GEOLOGIC AND GEOMORPHOLOGIC INTERPRETATION OF THE PERIMETER TRAIL, OURAY, COLORADO: A VIRTUAL FIELD TRIP APPLICATION

A Thesis

by

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ABSTRACT

Each year many people seek respite from their busy lifestyles by traveling to state or national parks, and national forests. The majority of these parks were established to help preserve natural heritage, including wildlife, forests, and the beauty of landscapes formed from years of geologic and geomorphologic processes. Although the public has the opportunity to enjoy the peaceful tranquility of nature, tourists are deprived of a more in-depth educational experience because they either lack a geologic background and or no interpretation or guide to the geology and geomorphology of the area exists. One such location that attracts a large number of tourists is the Perimeter Trail in Ouray, Colorado. The Perimeter trail is a ~9.3 km (~5.8 mi) trail that circumnavigates Ouray. Located in Southwestern Colorado, Ouray is situated in the San Juan Mountain Range, which is accessed by the “Million Dollar Highway.”

Ouray is a popular destination for summertime tourism because of its unparalleled scenery and historical significance, but it is also situated in an area that contains numerous geologic and geomorphic features. These features range from a textbook angular unconformity, to glacial and periglacial landscapes, to mass movement and fluvial features, which have been sculpted from metasedimentary, sedimentary, and volcanic rocks. In the study area, The San Juans have been modified by an array of major faulting events; glacial, landslide and fluvial activities; as well as volcanic processes.

Hiking the Perimeter Trail is an exceptional experience, but could be enhanced with the development of an interactive application that provides the public with a virtual tour guide. For an application of this nature to be useful, a presentation of the geology and geomorphology of the Perimeter Trail must be generalized, well-illustrated, and tied to specific geographic locations. Unfortunately, no such application exists to provide this information.

Thus, the objective of this thesis is to investigate the geology and geomorphology of the Ouray area, specifically focusing on the Perimeter Trail. Additionally, a major contribution of this thesis is the development of a smartphone, tablet, and computer application, which provides location-specific descriptions of the geology and geomorphology encountered on the Perimeter Trail.

The application is based on an interactive base map, which can be zoomed to various scales. The app hosts a locational service that uses the respective onboard GPS of the device to fix the location of the hiker on the trail. As a hiker traverses the trail, the application contains geographically specific waypoints that have generalized descriptions accompanied with well-illustrated photographs to convey an understanding of the respective geologic and geomorphologic features. The goal of this thesis is the development of a simple, yet effective application that guides hikers along the trail and contributes to expanding the knowledge of individuals who hike the Perimeter Trail.

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CONTRIBUTORS AND FUNDING SOURCES

Contributors

Part 1, faculty committee recognition

This work was supervised by a thesis committee consisting of Dr. Rick Giardino (advisor) and Dr. Jack Vitek of the Department of Geology and Geophysics, and Dr. Kevin Gamache of the Department of Water Resource Management.

Part 2, student/collaborator contributions

All other work conducted for the thesis was completed by the student independently.

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1. INTRODUCTION AND PROBLEM STATEMENT

The San Juan Mountains, known as “The Switzerland of America,” are located in Southwestern Colorado with peaks ranging in elevation from ~3,600 to 4,200 m (~12,000 to 14,000 ft) (Burbank and Luedke, 1984) (Figure 1). During the early to mid-nineteenth century, several small towns were founded in response to the gold and silver rush in the San Juans (Burbank and Luedke, 1984). The San Juan cities of Silverton, Telluride, Lake City, Ridgway, and Ouray have since become desired destinations for thousands of tourists every year. Throughout the year, these small, historic towns are crowded with tourists who visit the San Juans to enjoy the beauty and tranquility of nature. The primary focus of this thesis is the Perimeter Trial of Ouray, Colorado, which is located ~112 kilometer (~70 mi) north of Durango, Colorado, along Highway 550 (Figure 2). This highway is locally referred to as the “Million Dollar Highway” because of the millions of dollars in gold and silver ore that were transported during the mining boom of the 19th century and the associated expense required to construct the existing road (Burbank and Luedke, 1984).

