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Regolith Erosion at Grinnell Glacier, Glacier National Park

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ABSTRACT

Glacier National Park is located within a mountainous region in western Montana. Due to recent glaciation, moraines are present at the upper elevations throughout the park. These young moraines erode at a rapid pace when first exposed by melting ice due to: age, vegetation cover, local climate, and human/animal activity. Using repeat photography in conjunction with lab work I was able to determine that the Grinnell Glacier moraine's crest is lowering at a much faster pace than previously published rates. Conservation policy within the park should be adjusted to reflect this information and additional research should be conducted to determine if the sediment being eroded is affecting other aspects of the park.

INTRODUCTION AND MOTIVATION

Most research regarding moraine degradation has been conducted on moraines with different characteristics and/or environmental factors to those seen in Glacier National Park. Studies have either focused on mature moraines that have already stabilized, seeing very little change per year (Miller et al, 2010) or moraines located within vastly different climates (Putkonen et al, 2007) making comparison impossible. While these studies give us valuable insight into Earth's paleoclimate, it is important to better understand how young, rapidly changing moraines affect both the environmental and anthropogenic aspects of our ecosystem. The sudden influx of sediment after a slope is first formed and as it stabilizes can directly affect other elements of the environment such as: water quality, water levels, wildlife, and vegetation (Wines, 2014). This can also affect human factors at lower elevations such as: sediment buildup and accumulation near manmade structures, trail/road obstructions, and the aesthetic value lost due to habitat change (Wines, 2014).

Wilderness areas such as Glacier National Park hold a unique status because it is one of the few areas where humans interact with the environment while still maintaining a natural ecosystem. The high volume of people that visit the park each year and the pristine, alpine wilderness for which it is known is the perfect location to study how moraine degradation affects the ecosystem and humans relying on the natural resources this area provides.

The moraine located near Grinnell Glacier is unique in the fact that it has an extensive documentation regarding its history from when it was first discovered to the modern day. Oftentimes it is difficult to measure the evolution of slopes because neither the age of the slope nor its original form is known to the observer. In addition, rates of degradation can vary greatly depending many different factors (Colman and Pierce, 1986). The age of the moraine and how newly exposed it is, local climate, and composition all affect erosion rates. Normally this information would be unavailable to scientists but because the Grinnell Glacier moraine is located within a National Park much research involving climate, photography, water quality analysis, etc. has been conducted and well documented.

This research focuses on the erosion of glacial moraines, specifically the erosion of loose regolith on a lateral moraine flanking what was formerly the northern edge of Grinnell Glacier in

Glacier National Park, Montana. The information gathered will lead to a better understanding regarding the rate and cause of erosion of these slopes as well as the effects this will have on the region within and around the park.

PREVIOUS RESEARCH

Glacial sediment is extremely susceptible to erosion because of the large amounts of regional precipitation, lack of vegetation, and because the newly exposed sediment is much more prone to erosion (Hallet and Putkonen 1994). This unconsolidated sediment is unsorted, originating from the mountainsides flanking the glacier and from the bedrock beneath the glacier. This sediment accumulates along the margins of the glacier in the form of various landforms.

Various studies have been conducted all over the world using both relative dating (pebble counts, moraine profiling, and repeat photography) and absolute dating methods (cosmogenic isotope) to determine the age of glacial landforms.

After being deposited by ice, most large boulders will stay at the surface while fine-grained sediments are removed by wind, water, and gravity exposing additional boulders to the surface (Hallet and Putkonen, 1994). With time, these exposed boulders will be weathered into fine-grained sediment and transported downslope (Sampson and Smith 2006), (Hallet and Putkonen 1994). This removal of sediment creates features with a gentler slope and a decrease in elevation, flattening and widening with time (Hallet and Putkonen, 1994; Sampson and Smith, 2006). Knowing this, scientists can estimate the ages of these features by mapping their profiles (Sampson and Smith, 2006).

LOCATION AND HISTORY

With an area of 4,101 km^2, Glacier National Park (Fig. 1) was established in 1910 within a large, mountainous region in Northwestern Montana (Krimmel et al, 2002). Located on the Eastern side and directly adjacent to the continental divide in an area of the park known as East Glacier, the field area is found within a cirque formed by the surrounding Mt. Grinnell and Mt. Gould.

