ROCK GLACIER MORPHOLOGY AND MORPHOMETRY

IN GLACIER NATIONAL PARK,

NORTHWEST MONTANA, USA

by

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DEDICATION

For my parents,

Who have nurtured and supported my curiosity for the world in which we live.

ACKNOWLEDGEMENTS

Chiefly, I would like to offer my utmost, heartfelt thanks to my outstanding advisor and committee chair, Dr. David R. Butler. Dr. Butler's diligence, patience with my own neuroses, and care throughout the process of this thesis has been unparalleled. This thesis would not have been possible without his constant and warm encouragement, acumen, and his persistent reminders to 'work work work'! Dr. Butler is a scholar unequivocally committed to excellence and knowledge. His knowledge and wisdom has been edifying and will no doubt influence my work throughout my career—both academic and civilian.

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LIST OF ABBREVIATIONS

Abbreviation	Description
DEM	Digital Elevation Model
GE	Google Earth

ABSTRACT

Rock glaciers provide essential habitat and resources for species like the threatened pika (*Ochotona princeps*) throughout the western Cordillera of North America. However, the distribution of current and relict rock glaciers has not been thoroughly mapped. Glacier National Park has excellent records of true ice glaciers within the park's boundaries, but no comprehensive maps or information on the status of rock glaciers within the park. This thesis presents comparisons between active and relict groups of rock glaciers in the park in terms of their morphometry, morphology, and geographic positioning. My results illustrate that relict rock glaciers tend to be wider, less steep, and located at lower elevations than active rock glaciers. Relict rock glaciers are also almost exclusively located on the west side of the park whereas active rock glaciers are most common in north- to northeast-facing cirques east of the Continental Divide. My results will assist Park managers in better illustrating critical pika habitat throughout the park.

I. INTRODUCTION

It is no secret that cold regions around the globe have been experiencing increased rates of change, especially over the last century. North American glaciers are melting rapidly; some having recently lost the majority of their mass in the past few decades when compared to rates of change before 1850 (e.g. Hall and Fagre 2003; Moore et al. 2009). Permafrost is shallower and melting in some regions, alpine environments included, causing geomorphic changes in stability in the ground and at the surface (e.g. Gruber, Hoelzle, and Haeberli 2004; Gruber and Haeberli 2007) and in some cases, affecting human infrastructure (e.g. Bommer, Phillips, and Arenson 2010).

Rock glaciers, which are complex geomorphic landforms in high latitudes and altitudes, have garnered a recent interest in literature (Vitek and Giardino 1987; Stine 2013). Though studies have shown that rock glaciers do respond morphologically to temperature changes (e.g. Kellerer-Pirklbauer and Kaufmann 2012; Sorg et al. 2015), rock glaciers show a general robustness toward climate change in terms of stability. These landforms, which often exist near true glaciers, consist of pure ice or ice supersaturated debris covered by a top layer of coarse, blocky debris (Berthling 2011). Whereas the ice in true glaciers is exposed to ablation, ice stores in rock glaciers are protected by their outer debris layer, which acts as a buffer to changes in climate (e.g. Millar, Westfall, and Delany 2014).

In 1959, professors Clyde Wahrhaftig and Allan Cox produced a paper titled, "Rock glaciers in the Alaska Range", which is considered in literature as 'the single most influential paper on rock glaciers' (Berthling 2011; Stine 2013). Though rock glaciers first started appearing in academic papers as far back as 1900 (Spencer 1900; Wahrhaftig and Cox 1959), Wahrhaftig and Cox's paper (1959) was the first, most thorough and cohesive description of rock glacier characteristics and movement (Stine 2013).

Rock glaciers—which, for the most part, might be considered geomorphic cousins to true glaciers, as they tend to exist near glaciers in valleys that are glaciated and are sometimes derived from true glaciers (e.g. Vitek and Giardino 1987)—have become popular for reasons similar to the reasons true ice glaciers are studied. Rock glaciers are ubiquitous features of the periglacial environment that, while not numerous, are common and dominate their environment where they do exist (Vitek and Giardino 1987). Thus, rock glaciers significantly influence ecology and geomorphology within their domains, especially in non-glaciated valleys. In the United States, rock glaciers serve as habitats for creatures like the American pika (*Ochotona princeps*), small fossorial mammals that have a low tolerance for heat and rely upon the cool microclimate provided by rock glaciers for survival (Butler 2012; Millar, Westfall, and Delany 2014). Rock glaciers are also long-term stores of frozen water in periglacial environments (Azócar and Brenning 2010)—sometimes acting as a sort of aquifer in periglacial environments (e.g. Degenhardt and Giardino 2003; Rangecroft, Harrison, and Anderson 2015).

Much like true ice glaciers, rock glaciers provide records of climate activity. The talus and debris that cover the core or internal ice of rock glaciers create a buffer between the ice and external temperatures and insolation, generating a lag in the response of rock glaciers to external influences and determinants of change, while still capturing the effects of climatic conditions. Because of this, rock glaciers have been used extensively to study terrestrial paleoclimates and paleoclimatic change (e.g. Butler 1988; Konrad et al. 1999). They have also been used to study modern climate and modern climate change (e.g. Butler 1988; Sorg, et al. 2015), and even to infer conditions of water and former climatic conditions on extraterrestrial locations such as Mars (e.g. Dagenhardt and Giardino 2003; Whalley and Azizi 2003).

Rock glaciers are ubiquitous, useful, and provide insight. Understanding rock glacier change and dynamics in a modern sense could help scientists understand immediate responses and processes tied to rock glaciers. Though they are not as conspicuous as true glaciers, and their change is not as immediate, that does not mean that there is nothing to learn from these complex geomorphic features. One must know where these features are located, and what they are doing, however, in order to make further inferences.

II. PURPOSE OF RESEARCH

Purpose Statement

This research document serves two ultimate purposes. The first and primary purpose is to further explore the geography and expand geographic knowledge of Glacier National Park in Montana by compiling a database of the active and relict rock glaciers that exist within the park. This will allow for further understanding of the geography, geology, and morphology of the park to be used by both the park itself, as well as those wishing to study the park or region in further detail. Overall, this part of the research aims to answer the following questions:

- What is the geographic distribution of rock glaciers in Glacier National Park?
- Where are active rock glaciers in relation to relict rock glaciers?

The second purpose of this paper is to describe and compare morphometric variables between the park's relict and active rock glaciers. This part of the research aims to answer the following questions:

- Are active rock glaciers in the park morphometrically different from relict rock glaciers in the park?
- How do active and relict groups vary in elevation, size, slope, and aspect?

The findings of this analysis could be used as a basis for further research into the geographic and environmental variables at work within the park. Potential research could be done to examine the effects of climate change, temperature, or geology on the kinematics and rheology of existing rock glaciers in Glacier National Park.

Research Objective: Cataloguing Rock Glaciers

As stated previously, rock glaciers are ubiquitous landforms in high alpine environments. Though not the most numerous of land features in alpine mountain environments, they do exist in the dry, cold periglacial portions of mountains. For one reason or another however, there are understandably many parts of the world that are viable for rock glacier formation and existence that have not yet had the extent or existence of rock glaciers recorded and catalogued.

The rock glaciers in Glacier National Park, the study area for this thesis, are an example of this. Despite the popularity of the park for both recreation and research, the extent of rock glaciers is not publicly recorded or catalogued. However, with a preliminary examination of mountain valleys, using imagery from Google Earth, rock glaciers do exist in the park. Thus, the first question of the two-part research objective asks, "What is the geographic distribution, and what are the morphological and site characteristics of rock glaciers in Glacier National Park?" This part of the research aims to look at where in the park they are located, what are the site characteristics where rock glaciers occur, and what are their morphological characteristics?

Research Objective: Comparing Active and Relict Groups

In the past, papers have suggested that rock glaciers, much like true glaciers, provide a glimpse into the effects of climate change (e.g. Kääb, Haeberli, and Gudmundsson 1997; Konrad et al. 1999). Researchers have also suggested that rock glaciers are significantly influenced by insolation (e.g. Johnson, Thackray, and Van Kirk 2007), and gravity itself (Roer et al. 2008), amongst other things, inducing change and instability within rock glaciers. Although these factors are all important, the second question in this research paper simply asks—regardless of what environmental factors may or may not have contributed—How are relict and active rock glaciers in Glacier National Park alike and how are they different in their morphometry?

When examined on Google Earth's temporal slider, the images of rock glaciers appear to have little or no visible change in the satellite images over the course of about 25 years, between the years of 1990 and 2015, whereas their neighboring true glaciers have clearly dwindled and, according to authorities in Glacier National Park, are expected to be completely gone in the next few years (National Park Service 2015c). This thesis aims to understand the extent of both differences and similarities in the morphology and stability of rock glaciers in Glacier National Park, Montana. In order to determine change, this paper will examine most of the same variables used by Johnson, Thackray, and Van Kirk (2007) in their paper examining rock glacier distribution in the Lemhi Range of central Idaho. These variables are all geographic factors associated with each individual rock glacier, such as aspect, elevation, relief, and latitude and longitude.

III. BACKGROUND

It has only been in the past half-century that rock glaciers have received most of their attention and interest. Before 1959, when Clyde Wahrhaftig and Allan Cox (1959) published their paper describing rock glaciers in the Alaska Range, studies and mentions of rock glaciers were minimal. According to Wahrhaftig and Cox (1959), knowledge of rock glaciers has been around since at least 1900 when the probable first reference to a rock glacier was published in Spencer's paper titled 'A peculiar form of talus' (Spencer 1900). However, it was Capps (1910) who introduced the term 'rock glacier' in a paper published in the *Journal of Geology* about rock glaciers in the Wrangell Mountains of Alaska. Since Wahrhaftig and Cox (1959), thousands of papers have been published detailing aspects of rock glaciers—from rock glacier genesis and development (e.g. Hamilton and Whalley 1995; Humlum 1996; Isaksen et al. 2000) to discussions of rock glacier definition (e.g. Hamilton and Whalley 1995; Berthling 2011), as well as research describing regional rock glaciers (e.g. Wahrhaftig and Cox 1959; Berthling et al. 1998; Brenning 2005; Azócar and Brenning 2010) and detailing aspects of rock glacier change (e.g. Whalley and Azizi 1994; Isaksen et al. 2000; Haeberli et al. 2006; Lugon and Stoffel 2010). Background on rock glaciers is necessary for understanding their geography and existence. It is also important to understand the complexity of these cryogenic land features.

A Brief Description of Rock Glaciers

While not overly numerous, rock glaciers are still ubiquitous features within periglacial environments, included in areas of high latitude or altitude. Rock glaciers are complex entities that can be formed and exist in a number of ways. Though the formation processes and exact make-up of rock glaciers is still disputed (Vitek and Giardino 1987; Berthling 2011), overall, there are two morphological manifestations (ice-cored and ice-cemented) and three types of processes that are commonly accepted as valid origins for rock glaciers. As described by Berthling (2011), these processes range from, and include, mountain permafrost creep (e.g. Barsch and Jakob 1998; Haeberli et al. 2006), rock avalanches (e.g. Whalley and Azizi 2003), and glaciers (Humlum 1996). Regardless of their origins, active rock glaciers typically exist as either an ice core covered in an outer layer of rocky debris, or ice supersaturated debris flows (Berthling 2011).

<u>Conceptual Framework</u>

Figure 1 shows the physical controls on rock glacier formation and activity.

