# ANALYSIS OF THE MECHANICS OF THE OURAY, CO LANDSLIDE

An Undergraduate Research Scholars Thesis

By

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# ABSTRACT

Analysis of the Mechanics of the Ouray, Co Landslide. (May 2013)

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Mountain areas are prime locations for mass movement activity, as a result of their steep slopes and large amount of local relief. As a rapid mass movement phenomena, landslides are responsible for a considerable numbers of deaths around the world each year. Thus, mitigation plans, such as the "Multi-Hazard Mitigation Plan" published by the County of Ouray, CO, have been developed to identify the spatial and temporal characteristic of potential hazards to minimize impact on humans and real property. The Ouray area has numerous landslides that have been mapped, and a large-sized landslide in this region of the San Juan Mountains is locally referred to as the Amphitheater Landslide. Although the area has been mapped as a landslide, the exact size, extent, and cause of the landslide have not been determined because the complex geological history of the region masks much of the landslide. Identification of the landslide extent and the cause are fundamental to establishing potential risks associated with this landslide. The town of Ouray, which is situated on the floor of a glaciated valley down slope from the scarp of the landslide is situated aside the toe of the landslide. The landslide was mapped using high-resolution, color aerial photography and geomorphic mapping. The landslide is 81,834,372 $ft^2$,

composed of San Juan tuff mixed with glacial debris and underlain by the Molas Formation (i.e., weak shale beds). Preliminary examination suggested that the exposed Molas shale experienced strain and saturation during the last interglacial period resulting in decreased shear strength. The valley slopes are draped with moraines, which were emplaced in contact with the glaciers, (i.e., ice-contact), which resulted in slopes that exceeded the angle of repose for the material. As the climate warmed and the glaciers melted, the support that was provided by the ice contact melted and the resulting slopes are today in disequilibrium and prone to failure. This study provides an assessment of the mechanics of movement of the Amphitheater landslide, which can be used to help minimize similar potential hazards.

# ACKNOWLEDGMENTS

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I would like to thank Anna Ahlstrom who suggested the research to me to be done as an undergraduate research scholar's thesis. To all the graduate students past and present, and professors, whose advice led to the completion of this research, thank you.

Furthermore, I would like to thank the Honors and Undergraduate Research Scholar's Thesis committee for allowing me to represent The University of Texas A&M.

Thanks to the county of Ouray, Colorado for allowing us to perform this research and for any further assistance on future work in the Ouray area.

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# CHAPTER I

# INTRODUCTION

Mountain areas are prime locations for mass movement activity as a result of their steep slopes and large amount of local relief. The town of Ouray, CO, which is situated on the floor of a glaciated valley (Ahlstrom and Giardino, 2011), is prone to mass movement. Moreover, numerous landslides have been mapped in the Ouray Quadrangle (Luedke and Burbank, 1962) and along the southeast side of the Ouray Valley is situated a large landslide, locally referred to as the Amphitheater. This feature is thought to be the result of mass movement of material down slope during the Pleistocene (Ahlstrom and Giardino, 2011). The large numbers of landslides that have been mapped in the area strengthen the fact that Ouray is a prime location for such movements. All these dynamic landforms are the result of oversteepend valley sidewalls that have been shaped by glacial erosion, as well as lateral moraines deposited by glaciers (Luedke and Burbank, 1962). Because the moraines were emplaced in contact with the glaciers, (i.e., ice-contact) these landforms have slopes that exceed the angle of repose for the material. As the glaciers melted, the support that was provided by the ice was removed and the resulting slopes are today in disequilibrium and prone to failure.

Oversteepended slopes can produce a high-hazard risk that can result in mass movement hazards. As a result of its location, Ouray has a high susceptibility to various types of hazards. In an attempt to protect its citizens from such risks, the county of Ouray published a “Multi-Hazard Mitigation Plan” (Ouray, 2008). This plan was published to make its citizens aware of the associated possible hazardous events in the area. Landslides are responsible for large numbers of death each year. According to Petley *et al.* (2005), the estimated annual fatality rate from landslides is 4,928 people per annum. Although the locations of these hazards have been mapped, explanation and understanding of the process of movement of these features is lacking. This awareness is especially important because a US Forest Service Campground is located on the amphitheater deposit. Furthermore, the toe of the landslide has numerous structure built on it.

A preliminary analysis of the Amphitheater landslide (Ahlstrom and Giardino, 2011), suggests that the landslide rests on the Molas Formation (i.e., weak shale beds) and is composed of San Juan tuff. The authors suggest that the landslide was probably the result of the Molas Shale becoming saturated and failing. The trigger mechanism for the failure is unknown. However, the authors hypothesized that the exposed Molas shale experienced strain and saturation, which resulted in decreased shear strength associated with the shale. This resulted in slip movement, resulting in a landslide event. Nevertheless, one can ask: What are the mechanics of movement for the Amphitheater landside?

The purpose of this proposed research is to analyze the mechanics of the Ouray Amphitheater landslide. Through this study, an explanation for the processes that formed this landslide will be established. Thus, my hypothesis and null hypothesis are:

$H_1$: Preslide conditions of the material exceeded the threshold of the movement.

$H_0$: Preslide conditions did not exceed the threshold of movement.

The goal of analyzing the mechanics of this landslide is to determine the relationship between stress-strain relationships in the landslide and to develop a preliminary model of the movement.

In addition, the information gained from this research also has a practical application. My secondary goal is to present information learned from this research to the County of Ouray, so that the hazards and potential hazards associated with this landslide may be understood better. This study is intended to lead to a proper assessment of the mechanics of movement and help minimize similar hazards.

# CHAPTER II

# BACKGROUND

## Slope Stability

A ‘Landslide’ is a term used to describe a wide variety processes that result in the movement of slope forming materials down and outward as driven by gravity (Schuster R. L., 1978 ). In an assessment into the principles of a landslide, investigations must be made into the following areas: landslide features(Figure 1), landslide dimensions, landslide activity (grouped as: State of Activity, Distribution of Activity, and Style of Activity) (Varnes, 1978), state of activity, distribution of activity, style of activity, rate of movement, water content, materials, types of movement, and landslide processes Understanding the morphological differences of landslide types is essential in understanding the Ouray, Co Amphitheater Landslide.

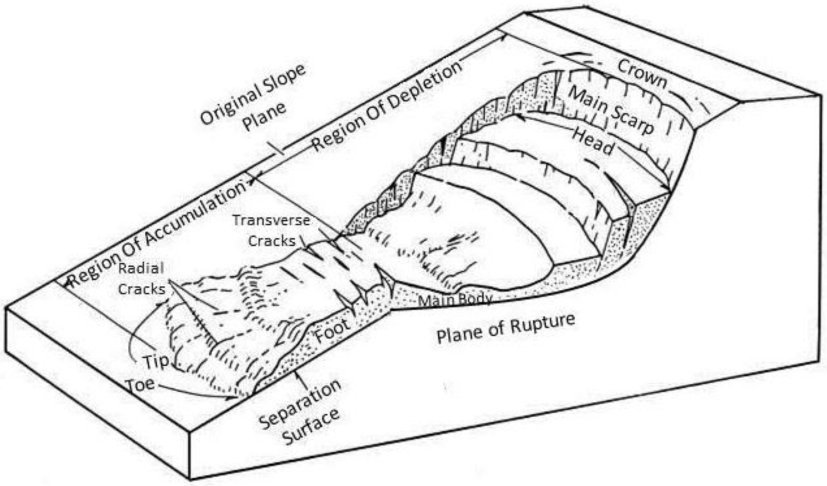


FIGURE 1. IDEALIZED LANDSLIDE DIAGRAM AND FEATURES (Modified from Varnes, 1978)

There are multiple systems used in the classification of landslides. Two classifications that satisfy the criteria needed for this research are by Sharpe in 1938 and Varnes in 1978. Varnes 1978 classification of landslides modified several previously existing classifications and is arranged by presenting the information based on the criteria of type of movement and the type of material involved (Table 1). Sharpe's 1938 classification incorporates the criteria of rate of movement and water content (Table 2). With regards to this research, there are three distinct types of kinematic movements associated with the Ouray landslide, which are falls, slides, and flows. Note that in Sharpe's classification, 'slip' corresponds to 'falls' and 'slides'.

### Falls

Falls in both rock and soils involve a mass of any size, that travels as a falling body from a cliff or a steep slope along a surface with little or no interaction with other solids, although bouncing and rolling may be part of the motion (Ritter, 2001). Rock fall conditions are favorable when slope failures result from: intense rainfall, steep hillside angle, debris in shallow hillside hollows or chutes, intersecting joints with orientations parallel to valley strike (Lee et al., 1997).