The glaciers responsible for the park's spectacular glacial landforms disappeared over 10,000 years ago. This extensive glaciation created the cirques where most modern glaciers are present today (Carrara, 1989). The glaciers that still exist today grew substantially during a worldwide cooling event known as the Little Ice Age (LIA). These glaciers reached their maximum size near the end of the LIA around 1850 C.E. (Ross and Rezak, 1959) and are an important draw for the park's 2.2 million annual visitors (Thomas et al, 2013).

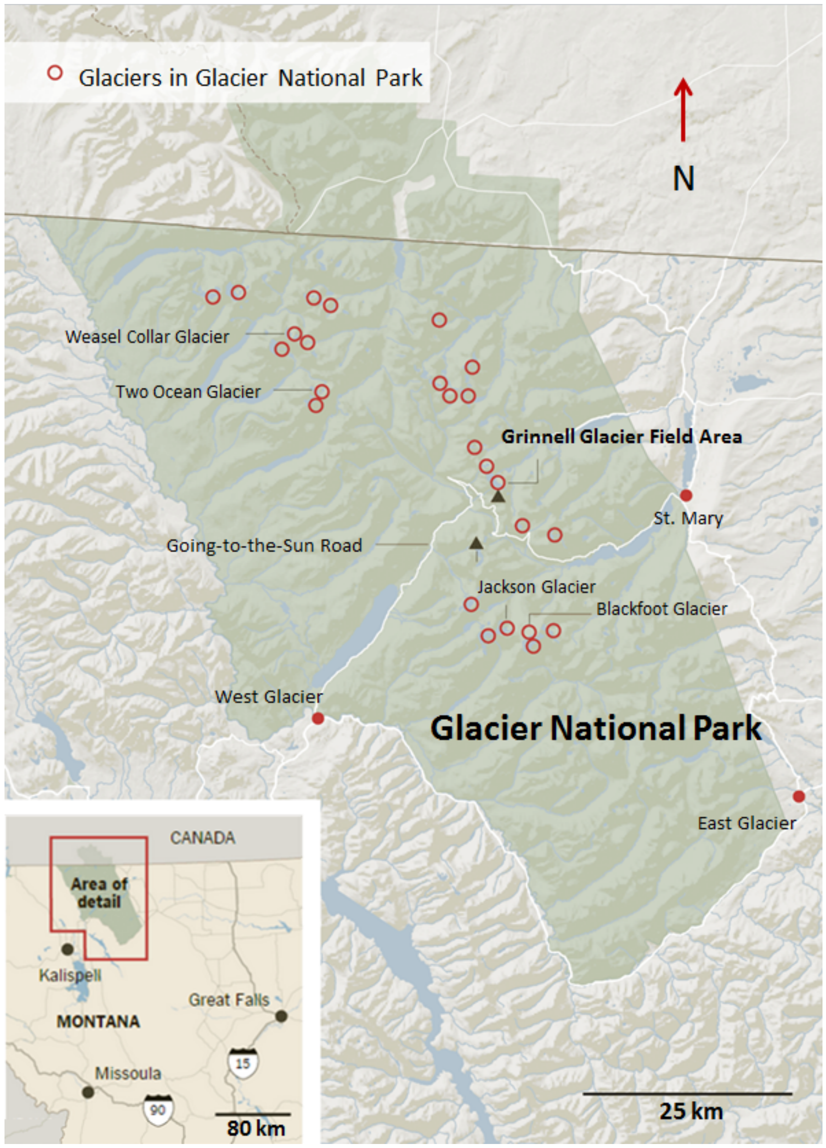


Figure 1. Map of Glacier National Park (Wines, 2014).

FIELD AREA

The area of interest (Fig 2.) is located within a cirque on Mt. Grinnell at an elevation of 1980 meters above sea level. This horseshoe shaped cirque is surrounded by near vertical cliffs and contains Upper Grinnell Lake and what remains of Grinnell Glacier. The field area is almost entirely composed of exposed bedrock. There is very little vegetation within the cirque. In the northwest portion of the cirque is a small ice covered bench roughly halfway up the cliff. Just beyond the bench is the bare ridge connecting Mt. Gould and Mt. Grinnell which makes up a portion of the famous "Garden Wall" as well as the Continental Divide. On the eastern portion of the cirque there is a prominent peak overlooking the valley below with a dramatic drop off on either side.