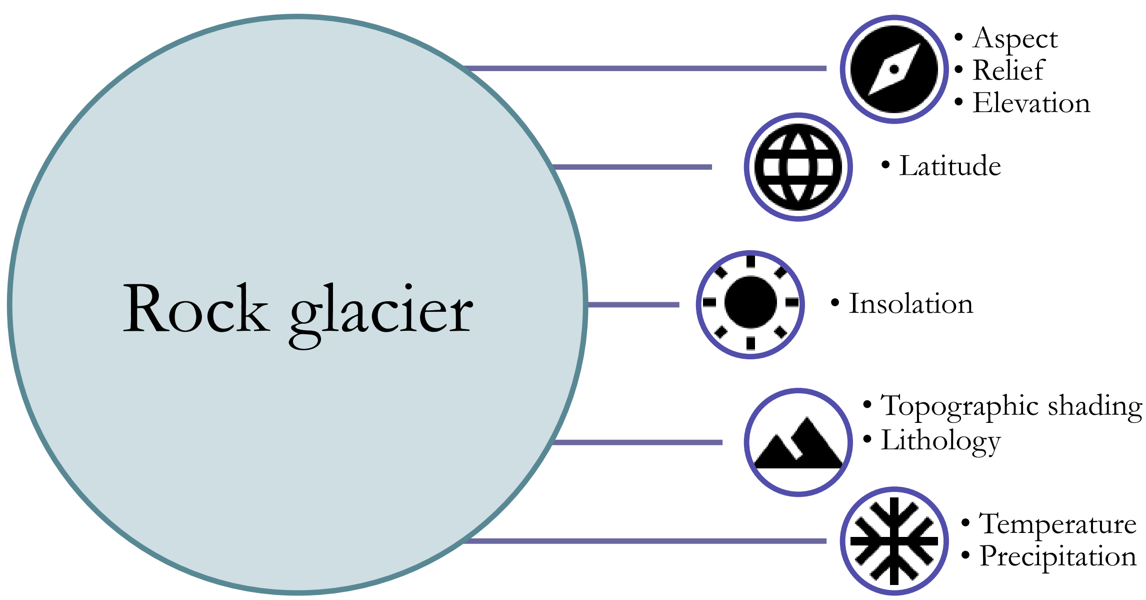

Figure 1: Conceptual web of rock glacier controls.

<u>The Importance of Rock Glaciers</u>

Although rock glacier genesis is disputed, the importance of these dominating features of periglacial ecosystems is not. These features actively contribute to and promote important geomorphic and ecologic processes for their respective regions. For example, rock glaciers serve as a method of debris transport in high mountain environments (Barsch and Jakob 1998; Brenning 2005; Weidenaar 2012). Rock glaciers act as a downward path and conduit for fast, gravitational mass movements (Barsch and Jakob 1998; Brenning 2005). This includes rockfall, avalanches, and small rockslides (Barsch and Jakob 1998; Brenning 2005). In contrast, the creeping ice and permafrost so often associated with rock glaciers helps to stabilize the detrital material that makes up and exists around these geomorphic features (Brenning 2005). In tandem with their importance as debris transports, rock glaciers maintain a hydrologic significance as well. Rock glaciers serve as long-term stores of water, with their active layer and sub-permafrost layer acting as an aquifer (Brenning 2005; Rangecroft, Harrison, and Anderson 2015). Icier rock glaciers with low penetrability may also act as an aquiclude, enhancing near-surface runoff in the active layer (Brenning 2005). Lastly, rock glaciers are local climate buffers (Millar, Westfall, and Delany 2012; Stine 2013), and as a result, they provide habitats for vulnerable wildlife (Butler 2012).

IV. LITERATURE REVIEW

In 1959, Clyde Wahrhaftig and Allan Cox published what is widely regarded as 'the single most influential paper on rock glaciers' (Berthling 2011, 98). Their paper, titled 'Rock glaciers in the Alaska Range,' sparked a global interest in these features, with the amount of papers published on the subject growing considerably since the mid-twentieth century (Stine 2013). Between the years 2000 and 2009, over 2000 papers were published regarding rock glaciers—a steep increase, even from the 1990s, which had fewer than 1000 papers on rock glaciers published in that decade (Stine 2013). Coupled with the increasing interest in the importance of rock glaciers and the cryosphere, a great deal of recent literature exists on the subject of rock glaciers, their dynamics, and descriptions of both active and relict rock glaciers within a specific region.

Naturally, literature upon this subject spans a spectrum of topics. However, the literature within this review will focus upon literature regarding regional descriptions of rock glaciers and discussions of active and relict rock glaciers. Regional descriptions of rock glaciers, both active and relict, provide the body of scientific literature, as well as regional researchers, with information on the geography of global rock glaciers. Since active rock glaciers are the subjects of many journal articles, studies on relict rock glaciers will be examined a little more closely, as there is often a reference to the respective regional active rock glaciers.

Regional Descriptions of Rock Glaciers

As previously mentioned, one of the objectives of this study is to record and describe rock glaciers and their immediate surroundings within Glacier National Park. This is to provide an overview detailing the morphometry and site characteristics of rock glaciers within the park. Though this is the first time that such a record has been compiled for

Glacier National Park, it is not the first time that morphological characteristics and classifications of activity have been compiled for rock glaciers within a region (e.g. Johnson, Thackray, and Van Kirk 2007; Scotti et al. 2013).

Johnson, Thackray, and Van Kirk (2007) discuss geographic controls on rock glaciers in the Lemhi Range of Idaho, and is an important influence on the choice of variables to be collected in my thesis. This paper is a study that details the regional situation of rock glaciers, down to each individual mountain cirque. Johnson, Thackray and Van Kirk's (2007) paper aimed at describing the geographic controls of rock glaciers in the range, using geographic variables to be used in this thesis. Similar to the research conducted in my thesis, Johnson, Thackray, and Van Kirk's (2007) paper manually examined photos from 171 mountain valleys and cirques in the Lemhi Range in central Idaho, recording geographic variables listed in previous sections for each cirque. They then described the controls that lithology and insolation seem to have on rock glaciers, as well as suggesting that rock glaciers in the range may be genetically related to protalus lobes—cryogenic, geomorphic formations very similar to rock glaciers.

A more recent study by Scotti et al. (2013) carries the similar task of cataloguing and compiling a regional inventory of rock glaciers. Though this study takes place in a region geographically unrelated to Glacier National Park, it shows some of the extent of rock glaciers throughout the world, as well as the sheer quantities of rock glaciers and related protalus ramparts that can potentially exist in one area. The site of the Scotti et al. (2013) study is that of Lombardy in the central Italian Alps. In such a fairly small study area, Scotti et al. (2013) 1514 rock glaciers, including active and relict forms, as well as 228 protalus ramparts.

After cataloguing the rock glaciers in their study area, Scotti et al. (2013) studied the geography of these landforms using methods similar to Johnson, Thackray, and Vankirk (2007). In their study, they found that active rock glaciers existed in locations of greater slope relief, situated in altitudinal zones between 2000 and 3000 m (Scotti et al. 2013). Whereas the rock glaciers in Johnson, Thackray, and Van Kirk's paper had a northeasterly slope aspect, rock glaciers in the Scotti et al. (2013) study tended to be located on northwesterly slopes. They note that this slope aspect seems to have quite a range of effects on the rock glaciers in the Italian Alps (Scotti et al. 2013). They note that, for example, size is related to whether or not a rock glacier has a northern slope aspect, in which case they tend to be smaller, or a western slope aspect, in which case they tend to be larger (Scotti et al. 2013).

Active and Relict Rock Glaciers

Literature has concluded that rock glaciers respond physically in different ways to different types of influences and change all the time. Some of these short-term changes in active rock glaciers include surface lifting and depression (e.g. Kääb, Haeberli, and Gudmundsson 1997; Sorg et al. 2015), recession and deterioration (e.g. Humlum 2000), movement downslope (e.g. Barsch and Jakob 1998), and mass shifting (e.g. Barsch and Jakob 1998; Lugon and Stoffel 2010). Comparing relict and active rock glaciers is still a comparison of time in which all of these things may have happened, but it is a greater scale of time that is mostly associated with a comparison of present and past climate (e.g. Hughes, Gibbard, and Woodward 2003; Matthews, Nesje, and Linge 2013), especially in regions where one would not expect to find permafrost-related structures (e.g. Hughes, Gibbard, and Woodward 2003).

Active rock glaciers are the rock glaciers most often analyzed because their influence on their environment is often greater than that of relict rock glaciers. Most of the papers handling relict rock glaciers do what this thesis is trying to do and look at the distribution of relict rock glaciers over a geographic extent (Winkler et al. 2015) This is often done usually by cataloguing relict rock glaciers in an attempt to explain regional paleoclimate—or former climatic conditions compared to those of the present (e.g. Hughes, Gibbard, and Woodward 2003; Harrison, Whalley, and Anderson 2008; Matthews, Nesje, and Linge 2013). The extent of ice and permafrost during the Late Pleistocene was much greater than it is today. Many of the papers that examine relict rock glaciers look at relict rock glaciers as indicators of Pleistocene permafrost extent for their respective regions.

There are papers that do look at relict rock glaciers as continuing influences on their environment. A study conducted by Winkler et al. (2015) examined the continuing ecological influences of rock glaciers once they reach relict status. Though these relict rock glaciers are devoid of an active frozen layer, some may continue to function as aquifers, with a basal till layer underneath the rock glacier, acting as the main aquifer body (Winkler et al. 2015).

Implications of planetary paleoclimate and the existence of water stores on places like Mars combine ideas from papers that look at relict rock glaciers as indicators of paleoclimate and groundwater stores. Rock glacier-like structures, as well as ice, have been found to exist on the surface of Mars (Degenhardt and Giardino 2003). These structures might still be active, or at least formed recently, and indicators of frozen water stores in an extraterrestrial environment (Degenhardt and Giardino 2003).

Summary

To summarize this chapter, much work has been done similar to the purpose and research carried out by this thesis. Regional inventories and descriptions of active and relict rock glaciers are quite common, and have been produced for locations with modern rock glaciers and relict rock glaciers, respectively and in tandem. Such locations include the Andes (e.g. Azócar and Brenning 2010; Rangecroft et al. 2014; Brenning 2015), the European Alps (e.g. Baroni, Carton, and Seppi 2004; Scotti et al. 2013), Norway (e.g. Matthews, Nesje, and Linge 2013), Alaska (e.g. Wahrhaftig and Cox 1959), and ranges in the Rockies of North America (e.g. Jahnke 2007; Johnson, Thackray, and Van Kirk 2007), to name a few. Similar to the methods used in this thesis, many of these regional inventories and descriptions of rock glaciers have used aerial imagery to explore rock glacier morphology (e.g. Wahrhaftig and Cox 1959; Kääb, Haeberli, and Gudmundsson 1997; Johnson, Thackray, and Van Kirk 2007). Reviews of relict rock glaciers often look at the paleoclimates of regions, and are able to provide insight into the paleoclimates of parts of the world that are below the modern line of permafrost (e.g. Hughes, Gibbard, and Woodward 2003; Harrison, Whalley, and Anderson 2008).

V. SITE

Glacier National Park is the study site for this paper (Figure 2). It is located in northwest Montana (48.6967° N 113.7183° W), stretching from U.S. Highway 2 as its southernmost boundary, with its northernmost boundary halting at the U.S. and Canadian border. The park sits with a footprint of 4,101 km^2, and is oriented lengthwise in a slightly northwest to southeast fashion, bisected through the center by the Continental Divide.