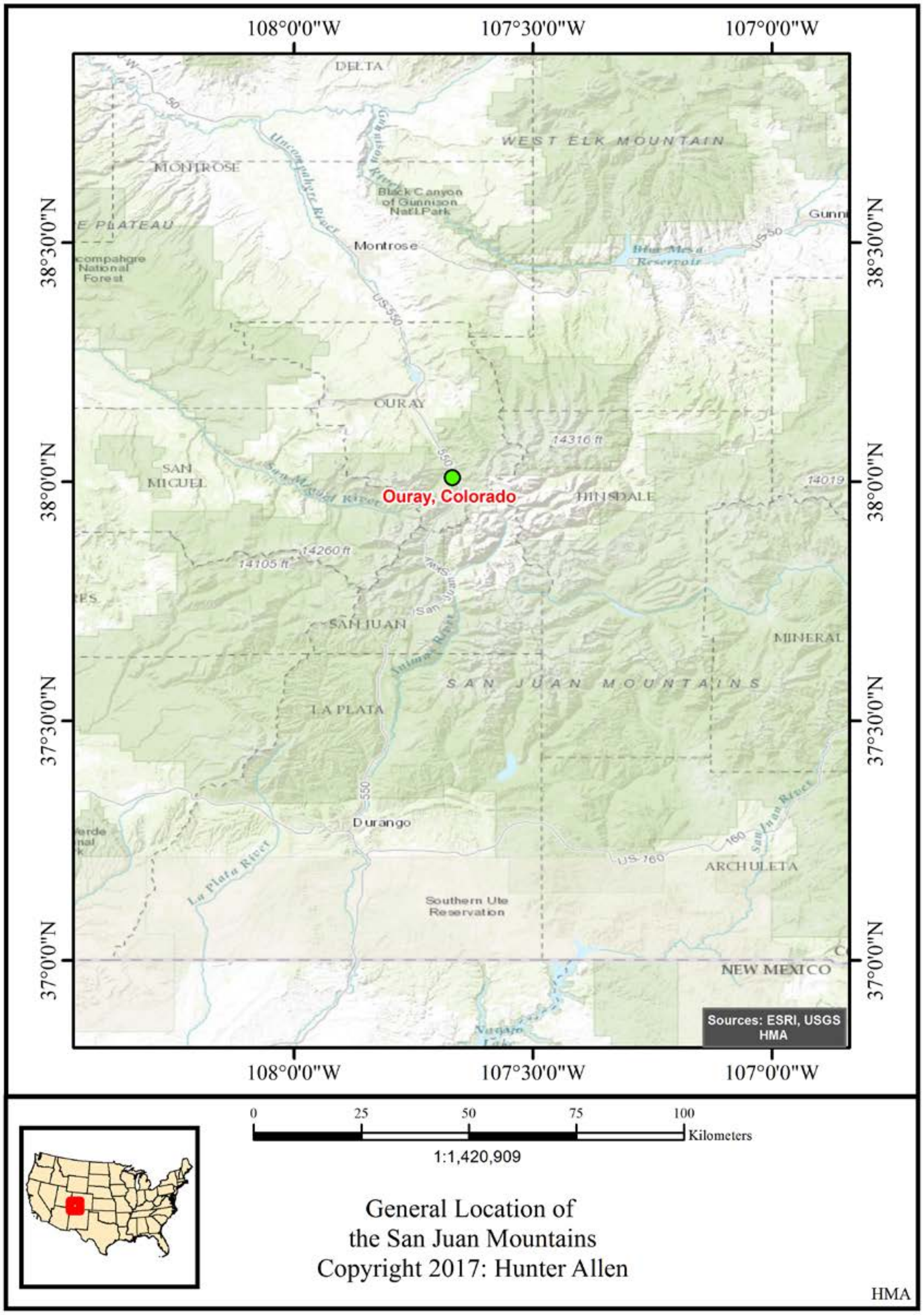

Figure 1: Map of the San Juan Mountains in Colorado and New Mexico.

Located within a glaciated valley and surrounded by high cliff walls, Ouray has picturesque views that one can only truly appreciate by experiencing in person. The city of Ouray, in partnership with the Colorado Forestry Service, and a local group of volunteers, has developed a ~9.3 km (~5.8 mi) hiking trail known as The Perimeter Trail. As seen in Figure 2, this hiking trail circumnavigates the town and provides residents and visitors the opportunity to take a moderately vigorous hike while experiencing an elevated perspective of the town and surrounding geology and geomorphology. Tourists hiking the trail have the opportunity to see and enjoy nature, but many lack the geological and geomorphological background necessary to appreciate the features encountered. The Perimeter Trail contains metamorphic, sedimentary, and volcanic rocks, as well as a textbook angular unconformity, exposed faults, anticlines, kink-folds, and various additional landforms (Moore, 2004). The Ouray Valley has been sculpted by a complex series of orogenic events, which include volcanic, glacial, periglacial, and mass movement, in addition to fluvial and sedimentary processes.