The northern portion of the study area is flanked by a lateral moraine with a measured height of roughly 60 meters and a length of over 500 meters (Fig. 3). The moraine is very steep with the inside slope being much steeper than the distal slope (Fig. 4). Deposited during the last glacial maximum, the moraine is composed of a light grey, fine-grained regolith with larger boulders of varying size dispersed over the entirety of the moraine. Because the moraine is partially composed of this fine-grained, pulverized limestone the deposited till has been dissolved by precipitation and weakly cemented making the moraine's surface very hard. Throughout the length of the moraine are small ravines, ranging from a few centimeters to a meter or more in width, leading from the crest to the bottom of the moraine. These ravines are the result of flowing water from the large amounts of precipitation this area experiences. Within the ravines are a higher percentage of rocks and boulders due to finer-grained sediment being washed away exposing the larger rocks.

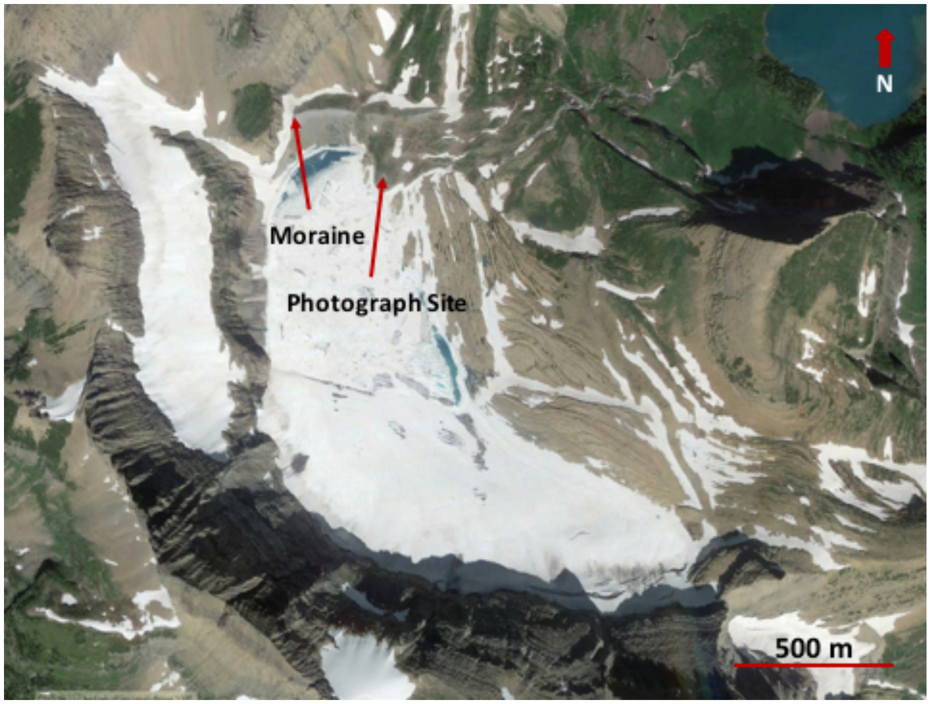


Figure 2. Grinnell Glacier Field area including (**A**) modern and historical photography site, and studied moraine (**B**).

Figure 3. Moraine of interest.

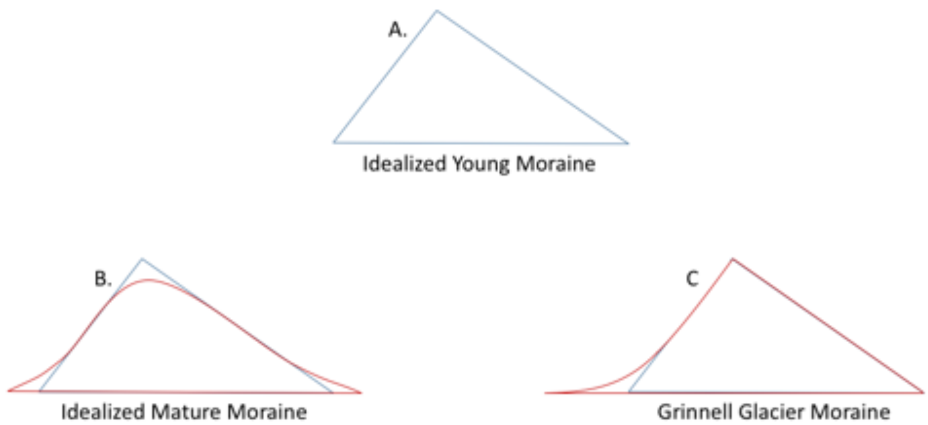


Figure 4. Idealized newly deposited moraine (A) compared with idealized mature moraine (B) and Grinnell Glacier moraine (C). All three moraines show proximal (left) and distal (right) slopes.

