tr>
<tr>
<td>Harts Pass Formation</td>
<td>marine sedimentary rocks</td>
<td>Powder</td>
<td>-</td>
</tr>
<tr>
<td>Panther Creek Formation</td>
<td>marine sedimentary rocks</td>
<td>Holman</td>
<td>-</td>
</tr>
<tr>
<td>Black Peak batholith, main phase</td>
<td>orthogneiss</td>
<td>Renny Pk</td>
<td>Hock Mtn</td>
</tr>
<tr>
<td>Midnight Peak Formation, volcanic member of</td>
<td>volcanic rocks</td>
<td>-</td>
<td>North Gardner</td>
</tr>
<tr>
<td>Oval Peak batholith</td>
<td>tonalite</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Oval Peak batholith, orthogneiss of</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Isabella Ridge, andesite of</td>
<td>andesite flows</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 1. North Cascade rock glacier lithology, as mapped by the USGS. With the USGS-assigned unit name, the general composition, and with active and inactive rock glaciers found in each unit.

<table>
<thead>
<tr>
<th>Star Peak</th>
<th>Average Range (m)</th>
<th>Average Spot Spacing (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Jul 2009</td>
<td>284</td>
</tr>
<tr>
<td></td>
<td>Sep 2009</td>
<td>268</td>
</tr>
<tr>
<td></td>
<td>Sep 2010</td>
<td>294</td>
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<table>
<thead>
<tr>
<th>Craggy Peak</th>
<th>Average Range (m)</th>
<th>Average Spot Spacing (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Jul 2009</td>
<td>358</td>
</tr>
<tr>
<td></td>
<td>Sep 2009</td>
<td>326</td>
</tr>
<tr>
<td></td>
<td>Sep 2010</td>
<td>360</td>
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Table 2. Average distance of the ILRIS-3D from each rock glacier at each scan. The difference in ranges is due to different Regions of Interest (ROI) that encompass more or less of the more distant surrounding terrain. The average spot spacing is the distance between adjacent laser pulses and varies as a function of the average range and user selection.
<table>
<thead>
<tr>
<th>Zone 1</th>
<th>X-axis</th>
<th>Y-axis</th>
<th>Z-axis</th>
<th>Length (m)</th>
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<tr>
<td>Zone 1</td>
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<td>-0.689</td>
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<tr>
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<td>0.118</td>
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<td>-0.843</td>
<td>0.097</td>
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<tr>
<td></td>
<td>0.427</td>
<td>-0.434</td>
<td>-0.794</td>
<td>0.070</td>
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<tr>
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<td>-0.528</td>
<td>-0.659</td>
<td>0.068</td>
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<tr>
<td></td>
<td>0.596</td>
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<td>0.059</td>
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</tr>
<tr>
<td>Average</td>
<td>0.330</td>
<td>-0.509</td>
<td>-0.506</td>
<td>0.071</td>
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<th>Z-axis</th>
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<td>0.293</td>
<td>-0.554</td>
<td>-0.779</td>
<td>0.029</td>
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<tr>
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<td>0.042</td>
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<td>-0.188</td>
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<td>0.070</td>
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<tr>
<td>Average</td>
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<td>-0.224</td>
<td>0.050</td>
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<table>
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<th>Z-axis</th>
<th>Length (m)</th>
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<td></td>
<td>0.409</td>
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<tr>
<td></td>
<td>0.543</td>
<td>-0.802</td>
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<tr>
<td></td>
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<td>-0.498</td>
<td>0.604</td>
<td>0.043</td>
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<tr>
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<td>0.808</td>
<td>-0.021</td>
<td>0.589</td>
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<tr>
<td></td>
<td>0.821</td>
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<td>-0.570</td>
<td>0.040</td>
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<tr>
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<td>0.990</td>
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<td></td>
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<tr>
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<td>0.775</td>
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<tr>
<td></td>
<td>0.613</td>
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<tr>
<td>Average</td>
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<td>0.057</td>
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<table>
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<th>Z-axis</th>
<th>Length (m)</th>
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<td>Zone 4</td>
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<td>0.186</td>
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<tr>
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<td>0.063</td>
<td>0.044</td>
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<table>
<thead>
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<th>Z-axis</th>
<th>Length (m)</th>
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<tbody>
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<td>Zone 5</td>
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<td>-0.968</td>
<td>-0.142</td>
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<td>0.125</td>
<td>-0.969</td>
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<tr>
<td></td>
<td>0.455</td>
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<td></td>
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<td></td>
<td>-0.570</td>
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<tr>
<td></td>
<td>-0.039</td>
<td>-0.650</td>
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<tr>
<td></td>
<td>-0.282</td>
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<tr>
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<td>-0.094</td>
<td>-0.806</td>
<td>-0.434</td>
<td>0.082</td>
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</tbody>
</table>