### Slides

A coherent mass separated by a zone of weakness, or on relatively thin zones of shear strain, undergoes slope movement over the underlying stable material (Clague and Stead, 2012). The movement is not simultaneous over the whole of what eventually becomes the surface of rupture; the volume of the displaced material enlarges down slope (Turner and Schuster, 1996). These may occur as translational slides, rotational slides, or a combination of the two.

| Type of Movement | Type of Material | | |
|---|---|---|---|
| | Bed Rock | Engineering Soils | |
| | | Coarse | Fine |
| Fall | Rock Fall | Debris Fall | Earth Fall |
| Topple | Rock Topple | Debris Topple | Earth Topple |
| Rotational Slide<br>Translational Slide | Rock Slide | Debris Slide | Earth Slide |
| Lateral Spread | Rock Spread | Debris Spread | Earth Spread |
| Flow | Rock Flow<br>(Deep Creep) | Debris Flow<br>(Shalow/Soil Creep) | Earth Flow |
| Complex | Combination of Movements | | |

TABLE 1. CLASSIFICATION OF MASS MOVEMENT TYPES IN DIFFERENT PARENT MATERIALS (Varnes, 1978)

| Movement | | | Material | | | | |
|---|---|---|---|---|---|---|---|
| Direction of movement | Type | Rate | Ice | Earth or Rock+Ice | Earth or Rock | Earth or Rock+Water | Water |
| Down and Outward Movement | Flow | Imperceptible | Glacial Transport | Rock Glacier, Soilfluction | Talus, Rock, and Soil Creep | Earth and Mud Flow, Soilfluction | Stream Flow |
| | | Perceptible, Slow to Rapid | | | | | |
| | Slip | Perceptible, Very Slow to Rapid | | Debris Avalanche | Slump, Debris Slide, Debris Fall<br>Rock Slide, Rock Fall | Debris Avalanche | |
| Primarily Vertical Movement | Subsidence | | | | | | |

TABLE 2. CLASSIFICATION OF MASS MOVEMENT BY RATE (Sharpe, 1938)

Rotational slides will penetrate to some depth along a curved concave upward surface where the rotation is about an axis that is parallel to the surface (Terzaghi, 1950). Vertical downward movement of the head of the displaced material may result, whereas the upper surface may tilt backwards towards the scarp (Turner and Schuster, 1996).

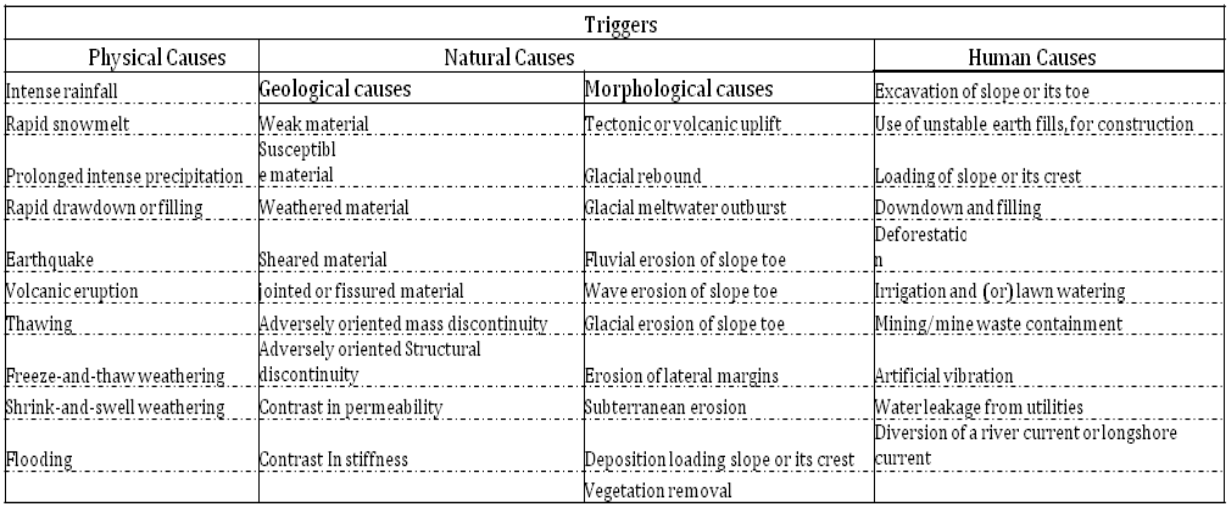
Translational slides are the predominantly occurring slide type. They occur when the material experiences increased shear stress and when the driving force equals and becomes greater than the resisting force, the coherent block will slide on a plane of weakness which typically parallels the slope of the ground (Varnes, 1978). Whereas the rotation of a rotational slide will eventually return the displaced mass to equilibrium, translation will continue on adequate slope.

## Flows

A flow is a spatially continuous movement in which materials within a displaced mass begin to resemble a viscous fluid when its velocity decreases and internally deforms as it moves down slope (Nilsen et al., 1979). Gradation from a slide to a flow is possible depending on water content, mobility, and evolution of the movement (Turner and Schuster, 1996).

## Causes of slope instability

Turner and Schuster 1996, groups the list of causes provided by Varnes (1978) into the three broad processes: increase in shear stresses, low strength of materials, and reduced shear strength. Below are landslide causes and triggering mechanisms based on Varnes (1978) distinction (Table 3).



| Triggers | | | |
|---|---|---|---|
| Physical Causes | Natural Causes | | Human Causes |
| Intense rainfall | **Geological causes** | **Morphological causes** | Excavation of slope or its toe |
| Rapid snowmelt | Weak material | Tectonic or volcanic uplift | Use of unstable earth fills, for construction |
| Prolonged intense precipitation | Susceptible material | Glacial rebound | Loading of slope or its crest |
| Rapid drawdown or filling | Weathered material | Glacial meltwater outburst | Downdown and filling |
| Earthquake | Sheared material | Fluvial erosion of slope toe | Deforestation |
| Volcanic eruption | jointed or fissured material | Wave erosion of slope toe | Irrigation and (or) lawn watering |
| Thawing | Adversely oriented mass discontinuity | Glacial erosion of slope toe | Mining/mine waste containment |
| Freeze-and-thaw weathering | Adversely oriented Structural discontinuity | Erosion of lateral margins | Artificial vibration |
| Shrink-and-swell weathering | Contrast in permeability | Subterranean erosion | Water leakage from utilities |
| Flooding | Contrast In stiffness | Deposition loading slope or its crest | Diversion of a river current or longshore current |
| | | Vegetation removal | |

TABLE 3. LANDSLIDE CAUSES AND TRIGGERING MECHANISMS (Highland and Bobrowsky, 2008)

# CHAPTER III

# METHODS

## Recognition and Identification

The first phase of this research is the recognition of the landslide itself from preliminary investigations done on the local landslide area. This includes regional terrain evaluation on susceptible landforms. Preliminary research suggests the existing problem had been completed only a year prior to the start of this project (Ahlstrom and Giardino, 2011). In addition, literature is compiled that present local geologic information about topography and general geologic structures and composition (Cross, Howe, and Irving, 1907; Larsen and Cross, 1956; Burbank, 1930, and 1940; Luedke and Burbank, 1962; Blair, 1996). This information comes from (a) topographic maps and geologic, pedologic, and engineering reports and maps, (b) collection of aerial photography or other remote-sensing systems, and (c) preliminary field reconnaissance (Rib and Liang, 1978).

Dr. Rick Giardino, my academic advisor, has identified this landslide as one in need of investigation and identification. From this, I began to follow the basic guidelines developed for landslide investigation and identification set by experienced professionals such as (Rib and Liang, 1978; Sowers and Royster, 1996).

Sowers and Royster define the field investigation portion of landslide analysis to have two essential purposes: (a) identify subjected sliding areas when planning future construction and (b) to define features of and environmental factors involved in an existing slide (Sowers and Royster, 1978). Important features to be considered for this investigation are: Topography, Geology, Groundwater, Weather, and History of slope changes. Two key factors necessary to understand, are the investigation area and the time span of the event.

The procedures used in this research follow five suggested stages of Sowers and Royster's planning process investigating (a) Site Topography, (b) Subsurface Exploration, (c) Surface Water and Ground Water, (d) Environmental Factors, and (e) A Correlation of Data.

### *Site Topography*

There are a wide range of techniques used to investigate landslides, but Clague and Stead divide them into two primary classes: remote sensing techniques, which examine the characteristics of the Earth's surfaces from a distance, and subsurface techniques, which examine the near-surface environment without excavation (Clague and Stead, 2012). Understanding the site topography (surface geometry) is the first clue to slope instability and the degree of landslide activity in the local area (Sowers and Royster, 1978). It is examined through the use of remote-sensing. . Remote-sensing for this research purposes include aerial photography and satellite imagery. Depicting morphological landslide features can provide useful information concerning the type of movement (Crozier, 1973).

The technique for analyzing and interpreting aerial photos is called pattern analysis (Rib and Liang, 1978). This technique is based on the principle that each landform exhibits distinct patterns in aerial photographs. Depending on geologic properties of formation and environmental constraints, similar landforms will exhibit the same patterns.