The proximal and distal slopes differ in appearance. The distal slope is less steep, has a more uniform slope, and has many more rocks covering its surface (Fig. 5) while the proximal slope is much steeper, has varying degrees of slope, has much larger and greater amounts of ravines, and has less boulders covering its surface (Fig. 6). The crest of the slope increases in elevation as you make your way towards the cliff wall. There are multiple areas along the crest where a depression is present (Fig. 3) creating a "saddle". The crest is very sharp with little to no rounding of the moraine's crest making walking along it's edge very difficult. Beyond the moraine is a talus slope which formed from the accumulated regolith from the cliff above. There are no noticeable paths leading from the main trail to the moraine and none leading up to the crest of the moraine. There did not seem to be any evidence of people or animals walking along the crest of the moraine. Both slopes were very steep, difficult to traverse, and devoid of vegetation making it unlikely that people or animals would attempt to climb them.

Figure 5. Moraine's distal slope.

Figure 6. Moraine's proximal slope.

CLIMATE

The climate of Glacier National Park varies considerably at different elevation. Extensive climate studies were conducted in 1956 and 1967 at various locations within the Park. Annual Precipitation near Babb, Montana, near the northeast entrance of the park is 51 centimeters, while precipitation in the field area surrounding Grinnell Glacier is estimated at 381 centimeters (Fig. 7). Mean annual temperatures for the Summit weather station (located on the southern edge of the park) vary between 0^{o} C – 3^{o} C. While the Summit weather station is located nearly 56 kilometers south of the Grinnell field area, and roughly 300 meters lower in elevation it still closely reflects the climate of the Grinnell Glacier field area (Johnson, 1980).

Period of Measurement	Elapsed Days	Precipitation (cm) Gage 1	Gage 2
Aug. 27, 1949 - July 20, 1950	327	317.75	0.00
July 21, 1950 - July 24, 1951	369	298.45	0.00
July 25, 195l - Ju1y 15, 1952	357	275.08	0.00
July 16, 1952 - July 31, 1953	381	271.53	0.00
Aug. 1, 1953 - Aug. 5, 1954	370	351.03	0.00
Aug. 6, 1954 - Aug. 10, 1955	370	277.37	0.00
Aug. 11, 1955 - Aug. 7, 1956	363	255.78	387.60
Aug. 8, 1956 - July 16, 1957	343	225.30	348.49
July 17, 1957 - July 17, 1958	366	200.41	294.13
July 18, 1958 - Aug. 4, 1959	383	283.46	468.88
Aug. 5, 1959 - July 21, 1960	352	273.56	423.16
July 22, 1960 - Aug. 8, 1961	383	249.68	334.77
Aug. 9, 1961 - Ju1y 26, 1962	352	221.23	308.36
July 27, 1962 -July 18, 1963	356	256.79	400.30
July 19, 1963 - July 30, 1964	378	242.57	366.78
July 31, 1964 - Aug. 12, 1965	378	259.08	416.56
Aug. 13, 1965 - Aug. 12, 1966	365	226.82	356.62
Aug. 13, 1966 - Aug. 10, 1967	363	264.16	374.40
Aug. 11, 1967 - July 25, 1968	350	222.76	404.11
July 26, 1968 - July 31, 1969	371	237.74	416.05

Figure 7. Precipitation and runoff in vicinity of Grinnell Glacier (1949-1969) (Johnson, 1980).

METHODS

Repeat photography is a well-established method to track the changes in an environment using a series of photographs taken from the same vantage point at different times. This method combines historical photographs and more modern ones (Fig. 8), comparing them by sight or with the use of computer programs such as Adobe Photoshop. While this method can be used in any location, many repeat photography studies have been conducted in close proximity to glaciers due to the more dramatic effects of recent climate change that these areas experience.