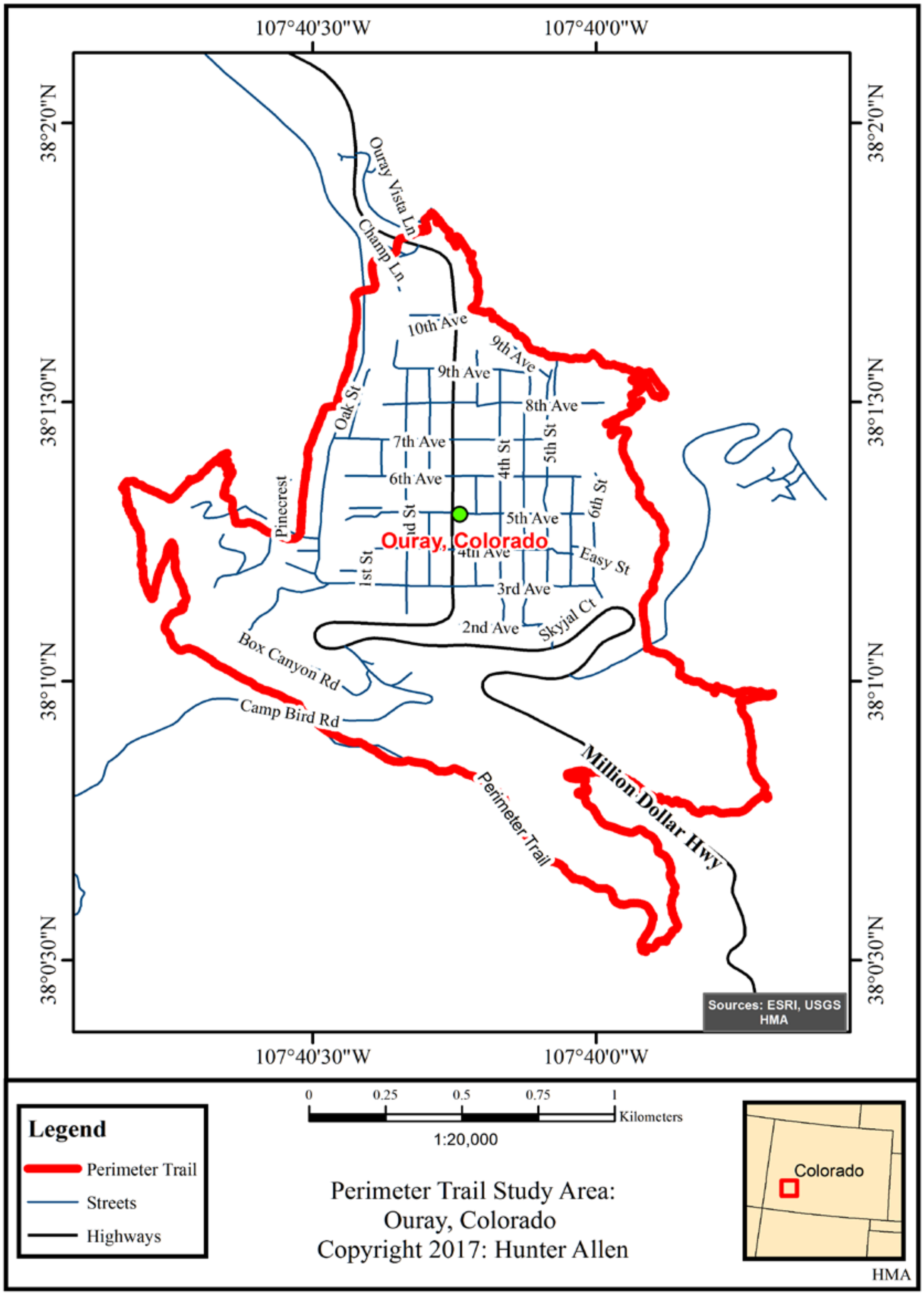

Figure 2: **Basemap displaying Perimeter Trail encompassing Ouray, Colorado.**

As of now, no means exist of learning about the geologic and geomorphologic features that shaped the landscapes encountered while hiking the Perimeter Trail, other than taking a personal, guided-tour. During my experiences mapping the geology and geomorphology of the Perimeter Trail, hikers would ask: “Where am I on the trail?”, “Do you know the nearest exit?”, “Why do the rocks look like that?” etc.

The goal of this thesis is to map and interpret the geology and geomorphology of the Perimeter Trail and develop a mobile application that may be accessed via smartphone, tablet, or computer. The mobile application will provide an interpretation and explanation of the geology and geomorphology of the Perimeter Trail. This application allows hikers to experience a virtual tour guide of the Perimeter Trail and may be accessed for gratis *via* the link in the appendix. Thus, this thesis will create, through an application, a more effective way of appreciating and understanding the surrounding landscapes as one traverses the Perimeter Trail.

Development of the application was accomplished by using mobile technologies incorporated with a Geographic Information System (GIS) and location-based services to provide geologic, geomorphologic, and supplemental information with respect to the user’s location on the Perimeter Trail.

2. LITERATURE REVIEW AND PREVIOUS WORKS

The development of tour guides has progressed through the last several decades. These guides range from paper brochures and audiowalks, to the more traditional, group-led tours, in which a tour guide leads groups along pre-defined routes. As technology has advanced, the use of mobile technologies has become commonplace in the development of tour guides.

In the late 1960s, modern technology made one of its earliest appearances in tour-guide development in the United States. Rosenberg (1985) reported that Larry Johnson was the first to develop cassette-recorded audio tours that were supplemented by small, colorfully illustrated booklets. The recorded cassette tape and illustrated booklet tour-guides were developed for national parks, museums, and cities to discuss the history, geology, scenic waypoints, and accommodations associated with the respective tour. During the early 21st century, audiowalk tour-guides, in the form of a compact disc (CD), were introduced (Bradley, 2012).

Bradley (2012) discussed the development of several public audiowalks and how they impacted the public. Bradley (2012) goes on to say that audiowalks provide users, “A series of sound files designed to be listened to at various points or sections along a pre-defined route.” (Bradley, 2012 p.100). Recorded and produced as a CD, these audiowalk tour-guides were designed to be played using a portable device. Audiowalks became an increasingly popular way to experience tour-guides with the introduction of the iPod® in 2001. (Bradley, 2012.) These audiowalk tour-guides further pushed the envelope for tour-guide development and allowed a more simplified way for users to learn at their own pace.