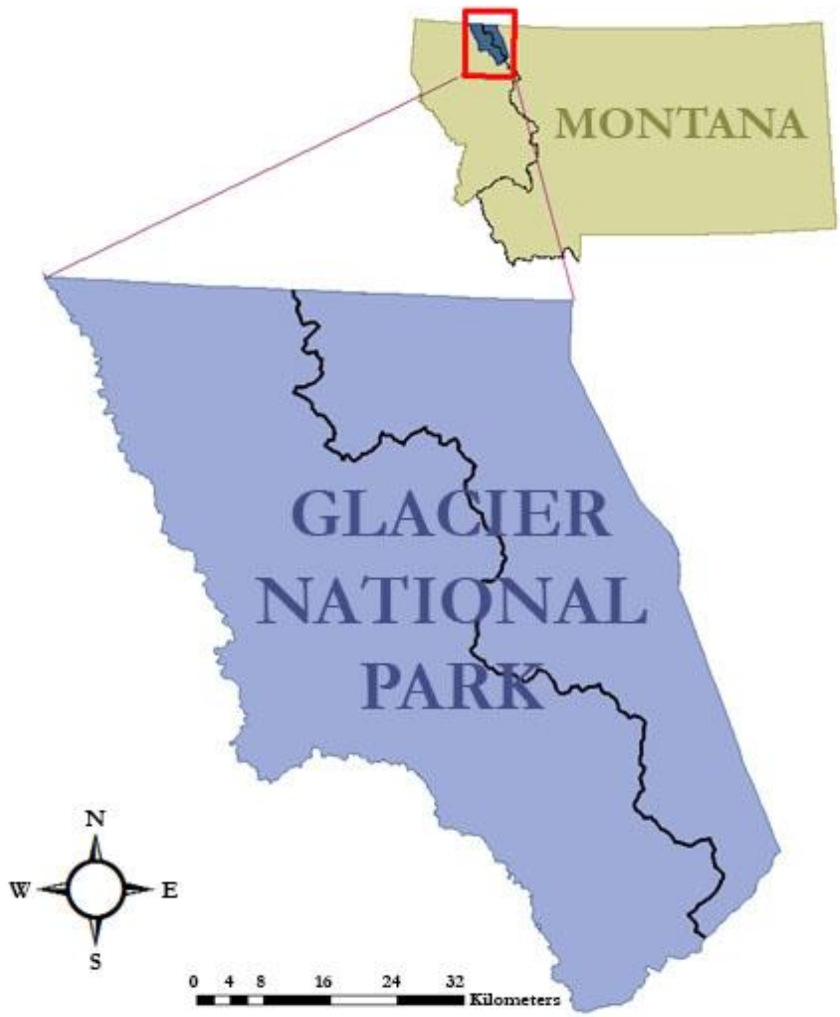

Figure 2: Map showing Glacier National Park and location within Montana.

The natural landscape of the park is mountainous and home to Pleistocene and Neoglacial glacially eroded landforms (Butler and Walsh 1990). It contains a portion of the northernmost belt of the United States Rocky Mountains, including the Livingston Range in the northwest quarter of the park, and the Lewis Range, which span the length of the park from the north-central to the southernmost end of the park (Butler et al. 2003). These ranges, along which runs the Continental Divide, serve as a determinant for the climate of Glacier National Park, splitting the park between a wet, Pacific maritime climate to the west and a dry, continental climate to the east (Finklin 1986; Butler et al. 2003; National Park Service 2015a).

Because of the shallow seas that once covered the region, much of Glacier National Park's lithology is sedimentary, ranging in age from Precambrian to Holocene (Ross and Rezak 1959). It is comprised mostly of Precambrian sedimentary and metasedimentary limestones and Belt Series argillites that are widely distributed and thinly bedded (Butler et al. 2003). The geology of Glacier National Park has provided little resistance to erosion by glaciers in the park (Butler et al. 2003), with the glaciers scraping off some of the uppermost geologic layers of the park and exposing older strata below the surface (National Park Service 2015b).

Glacier National Park is home to 25 true glaciers (National Park Service 2015c) (Figure 3) and a number of icy structures, including rock glaciers, protalus lobes, and permafrost, particularly located up in mountain cirques or on mountain slopes. The glaciers of the park have aided in eroding away at the landscape, churning and transporting debris and sediments and forming steep glacial moraines. Glacier-melt from higher elevations has created numerous tarns and glacial lakes at both high and low elevations, and contribute to the Park's rivers. These bodies of water supply the park with important fresh water for local flora and fauna.

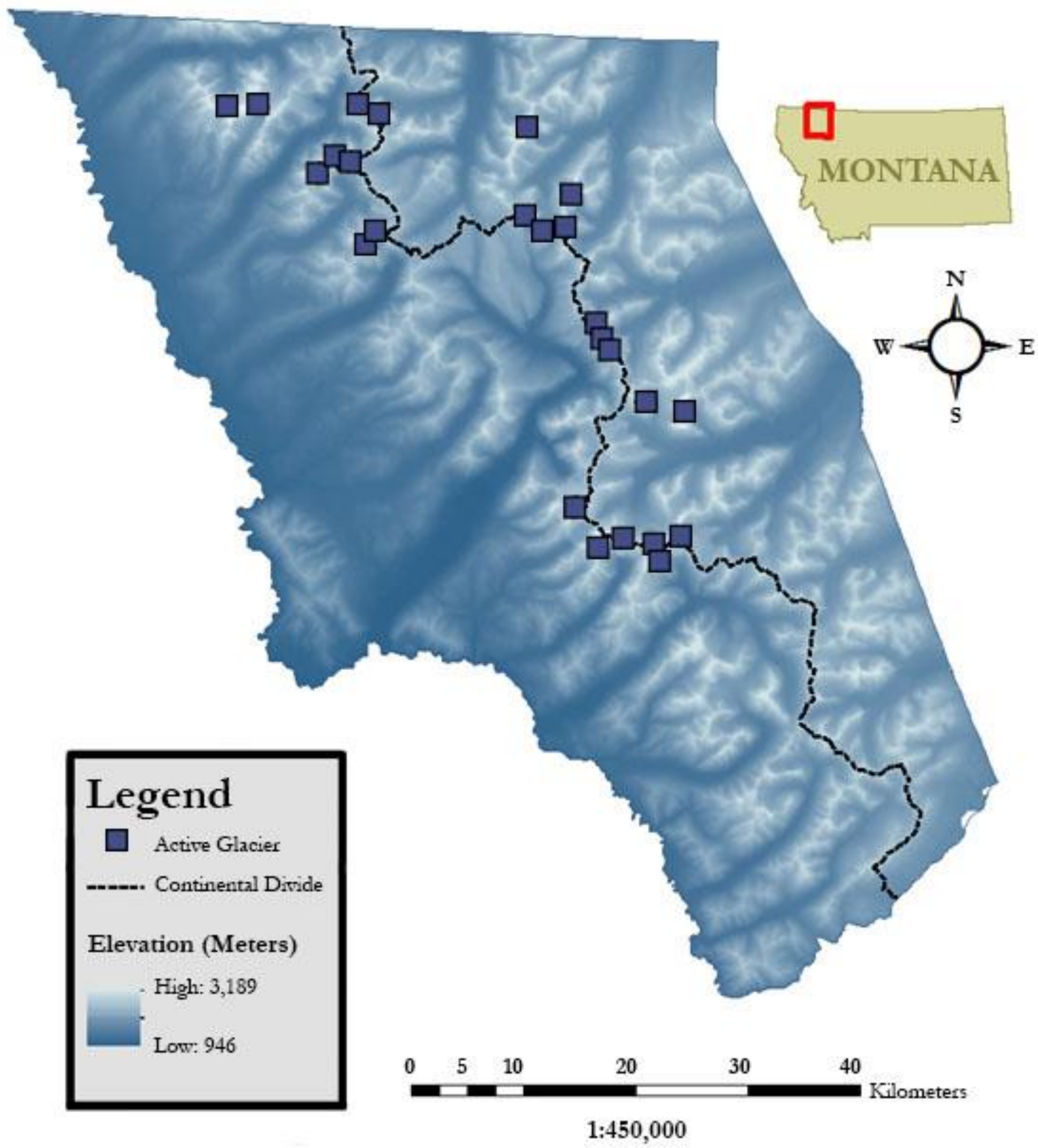

Figure 3: Location map of glaciers in Glacier National Park. Modified from Fagre (2010).

Rock glaciers exist in the park in high, mountain cirques—they require shade and protection from insolation, often provided by tall and steep cirque walls, as well as ready access to a talus supply. Rock glaciers are sensitive to the geologic make-up of its talus supply—better maintained with clasts that are less porous, preventing external influences from reaching the interior ice as easily (Johnson, Thackray, and Van Kirk 2007). Low permeable clasts such as quartzite and argillite are spread throughout the park as a result of the ancient Belt Sea, creating a lithological setting agreeable to the formation and preservation of rock glaciers. Combined with the knowledge of the presence of glaciers, past and present, it was expected that rock glaciers would be found in the park.

VI. HYPOTHESES

As stated in Chapter II, one of the goals of this thesis is to analyze the differences between active and relict rock glaciers within Glacier National Park. As such, this research's aim is to test the null hypothesis, which state that there are no statistical difference between the morphology of active and relict rock glaciers. Furthermore, the null hypothesis will be subdivided by each variable examined in relation to relict and active rock glaciers to a total of six sub-null hypotheses. These sub-null hypotheses are as follows:

- H_0- No statistical difference exists between head elevation of active and relict groups.
- H_0- No statistical difference exists between toe elevation of active and relict groups.
- H_0- No statistical difference exists between the relief of active and relict groups.
- H_0- No statistical difference exists between the slope of active and relict groups.
- H_0- No statistical difference exists between widths of active and relict groups.
- H_0- No statistical difference exists between lengths of active and relict groups.

VII. DATA AND METHODS

Data used for the purpose of this thesis consists of a catalogue of the rock glaciers found throughout Glacier National Park. These data were located using imagery provided by Google Earth. Google Earth was used for this section of the analysis because of its accessibility. Many of the active rock glaciers in the park are not accessible by foot, and funding to visit the park was unavailable. Therefore, Google Earth served as a suitable alternative for the exploration of the park.

In order to gather information on the rock glaciers in Glacier National Park, they first had to be located. Each cirque and valley wall in the park was searched individually for the presence of rock glaciers. Once the presence of rock glaciers was discovered, they were assigned names related to their surrounding toponymy and labelled with the marking tool in Google Earth. Then, using the temporal slider on Google Earth, a month and year was selected for the clarity of the imagery. In the specific case of this research, July of the year 2013 was selected because of the general lack of shading from topography, snow cover, and obstruction by clouds.

Once each rock glacier was located and named, then a set of morphometric variables for each rock glacier was determined using Google Earth's toolset. These variables include latitude and longitude, slope aspect, minimum and maximum elevations, relief, calculated slope angle, and status—whether relict or active. Most of the variables for these data were selected in regards to a study on the Lemhi Range rock glaciers in central Idaho examining geographic determinants of rock glacier existence in the high mountain valleys (Johnson, Thackray, and Van Kirk 2007). Figure 4 shows how measurements were taken. For length, width, and aspect, Google Earth's ruler tool was used. While length and width were taken at the longest and widest point.

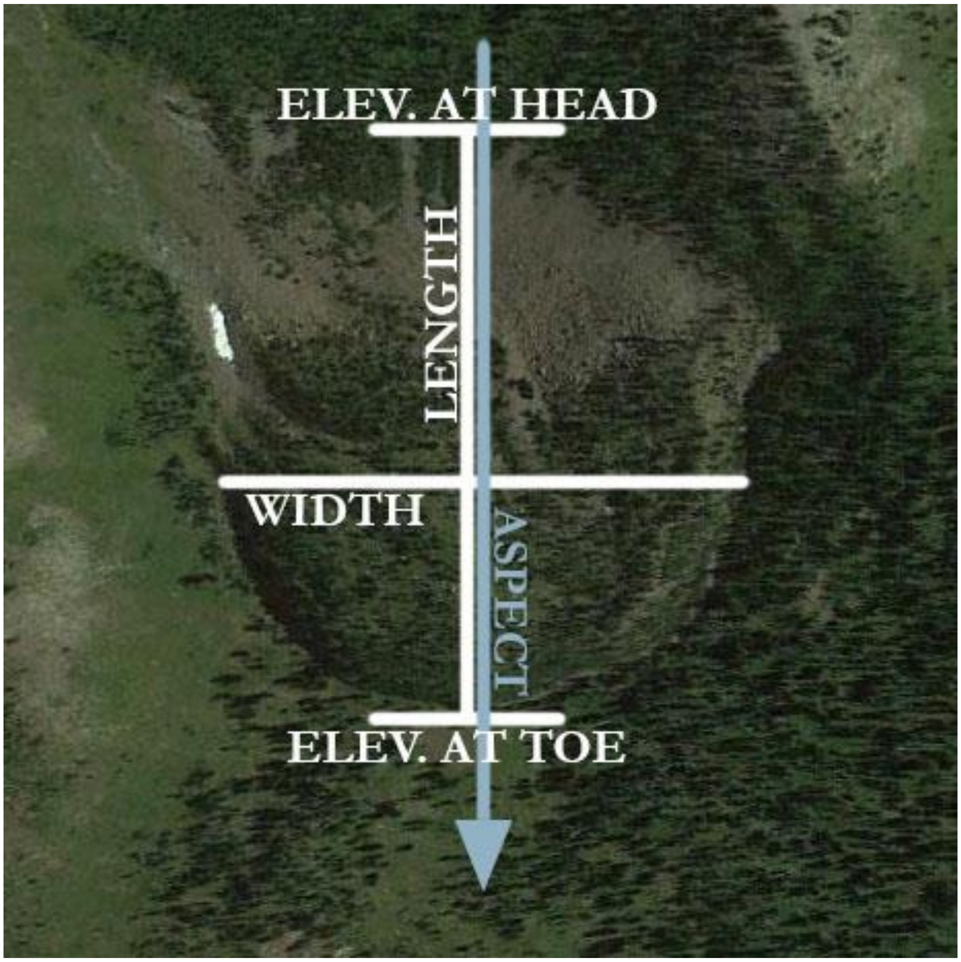

Figure 4: Rock glacier measurements taken for variables.