In most parts, the Ouray Amphitheater Landslide is covered by vegetation, but its large size and its gradational variability allows mapping and boundary construction of this landslide to be possible. The first maps generated were a 36 x 36 high resolution aerial photograph of the landslide, and a 36 x 36 topographic map overlaid over a aerial photo of identical scale 1 : 24000 (Figure 2).

FIGURE 2. AERIAL/TOPOGRAPHIC OVERLAY

Topographic maps show size, shape, and distribution of features on the surface of the earth (Rib and Liang, 1978). The new map was vital because it utilized the simplicity of a topographic map and the detail of an aerial photograph, all on one map. They list several advantages to using aerial photography in landslide investigations which are:

1. Photographs present an overall prospective of a large area (when examined with a stereoscope, overlapping aerial photographs provide a three-dimensional view);
2. Boundaries of existing slides can be easily delineated;
3. Surface and near-surface drainage channels can be traced;
4. Important relations in drainage, topography, and other natural and man-made elements that seldom are correlated properly on the ground become obvious on the photograph;

5. A moderate vegetative cover seldom blankets details to the photo interpreter as it does to the ground observer;
6. Soil and rock formations can be seen and evaluated in their undisturbed state;
7. Continuity or repetition of features is emphasized;
8. Routes for field investigations and programs for surface and subsurface exploration can efficiently be planned;
9. Recent photographs can be compared to old ones to examine the progressive development of slides;
10. Aerial photographs can be studied at any time, in any place, and by any person; and
11. Though the use of aerial photographs, information about slides can be transmitted to others with a minimum of ambiguous description.

The patterns used in aerial interpretation are Topographic Expression, Drainage and Erosion, Soil Tones, Vegetation, and Culture (Rib and Liang, 1978).

The features of topographic expression important in the analysis of the Ouray landslide are the topography, shape, and relative relief. Drainage and erosion patterns reflect the conditions of the underlying soil and rock (Rib and Liang, 1798). According to Sowers and Royster, 1978, a Distorted pattern, interrupted by haphazard deposits is characteristic of glaciated areas. Soil tones are important in aerial interpretation except for severe vegetative cover, when analyzing soil properties and moisture content. Dark tones represent high soil moisture content and light tones represent low moisture content. Vegetation patterns reflect soil moisture conditions and represented stresses. Culture examined from aerial photographs, represent humans influence and adjustment to local terrain.

### *Subsurface Exploration*

Aerial mapping gives a fundamental understanding of the processes associated with the landslide. And to create a model of the landslide history, geologic reconnaissance and statigraphic data of the study area, subsurface maps such as geologic maps, profiles, and cross sections is required. This is used to determine whether pre-slide conditions exceeded the threshold of the movement. The ‘Geologic map of the Ouray quadrangle, Colorado’ courtesy of Robert G. Luedke and Wilbur S. Burbank, combines aerial mapping with subsurface stratigraphy explaining there relationship graphically. This research focuses on the same relationship to identify the landslide threshold conditions.

## Study Area Description

At 7,800 ft, the town of Ouray, Colorado is nestled in a glacial-carved valley in the Western San Juan Mountains. Known for its scenic beauty and location, Ouray has adopted the nickname ‘The Switzerland of America.’ The southeast side of the Ouray valley, specifically confined within: (1.Lat: 38° 01' 59" N, Lon: 107° 37' 40" W) (2.Lat: 38° 01' 48" N, Lon: 107° 41' 14" W) (3.Lat: 37° 59' 41" N, Lon: 107° 40' 48" W) (4.Lat: 37° 59' 52" N, Lon: 107° 36' 57" W) sits a large landslide referred to as the Amphitheater (Figure 3). The maximum elevation of the scarp is at 12,338 ft and extends to the bottom of the toe at 7,707 ft. There are many landslides within the Ouray Quadrangle, mapped by Luedke and Burbank, 1962.

The western San Juan Mountains are composed of igneous, sedimentary, and metamorphic rocks. The mountains surrounding Ouray are caped with volcanic debris from a blowout just north of the amphitheater during the Tertiary age. They were carved out by glacial erosion during the Pleistocene age to give them the deep valley and obvious topography observed (Figure 4).

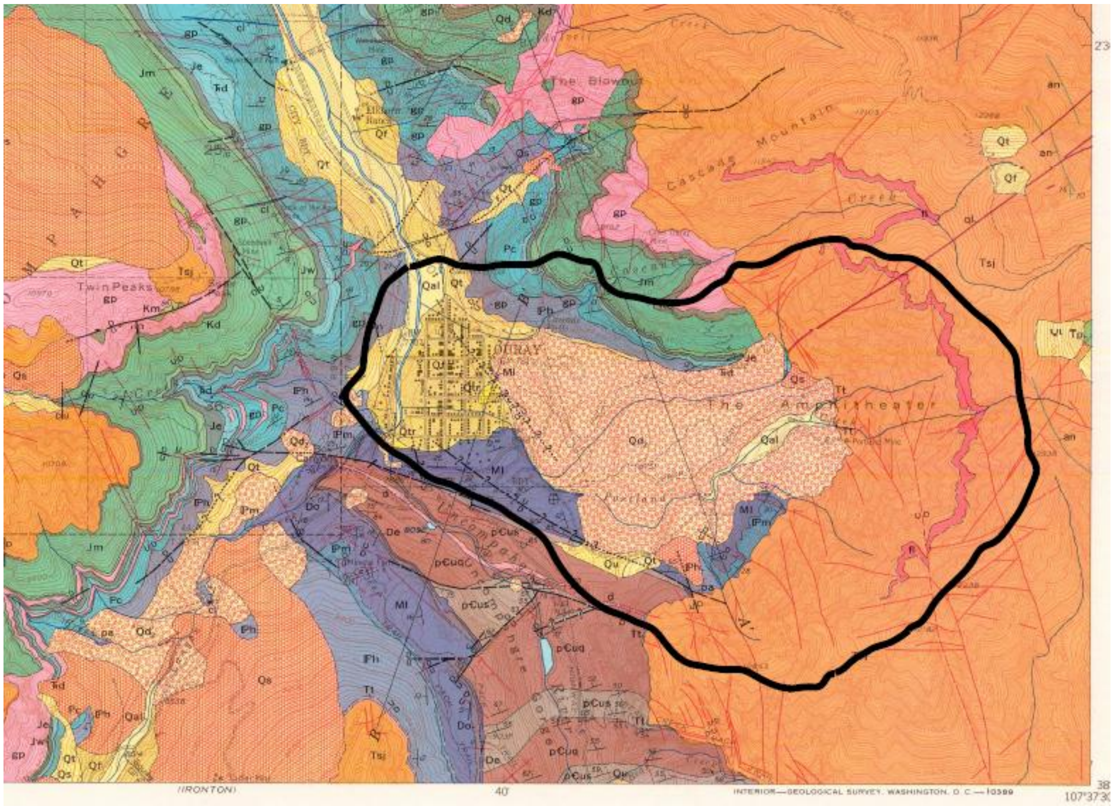


FIGURE 3. OURAY, CO AMPHITHEATER LANDSLIDE

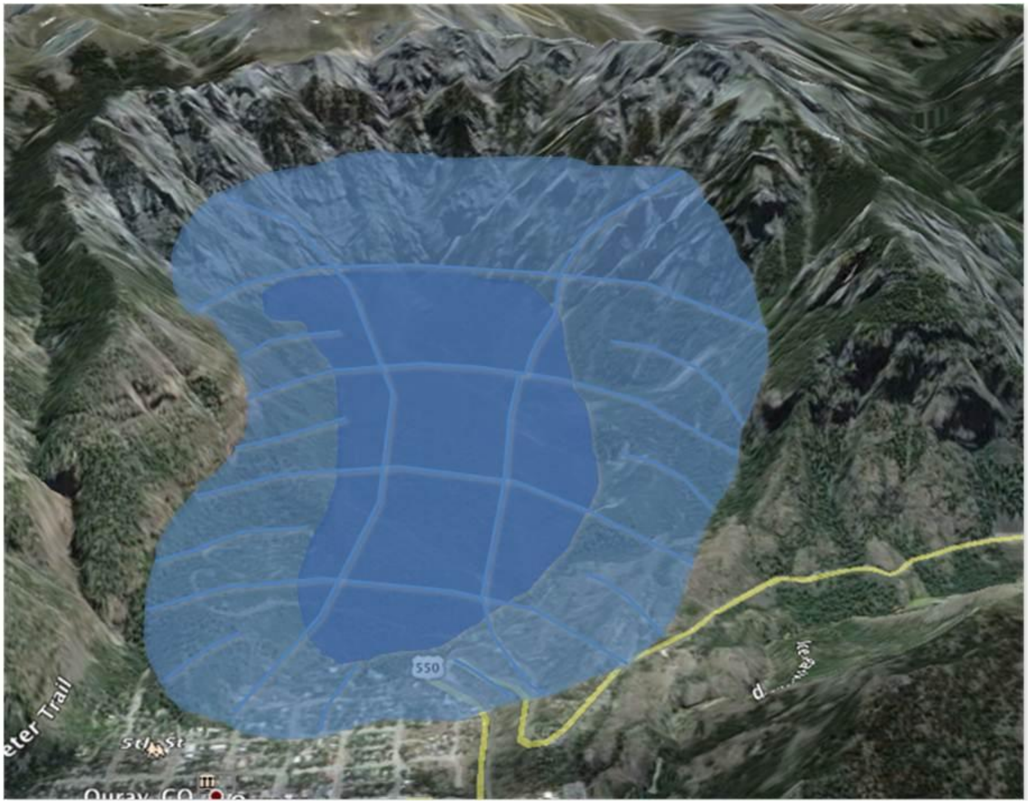


FIGURE 4. EXTENT OF AMPHITHEATER GLACIER

During periods of warming, the glaciers melted removing the ice contact support, and adjustment is now taking place.