Table 3. List of vectors for zones depicted in Figure 9 and 11. Axes values are unit vector components in an X-Y-Z coordinate system. Lengths are the length of the vector and are taken to be displacement of the rock glacier.
Table 4. Logger depths below regolith in meters at Craggy Peak (Cp) and Star Peak (Sp)

<table>
<thead>
<tr>
<th>Depth (m)</th>
<th>CpS1</th>
<th>CpS2</th>
<th>CpS3</th>
<th>SpS1</th>
<th>SpS2</th>
<th>SpS3</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>a</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>b</td>
<td>1.15</td>
<td>1.15</td>
<td>0.85</td>
<td>b</td>
<td>0.75</td>
<td>0.75</td>
</tr>
<tr>
<td>c</td>
<td>2.3</td>
<td>2.3</td>
<td>1.7</td>
<td>c</td>
<td>1.5</td>
<td>1.5</td>
</tr>
</tbody>
</table>

Table 5. Winter precipitation data from PRISM for Craggy Peak (Cp) and Star Peak (Sp) measurement sites, with nearest high-elevation SNOTEL sites, Hart’s Pass (Hp) and Lyman Lake (Ll). SNOTEL sites and PRISM snow depth data are converted from average SWE using an average snow density (0.315) based on the Lyman Lake SNOTEL readings for the same time period (NRCS Climate Center, 2011).

<table>
<thead>
<tr>
<th>SWE (mm)</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hp wy10</td>
<td>144</td>
<td>376</td>
<td>458</td>
<td>637</td>
<td>701</td>
<td>821</td>
<td>929</td>
</tr>
<tr>
<td>Cp PRISM</td>
<td>70</td>
<td>191</td>
<td>320</td>
<td>438</td>
<td>515</td>
<td>594</td>
<td>656</td>
</tr>
<tr>
<td>Cp PRISM wy10</td>
<td>103</td>
<td>210</td>
<td>249</td>
<td>348</td>
<td>397</td>
<td>457</td>
<td>541</td>
</tr>
<tr>
<td>Ll wy10</td>
<td>119</td>
<td>503</td>
<td>574</td>
<td>879</td>
<td>1044</td>
<td>1232</td>
<td>1402</td>
</tr>
<tr>
<td>Sp PRISM</td>
<td>121</td>
<td>365</td>
<td>639</td>
<td>887</td>
<td>1049</td>
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<td>Sp PRISM wy10</td>
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<td>381</td>
<td>479</td>
<td>678</td>
<td>750</td>
<td>825</td>
<td>912</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>Snow Depth (m)</th>
<th>Hp wy10</th>
<th>Cp PRISM</th>
<th>Cp PRISM wy10</th>
<th>Ll wy10</th>
<th>Sp PRISM</th>
<th>Sp PRISM wy10</th>
</tr>
</thead>
<tbody>
<tr>
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<td>0.223</td>
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<td>1.822</td>
<td>2.030</td>
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<td>1.717</td>
<td>4.451</td>
<td>3.861</td>
<td>2.896</td>
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</table>
Table 6. Star Peak (SP) and Craggy Peak (CP) shallow sensor (a) deep sensor (c) correlated (R-value) with modeled air temperature. Craggy Peak string one shallow sensor would be Cp1a. See Table 4 for logger depths.