In 2007, the Apple iPhone® and other comparable smartphones were released to the public. The release of the smartphone has allowed developers to take the aforementioned tour-guide styles and convert them into a more modern, immersive, virtual, and user-friendly format. Virtual tour-guides provide multimedia elements in the form of annotated photographs, videos, audio narratives, and other supplemental information with respect to the user's specific geographic location. The advances in smartphone technology have allowed tour-guides to become more accessible and user-friendly to the general public, as well as useful to professionals in multiple disciplines.

As part of this thesis, I ventured to create a tour-guide application that utilized technology specific to the disciplines of geology and geography. A Geographic Information System (GIS) is, "A computer system for managing spatial data" (Bonham, 2014). In this case, the word *geographic* implies that there location attribute is associated with the data provided by the system. The data-location attribute refers to latitude, longitude, and elevation values that allow for the system to correctly identify the precise geographic location of the data (Bonham, 2014). *Information* refers to the idea that the culmination of the input data has the potential to produce informative information such as maps, graphs, tables, etc. (Bonham, 2014). *System* implies that a Geographic Information System is comprised of several interrelated and linked components that have various functions (Bonham, 2014). These defining principles of a Geographic

Information System are what allow users to capture, manipulate, transform, visualize, model, and develop their data in an effective manner.

A substantial learning experience can be developed by combining GIS with mobile technologies to create a virtual geologic experience. This integrated approach to education is the focus of numerous international organizations, government entities, and educational institutions (Adamuti-Trache and Sweet, 2014).

Using mobile learning as a way to better supplement education while in the field is an important concept that is highlighted by Jarvis et al., (2015). They demonstrated that implementing the use of mobile-learning devices combined with a GIS system can introduce students to a new way of learning. Students were exposed to a course module that was designed to assist in exploring the economic, cultural, and social geographies of life in Dublin, Ireland. In doing so, Jarvis et al., (2015) were able to provide an intellectually challenging approach to learning that assisted with the development of the students' observational abilities in context. Based on their research, I will use a similar framework as Jarvis et al., (2015) to create a mobile application that educates users on the geology and geomorphology of the Perimeter Trail *via* way of learning through participation. Sfard (1998) has shown that this type of learning through participation is an excellent educational approach.

In addition to the previous tour-guide styles, the use of mobile applications as tools for learning has become the focus for many disciplines. The New York State Geological Association Guidebooks are beginning to be converted into kml files that may be read by Google Earth® (Muller, 2013). As of November, 2012, there were 219 field trips from 28 different guidebooks that have been made available as a .kml or .kmz file. These .kml and .kmz files serve as great learning tools that can help educate the public. (Muller, 2013)

Stafford and Webb (2015) created a mobile field trip designed to provide background information and receive feedback from the participants. Stafford and Webb (2013) designed this application for a small group of students in Cheltenham England. One of the goals was to investigate the effectiveness of mobile applications in the field of education. Their results concluded that using mobile applications are indeed an effective way to create several more potential learning opportunities (Stafford and Webb, 2013).

An additional example of how applications are being used as a means of education is in Graz, Austria. Pirker et al., (2014) developed a game-based scavenger hunt for children that enabled them to learn facts about the city. The developers of the scavenger hunt application state that the use of mobile applications are becoming more accessible and common in households. From 2011 to 2013, the percentage of mobile devices increased from 52% to 75% (Pirker et al., 2014). The accessibility of these mobile devices and the systems being developed for location-based applications has opened the door for a pedagogical contribution.

In a study by Welsh et al., (2015), mobile devices were examined by researchers to determine their effectiveness as learning devices. Specifically, Welsh et al., (2015) implemented the use of mobile devices in six field trips. The key findings suggest that the portability and multi-function capabilities of the mobile device were the major strengths (Welsh et al., 2015). A concern of using these mobile devices in the field was how inclement weather could potentially negatively impact the equipment. This was negated by the use of a simple protective case (Welsh et al., 2015).

The people of the 21st century have witnessed some of the greatest and most well-known technological advances in existence. Our mobile smartphone devices contain more computing capabilities than the computers used for the Apollo space missions (Puiu, 2016). Figure 3 was developed by the PewResearch center in 2002 and shows the percentage of United States adults who own mobile phones. The latest published statistic estimates that 95% of Americans own a mobile device of some kind ("Mobile Fact Sheet," 2017). Of that 95%, approximately 77% of Americans have a smartphone. The United States Census Bureau states that ~ 325 million people live in the U.S, as of February 7th, 2107. This equates to approximately 250 million smartphones circulating the United States, and this number continues to grow. As the general public gains greater accessibility to more advanced technology, an increased desire will occur for applications such as mine, which help enrich real-world experiences with technology-based learning.