A.

B.

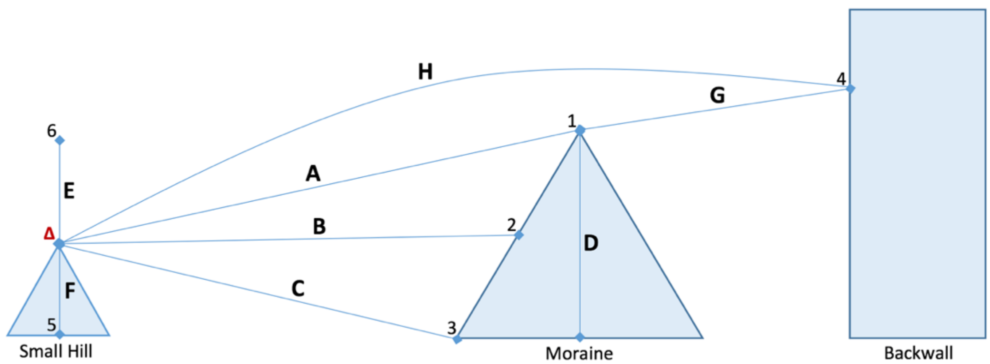
Figure 8. Historical photograph (A) and modern photograph (B).

The camera used is a Nikon S8200, 14-megapixel camera. Because C. Morrison did not make note of the height in which he took his pictures, it was important to take multiple pictures at various heights (0.35 m, 1.32 m, and 1.53 m) in order make as accurate a reproduction of the original photoset as possible. To compare the photographs, Adobe Photoshop was utilized which allowed comparison between modern photographs with their corresponding historical photograph. The Adobe software allows users to crop and position photographs to better match the historical photoset available online at high-resolution. In addition, Photoshop software allows users to overlay separate photographs using static landscape features to better compare the similarities or changes between the photographs.

The historical photographs used for the study of Grinnell Glacier were obtained from the National Snow and Ice Data Center (NSIDC). The original photographs were taken by Charles C. Morrison for the Glacier Photograph Collection in Boulder, Colorado in July of 1958. Each photograph was labeled by C. Morrison with an identifying number, a Δ symbol, and an arrow symbol. Each of these photographs corresponds with a Δ and a unique arrow on site that has been painted onto a prominent boulder to mark the location where the photoset was taken. In addition, the data attached with each photograph when downloaded from the NSIDC website included the GPS coordinates of the photoset.

On site elevation was measured using a GPS. Other measurements of the moraine were taken using a laser range finder. This device was used to measure the distance and angle of the target from the location where the measurements were taken (Fig. 9). Multiple measurements were taken for each site and averaged. Physical measurement of the moraine was impossible due to the steepness and long distances between the various measurement sites.

A.



B.

Measurement	Distance/Height (Meters)
A	344.33
B	294.67
C	218.33
D	63.07
E	47.53
F	17.53
G	46.87
H	404.6
E + F	65.07
A + G	391.2

Figure 9. Diagram (A) showing measurements (B) taken using a laser range finder.

The height of the modern day moraine was found using a GPS (2,028 m) and Laser Range Finder (2,031.53 m) along with online resources such as: Google Earth (2,033 m) and USGS topographic maps (2,026.92 m). Height of photo site (Δ) was found using GPS (1,984 m) and Google Earth (1,984 m).

The reasoning behind using multiple tripod heights is to best duplicate the original photograph taken in 1958. Any change in camera height will affect the angle at which the picture is taken. Because we do not know the height of the moraine when the original photograph was taken, we can use geometry (congruency of triangles law) to determine how differences in camera height can affect the perceived height of the moraine (Fig. 10).

A.

B.