<table>
<thead>
<tr>
<th></th>
<th>Interval 1</th>
<th>Interval 2</th>
<th>Interval 3a</th>
<th>Interval 3b</th>
<th>Interval 4</th>
<th>Interval 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sp1a</td>
<td>0.9458</td>
<td>0.8283</td>
<td>0.6625</td>
<td>-0.1523</td>
<td>0.2815</td>
<td>0.7103</td>
</tr>
<tr>
<td>Sp2a</td>
<td>0.9744</td>
<td>0.6886</td>
<td>0.4527</td>
<td>0.5610</td>
<td>0.5859</td>
<td>0.8435</td>
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<tr>
<td>Sp3a</td>
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<td>0.7055</td>
<td>0.5865</td>
<td>0.5783</td>
<td>0.4430</td>
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<tr>
<td>Sp1c</td>
<td>0.4739</td>
<td>0.7510</td>
<td>0.4519</td>
<td>-0.4974</td>
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<tr>
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<td>0.5710</td>
<td>0.4718</td>
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</tr>
<tr>
<td>Sp3c</td>
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<td>0.7795</td>
<td>0.6558</td>
<td>0.3947</td>
<td>0.3316</td>
<td>0.6583</td>
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<tr>
<td>Cp1a</td>
<td>0.8724</td>
<td>0.7198</td>
<td>0.2721</td>
<td>0.0003</td>
<td>0.6174</td>
<td>0.9194</td>
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<td>0.7784</td>
<td>-0.6712</td>
<td>0.4511</td>
<td>-0.1384</td>
<td>0.5358</td>
</tr>
<tr>
<td>Cp3a</td>
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<td>0.7655</td>
<td>0.7089</td>
<td>0.4329</td>
<td>0.3947</td>
<td>0.8913</td>
</tr>
<tr>
<td>Cp1c</td>
<td>0.4731</td>
<td>0.4033</td>
<td>-0.6603</td>
<td>-0.1910</td>
<td>0.3344</td>
<td>0.5608</td>
</tr>
<tr>
<td>Cp2c</td>
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<td>0.6544</td>
<td>-0.6576</td>
<td>0.4236</td>
<td>-0.1197</td>
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</tr>
<tr>
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<td>0.6379</td>
<td>-0.5670</td>
<td>0.3079</td>
<td>-0.3758</td>
<td>0.5940</td>
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</tbody>
</table>

Table 7. Average temperatures (˚C) of temporal intervals at each rock glacier. Interval 3 approximates the BTS and Interval 4 approximates the Zero Curtain (when the release and absorption of latent heat due to freeze/thaw of snow/ice causes ground temperature to stabilize at 0˚). All temperatures have a +/1 ˚C associated with logger error.

<table>
<thead>
<tr>
<th></th>
<th>Interval 1</th>
<th>Interval 2</th>
<th>Interval 3</th>
<th>Interval 4</th>
<th>Interval 5</th>
</tr>
</thead>
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<td>-2.58</td>
<td>0.51</td>
<td>11.61</td>
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</tr>
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References


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Appendix 1: TLS processing

The goal of this section is to describe the detailed procedure for surveying, aligning, and comparing the data collected using Optech’s ILRIS-3D terrestrial laser scanner (TLS). In the scheme of my thesis my goals for the TLS were to detect, quantify and describe any movement on two North Cascade rock glaciers. To accomplish these goals, I scanned each rock glacier three times: in July 2009, September 2009, and September 2010. Scans from time period were compared to each other to ascertain any movement. Because of problems to be discussed in the Results of this appendix, only the Craggy Peak rock glacier was successfully processed.

1.0 Surveying

1.1 Scan Targets

In the case of this study the scan targets were rock glaciers covered with highly reflective granitic boulders. The Craggy Peak rock glacier is in a north-facing cirque bounded closely on three sides by bedrock. The scanner was placed immediately across and some 250 meters from the rock glacier on a bedrock surface (Figure 1a). The Star Peak rock glacier is on the northeast side of a ridge coming out of a more open cirque, and is bounded on two sides by bed rock. Since this rock glacier is in more open terrain, the only vantage point is from the south side looking perpendicular to the feature’s long axis (Figure 1b).
Figure A1. Craggy Peak rock glacier. Aerial photo (A) with the scanner location circled in red and photograph (B) of the rock glacier from the scanner location.
Figure A2. Star Peak rock glacier. Upper image is an aerial photo with the scanner location circled in red. The lower image is photograph of the rock glacier from the scanner location.
1.2 Scanner settings

All scans were taken using the Extended Range option and Step Stair scan type. Spot Spacing, the distance between the centers of each laser pulse, varied and is reported below.

<table>
<thead>
<tr>
<th>Star Peak</th>
<th>Spot Spacing (m)</th>
<th>Avg Distance (m)</th>
<th>Angle Spacing (°)</th>
<th>Spot Spacing at 500m</th>
<th>Spot Spacing at 100m</th>
<th>Spot Spacing at Front</th>
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</table>

Table A1. Scanner reported settings. Spot Spacing is the distance between laser pulses at the average distance to the target. Angle spacing is the angle between the spots spacing.