The ‘bowl’ like Amphitheater was originally carved out by a glacial cirque during the Pleistocene. This was a result of a convergence of two glaciers, one trending north-west, and the other, trending north east (Figure 9). Surcharge of material was added to the original valley, increasing the length and height of the valley during glacial growth. The cirque or amphitheater shape is a result of the extra burdens applied to the valley where the convergence zone and accompanying rocks aided in the weathering and erosion of the valley. Ice segregation weathering and glacial abrasions from the accompanying rocks creates fractures in the rock face. These fractures which were created under high friction caused ice in the immediate vicinity to melt and fill the fracture. The pore water then freezes, expanding, by 9 percent, the fracture it is already in. With the movement of the glacier, that pore water moves too, ‘plucking’ the related rock from the wall face (Egholm *et al, 2012*). Glacial Deposits are landforms that commonly exhibit landslides (Schuster and Krizek, 1978).

Natural changes in the environment can create significant effects on slope stability. The geologic and environmental history can determine the conditions leading to the land movement and hint at potential instability (Schuster and Krizek, 1978). The ultimate dynamic factor influencing most landslides, conveyed by multiple components of weather, is Climate (Schuster and Krizek, 1978).

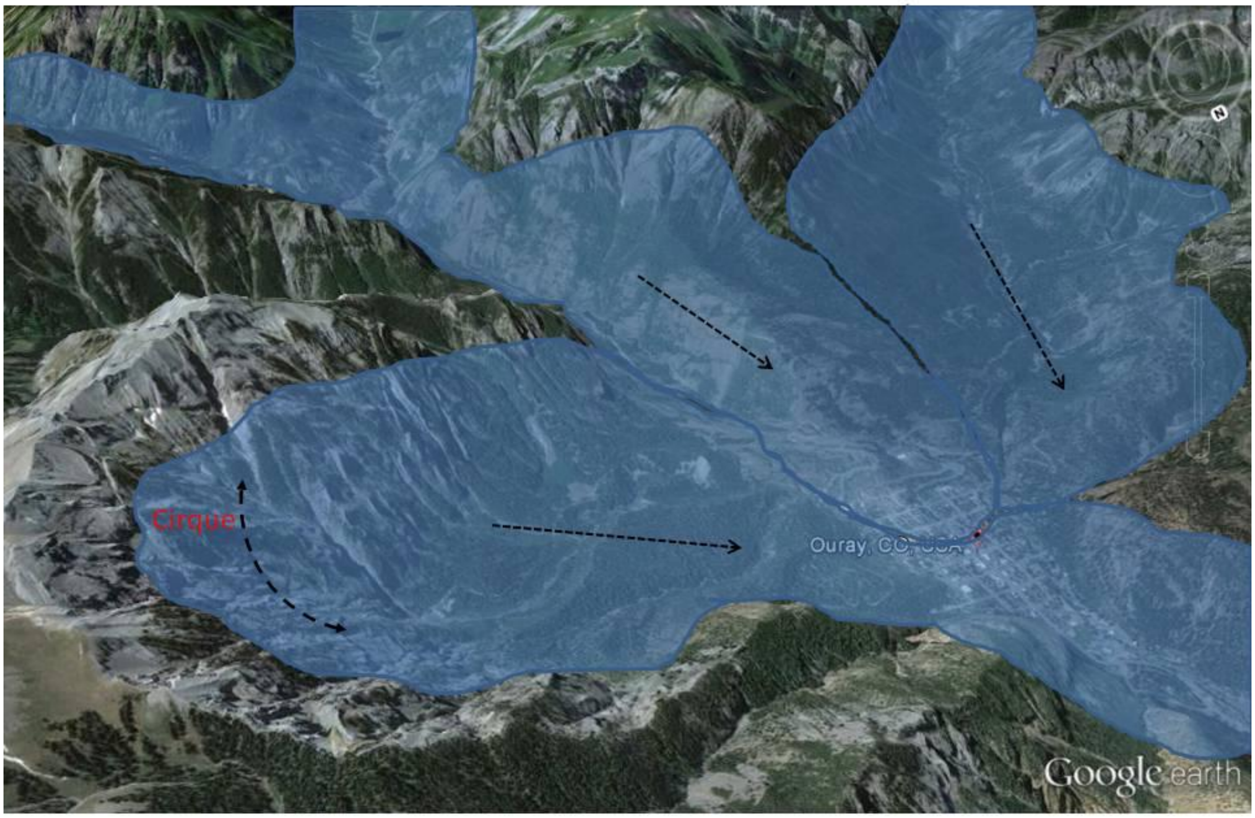
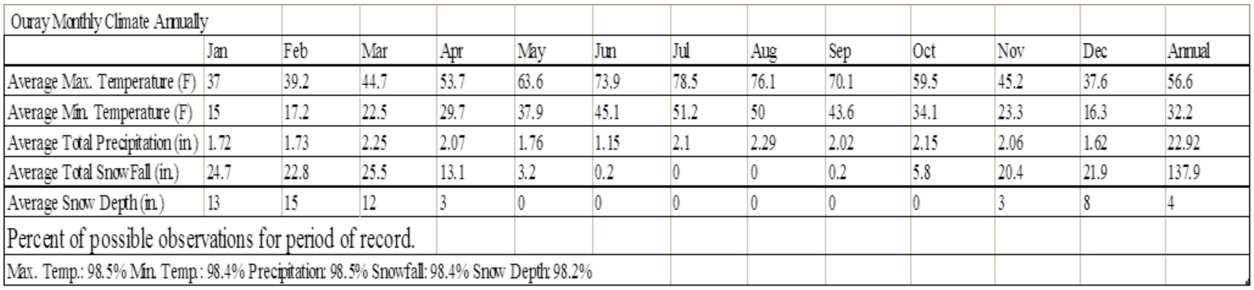


FIGURE 5. CONVERSION OF MULTIPLE GLACIAL LOBES

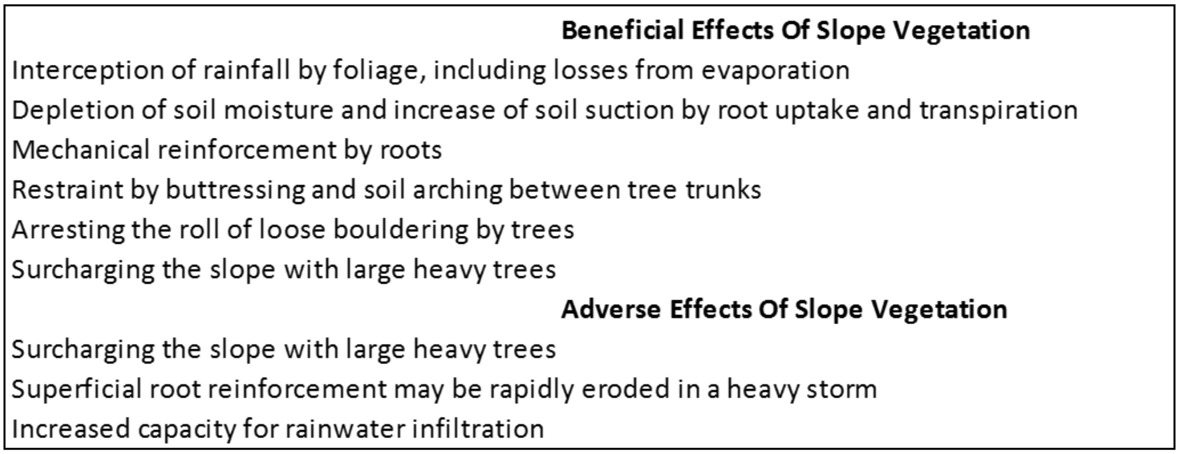
The climate in Ouray is semi-arid, temperature and precipitation ranges widely (Table 4), with values being slightly increased at greater elevations of the Amphitheater (Ouray, 2008). On average, there are 127 days annually that are frost-free. And because it endures freezing winters, periglaciation is possible.