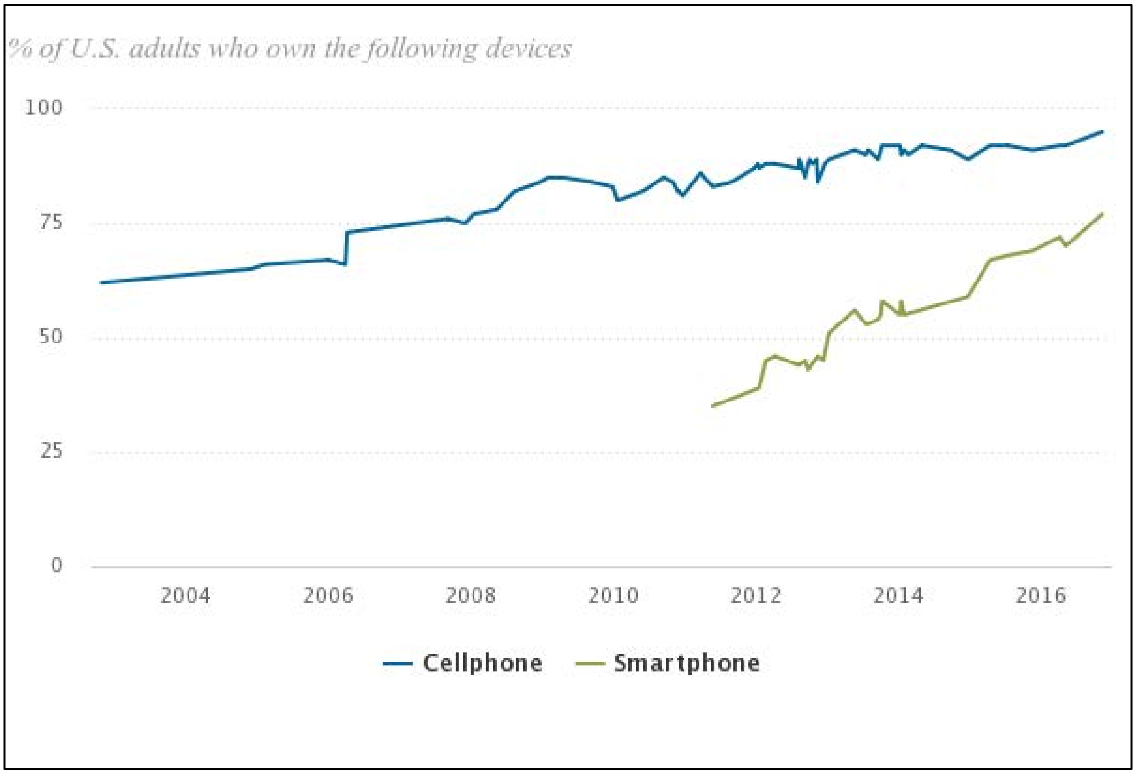

Figure 3: Mobile phone ownership over time ("Mobile Fact Sheet," 2017).

3. STUDY AREA DESCRIPTION

The San Juan Mountains have an extensive geological and geomorphological history. Research on the San Juan Mountains can be traced back to the early 1900s (e.g. Atwood and Mathers, 1932, Howe, 1903, Burbank et al., 1962). Atwood and Mathers (1910-1924), mapped the basic geomorphology and geology from Ouray to Durango. Luedke and Burbank (1962) mapped the geology of the Ouray 7 ½ minute quadrangle, which provided the foundation for the majority of research that has been produced since.

The geologic history of the San Juan Mountains is complicated. The formation of this mountain range is attributed to a combination of deposition in seaways, deltas, and rivers. Mountain building events, such as folding and faulting, as well as volcanic activity including lava flows, ash falls, and igneous intrusions have occurred. Lastly, the area has been exposed to erosive processes, including glaciation, mass movement, and fluvial (Moore, 2005). The San Juan Mountain Range covers ~16,093 km^2 (~10,000 mi^2) and extends roughly 144 km^2 (90 mi) in the East and West directions and ~112 km^2 (~70 mi^2) in the North and South directions (Mather, 1957). The center of my study area is located at 107°40'17.53" longitude and 38° 1'18.08" latitude in Ouray, Colorado. Ouray is located within the USGS 7- 1/2 minute Ouray Quadrangle.

Many of the aforementioned geologic and geomorphic characteristics of the San Juan Mountains can be seen in the river gorges and cliffs surrounding the town of Ouray, Colorado. One can stand in the middle of the town and rotate 360 degrees and see rocks that range from the Precambrian to the Quaternary (Moyer et al., 1961). The erosional features created from thousands of years of glacial, fluvial, and other surficial processes formed numerous river gorges and cliff outcrops in the area surrounding Ouray. Additionally, the Ouray area clearly displays geologic and geomorphologic features such as a textbook angular unconformity, erosional unconformities, anticlines, folds, faults, dikes, sills, glacial features, mass movements, and talus deposits. A general stratigraphic column that represents the Ouray area can be seen in Figure 3.