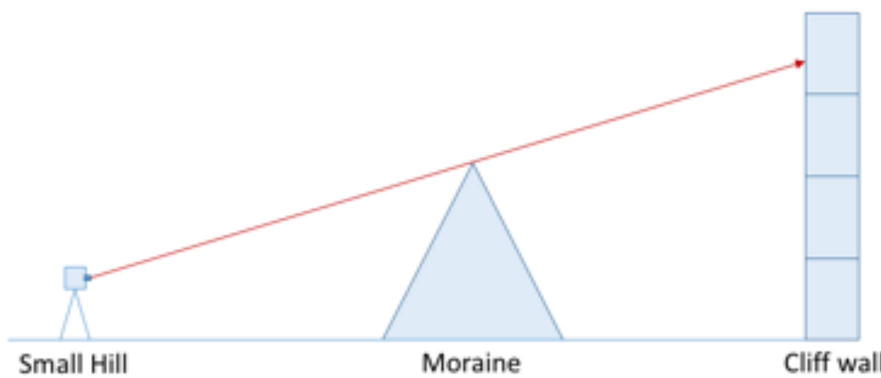


Figure 10. Diagram showing how varying camera height (**A**) and camera distance from subject in relation to the Cliff wall (**B**) can alter perceived moraine height.

RESULTS

Important differences were found when using computer software to compare modern day photographs with historical photographs (Fig. 11). Analysis of the photographs showed major differences between the two moraines. While still following the same channels, many ravines present in the older moraine are more incised in the modern moraine. There is much more vegetation along the proximal slope on the modern moraine. The position and number of large rocks on the moraine surface has changed, though some boulders are still present in both photographs.