| Ouray Monthly Climate Annually | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | Annual |
| Average Max. Temperature (F) | 37 | 39.2 | 44.7 | 53.7 | 63.6 | 73.9 | 78.5 | 76.1 | 70.1 | 59.5 | 45.2 | 37.6 | 56.6 |
| Average Min. Temperature (F) | 15 | 17.2 | 22.5 | 29.7 | 37.9 | 45.1 | 51.2 | 50 | 43.6 | 34.1 | 23.3 | 16.3 | 32.2 |
| Average Total Precipitation (in.) | 1.72 | 1.73 | 2.25 | 2.07 | 1.76 | 1.15 | 2.1 | 2.29 | 2.02 | 2.15 | 2.06 | 1.62 | 22.92 |
| Average Total SnowFall (in.) | 24.7 | 22.8 | 25.5 | 13.1 | 3.2 | 0.2 | 0 | 0 | 0.2 | 5.8 | 20.4 | 21.9 | 137.9 |
| Average Snow Depth (in.) | 13 | 15 | 12 | 3 | 0 | 0 | 0 | 0 | 0 | 0 | 3 | 8 | 4 |
| Percent of possible observations for period of record. | | | | | | | | | | | | | |
| Max. Temp.: 98.5% Min. Temp.: 98.4% Precipitation: 98.5% Snowfall: 98.4% Snow Depth: 98.2% | | | | | | | | | | | | | |

TABLE 4. OURAY MONTHLY CLIMATE SUMMARY (NOAA, 2013)

Vegetation on a slope can be enhance slope stability or may have an adverse effect due to the complex interaction of mechanical and hydrologic factors (Sharma, *et al.*, 1996). Although slope vegetation is typically a beneficial form of erosion control, the overall effects of slope vegetation are multiple and variable, as seen in figure 6. The vegetation in Ouray consists of piñon, juniper, sagebrush, oak brush, and ponderosa pine, with dense spruce/fir forests in the Alpine Zone (Ouray, 2008). Vegetation at the time of failure is thought to be minimal, if any, because of Glacial action.



**Beneficial Effects Of Slope Vegetation**

Interception of rainfall by foliage, including losses from evaporation
Depletion of soil moisture and increase of soil suction by root uptake and transpiration
Mechanical reinforcement by roots
Restraint by buttressing and soil arching between tree trunks
Arresting the roll of loose bouldering by trees
Surcharging the slope with large heavy trees

**Adverse Effects Of Slope Vegetation**

Surcharging the slope with large heavy trees
Superficial root reinforcement may be rapidly eroded in a heavy storm
Increased capacity for rainwater infiltration

FIGURE 6. EFFECTS OF SLOPE VEGETATION. (Boyce, G. M., 1996)

## Correlation of Data

As data is collected, organizing it into accumulations of material that easily depict three dimensional representations simplifies the data’s connectivity. Three efficient ways of doing so is by the creation of aerial variation maps, cross sections, time-based observations, and correlations.

# CHAPTER IV

# RESULTS

The landslide has an area of 81,834,372 $ft^2$ and is composed of San Juan tuff mixed with glacial deposits. It is underlain by the Molas Formation (i.e., weak shale beds), at an initial dip of $22^0$. From cross sectional analysis, the landslide is determined to have initially started as a rotational slide and proceeded as a planer slide following the thin shale bed of the Molas shale (Figure 7).

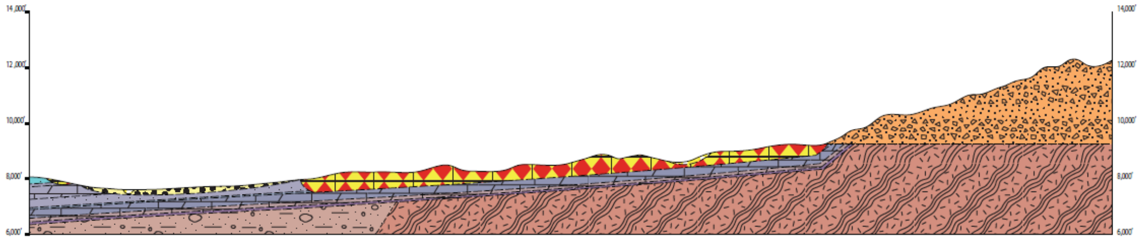


FIGURE 7. OURAY AMPHITHEATER LANDSLIDE CROSS SECTION

The slide is a result of an over steepening of the valley walls from glacial erosion during the last interglacial of the Pleistocene age. The amphitheater was created by a glacial cirque formation at the convergence point of multiple glacial lobes, giving it a steep bowl shape. The valley slopes are draped with moraines, which were emplaced in contact with the glaciers, (i.e., ice-contact), which resulted in slopes that exceeded the angle of repose for the material. The angle of repose is the maximum angle at which a mass can rest on an inclined plane without sliding down as a result of gravity. The thresh hold of movement for this slip, the average slope over which the slide moves, is reached when the angle of repose ($\alpha$) = $20.9^0$, and the coefficient of friction ($\mu$) = .3838.

Other geometric dimensions measured and calculated are a horizontal run out distance of 11,289 ft and a maximum run up/down of 1,594 ft. The landslide has a net vertical fall of 4,333 ft and a displacement scarp of 2,739 ft. The landslide had a total slip volume of 176,994,271.6 ft$^3$(figure 8), sliding at an average velocity of 319.39 ft/s.

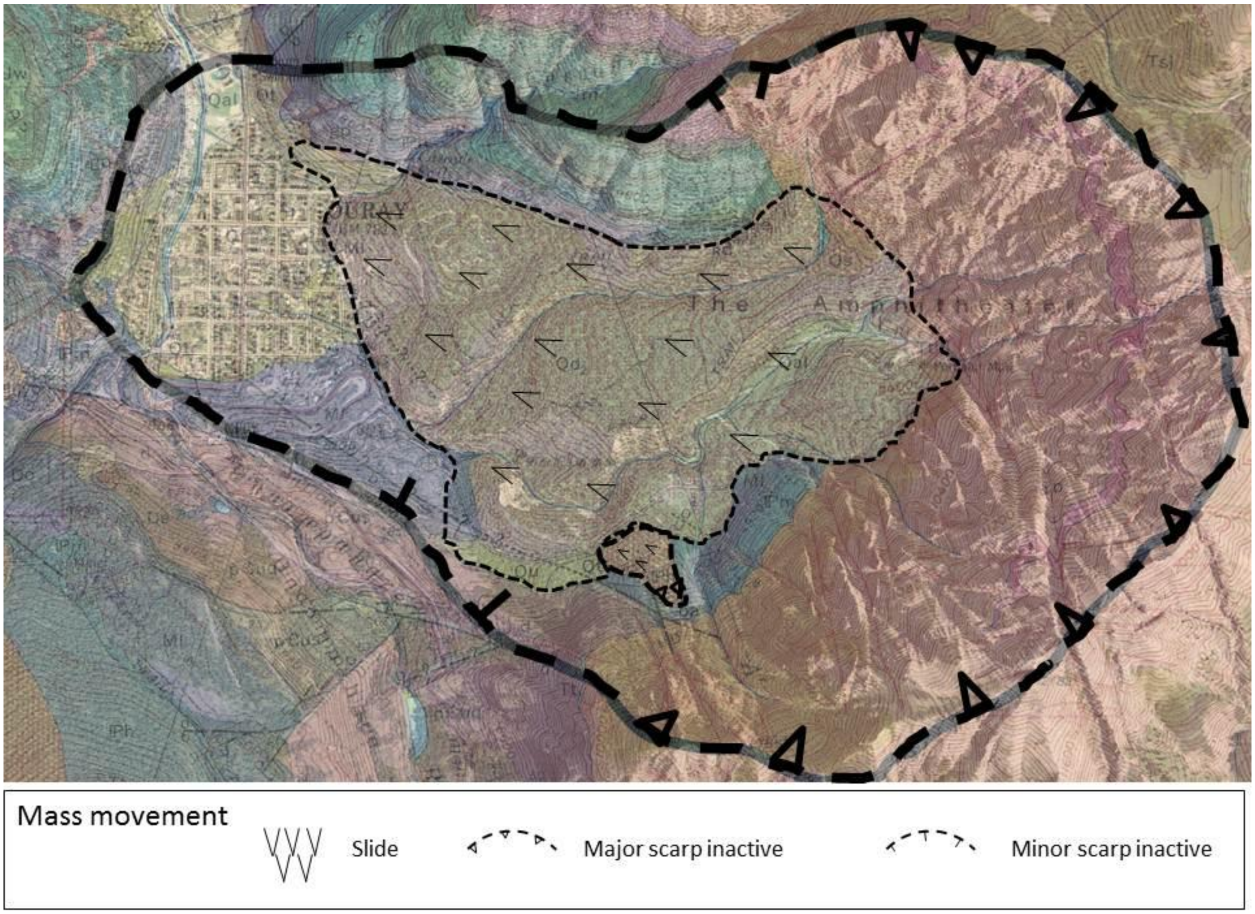


FIGURE 8. GEOLOGIC MASS MOVEMENT MAP

A description of the slope form of movement is explained by a combination of other added processes. As the climate warmed and the glaciers melted, the support that was provided by the ice contact melted and the resulting slopes are today in disequilibrium and prone to failure. Preslide conditions of the material include excess mass and a shale bed dip angle of $22^0$ that slightly exceeds the threshold of $\alpha = 20.9^0$. Preliminary examination suggested that the exposed Molas shale experienced strain and saturation during the last interglacial, which resulted in decreased shear strength associated with the shale.