1.3 Scanning

The following criteria are ideal when selecting a scanning location: 1) stable platform on which to place the tripod (preferably bedrock), 2) an unobstructed encompassing view of the target from sufficient elevation. A stable platform is preferable because it insures that repeat scans can be carried out from the same location. If the location is rigorously located using survey grade GPS, one can take advantage of the full capabilities of the scanner and align scans much more quickly and accurately. However, one can use many of the stable features (such as bedrock benches) identifiable in the region of interest in each scan to align scans well without the scanner being in precisely the same location. The drawback to this method is the difficulty in quantifying scanner error.

The line-of-sight nature of the scanner necessitates a good vantage point from for scanning
where as much as the target is visible as possible. Sufficient elevation to more oblique targets must also be achieved as holes in point clouds appear when topographic features block laser pulses. Surfaces at low angles will also return a lower point density and intensity, which in turn increases interpolation error when processing data. Therefore, the preferred scanner orientation to the target surface is as close to a right angle as possible, that is, better pulse returns are achieved from a vertical wall (e.g. cliff) than from a flat surface (e.g. beach).

2.0 Data Processing

LiDAR data was processed using a combination of programs developed by Optech and Innovmetric. I quantified movement as depicted by the scans using the following flow chart:

1) Converted the raw files using Parser to the .pif file format used by Polyworks, 2) imported the .pif files into the Polyworks IMAlign module
   a. aligned/combined temporally congruent scan
   b. overlayed spatially congruent scans
3) imported datasets and alignment matrices from IMAlign to Polyworks IMsurvey module
   a. create vectors between datasets
   b. run comparisons

2.1 Parser

I converted the raw scan data to .pif files using Parser. The raw data was such that it required no manipulation beyond the default settings in that program.

2.2 IMAlign

The .pif files were imported to IMAlign following the procedure delineated in Optech’s Polyworks User Manual. All scans were imported at full resolution, sub-sampling 1/1, and spherical grids were created using the parameters in each scan’s parsing log. Temporally congruent scans, i.e. the scans from one scanning session, were aligned or spliced together using the N-point pairs alignment tool. The same features in the overlap between scans were selected and subsequently
aligned. In selecting these points, I found that one gets better alignment if points are selected as shown Figure 2.

Figure A3. Example of best alignment point picking. These are screenshots from IMalign of the 2010 scan from Craggy Peak. Colored dots are the same points in each scan. Points are spread out along the x-axis as well as the y-axis insuring good agreement when aligning.

One string of points running in a line along the long axis of the scan allowed rotation away from that line between scans after alignment. While much of this problem can be corrected using the Best-fit alignment and Comparison tool, a better technique is to pick points a wider spread of points. I generally picked between 5 and 15 points depending on my alignment results. Visual inspection of the aligned scans proved to be a good indicator of the alignment quality. One would look for mottled colors on flatter surfaces where the scans overlap as well as agreement of boulder edges.
Once composite images of the whole target were created for each scanning episode, I overlaid the composite images from different scan episodes over each other. I located stable bedrock features around the rock glacier target and then deleted the rock glacier, the area where I expected movement. I then aligned the composites using points on the bedrock, ran Best-fit alignment and comparison, and exported the alignment matrices for each scan.

2.3 IMSurvey

In IMSurvey, the first step was to import a reference data set. For the purposes of my study, the reference data set was the composite scan of Sep 2009 scan of Craggy Peak rock glacier. I imported this point cloud as an IMAlign project and then applied the alignment matrices I created from the overlay. The second scan, Sep 2010 of Craggy Peak, I imported as a polygonal model into the same IMSurvey workspace and likewise aligned it. A polygonal model was used to facilitate a better comparison between the two scans. Comparing, points, the first scan, to a model, the second scan, negated the need that every point recorded by the scanner be the same in the two compared data sets. Here, I used two different techniques to detect movement: the Comparison Tool, and a
technique I will call vector picking. In some circumstances these two methods can be used in conjunction.

2.3.1 Comparison Tool

The Comparison Tool in IMSurvey is powerful because, for a given selection, it will allow a user to compare every point in one data set to every point or a surface in another data set. The two most useful comparison options in this tool are the “shortest” method and the “vector” method. The shortest method essentially searches in a radius around each point on the reference data set for the closest point or surface on the other data set. It then calculates this distance. The vector method is useful because it allows the user to compare the two scans along a given vector. Once the user defines the vector, the program searches from every point on the reference scan along that vector until it finds the next closest point on the other scan. Both of these methods are useful if one is comparing changing surfaces that are evolving quickly and may not have the same geomorphic shape scan to scan. Examples of good potential landforms for these methods are a rapidly moving landslides or rock falls. However, in the case of this study, these methods are somewhat limited because the rock glacier surface is not changing rapidly as the movement is a result of internal deformation and/or sliding of ice. Therefore, the drawback of the “shortest” method of comparison is that the program does not pick the same points between the two scans. That is, a boulder may move downslope but the program will draw its error vector from a given point on the reference boulder to the surface behind where the boulder was on the data scan, instead of calculating the distance between the reference boulder and the data boulder.