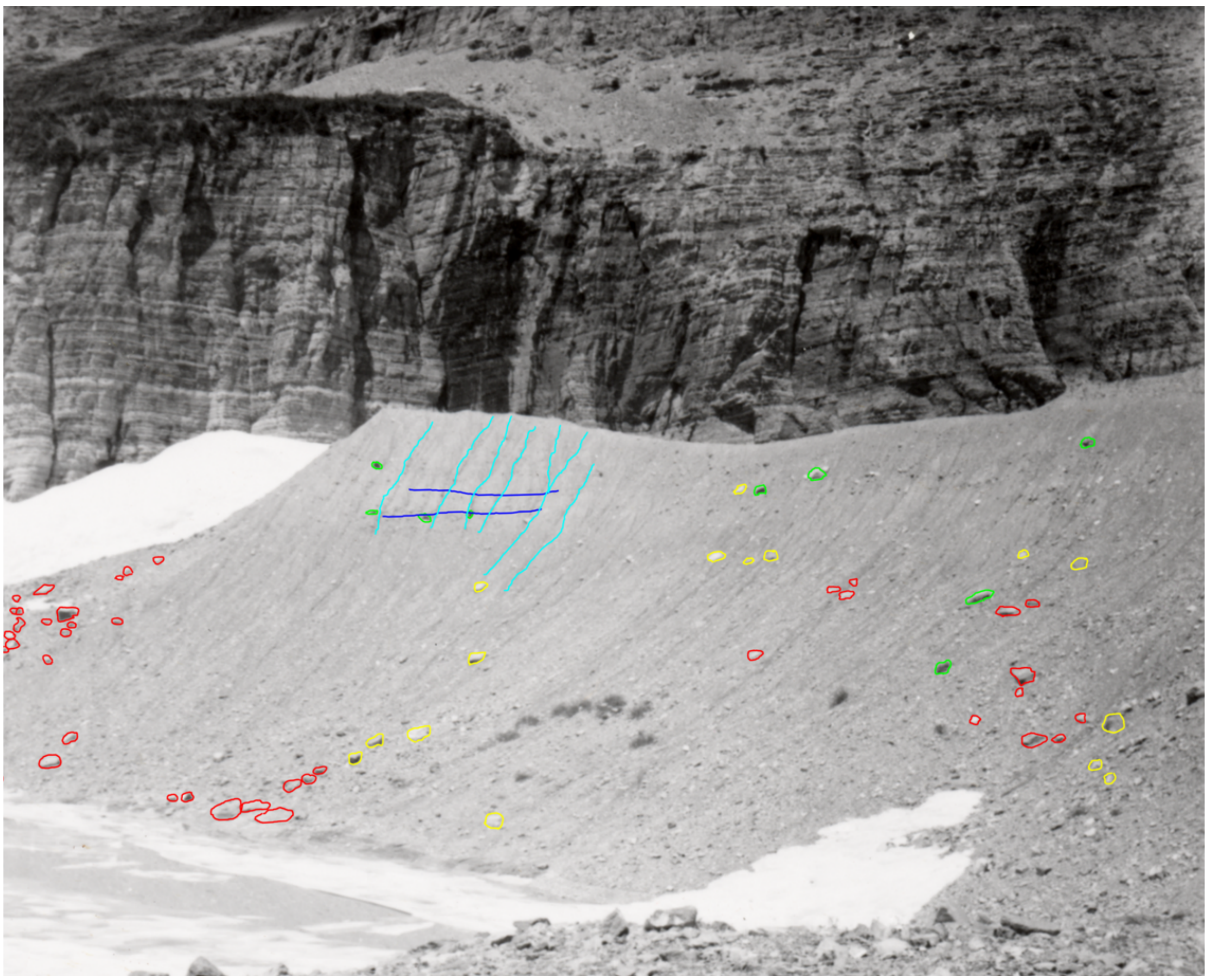


Figure 11. Overlay comparison between historical and modern photographs. Red represents boulders present in both historical and modern photographs, yellow represents possible boulder

similarities between photographs, green represents boulders present in historical but not modern, light blue represent ravine channels present in both, dark blue represents stratigraphy present in both photographs.

While the general shape and composition of the moraine has remained the same, by comparing the two photographs one can see that has been a dramatic change in crest height during the 56-year timespan between photographs. The current height of the moraine is 65.07 m. Utilizing the modern measurements and the stratified cliff wall as a tool for reference it is possible to estimate the height of the historical moraine to be roughly 67.57 m tall. Because the perceived elevation of the historical moraine is affected by camera height at the photography site it is necessary to see how the height at which the photo was taken affects the perceived height of the moraine in the historical photographs (Fig. 12). Geometry was used to calculate these numbers. It is necessary to compare specific values for both the modern and historical photographs to better understand how camera height affects perceived moraine height (Fig. 13).

When the values of the historical camera height at its highest and lowest points (0.35 and 1.85 meters above ground surface) is compared with modern camera height (1.35 meters) one can see that the perceived height of the moraine ranges from 1.82 - 2.97 meters in 56-year timespan. (0.033 - 0.053 meters/year). A plausible scenario is that each photograph was taken at 1.35 meters above ground surface. In this scenario the crest lowering is 2.50 meters.

Camera Height (Meters)	Amount Gained/Lost (Meters)	Perceived Moraine Height (Meters)
1.85	0.43	68.00
1.35	0	67.53
0.50	-0.72	66.85

Figure 12. Perceived moraine crest lowering depending on camera height. Camera height is meters above photo site (elevation 1,984 m). Height of moraine calculated from lakeshore elevation to crest.