Assessment of the mechanics of movement of the Amphitheater landslide is important to help minimize similar potential hazards. Thus this area is in need of risk and hazard evaluation.

# CHAPTER V

# DISCUSSIONS AND CONCLUSIONS

## Calculations

An analysis of the topography of the area using remote sensing techniques, created a model of the landslides structure in cross section. This allowed for the identification of the form of slope failure and its geometry (figure 9). The extent of the slide was established be measurements taken for maps. This includes measurement of the total vertical fall (H), the net vertical fall (h), and the horizontal distance of movement (X) which is the run out distance of the slide mass.

Using the Equation: $\mu = \frac{h}{X} = Tan\ \alpha$ , the average coefficient of friction (μ) and the angle of repose which is the threshold at the average slope over which the slide moves (α), are calculated. Also the maximum run up/down distance (r) is calculated by: $H - h = r$. Using the 'r' value, the average velocity (v) that the slide traveled was calculated by $v = \sqrt{(2gr)}$ where 'g' is the slides acceleration due to gravity.

The volume of the slide is a point on a graph by Scheidegger, 1973, which is a correlation of the calculated coefficient of friction (μ) to volume (V) from established large landslides.

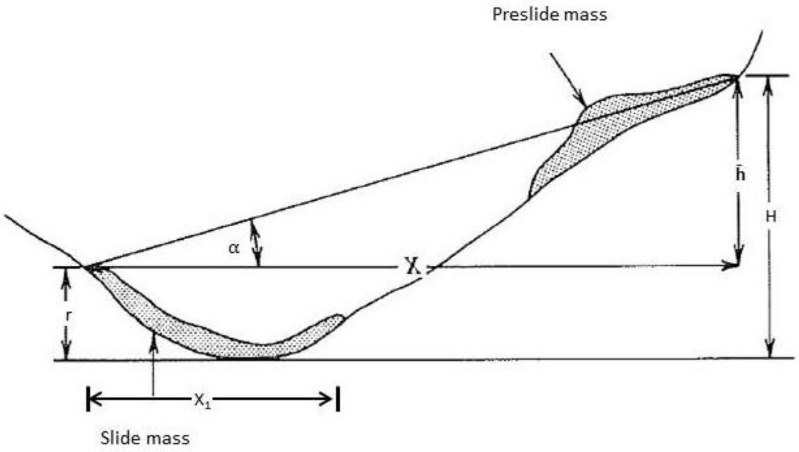
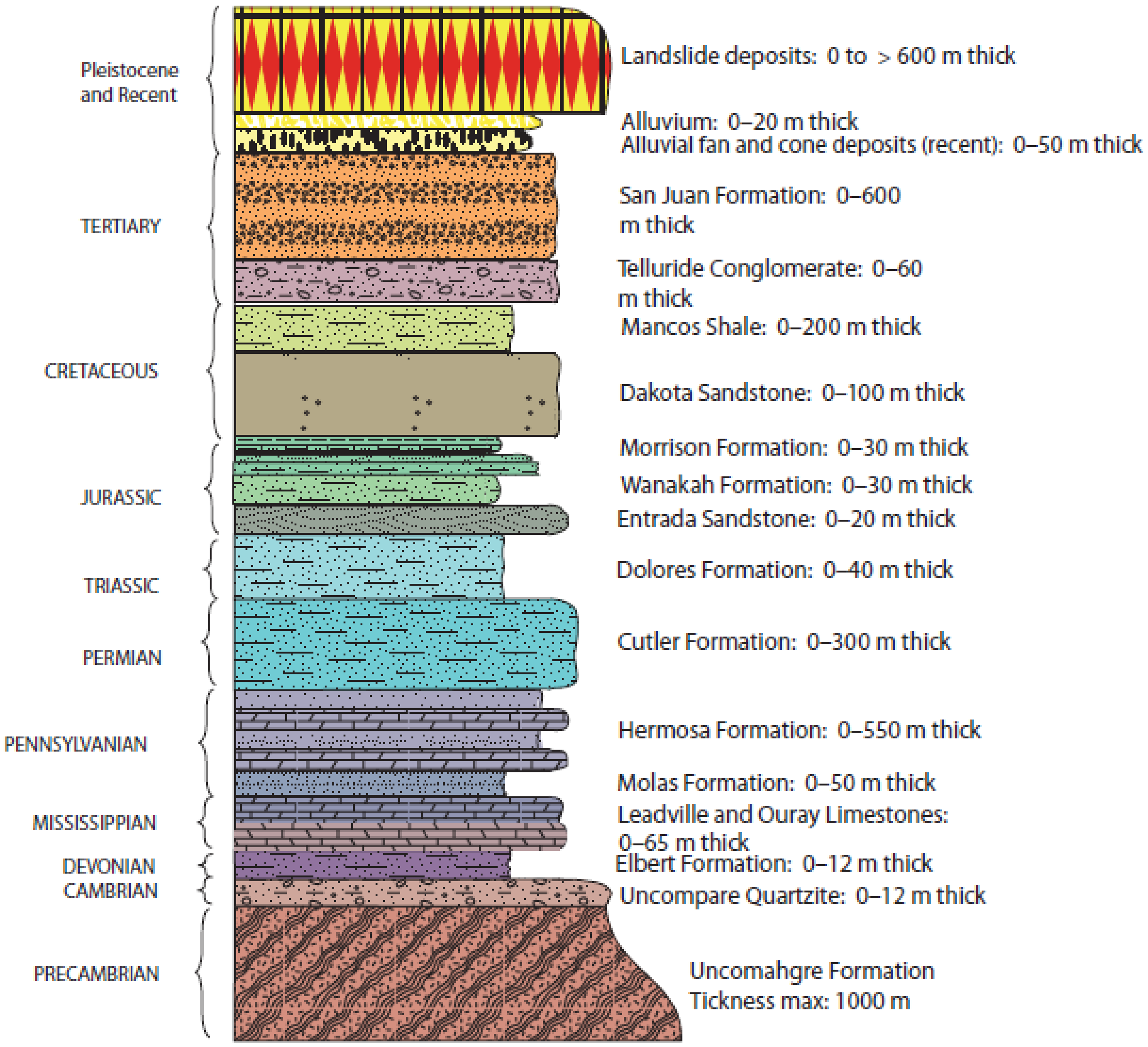


FIGURE 9. GEOMETRY OF LANDSLIDE. (Modified from Costa and Baker, 1981)

## Explanation

As viewed from cross section (Figure 7), the Leadville Limestone (Ml) of Mississippian age is the base rock, on top of which (landslide deposits, volcanic debris, etc.) accumulates. As seen from the stratigraphy in the Ouray quadrangle (figure 10), the Leadville Limestone (Ml) is proceeded by the Molas formation (Pm) of Pennsylvanian age at an erosional unconformity with an irregular surface (Luedke and Burbank, 1962).


Pleistocene and Recent
TERTIARY
CRETACEOUS
JURASSIC
TRIASSIC
PERMIAN
PENNSYLVANIAN
MISSISSIPPIAN
DEVONIAN
CAMBRIAN
PRECAMBRIAN
Landslide deposits: 0 to > 600 m thick
Alluvium: 0–20 m thick
Alluvial fan and cone deposits (recent): 0–50 m thick
San Juan Formation: 0–600 m thick
Telluride Conglomerate: 0–60 m thick
Mancos Shale: 0–200 m thick
Dakota Sandstone: 0–100 m thick
Morrison Formation: 0–30 m thick
Wanakah Formation: 0–30 m thick
Entrada Sandstone: 0–20 m thick
Dolores Formation: 0–40 m thick
Cutler Formation: 0–300 m thick
Hermosa Formation: 0–550 m thick
Molas Formation: 0–50 m thick
Leadville and Ouray Limestones: 0–65 m thick
Elbert Formation: 0–12 m thick
Uncompare Quartzite: 0–12 m thick
Uncomahgre Formation
Tickness max: 1000 m