For length, width, and aspect, Google Earth's ruler tool was used. While length and width were taken at the longest and widest points of the rock glacier, perpendicular to one another, aspect was taken generally across the rock glacier from the cirque wall. Elevation was taken from markers placed separately, one at the toe and one at the head of the rock glacier.

These variables were compiled into an Excel spreadsheet, where slope and relief were calculated using the elevation data obtained. The coordinates were then formatted appropriately and used to plot rock glacier locations in ArcMap. A simple map was compiled showing the locations of rock glaciers within the park, with active and relict rock glaciers marked in separate colors (Figure 5). Then, these data were made ready for use in IBM's SPSS for statistical analysis.

Though Google Earth is readily available to the general population, its accuracy is contested—especially in remote areas. Therefore, USGS Digital Elevation Model (DEM) (U.S. Geological Survey 2015) data were used to compare to the results from Google Earth. Since the rock glaciers had already been located, the area of the rock glaciers were digitized using ArcMap's polygon editor with Esri's 2016 World Imagery as the reference basemap for rock glacier shape. From there, area, maximum length and width, and maximum and minimum elevations were calculated, as well as slope and relief, using data from the DEMs and tools in the ArcMap toolbox. These derived variables were also put into an Excel spreadsheet and formatted for use in IBM's SPSS.

Statistical analysis for this thesis included a simple Mann-Whitney *U* test run on SPSS to look for differences between groups across the range of variables. One test was run for data gathered from Google Earth to compare active and relict rock glacier groups across the six variables—maximum and minimum elevations, length, width, relief, and slope. Then, a second Mann-Whitney *U* test was conducted on data collected from the DEMs to compare to data collected from Google Earth.

Limitations of Data and Methods

Although the study conducted for this research attempts to be as thorough as possible, some limitations to its execution exist. Many of the limitations to the research stem from the reliance upon aerial imagery and Google Earth to conduct the visual analysis of existing rock glaciers. Rock glaciers occur more often than not in remote areas of high elevation. This means that they are not very accessible by foot, and are therefore difficult to examine in the field. Because of this, aerial imagery is necessary and useful, but limited.

The first problem with aerial imagery comes with the lack of detail with which rock glaciers may be examined, sometimes worsened by obstructions from cloud cover, snow cover, or topography. Small details that may be seen clearly in person may be missed using aerial photography. Inactive rock glaciers often support rich layers of lichen upon the outer layer of their debris front (Wahrhaftig and Cox 1959). Unlike relict rock glaciers, which have an unmistakable presence of vegetation (Burga et al. 2004), lichens are nearly impossible to see from aerial photography, and thus a rock glacier might look active, but may not actually be so.

It is noted that error may exist in identifying some of the rock glaciers. Though care has been taken to ensure a high level of confidence in accuracy, some 'rock glaciers' may look like rock glaciers, but perhaps be something else and are erroneously recorded. Since field access is not possible for this thesis, the reliance on imagery from multiple sources will likely inhibit the accuracy of measurements to some degree. While great pains will be taken to ensure the accuracy of morphometric measurements, it is sometimes difficult to determine where points on rock glaciers truly end and begin using aerial imagery. Shadows from ridge walls or clouds, cloud cover, and snow or ice cover could also prevent detailed examinations of mountain cirques or accurate morphometric data, as well as human error.

VIII. RESULTS

Cataloguing Rock Glaciers in Glacier National Park

The methods for how Google Earth was used to catalogue rock glaciers are listed in the previous chapter, however the rock glaciers selected for this thesis were geomorphic features chosen because they fit the general physical description of a rock glacier. These landforms had a lobate, tongue, or spatulate shape with apparent ridges and furrows throughout the feature, and access to a supply of talus. Vegetation presence and steepness of the termini of the rock glaciers were examined to determine whether or not a rock glacier was to be classified as active or relict. For the purpose of this thesis, a steep front and a lack of vegetation was indicative of an active rock glacier, whereas the presence of vegetation, and a rounded, collapsed front on the rock glaciers indicated a relict status (e.g. Whalley and Martin 1992; Barsch 1996; Baroni, Carton, and Seppi 2004; Janke 2007)

In all, the park yielded a total of 27 rock glaciers. Figure 5 below shows the distribution of active and relict rock glaciers within the boundaries of the park, and in relation to the Continental Divide, marked by the black line running through the center of the park. There were a total of 14 relict rock glaciers and 13 active rock glaciers, as marked on the map by red and green respectively. The rock glaciers had a very clear distribution between the groups to be explained more explicitly in the following sections.

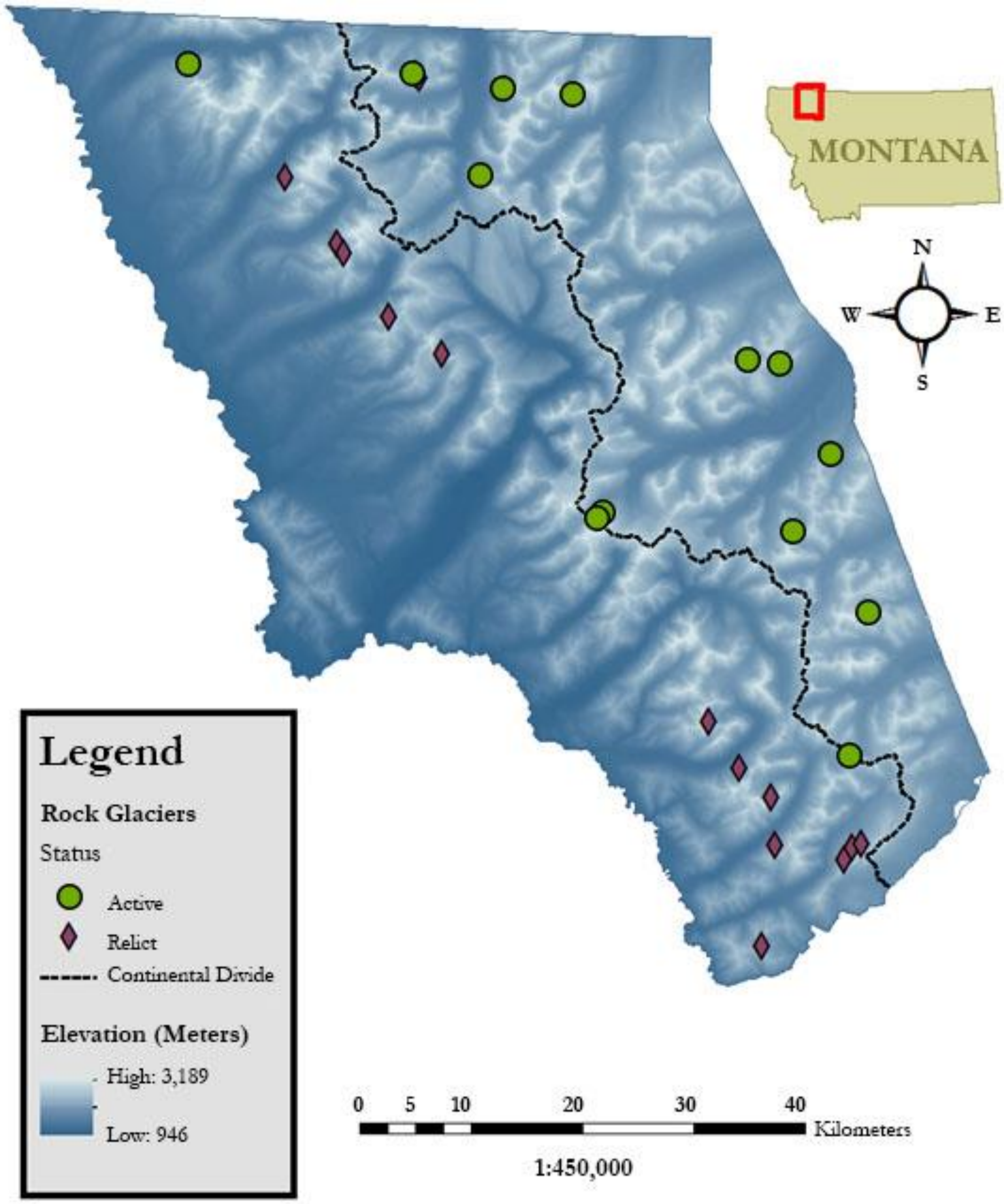

Figure 5: Geographic distribution of rock glaciers in Glacier National Park.

<u>Active Rock Glaciers</u>

The high mountain cirques in Glacier National Park fit the conditions required for rock glacier genesis as alpine periglacial environments—especially on the east side of the park. Active rock glaciers were found almost exclusively east of the Continental Divide on northerly-facing slopes. This side of the park is marked by dry, cold, sometimes arctic conditions in the high mountain cirques as it is the leeward side of the park. Only one of the active rock glaciers, the Kintla rock glacier, exists west of the Divide (Appendix A). This rock glacier is in the far north of the park where the climatic conditions of today are amenable to the formation of a rock glacier. Active rock glaciers are dispersed fairly evenly from the middle of the park and to the north.

The following figures (Figures 6 – 10) show examples of five of the active rock glaciers found within the park. Each of these images were captured from Google Earth's imagery for July of 2013 at an eye elevation of 3048 meters.

Bear rock glacier (Figure 6), is a tongue-shaped rock glacier and the largest active rock glacier found in terms of sheer size—length, width, and area. Bear rock glacier is located in the far north of the park to the east of the Divide. It has very clear transverse ridges and furrows, as well as an active talus supply and persistent snow cover.

Figure 6: Active rock glacier near Bear Mountain.

East Flattop rock glacier (Figure 7) is a moderately sized, tongue-shaped rock glacier found in the central latitudes of the park to the far east. It is smaller than Bear, but like Bear offers clear transverse ridges and furrows, as well as a steep front.

Figure 7: Active rock glacier near East Flattop Mountain.

The Lonely Lakes rock glacier (Figure 8) is a piedmont type rock glacier near the Lonely Lakes in Glacier National Park. It appears to be sourced from near the east side of the small glacier in the lower left-hand portion of Figure 8, and has moved around the moraine at the snout of the glacier.

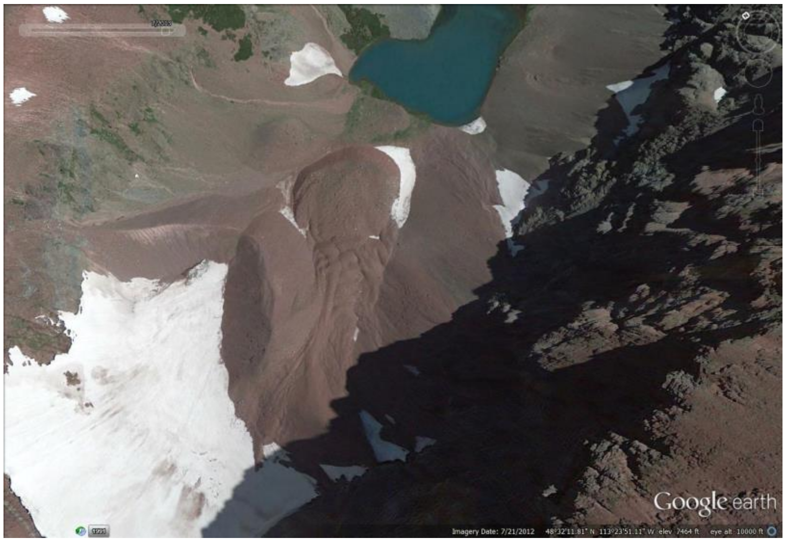

Figure 8: Active rock glacier near Lonely Lakes.