In the vector direction method the drawback is defining the direction of movement and the assumption that whole surfaces are moving in the same direction. In the case of the rock glaciers, there are many zones that are moving in different directions and defining each of those zones is a
tedious process. Moreover, point coverages in the two scans are different. In the reference scan there may be areas that have many more points than the same area in the data scan. This may be due to left over snow during one scan or, as is often the case in this study, different Spot Spacings. The data scan (the polygonal model) may have fewer points than the reference scan, thus, because of lower resolution, creating a less accurately interpolated model. The problem with both methods is that they do not compare the same zones or features on each scan but simply search for the nearest point (Figure 4).

Figure A5. Visualization of different techniques. The black line is the reference surface and the gray line is the data surface. Colored dots are the same points on each surface. The top image is a visualization of the Shortest method, where actual movement is to the right but the program detects upward change. The bottom image is a visualization of vector picking, where the same points are manually chosen on each image and a vector is draw between them.
Vector Picking

Vector picking is the method I used to mitigate the problems discussed above. This procedure entails manually finding the same features on each scan and drawing a vector between them (Figure 5). Using this method, one is limited by how many vectors can be picked, since this can be a time consuming process and care must be taken to not skew the results by carelessly picking points. If enough vectors are generated one can gain some understanding of the different movement zones and, if point coverage is good enough, can then run a vector comparison based on those results.

Figure A6. Vector Picking. The gray is the reference data set, and the green wireframe is the polygonal model. The red arrow is a vector anchored on the reference dataset and on the model pointing in the direction of movement.
3.0 Results

Of the two rock glacier targets, only Craggy Peak was successfully processed. Problems pertaining to the topography surrounding Star Peak rock glacier led to difficulty in aligning overlying scans. The only stable bedrock features were more than 500 meters away on the opposite side of the target, thus there were no good aligning points on the near side or toward the front of the rock glacier. Therefore problems arose when attempting to overlay scans. Moreover, there seemed to be some differences between the point clouds that I can only attribute to disparity in the Spot Spacing interval. The bedrock features never seemed to align perfectly and were always off slightly. This could either be due to interpolation error in point clouds or scanner error reading the returns.

For Craggy Peak, comparisons run using both the shortest and vector method gave a mean movement of 3.5-7 cm. However, the standard deviations in these runs were large, 15-17 cm. I attribute this to different scan resolutions and point coverages. The comparison tool was useful when ascertaining the quality of the overly. Comparison runs on just the bedrock features returned a mean error of -0.1 cm and a standard deviation of 2.8 cm. This indicates that the alignment was very good and lends confidence to the assumption that any measured movement on the rock glacier surface was “real”.

The vector picking method on the Craggy Peak rock glacier revealed very small amounts of movement but in directions that one would expect. The upper portion of the rock glacier appears to have moved parallel to the slope and slightly into the surface indicating a deflation of the surface. Toward the front of the rock glacier, the vectors begin to fan out radially and adopt an upward component indicating a possible inflection. Magnitudes ranged from 3.5 cm near the front to 7-9 cm toward the top, also consistent with what one would expect.
4.0 Suggestions and Musings for future work

In this project, no reflective targets were set up and geo-referencing was not implemented. All processing relied on recognizable features in the scan area. While this procedure appears to have worked, it is not ideal. High precision reflective targets would both reduce human error and expedite processing. For rigorous scientific study, scanner locations should be benchmarked and geo-referenced and semi-permanent targets should be placed whenever possible. Moreover, care should be taken to produce the same resolution of scan each time. This would help the user
differentiate between scanner error and processing error.

A final issue not covered in this discussion is the sheer size of the data clouds. Aligned mid-resolution Craggy Peak scans still contained $2.5 \times 10^7$ points and one Polyworks Workspace quickly could bloom into 10 gigabytes of data. Comparisons could take hours and simple panning and viewing of point clouds and vector drawing could become slow processes. Of course this produces a huge processing drain on the computer. Future researchers would do well to try to minimize their point cloud sizes and take high resolution scans of only areas of the greatest interest.