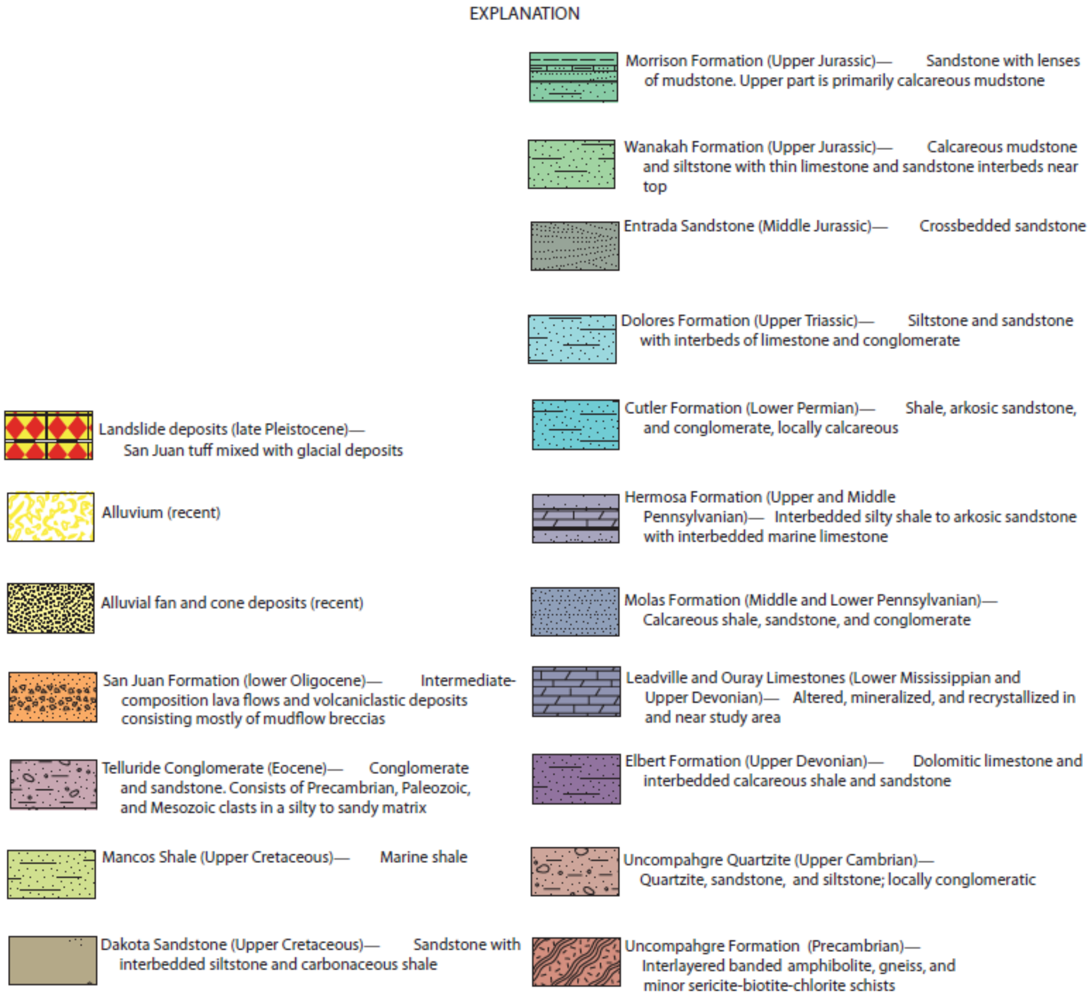


FIGURE 10. STRATIGRAPHY OF THE OURAY, COLORADO QUADRANGLE. (Yager and Bove, 2007)

The Molas formation (Pm), otherwise known as the Molas Shale, is composed of lenticular beds at varying thickness of calcareous shales and sandstones, and conglomerates of chert fragments and clay/sand matrix. Its thickness ranges from 40 to 60 feet due to its contact with an erosional base.

Piteau and Peckover suggest that when analyzing the lithology of rock masses and their physical properties, it is most important to understand the nature of the mineral assemblage and the strength of their bonds (Piteau and Peckover 1978, 194). Thus, for the Molas shale, it is important to understand the geologic processes that lead to the formation of degradable materials from sedimentary rocks. Terzaghi and Peck describe this process: “As the thickness of the overburden increases from a few tens of feet to several thousands, the porosity of a clay or silt deposit decreases; an increasing number of cohesive bonds develops between particles as a result of molecular interaction, but the mineralogical composition of the particles probably remains practically unaltered. Finally, at very great depth, all the particles are connected by virtually permanent, ridged bonds that impart to the material the properties of real rock. Yet, all the materials located between the zones of incipient and complete bonding are called shale. Therefore, the engineering properties of any shale with given mineralogical compositions may range between those of a soil and those of a real rock.” (Terzaghi and Peck 1967, 425 – 426) The understanding of this process is fundamental to analysis of the Ouray landslide because of the effects of its reverse process, unloading.

Walkinshaw and Santi propose a revere process of unloading. As the load decreased, the shale will expand horizontally under almost constant dimensions. The interpartical bonds of the shale begin to break and regularly spaced joints form. The spacing of the joints vary with depth and at 30 m, they are meters apart and closed. The differential movement between the blocks at shallower depth forms intermediate joints which open allowing moisture to infiltrate. The increase in moisture content will cause a decrease in shear strength, possibly creating new fissures (Walkinshaw and Santi, 1996).

As the glaciers melted, the support from the contact with the glaciers ( i.e., Ice contact) was removed. The thin shale bed of the Molas formation began to expand and fissure, being filled by the moisture of the melting glacier. Because the bed angle of 22° exceeded the angle of the movement of the threshold at 20.9°, the excess load was greater than the decreased shear strength of the thin Molas shale bed which result in the failure. From cross-sectional analysis, it appeared that the movement began as a rotational at the immediate boundary of the exposed Molas shale. But, proceeded down slope as a planar slide following the contact with the shale. As the mass slowed, the continued momentum of material began piling up in a up slope direction, increasing the thickness of the planar slide mass up slope. The slide mass resulted in an unstratified unit of debris and glacial deposits mixed with the San Juan Tuff.

## Mitigation

The Ouray, Colorado Amphitheater Landslide age is classified using modern remote sensing techniques, applied to McCalpin, 1984, age classification system (McCalpin, 1984) . The head scarp is vegetated and contains normal dendritic channels as seen from aerial photograph as containing medium dark soil tones, representing medium to high moisture content in un vegetated areas. The vegetation within the amphitheater is the same age, type and density as the surrounding terrain. The toe is overlapped by moraines indicating that glacial action occurred preslide and postslide. According to McCalpin's age classification system, the landslides is 'Inactive-Old' and absolute estimated age is about 10,000 years occurring during one of the later interglacial periods of the Pleistocene age.

The town of Ouray, Colorado is situated on the floor of a glaciated valley down slope from a massive Amphitheater Landslide. There are many landslides occurring in this area that pose a threat to the loss of life and property. Assessment of the mechanics of movement of the Amphitheater landslide is important to help minimize similar potential hazards. Thus this area is in need of risk and hazard evaluation. The purpose of this proposed research is to analyze the mechanics of the Ouray Amphitheater landslide. Through this study, an explanation for the processes that formed this landslide will be established. Thus, my hypothesis and null hypothesis are:

- H1: Preslide conditions of the material exceeded the threshold of the movement.
- H0: Preslide conditions did not exceed the threshold of movement.

The findings will be presented to the County of Ouray, so that the risks associated with this landslide may be better understood.

From the analysis, the landslide is determined to be a planar slide of 176,994,271.6 $ft^3$, composed of San Juan tuff mixed with glacial deposits. The slide has a horizontal run out distance of 11,289 ft on a threshold angle of $20.9^0$. The slide is a result of an over steepening of the valley walls from glacial erosion during the last interglacial of the Pleistocene age when the exposed Molas shale experienced strain and saturation resulting in decreased shear strength associated with the shale when the support of ice contact was removed. This analysis has led to the identification of similar areas in geologic situations that suggest that they are prone to future failure. Application of the methods used to investigate the Amphitheater landslide are applied to the other areas. The area that poses a threat to the loss of life and property, have been mapped out in the map of hazards (Figure 11).