The Gunsight rock glaciers (Figure 9) are unique in that they are both sourced from the same cirque wall and talus supply, but because the lobes are travelling in different directions, I have chosen to categorize them as two separate rock glaciers. These rock glaciers are sourced from what appears to be a terminal moraine, with the ice above the rock glaciers likely a remnant glacier.

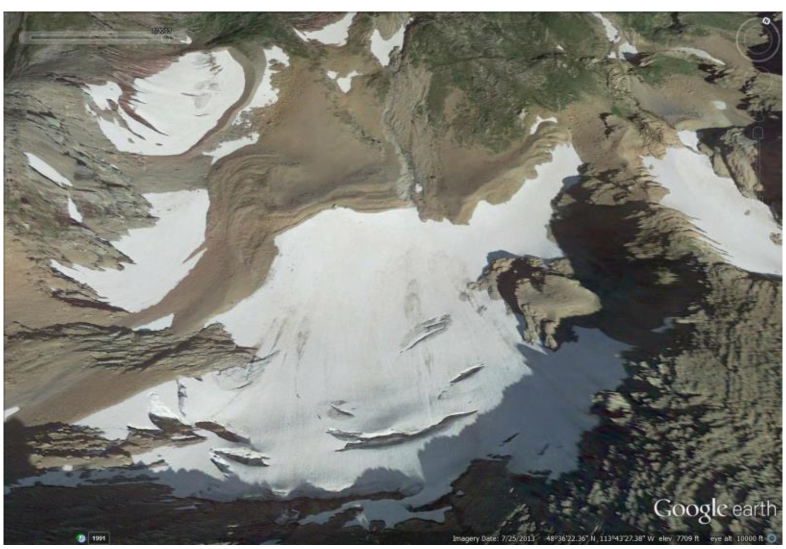

Figure 9: Two active rock glaciers near Gunsight Mountain.

The Medicine Owl rock glacier (Figure 10) is a smaller, tongue-shaped rock glacier that appears to be emerging from the moraine of the upslope glacier—the remains of which can be seen to the south southwest of the Medicine Owl rock glacier. This rock glacier, like the Lonely Lakes rock glacier (Figure 8) and the Gunsight Mountain rock glaciers (Figure 9), may be derived from an ice-cored moraine or the glacier itself.

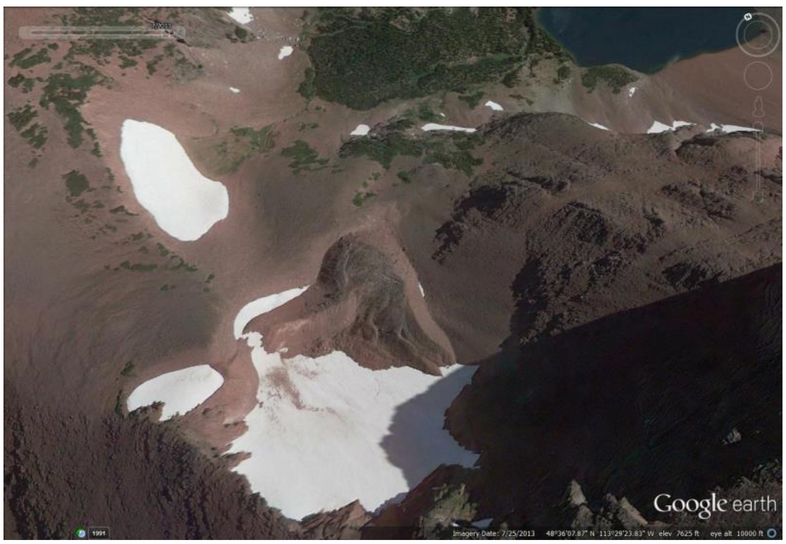

Figure 10: Active rock glacier near Medicine Owl Lake.

<u>Relict Rock Glaciers</u>

Relict rock glaciers were found almost exclusively west of the Continental Divide on northerly-facing slopes. This side of the park is currently marked by warmer, wetter Pacific inland maritime conditions as it is the windward side of the park. Only one of the relict rock glaciers, the Shaheeya rock glacier, exists to the east of the Divide to the far north of the park. Dispersion of relict rock glaciers includes a cluster in the southwest portion of the park near the Divide, with a few scattered through the upper middle portion of the west side.

Relict rock glaciers reach further south and west than the active rock glaciers of Glacier National Park. The geographic dispersion is likely an indicator of a colder, drier paleoclimate that reached further south and west, permitting rock glacier genesis. It is speculated that many of these relict rock glaciers are probably Pleistocene rock glaciers, when this region of North America was colder and highly glaciated. The following figures (Figures 11 – 15) show examples of five relict rock glaciers. Each of these images were captured from Google Earth's imagery for July of 2013 at an eye elevation of 3048 meters.

The Snowslip rock glacier (Figure 11) is a relict rock glacier found to the far south in the park. It is small, but maintains a very distinct lobate shape. This relict rock glacier in particular is highly vegetated, with no distinct clastic barrier between the vegetation on the rock glacier and in the cirque itself.

Figure 11: Relict rock glacier near Snowslip Mountain.

East Little Dog rock glacier (Figure 12) is another lobate rock glacier that had a flow to the east down a ridge near Little Dog Mountain in the south of the park. Though this rock glacier is relict, as judging by the vegetation growing on the ridges of the extinct rock glacier, it still maintains the furrows and ridges from when it was active.

Figure 12: Relict rock glacier to the east near Little Dog Mountain.

West Little Dog rock glacier (Figure 13), a lobate rock glacier, appears to have flowed to the west on the opposite side of the ridge down which East Little Dog (Figure 12) flowed near Little Dog Mountain. This rock glacier also shows vegetation growth, and has a gently sloped front from when this rock glacier was active.

Figure 13: Relict rock glacier to the west near Little Dog Mountain.

The Sheep rock glacier (Figure 14) is a small, thin, tongue-shaped relict rock glacier on a northwest slope near Sheep Mountain. This rock glacier is marked by a gently sloping, vegetated front. Its ridges and furrows are still apparent, though they are milder in steepness than the sharper, more distinct ridges found on active rock glaciers.

Figure 14: Relict rock glacier near Sheep Mountain.

The Saint Nicholas rock glacier (Figure 15) is a tongue-shaped rock glacier found in the southwest portion of the park. Like the relict rock glaciers mentioned previously, Saint Nicholas is vegetated, with a mildly sloped terminus.

Figure 15: Relict rock glacier near Mount Saint Nicholas.

Comparing Active and Relict Groups

Once the rock glaciers were located and their variables recorded from Google Earth, data from the rock glaciers were then analyzed in SPSS using a Mann-Whitney *U* test to check for major statistical differences between groups for the six variables listed previously and in Tables 1, 2, and 3. A Mann-Whitney *U* test was used because of the size of the sampling data (n=27), and because this thesis did not want to make any assumptions about the underlying distribution. For this thesis, a *p*-value of 0.05 was used to determine significance in both the Google Earth and the DEM analysis. Tables 1 and 2 show the results from the Mann-Whitney *U* tests looking to disprove the null-hypotheses listed in chapter VI for the Google Earth and DEM analyses, respectively.

Table 1: Mann-Whitney *U* results, Google Earth

		Elevation at Head†	Elevation at Toe†	Relief‡	Slope	Length†	Width†
Relict	**Minimum**	1,815.41	1,681.60	26.21	8.53º	92.99	138.55
	Median	1,988.54	1,935.35	93.42	15.80º	298.04	257.08
	Maximum	2,344.55	2,173.56	301.45	26.10º	728.12	484.73
Active	**Minimum**	2,094.05	1,966.90	47.24	12.95º	123.16	52.86
	Median	2,262.62	2,108.33	112.78	23.70º	208.21	160.04
	Maximum	2,393.01	2,294.87	229.52	34.22º	679.74	304.01
	***p*-value**	0.001*	<0.001*	0.467	0.003*	0.308	0.023*

† Units in meters
* Statistically significant differences

The results from the test showed that there were statistically significant differences between groups in four of the variables tested. These variables were elevation at head, elevation at the toe, slope, and width.

Elevation

When compared to relict rock glaciers, active rock glaciers occur at higher elevations, with the median elevation at the head of a rock glacier being around 2260 m, and the median elevation at the toe of an active rock glacier being about 2110 m. Both of these medians for relict rock glaciers lie below 2000 m in the cirques of the park. All rock glaciers, however, are located at elevations above 1680 m.

Relief and Slope

Relief between active and relict groups of rock glaciers showed no statistical difference. This is likely because of the geomorphic controls on rock glacier growth and lateral size. In terms of slope, active rock glaciers tend to be steeper, with a median slope of about 24 degrees. Relict rock glaciers have a median slope of about 16 degrees.

Aspect

In general, rock glaciers in Glacier National Park were located in northerly-facing cirques. The aspects of the rock glaciers were typically somewhere on a spectrum between the northwest and the northeast. Only one rock glacier did not have a northerly-facing aspect, and that rock glacier was the Wahcheechee rock glacier to the north of the park (Appendix A). Wahcheechee rock glacier has a southwestern aspect.

Length and Width

Length and width were grouped for purposes of discussing size. The results of the Mann-Whitney *U* test show that it is the relict group that is generally wider than the active group with a median width of about 260 m. There were far more lobate rock glaciers in the relict group than in the active group. Though there was no statistical difference indicated between groups in terms of length—probably again because of the geomorphic controls on rock glacier growth and lateral size—relict rock glaciers tended to be a bit longer with a median length of about 300 m versus the median length of the active group at about 210 m. The smallest rock glacier from the Google Earth analysis, in terms of length, is about 93 m long and a relict rock glacier. The smallest active rock glacier is not much longer than the smallest relict rock glacier at 123 m, but the active rock glacier group has the thinnest rock glacier, with a width of merely 52 m. This width is compared to the relict group's thinnest rock glacier at 139 m. The greater size of relict rock glaciers might be attributed to a colder, slightly wetter climate that allowed rock glaciers to grow to larger sizes than the active rock glaciers existing presently.

DEM and Google Earth Data Comparison

Once the Google Earth results were analyzed, an analysis using DEMs from the USGS National Map Viewer (2015) was run to compare to the Google Earth results. Tools used to analyze DEMs, such as ArcGIS—as was used in this study—are not as readily available to the general public, though DEM data has a much smaller margin of error. Table 2 shows the results achieved from DEM analysis where rock glaciers were digitized, and their variables acquired by the computer using tools in ArcMap. The variables for the DEM analysis were the same, with the addition of area.

Table 2: Mann-Whitney *U* results, DEMs

		Elevation at Head†	Elevation at Toe†	Relief†	Slope	Length†	Width†
Relict	*Minimum*	1,920.10	1,690.31	95.23	13.51°	235.65	172.58
	Median	2,078.89	1,937.90	194.98	18.17°	384.58	323.39
	Maximum	2,406.43	2,172.08	399.92	32.68°	850.55	612.26
Active	*Minimum*	2,098.05	1,979.18	31.10	15.42°	93.67	53.95
	Median	2,252.21	2,103.55	154.68	25.57°	263.83	199.15
	Maximum	2,482.70	2,300.37	251.39	47.19°	611.18	382.51
	p-*value*	0.007*	<0.001*	0.047*	0.012*	0.006*	0.007*

† Units in meters
* Statistically significant differences

The DEM analysis resulted in a few differences when compared to the Google Earth results. It is clear by comparing the results (Table 3) that the medians of each group are different. Some medians varied more dramatically than others, but none of the differences were unreasonable or beyond expectation. The biggest difference between the Google Earth and DEM analyses, however, is the fact that all groups show differences when subjected to the Mann-Whitney *U* test. Where the Google Earth analysis shows that there was no significant difference of relief and length between the two groups, the DEM analysis shows that there are differences—with relict rock glaciers having greater relief and length than active rock glaciers.