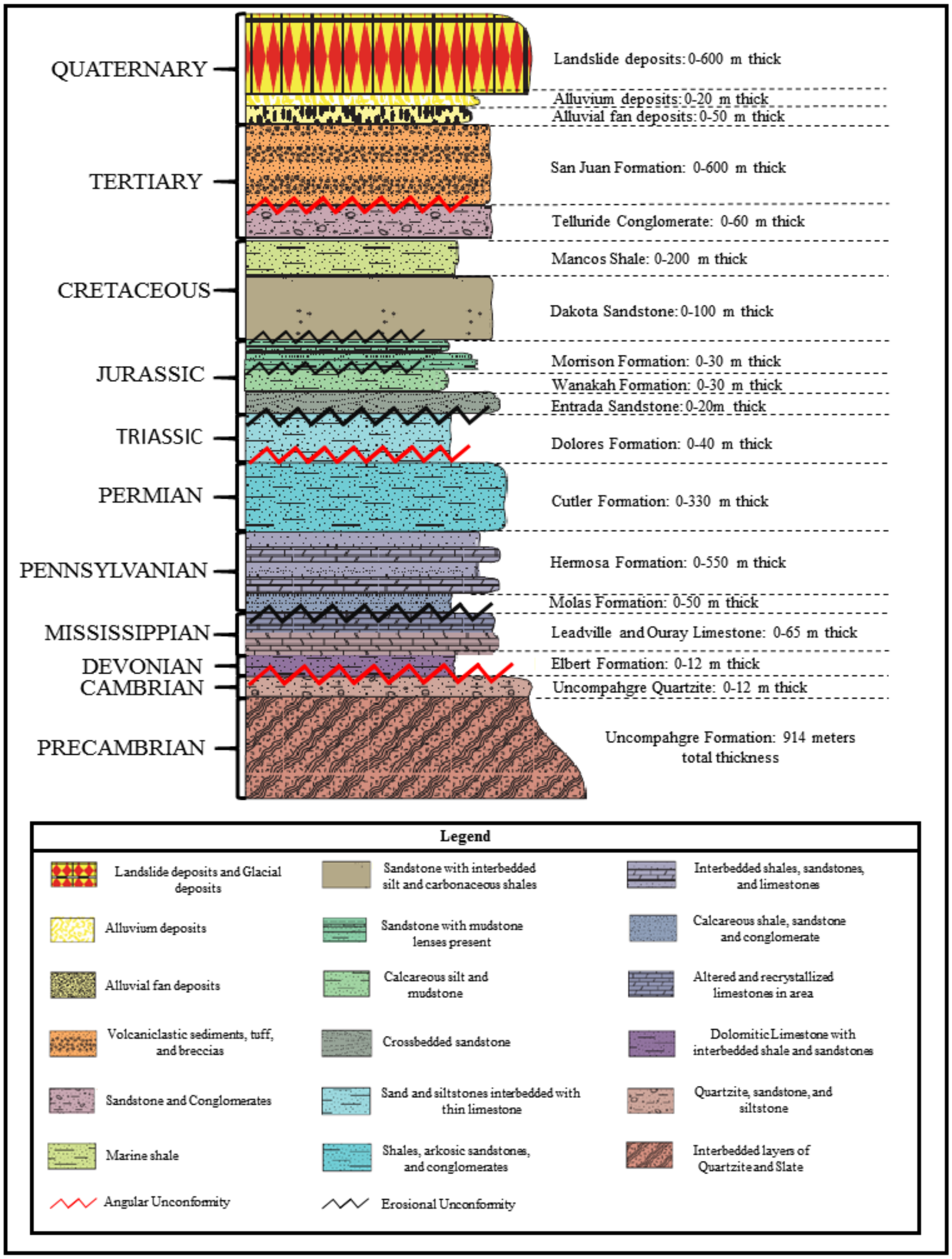

Figure 4: General Stratigraphic Column of the Ouray, Colorado Area.

3.1 General Geology and Geomorphology

Geologically, the presence of metasedimentary, metamorphic, sedimentary, and igneous rocks surround the Ouray area (Figure 4). The basal unit in the Ouray area is the Precambrian Uncompahgre Formation. This formation can best be seen in the Uncompahgre River Gorge south of Ouray. The Uncompahgre Formation has a total thickness of ~914 m (3,000 ft.) This formation consists of alternating thick bands of quartzite 30-40 m (98-131 ft) and thinner beds of slate 5-10 m (16-32 ft). The contact with the overlying Devonian units is recognized everywhere in the area as an angular unconformity, suggesting that the previously flat-lying Uncompahgre Formation was uplifted by various mountain-building events and was eventually eroded and truncated (Luedke and Burbank, 1962). The Elbert and Ouray Limestone formations of Devonian age unconformably overlay the Precambrian Uncompahgre Formation. The Elbert Formation is comprised of thinly-bedded sandy limestones, calcareous shales, and sandstones.