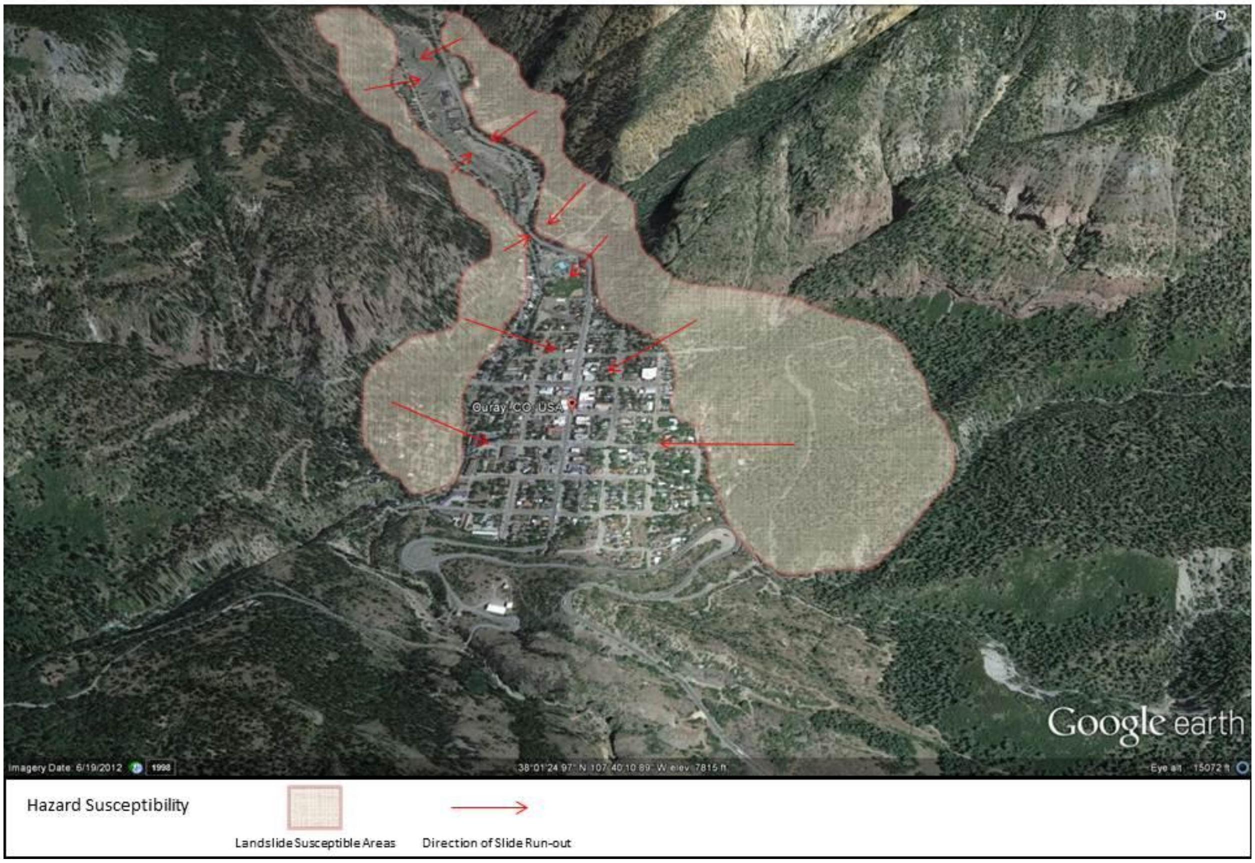


FIGURE 11. HAZARD SUSCEPTIBILITY MAP

# REFERENCES

2008, Ouray County Multi-Hazard Mitigation Plan: Colorado, county of Ouray and assistance from AMEC, Earth and Environmental, Denver, CO

Abramson, L. W., Lee, T. S., Sharma, S., and Boyce, G. M., 1996, *Slope stability and stabilization methods*, New York, New York : John Wiley & Sons; Second Edition.

Ahlstom, A.K., and Giardino, J. R., 2011, The Ouray Amphitheater Landslide: A preliminary Analysis., Presentation: Geological Society of America *Abstracts with Programs*, Vol. 43, No. 5, p. 445

Blair, R., 1996a, Western San Juan Mountains : Their Geology, Ecology, and Human History, University Press of Colorado.

Boyce, G. M., 1996, Slope stability and stabilization methods, New York, New York : John Wiley & Sons; Second Edition

Brunsden, D., 1984, *Slope instability*, Chichester [West Sussex] ; New York, Chichester West Sussex ; New York : Wiley.

Burbank, W.S., 1930, Revision of the geologic structures and stratigraphy in the Ouray district of Colorado, and its bearing on ore deposition. In Luedke, R. G., and Burbank, W. S., 1962, Geology of the Ouray Quadrangle, Colorado: United States geologic survey, government printing office.

Burbank, W.S., 1940, Structural control of ore deposition in the Uncompahgre district, Ouray County, Colorado, with suggestions for prospecting. In Luedke, R. G., and Burbank, W. S., 1962, Geology of the Ouray Quadrangle, Colorado: United States geologic survey, government printing office.

Clague, J. J., and Stead, D., 2012, *Landslides : Types, Mechanisms and Modeling,* Cambridge, GBR, Cambridge University Press, 436 p.:

Costa, J. E., and Baker, V. R., 1981, Surficial Geology: Building with the Earth, John Wiley & Sons; 1st edition (1981), p. 498.

Cross, Whitman, Howe, Ernest, and Irving, J.D., 1907, Description of the Ouray Quadrangle [Colorado]. In Luedke, R. G., and Burbank, W. S., 1962, Geology of the Ouray Quadrangle, Colorado: United States geologic survey, government printing office.

Crozier, M.J. 1973. *Techniques for the Morphometric Analysis of Landslips*. *Zeitschrift für Geomorphologie* N.F., Vol. 17, No. 1, pp.78-101.

Egholm, D. L., *Et al.*, 2012. *On the importance of higher order ice dynamics for glacial landscape evolution*, GEOMORPHOLOGY, v. 141, pp. 67 - 80

Giardino, J. R., 1971, A comparative analysis of slope characteristics for the Colorado plateau: Arizona State University.

Highland, L. M., and Bobrowsky, P., 2008, The landslide handbook – a guide to understanding landslides. UGSG Circular 1325, p. 64

Larsen, E.S., Jr., and Cross, Whitman, 1956, Geology and petrology of the San Juan region, south-western Colorado. In Luedke, R. G., and Burbank, W. S., 1962, Geology of the Ouray Quadrangle, Colorado: United States geologic survey, government printing office.

Lee, F. T., Odum, J. K., and Lee, J. D. 1997. Slope failures in northern Vermont, USA. *Enviornmental and Engineering Geoscience.* 3:161-82.

Luedke, R. G., and Burbank, W. S., 1962, Geology of the Ouray Quadrangle, Colorado: United States geologic survey, government printing office.

McCalpin, J. 1984. Preliminary age classification of landslides for inventory mapping.

NOAA's National Weather Service, 2013, Ouray Colorado. https://nwschat.weather.gov/p.php?pid=201302272011-KGJT-NOUS45-PNSGJT

Nilson. T. H. ; Wright, R. H. ; Vlassic, T. C. ; and Spangle, W. E., 1979, *Relative Slope Stability and Land-Use Planning in the San Francisco Bay Region California*, United States Geological Survey Professional Paper No. 944: United States Printing Office, Washington, D.C., 96 p.

Petley, D.N., Dunning, S.A., Rosser, N.J., 2005, The analysis of global landslide risk through the creation of a database of worldwide landslide fatalities: Landslide Risk Management, p. 367-374.

Piteau, D. R., and Peckover, F. L., 1978, *Landslides, analysis and control*, Transportation Research Board Special Report No. 176., Washington: National Academy of Sciences., p. 194

Rib, H.T., Liang, T. 1978. Recognition and Identification. In Landslide Analysis and Control, Schuster RL, Krizek RJ (eds). Washington Transportation Research Board Special Report 176. National Academy of Sciences: Washington DC; 34–80.

Ritter, D.F., Kochel, R.C., and Miller, J.R., 2001, Process Geomorphology: New York, McGraw-Hill Science/Engineering/Math; 4th ed., 2 p.

Scheidegger, A. E., 1973, On the prediction of the reach and velocity of catastrophic landslides: Rock Mechanis, v. 9, p. 231 - 236

Schuster, R. L., and Krizek, R. J., 1978, *Landslides, analysis and control*, Transportation Research Board Special Report No. 176., Washington: National Academy of Sciences.

Sharpe, C. F. S., 1960, *Landslides and related phenomena; a study of mass-movements of soil and rock*, Paterson N.J., Pageant Books

Terzaghi, K. 1950. Mechanism of landslides. In *Application of geology to engineering practice,* pp. 83-1123. Ed. By S. Paige. Geol. Soc. America Berkey Vol.

Terzaghi, K., and R. Peck. 1967. *Soil Mechanicas in Engineering Practice.* John Wiley & Sons, New York, pp. 425 – 426. In Turner, A. K., and Schuster, R. L., 1996, *Landslides: investigation and mitigation*, Transportation Research Board, Special Report 247, Washington, DC: National Academy Press.

Turner, A. K., and Schuster, R. L., 1996, *Landslides: investigation and mitigation*, Transportation Research Board, Special Report 247, Washington, DC: National Academy Press.

Varnes, D. J., 1978, Slope Movement Types and Processes. In Shuster, R. L. and Krizek, R. J. (editors), 1978, Landslides: Analysis and Control: Transportation Research Board Special Report No. 176, Washington, D. C.,

Walkinshaw, J. L., and Santi, P. M., 1996. *Landslides: investigation and mitigation,* Transportation Research Board, Special Report 247, Washington, DC: National Academy Press.

Yager, D. B., and Bove, D. J., 2007 , Geologic Framework., Chapter E1 *of* Integrated Investigations of Environmental Effects of Historical Mining in the Animas River Watershed, San Juan County, Colorado. USGS, Professional Paper 1651.