Table 3: Mann-Whitney *U* results comparison

	Analysis		Elevation at Head†	Elevation at Toe†	Relief‡	Slope	Length†	Width†
Relict	*GE*	*Minimum*	1,815.41	1,681.60	26.21	8.53º	92.99	138.55
	DEM	*Minimum*	1,920.10	1,690.31	95.23	13.51º	235.65	172.58
	GE	*Median*	1,988.54	1,935.35	93.42	15.80º	298.04	257.08
	DEM	*Median*	2,078.89	1,937.90	194.98	18.17º	384.58	323.39
	GE	*Maximum*	2,344.55	2,173.56	301.45	26.10º	728.12	484.73
	DEM	*Maximum*	2,406.43	2,172.08	399.92	32.68º	850.55	612.26
Active	*GE*	*Minimum*	2,094.05	1,966.90	47.24	12.95º	123.16	52.86
	DEM	*Minimum*	2,098.05	1,979.18	31.10	15.42º	93.67	53.95
	GE	*Median*	2,262.62	2,108.33	112.78	23.70º	208.21	160.04
	DEM	*Median*	2,252.21	2,103.55	154.68	25.57º	263.83	199.15
	GE	*Maximum*	2,393.01	2,294.87	229.52	34.22º	679.74	304.01
	DEM	*Maximum*	2,482.70	2,300.37	251.39	47.19º	611.18	382.51
	GE	p-*value*	0.001*	<0.001*	0.467	0.003*	0.308	0.023*
	DEM	p-*value*	0.007*	<0.001*	0.047*	0.012*	0.006*	0.007*

GE = Google Earth
† Units in meters
* Statistically significant differences

Relief and length were the greatest discrepancies between results, with the median relict rock glacier being almost 100 m longer with the results of the DEM. An even greater discrepancy was found between minimum lengths in the relict group—with the Google Earth analysis yielding a minimum length of 93 m and the DEM analysis yielding a minimum length of 236 m. Naturally, these results affected the differences in relief between studies. For the Google Earth analysis, a minimum relief of 26 m was listed for relict rock glaciers, but the DEM analysis resulted in a minimum relief of 95 m – a 69 m difference.

In the Google Earth analysis, length was already listed as greater for the relict group, but there was no significant difference between the two groups. As the DEM analysis shows, length is clearly greater in the relict group, with a median length of about 385 meters versus 264 meters in the active group, and the significance is marked (Table 2). The probable explanation as to why length is greater in the relict group does not change—this analysis only reaffirms that relict rock glaciers are that much bigger than active rock glaciers. The

DEM results on length further supports the claim that the paleo- conditions were better for the genesis and growth of the relict rock glaciers in Glacier National Park.

IX. DISCUSSION

Geography of Glacier National Park Rock Glaciers

The geography and spatial distribution of rock glaciers, both active and relict, provides insight to climatic conditions (Baroni, Carton, and Seppi 2004). Rock glaciers form best in a cold, dry, continental climate, at elevations where the mean annual air temperature is less than 0°C (Harris 1981). In Glacier National Park, these conditions are illustrated by the locations of active rock glaciers (Figure 5) on the east side of the park and at high mountain elevations, typically above 1900 m (Table 3). As has been previously discussed, the distribution of relict rock glaciers, on the other hand, is indicative of a colder, drier palaeoclimate in which the 0°C isotherm existed at a lower elevation in the park's cirques and valleys.

Though the park is still home to about 25 active true glaciers, many of the park's active rock glaciers exist independently of glacial features. However, some probably originated from true glaciers or ice-cored moraines. Ground-penetrating radar would indicate whether these rock glaciers are ice-cemented or ice-cored, but because access to rock glaciers and ground-penetrating radar were unavailable for the analysis, any comment as to the origins of the rock glaciers is purely speculation. Presence of glacial remnants at the heads of rock glaciers like Medicine Owl (Figure 10), East and West Gunsight (Figure 9) and Lonely Lakes (Figure 8) are apparent. Medicine Owl and Lonely Lakes rock glaciers are especially likely to be glaciogenic rock glaciers due to their proximity to glacial moraines.

Statistical Results

Elevation

The elevation distribution for both active and relict rock glaciers makes sense. As has been stated previously, relict rock glaciers were active at a time when temperatures were colder and drier further south and west. As a result, paleo- conditions permitted them to form lower in valleys and cirques. As Earth has warmed and the 0˚C isotherm has moved north, it has also moved higher into the mountains. Thus, active rock glaciers require conditions only available in high mountain cirques in order to form. This would explain the high elevations of active rock glaciers in Glacier National Park.

Relief and Slope

Since active rock glaciers occur at higher elevations—and thus on steeper slopes—it stands to reason as to why active rock glaciers are steeper than relict rock glaciers. On the other hand, relict rock glaciers are larger and longer, and generally have a greater relief than active rock glaciers, which are quite small in comparison.

Aspect

Figure 1 shows topography and aspect as one of the geographic controls of rock glacier genesis. Rock glaciers form best on the sides of mountain cirques that receive less insolation, and are thus generally cooler in temperature. In the Lemhi range, the aspect of these cirques is typically northerly-facing (Johnson, Thackray, and Van Kirk 2007). Based on this study, it was expected that rock glaciers in Glacier National Park would have similarly facing aspects—and the assumption was correct. Rock glaciers in the park have generally northerly-facing aspects.

Length and Width

Modern climatic conditions for rock glacier genesis are inhibiting compared to the paleoclimate in which relict rock glaciers formed in Glacier National Park. As a result, active rock glaciers are generally smaller than relict rock glaciers in terms of length and width—this held true for both the DEM and Google Earth results.

DEM and Google Earth Data Comparison

The results of the DEM analysis only serve to amplify the results of the Google Earth analysis. In no way do they refute the conclusion of the Google Earth study. Length and relief between groups change in significance, but still result in longer relict rock glaciers. As relict rock glaciers proved to be longer and larger than the active, modern rock glaciers, it stands to reason that the group would show greater relief. Though relict rock glaciers are generally less steep than active rock glaciers, they reach further down their cirque and valley walls than active rock glaciers, and thus cover a greater difference in elevation. It is unknown as to why the active group on the Google Earth analysis had a greater relief, but the results from the DEMs make more sense. This is most likely due to the greater accuracy of the DEMs.

A Brief Comparison of Glaciers and Rock Glaciers

Though this analysis does not focus on true glaciers, an anecdote did need to be made on how rock glaciers are changing annually versus true glaciers. This analysis is based upon purely visual observations using aerial imagery from Google Earth during the process of finding the rock glaciers. It involved no statistical or heavy analysis component, but is used, rather, to reaffirm the importance and stability of rock glaciers as true glaciers dwindle.

Figure 16 compares the locations of rock glaciers and active true glaciers with an area greater than 0.1 km^2 as of 2010 (Fagre 2010). The true glaciers, which do not exist in the far south of the park, are largely active in cirques located almost exclusively along the Continental Divide, where precipitation is greater (National Park Service 2015d). This precipitation is what likely permits the true glaciers to maintain their active status for a longer period. Active and relict rock glaciers, on the other hand, are mostly located in cirques away from the Continental Divide. Active rock glaciers exist closer to the edges of the park, and are less uniform in their distribution from the Continental Divide than relict rock glaciers. Active rock glaciers are located in the rain shadow of the park, but exist in areas that likely provide just enough precipitation to maintain their activity.

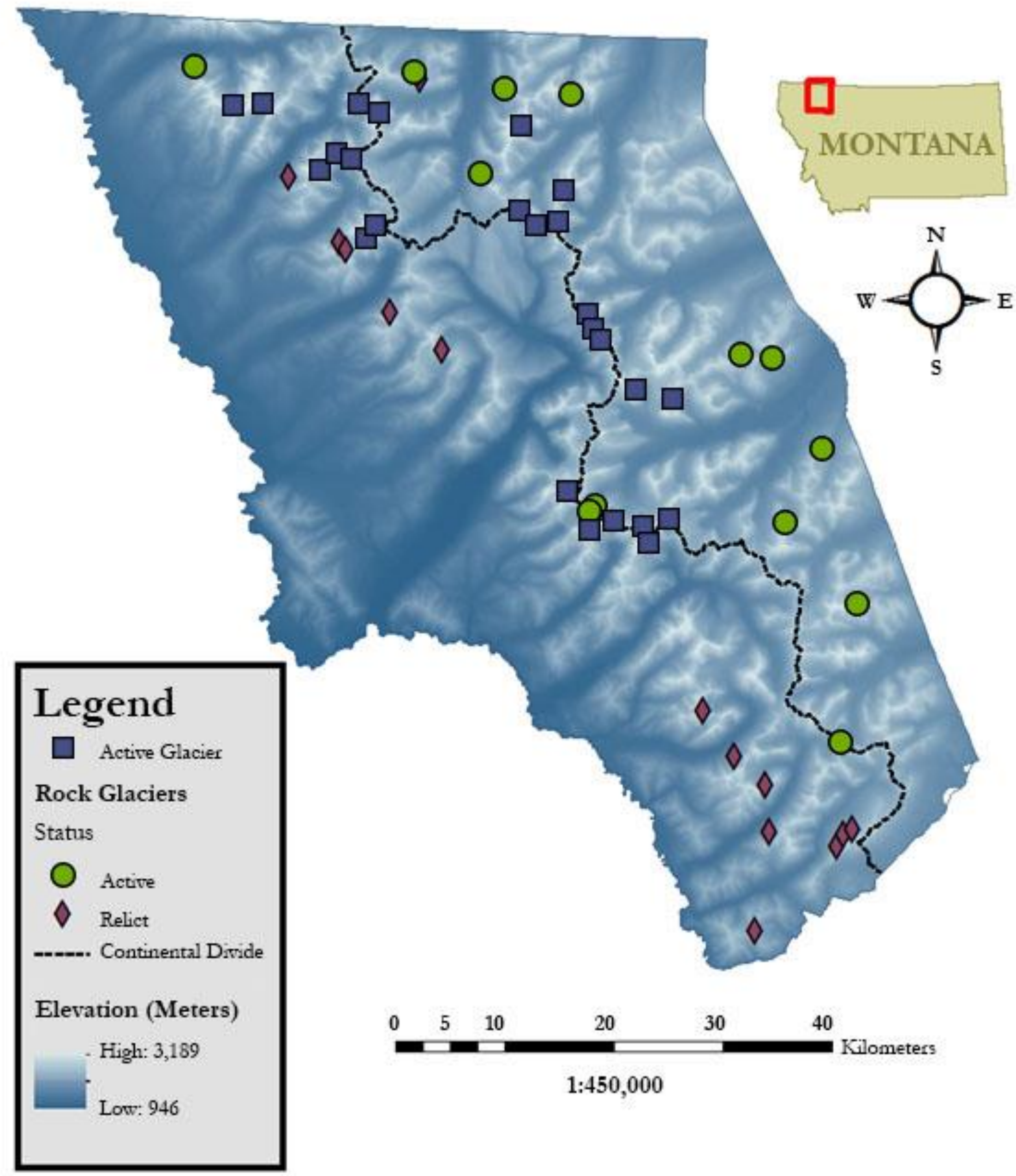

Figure 16: Geographic distribution of true ice and rock glaciers.

Figures 17 through 20 are a series of comparison images showing the annual variability in the span of one year. For this comparison, two ‘benchmark’ glaciers and rock glaciers have been selected from each group, making four comparison figures. All four were taken from the same month, July, in the years 2012 and 2013. These images were selected to show how each landform can potentially change over the span of a year.

Figure 17 shows the Grinnell Glacier of Glacier National Park. As the following images will show, 2012 experienced greater snow cover longer into the year, but in 2013, part of the glacier had ablated and some of the snow cover melted away. Annually, Grinnell Glacier sees some exposure of the Upper Grinnell Lake forming around the glacier.

Figure 17: Changes in Grinnell Glacier between 2012 and 2013.

Figure 18 shows a comparison between years for the Sperry Glacier. Similar to the Grinnell comparison (Figure 17), Sperry shows a greater extent of snow and ice cover in 2012, but in 2013, an amount has melted—including some ice, exposing bedrock and a couple of small tarns.