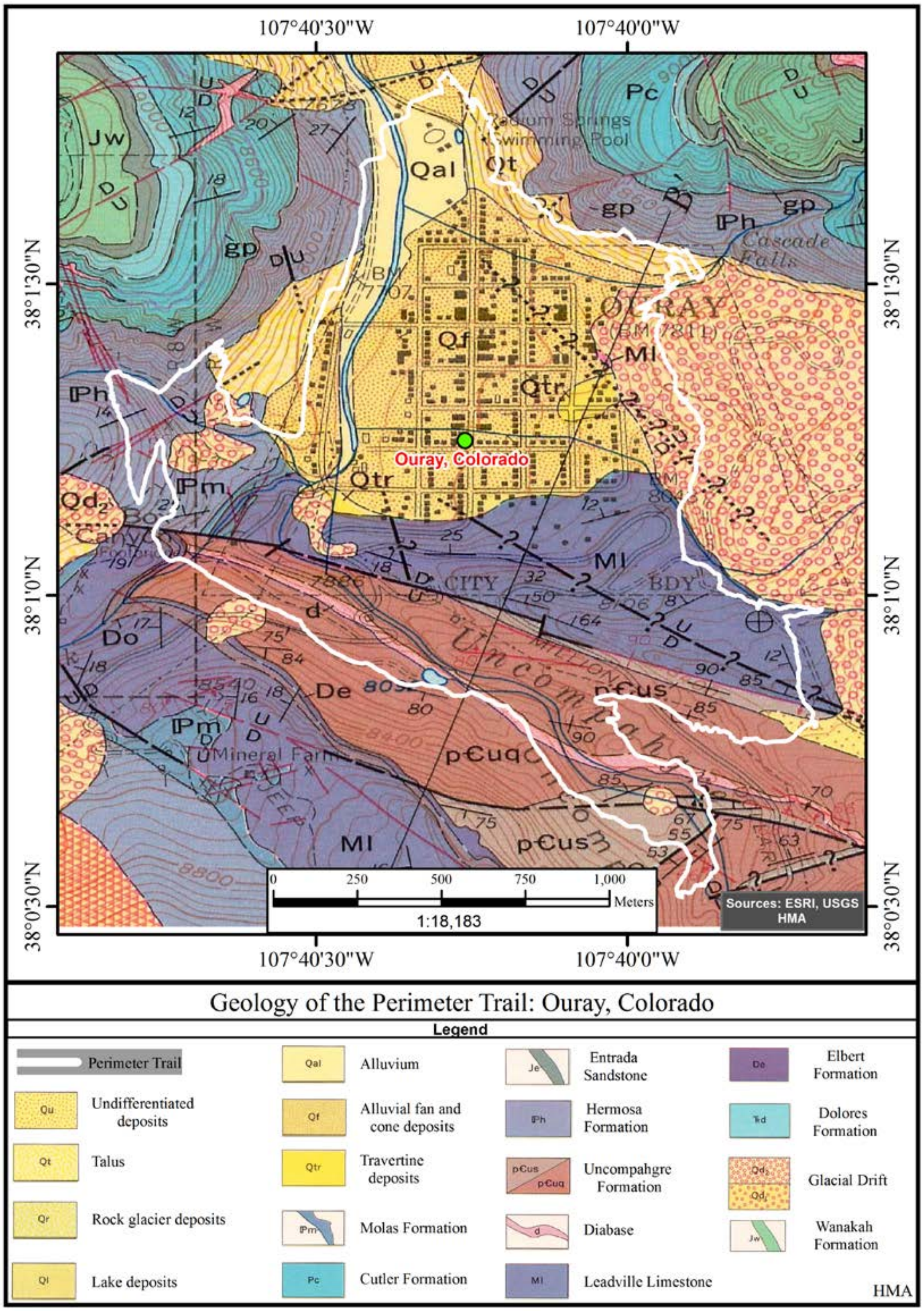

Figure 5: Ouray Perimeter Trail overlain onto Geologic map. Edited from USGS Ouray Geologic Quadrangle.

This formation ranges in thickness from 9 m (30 ft) to 15 m (50 ft) and appears to have a gradational contact with the overlying Ouray Limestone Formation (Luedke and Burbank, 1962).

The Ouray Limestone Formation is ~21 m (70 ft) thick in the area and is predominantly comprised of a dolomitized gray-to-white medium-grained limestone. The base of this formation is locally recognized as a conglomeratic sandy limestone, but is more regionally recognized by a gradational contact with the underlying Elbert Formation (Moore, 2005). The top of the Ouray Limestone is also regionally known to be a conformable, gradational contact with the overlying Leadville limestone of Mississippian age.

The Leadville Limestone was deposited during the Mississippian and is generally divided into two main sub-units within the Ouray area. The lower sub-unit, a cliff forming dolomitic limestone, is predominantly dark-gray or brown, massively bedded, and with few fossils present. The upper step-like sub-unit consists of gray-to-brown, crystalline limestone in thick beds (Luedke and Burbank, 1962). The Leadville Limestone is ~60 m (200 ft) thick in the area and is unconformably overlain by the Molas Formation of the Pennsylvanian.

The Molas Formation is poorly exposed and only outcrops to the south of Ouray. This formation is ~12-18 m (40-60 ft) thick and is composed of thin-to-thick, flat-lying beds of red, reddish-brown shale. Thin layers of sandstones and conglomerates are also associated with the formation (Luedke and Burbank, 1962). This formation is conformable and gradational with the overlying Hermosa Formation of the Pennsylvanian.