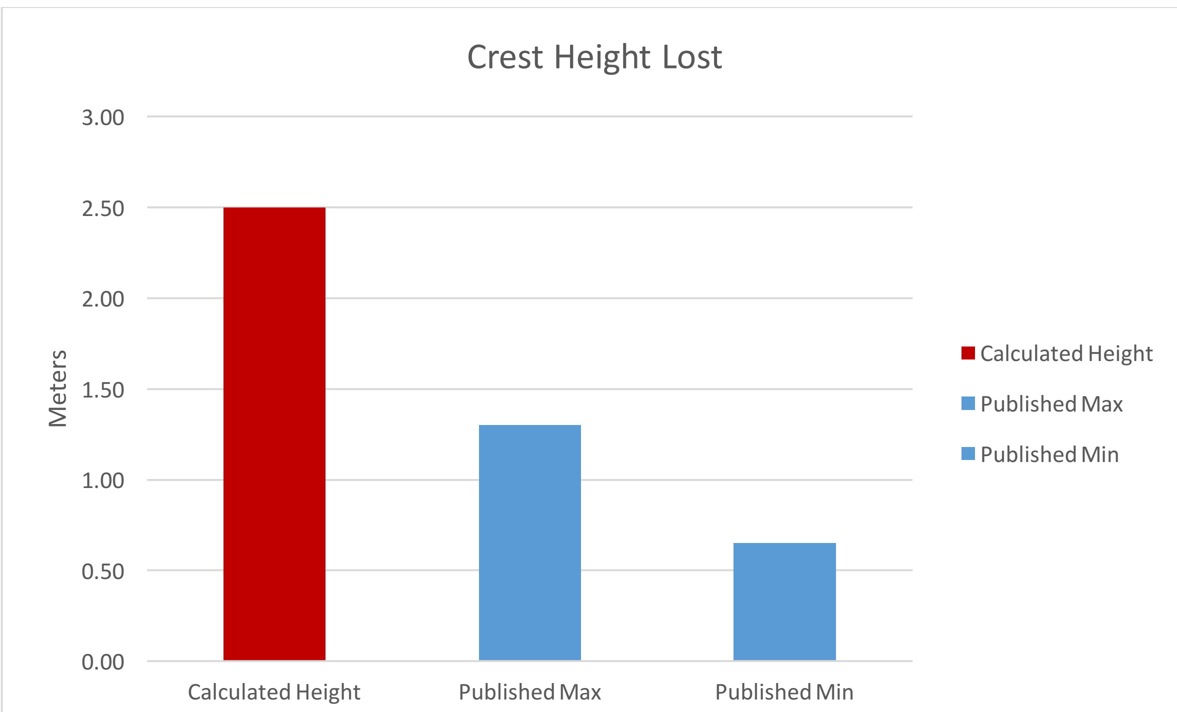


Figure 13. Comparison of modern moraine crest lowering rate with previously published maximum and minimum crest lowering rates (Published Max and Published Min respectively) at 1.35 camera height (Martin and Church, 1997).

DISCUSSION

The most likely explanation why the moraine is eroding at such a high rate is due to a combination of factors. The region's high precipitation rates, lack of vegetation, and young moraine age all contribute to the slope degradation. The differences observed in the proximal and distal slopes requires more explanation.

Over steepening of the proximal slope can explain the observed difference in rock cover between the two sides of the moraine. In this proposed scenario, the proximal slope is primarily controlled by mass movement events with no time for the fine-grained regolith to erode away and expose larger boulders. The opposite is true of the distal slope. The reason for the difference in primary degradation is unknown, though it is possible that the proximal slope was originally deposited at a steeper angle, creating a slope that is more prone to landslide and thus exhibiting features present today. Another contributing factor to the observed steepness of the slope is because the moraine is, in part, composed of limestone regolith and cemented together by the dissolved limestone. The remnants of these landslides are located on the lower portions of the slope or within Upper Grinnell Lake which explains the gentle slope near the lakeshore. Conversely, the distal slope is less steep and more uniform, without the obvious gentling of the slope at the base of the moraine. These landslides are also the reason for little to no rounding of the moraine crest.

The rate of erosion found at the Grinnell Glacier moraine is unsustainable. Eventually the slope will begin to stabilize with increased age and with that less annual crest height loss. It is very likely that current conservation policies within Glacier National Park are based on research conducted on more mature moraines. These mature moraines have already stabilized are thus much less vulnerable to premature degradation from factors such as human activity and increased precipitation from climate change. To prevent premature degradation and preserve these glacial landforms in their natural state for future generations revision of park policies may be necessary. These changes may limit access to some areas of the park, specifically areas susceptible to erosion, and would aim to protect not only the natural landscape but also wildlife that is affected as well.

CONCLUSIONS

Over the a 56-year period there has been a rapid decrease in moraine crest height for the lateral moraine north of Grinnell Glacier. Repeat photography was utilized along with field measurements, computer modeling and analysis to determine the causes and rate of crest lowering at this site. According the the calculations provided here (Fig. 12) the amount of crest lowering falls within the range of 1.82 - 2.97 meters in 56-year timespan (0.033 - 0.053 meters/year). This is an unprecedented rate of moraine height loss. This crest lowering was caused by a variety of factors including: the region's high precipitation rates, lack of vegetation, and the young age of the moraine. Possibly the largest contributing factor is the probable landslides occurring on the moraine's proximal slope.

This large influx of sediment into the environment can have dramatic effects on the region's ecosystem affecting not only the park, but also areas that depend on the glaciers that these moraines are associated with for water resources. Revised conservation efforts by the National Park Service may be necessary in order to best conserve this fragile ecosystem. There are over 150 sites within Glacier National Park that have newly exposed glacial landforms like those found in the Grinnell Glacier field area. More research can and should be conducted at these sites to better understand how the unprecedented rate of moraine erosion found at Grinnell Glacier (and likely at the other 150 sites) directly affect the various aspects of the region.

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