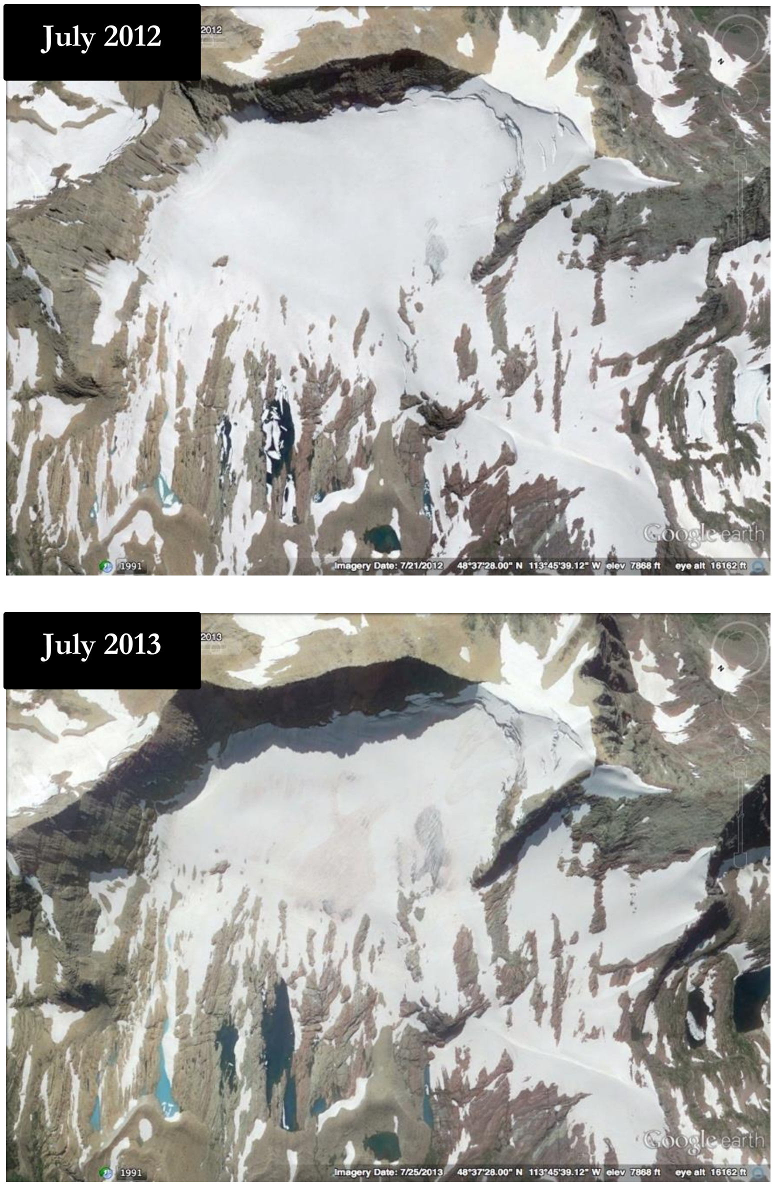

Figure 18: Changes in Sperry Glacier between 2012 and 2013.

The ice in true glaciers is exposed directly to the elements, this allows for quick rates of ablation from environmental weathering including melting from insolation and heat, as well as wind erosion. Rock glaciers, on the other hand, have a protective layer of debris that insulates the ice within and protects it from the environment. As discussed earlier, thermal regimes of active rock glaciers and similar periglacial formations, tend to be lower than the surrounding soils and bedrock (Millar, Westfall, Delany 2014). The protective debris covering lends to a stability in rock glaciers that true glaciers do not have.

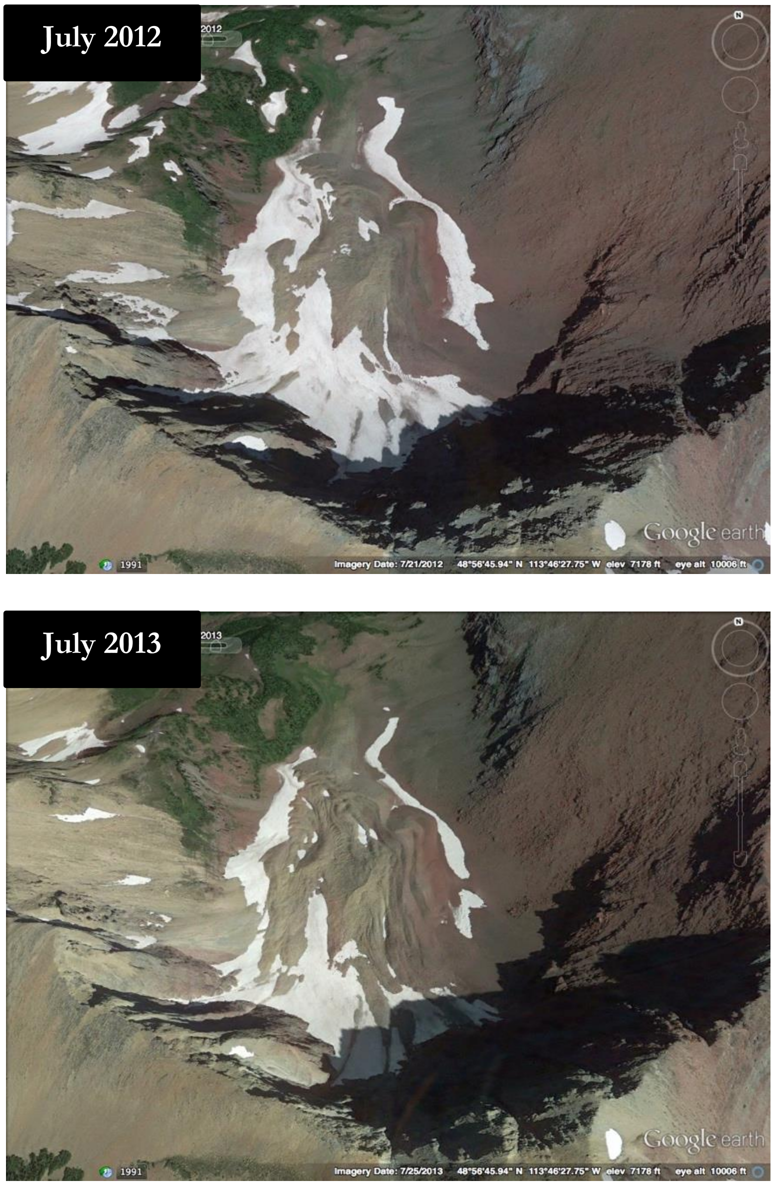

Figure 19: Changes in Bear rock glacier between 2012 and 2013.

Figure 19 shows the Bear rock glacier in July of the years 2012 and 2013. No change is apparent in the structure of the rock glacier. The only 'change' noticeable is the change in snow cover between years, but not the size or extent of the rock glacier itself. East Flattop in figure 20, like Bear rock glacier in figure 19, shows no significant structural change between the two years.

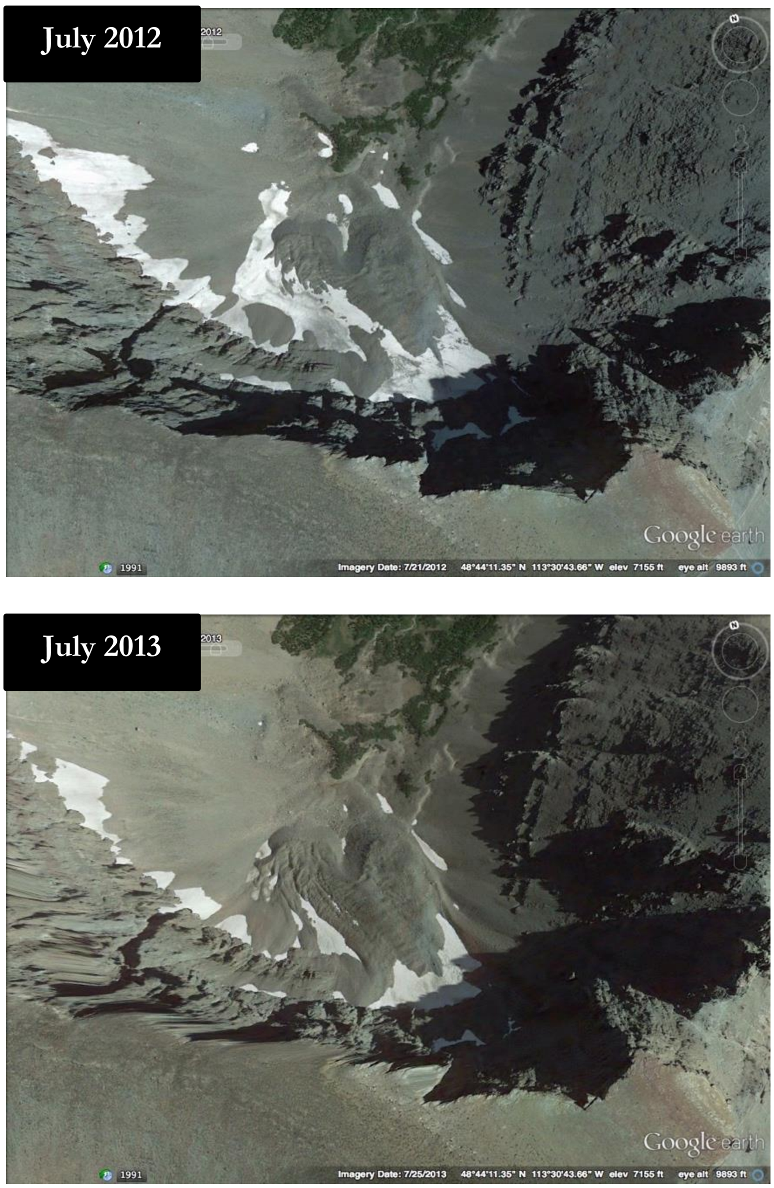

Figure 20: Changes in East Flattop rock glacier between 2012 and 2013.

Because of the relative geomorphic stability of rock glaciers, these features are going to become more and more important as true glaciers melt. Though the disappearance of true glaciers has greater implications over the ecological and hydrological regime of Glacier

National Park, rock glaciers will serve, in some areas, as alternative sources of water and habitat. Rock glaciers will do this with storages of ice and water, as well as cool microclimates resulting from stored ice. Rock glaciers in Glacier National Park will likely not provide the same extent of resources across the park as glaciers do, but they will soon be much of what the park has—and are very important in terms of storing water (Azócar and Brenning 2010).

X. CONCLUSION

Overall, this thesis is a two-part project. The first objective of this thesis is to catalogue the existence of rock glaciers within Glacier National Park. This aspect is potentially important because an accessible catalogue of existing rock glaciers in the park has not existed before now. Active, ice-storing rock glaciers are important to the park's ecology as stores of water and as habitats for vulnerable fauna such as the American pika (*Ochotona princeps*), which are poor thermoregulators. This catalogue of rock glaciers in Glacier National Park provides a further understanding of the park that could be useful in conservation efforts toward vulnerable fauna like the pika. Similarly, this thesis expands the knowledge of geography in regards to the park.

The general geography of rock glaciers in the park is very clear. Active rock glaciers occur in northerly-facing cirques almost exclusively east of the Continental Divide in high mountain elevations, where high winds keep climate relatively dry and cold. On the other hand, relict rock glaciers exist almost entirely to the west of the Continental Divide. Like active rock glaciers, they, too, exist in northerly-facing cirques and valleys.

The second part of this thesis is to examine the morphological and morphometric differences between active and relict groups of rock glaciers in the park. The results of this study indicated that active rock glaciers occur at higher elevations and are steeper than relict rock glaciers, which are wider and—though not statistically significant by the Google Earth results—slightly longer than active rock glaciers. Though the two groups differ in most variables, geographic controls for rock glacier formation and flow likely explains the reason relict and active rock glaciers are similar in their relief and even length.)

Though Google Earth was used for the main analysis of this thesis due to its accessibility as a geospatial tool, DEM measurements showed that relict rock glaciers are definitely longer and have a greater relief than active rock glaciers. Though the results of the Google Earth analysis were within reasonable explanation, the medians from the results of the DEM analysis, especially with regards to relief, were more sensible.

The location and morphometries of relict and active rock glaciers offer a climatic comparison between today's climate in the park and the paleoclimate for the region thousands of years ago—which was colder and drier further south and west than the present. Further research suggestions might include investigating the park's paleoclimate to gain further insight into the relict rock glaciers found within the park.

The main purpose of this thesis was to be a general description and survey of rock glaciers in the park. This newfound knowledge can be used as a foundation for potential research examining subjects that are not necessarily centered on rock glaciers. This might include research such as past and present climate in Glacier National Park, ecological studies for the local flora and fauna, studies examining water resources within the park, and research enquires examining the park's cryogenic features. Further rock glacier research for the park might include rock glacier response to climate change in the park, contemporary rock glacier movement, and whether or not rock glaciers in the park are ice-cemented or ice-cored.

APPENDIX SECTION

APPENDIX A: ROCK GLACIER DATABASE, GOOGLE EARTH

name	Latitude	longitude	asp_deg	adj_deg	aspect
Quartz	48°49'15.55"N	114° 3'30.40"W	325.19	-34.81	NW
Statuary	48°23'11.75"N	113°30'15.94"W	320.46	-39.54	NW
Bowman	48°52'20.17"N	114° 7'25.98"W	318.51	-41.49	NW
Sheep	48°20'53.28"N	113°29'53.35"W	301.81	-58.19	WNW
Saint Nicholas	48°24'36.23"N	113°32'40.55"W	298.97	-61.03	WNW
Ole	48°20'18.81"N	113°24'50.10"W	296.76	-63.24	WNW
Little Dog West	48°20'52.64"N	113°24'19.22"W	291.41	-68.59	WNW
Ruger	48°44'5.57"N	113°55'30.06"W	70	70	ENE
Shaheeya	48°57'25.22"N	113°57'55.29"W	63.05	63.05	ENE
Little Dog East	48°21'8.14"N	113°23'37.93"W	49.75	49.75	NE
Wolf Gun North	48°45'50.93"N	113°59'27.95"W	34.05	34.05	NE
Snowslip	48°15'59.44"N	113°30'37.11"W	21.77	21.77	NNE
Logging	48°48'50.14"N	114° 2'59.11"W	3.2	3.2	N
Cloudcroft	48°26'47.60"N	113°35'2.92"W	1.07	1.07	N
Gunsight East	48°36'35.87"N	113°43'23.40"W	357.71	-2.29	N
Otokomi	48°44'25.66"N	113°33'7.17"W	354.12	-5.88	N
Wahseeja	48°57'39.63"N	113°58'9.48"W	345.34	-14.66	NNW
East Flattop	48°44'17.10"N	113°30'48.00"W	343.4	-16.6	NNW
Gunsight West	48°36'27.86"N	113°43'42.22"W	322.73	-37.27	NW
Wahcheechee	48°52'53.87"N	113°53'2.35"W	220	-140	SW
Lonely Lakes	48°32'17.42"N	113°23'47.81"W	39.41	39.41	NE
Curly Bear	48°39'54.97"N	113°26'45.19"W	31.43	31.43	NNE
Kintla	48°57'37.61"N	114°14'51.24"W	25.1	25.1	NNE
Medicine Owl	48°36'9.97"N	113°29'22.94"W	24.96	24.96	NNE
Grizzly	48°25'25.74"N	113°24'41.77"W	18.66	18.66	NNE
Bear	48°56'57.34"N	113°46'32.29"W	0.38	0.38	N
Goat Haunt	48°57'7.16"N	113°51'36.68"W	0.12	0.12	N

name	elev_head_ft	elev_head_m	elev_toe_ft	elev_toe_m	relief
Quartz	6056	1845.89	5741	1749.88	96.01
Statuary	6688	2038.53	6573	2003.47	35.05
Bowman	5956	1815.41	5517	1681.60	133.81
Sheep	6272	1911.73	5786	1763.59	148.13
Saint Nicholas	6174	1881.86	5577	1699.89	181.97
Ole	6470	1972.08	6285	1915.69	56.39
Little Dog West	6559	1999.21	6447	1965.07	34.14
Ruger	6470	1972.08	6384	1945.87	26.21

Shaheeya	7692	2344.55	7131	2173.56	170.99
Little Dog East	6620	2017.80	6315	1924.84	92.97
Wolf Gun North	6489	1977.87	6314	1924.53	53.34
Snowslip	6771	2063.83	6463	1969.95	93.88
Logging	7124	2171.42	6864	2092.17	79.25
Cloudcroft	7524	2293.34	6535	1991.89	301.45
Gunsight East	7639	2328.40	7183	2189.41	138.99
Otokomi	7203	2195.50	6917	2108.33	87.17
Wahseeja	6977	2126.62	6604	2012.92	75.60
East Flattop	7423	2262.56	6881	2097.35	165.20
Gunsight West	7851	2393.01	7327	2233.30	159.72
Wahcheechee	7120	2170.20	6919	2108.94	61.27
Lonely Lakes	7676	2339.67	7296	2223.85	115.83
Curly Bear	6873	2094.92	6564	2000.73	94.18
Kintla	6937	2114.42	6453	1966.90	147.52
Medicine Owl	7684	2342.11	7529	2294.87	47.24
Grizzly	7476	2278.71	7106	2165.94	112.78
Bear	7538	2297.61	6785	2068.09	229.52
Goat Haunt	6953	2119.30	6662	2030.60	88.70

name	lin_dist	lin_width	avg_slope	park_side	status
Quartz	215.48	162.1	0.45	West	Relict
Statuary	129.15	394.3	0.27	West	Relict
Bowman	372.12	254.97	0.36	West	Relict
Sheep	492.67	168.73	0.30	West	Relict
Saint Nicholas	728.12	350.97	0.25	West	Relict
Ole	208.52	138.55	0.27	West	Relict
Little Dog West	224.06	374	0.15	West	Relict
Ruger	92.99	380.18	0.28	West	Relict
Shaheeya	473.76	209	0.36	East	Relict
Little Dog East	353.68	331.37	0.26	West	Relict
Wolf Gun North	266.41	222.38	0.20	West	Relict
Snowslip	329.66	259.19	0.28	West	Relict
Logging	246.52	147.97	0.32	West	Relict
Cloudcroft	613.41	484.73	0.49	West	Relict
Gunsight East	359.99	169.12	0.39	East	Active
Otokomi	192.1	155.33	0.45	East	Active
Wahseeja	144.73	304.01	0.52	East	Active
East Flattop	362.44	245.26	0.46	East	Active
Gunsight West	379.46	261.55	0.42	East	Active

Wahcheechee	123.16	59.42	0.50	East	Active
Lonely Lakes	344.79	138.41	0.34	East	Active
Curly Bear	176.33	52.86	0.53	East	Active
Kintla	350.62	84.28	0.42	West	Active
Medicine Owl	208.21	224.6	0.23	East	Active
Grizzly	164.86	160.04	0.68	East	Active
Bear	679.74	273.13	0.34	East	Active
Goat Haunt	202.08	137.94	0.44	East	Active

These data were collected for this table in 2015 using Google Earth and its related tools from July, 2013 (Google Earth 2015).

APPENDIX B: ROCK GLACIER DATABASE, DEM

name	latitude	longitude	elev_toe	elev_head	relief
Bowman	48°52'20.17"N	114° 7'25.98"W	1690.311	1920.102	229.790
Cloudcroft	48°26'47.60"N	113°35'2.92"W	1995.498	2279.002	283.504
Little Dog East	48°21'8.14"N	113°23'37.93"W	1925.708	2069.516	143.807
Little Dog West	48°20'52.64"N	113°24'19.22"W	1950.922	2079.432	128.510
Logging	48°48'50.14"N	114° 2'59.11"W	2077.468	2237.634	160.166
Ole	48°20'18.81"N	113°24'50.10"W	1854.817	2147.237	292.420
Quartz	48°49'15.55"N	114° 3'30.40"W	1753.900	1991.802	237.901
Ruger	48°44'5.57"N	113°55'30.06"W	1950.100	2078.350	128.251
Saint Nicholas	48°24'36.23"N	113°32'40.55"W	1695.512	2095.434	399.922
Shaheeya	48°57'25.22"N	113°57'55.29"W	2172.075	2406.429	234.354
Sheep	48°20'53.28"N	113°29'53.35"W	1760.443	2024.762	264.318
Snowslip	48°15'59.44"N	113°30'37.11"W	1976.526	2071.752	95.226
Statuary	48°23'11.75"N	113°30'15.94"W	2001.039	2157.437	156.398
Wolf Gun North	48°45'50.93"N	113°59'27.95"W	1918.590	2026.810	108.220
Bear	48°56'57.34"N	113°46'32.29"W	2073.232	2266.244	193.012
Curly Bear	48°39'54.97"N	113°26'45.19"W	2008.413	2098.046	89.632
East Flattop	48°44'17.10"N	113°30'48.00"W	2097.533	2252.211	154.678
Goat Haunt	48°57'7.16"N	113°51'36.68"W	2040.281	2126.298	86.018
Grizzly	48°25'25.74"N	113°24'41.77"W	2166.195	2328.847	162.652
Gunsight East	48°36'35.87"N	113°43'23.40"W	2191.342	2397.813	206.470
Gunsight West	48°36'27.86"N	113°43'42.22"W	2237.295	2429.045	191.750
Kintla	48°57'37.61"N	114°14'51.24"W	1979.179	2144.014	164.835
Lonely Lakes	48°32'17.42"N	113°23'47.81"W	2231.314	2482.701	251.387
Medicine Owl	48°36'9.97"N	113°29'22.94"W	2300.370	2368.090	67.720
Otokomi	48°44'25.66"N	113°33'7.17"W	2119.497	2195.781	76.284
Wahcheechee	48°52'53.87"N	113°53'2.35"W	2103.545	2134.646	31.101
Wahseeja	48°57'39.63"N	113°58'9.48"W	2017.465	2100.854	83.389

name	lin_width	lin_dist	avg_slope	Area	park_side	status
Bowman	320.364	630.566	19.709	119196	West	Relict
Cloudcroft	390.773	382.486	25.861	116375	West	Relict
Little Dog East	556.376	386.672	16.411	150951	West	Relict
Little Dog West	612.259	273.093	13.507	104547	West	Relict
Logging	275.96	296.207	24.936	58930	West	Relict
Ole	345.171	809.736	20.525	159368	West	Relict
Quartz	172.577	361.734	32.677	39471	West	Relict
Ruger	502.035	297.751	20.455	111576	West	Relict

Saint Nicholas	326.424	850.551	16.635	220271	West	Relict
Shaheeya	213.494	536.384	15.715	55387	East	Relict
Sheep	183.295	703.116	16.618	93232	West	Relict
Snowslip	274.339	333.23	16.025	67384	West	Relict
Statuary	312.405	235.65	24.688	67140	West	Relict
Wolf Gun North	341.643	396.249	16.395	87859	West	Relict
Bear	333.249	611.176	19.476	145606	East	Active
Curly Bear	142.289	147.667	34.879	11867	East	Active
East Flattop	277.975	289.909	25.573	57952	East	Active
Goat Haunt	165.249	186.932	28.732	25704	East	Active
Grizzly	201.854	125.978	47.186	20051	East	Active
Gunsight East	199.148	326.546	24.867	45979	East	Active
Gunsight West	382.509	499.255	24.625	95913	East	Active
Kintla	137.693	306.949	24.937	24365	West	Active
Lonely Lakes	135.772	315.67	26.339	35797	East	Active
Medicine Owl	214.677	263.833	15.424	39580	East	Active
Otokomi	164.022	169.38	29.902	22394	East	Active
Wahcheechee	53.947	117.082	21.799	3534	East	Active
Wahseeja	277.346	93.674	31.529	19431	East	Active

These data were collected for this table in 2016 using 1/3 arc-second DEMs from the USGS National Map Viewer. The quadrants used were titled Kalispell E and Cut Bank W (U.S. Geological Survey 2015).

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