The Hermosa Formation outcrops as a series of gray and red ledges and cliffs. This formation is ~440 m (1,450 ft) and can be subdivided into three components as described by Burbank et al., (1962). The basal 140 m (450 ft) of the Hermosa Formation is comprised of green, gray, and red sandstone, siltstone, and shales. The sandstones associated with the basal unit are fine to coarse grained. The siltstone and shales have mica associated with their lithology and are sometimes separated by dark, dense limestones near the base (Luedke and Burbank, 1962). The middle section of the Hermosa Formation, which is ~213 m (700 ft) thick, is dominantly comprised of a red-to-light-red coarse-grained sandstone, siltstone, and shale that form massive beds 15-24 m (50 -80 ft) in thickness. The upper most 90 m (300 ft) of the Hermosa Formation is dominated by sandstones and conglomerates with interlayered shale and limestone. The lithology of the sandstone is coarse-grained, and pink-to-red. The limestone layers are fined-grained, fossiliferous, and gray in color. The shales are generally micaceous, somewhat silty and gray to red in color (Luedke and Burbank, 1962). The upper most section of the Hermosa Formation is conformably overlain and closely resembles the above Cutler Formation of the Permian.

The step-like benches of the overlying Cutler Formation form cliffs as a result of preferential erosion of the weaker beds. In the areas where the Cutler Formation is preserved, the formation is generally divided into two sub-units. The lower unit consists of ~440 m (1,450 ft) of generally red-to-brown interbedded siltstones, shales and fine to coarse-grained sandstones (Moore, 2005). The shales and siltstones are generally calcareous, sandy, and micaceous whereas the sandstones are arkosic and fine-to-coarse-grained with few conglomeratic lenses (Moore, 2005). The upper portion of the Cutler Formation is ~167 m (550 ft) and is comprised predominantly of sandstone with few shales and mudstones. Additionally, few very-coarse conglomeratic beds that are upwards of 12 m (40 ft) thick that contain rock fragments up to 25.4 cm (10 in) in diameter are present. The best exposure of the Cutler Formation is found in the cliffs north of Ouray, but is also present on the western facade of Ouray. The Cutler Formation varies in thickness from 0-600 m (0-2,000 ft) as a result of an angular unconformity (Luedke and Burbank, 1962).

The Dolores Formation is late Triassic and generally outcrops as steep slopes, benches, or cliffs and ranges in thickness from 12-40 m (40-130 ft) (Moore, 2005). The lower portion of the Dolores Formation is generally massively bedded with the dominant lithology being sand and siltstone. The upper portion of the Dolores Formation has thin beds of alternating sandstone and siltstone. The sandstones of the Dolores Formation are generally reddish-brown in color and exhibit cut-and-fill, as well as cross stratification bedding structures (Moore, 2005). The Dolores Formation is best seen in the canyon walls north of Ouray towards Ridgway (Moore, 2005). The Dolores Formation is unconformably overlain by the Entrada Formation.

The Entrada Formation is Mid-Jurassic and outcrops as white-to-buff, steep cliffs (Moore, 2005). The dominant lithology of the Entrada Formation is a fine-to-very-fine-grained, cross-bedded sandstone with a finer-grained matrix (Moore, 2005). This formation ranges in thickness from ~13-24 m (~45-80 ft) depending on where it is measured as a result of the erosional unconformity at its base. The Entrada Formation is overlain by the Wanakah Formation.

The Wanakah Formation is Jurassic and ranges in thickness from ~25 to 38 m (85 to 135 ft). The Wanakah Formation contains three members: The Pony Express Limestone, the Bill Creek Sandstone, and an upper-shaly interval (Luedke and Burbank, 1962). The Pony-Express Limestone is the basal unit of the Wanakah and is dominantly comprised of a dark-gray limestone that is generally characterized by a wavy bedding pattern. In one locality, the Pony Express Limestone is capped with a thick layer of Gypsum (Moore, 2005). The Bill Creek Sandstone is a gray-to-light-gray, and sometimes yellow-gray sandstone. This sub-unit is rarely well exposed and ranges in thickness from 4 to 7 m (14-25 ft). The top, shaly sub-unit is comprised of ~12-22 m (40-75 ft) thick interbedded claystone, sandstone and siltstones that are generally reddish-brown. The Morrison Formation overlies the Wanakah Formation.

The Morrison Formation is Jurassic and is ~213 m (700 ft) thick where it is not eroded. This formation outcrops as steep cliffs and ledges. It is generally divided into two sub-units: The lower Salt Marsh sub-unit and the upper Brushy Basin sub-unit. The Salt Marsh unit of the Morrison Formation consists of fine-to-medium grained sandstones interbedded with mudstones and sparse limestone beds. The sandstones are typically white-to-yellow white. The sands in the Salt Marsh unit exhibit cross-bedding and contain occasional ripple marks (Moore, 2005).

The upper Brushy Basin sub-unit of the Morrison Formation predominantly consists of mudstones with few sandstones and limestone beds dispersed throughout. The mudstone is generally calcareous and well indurated (Moore, 2005). The Morrison Formation can be seen near the top of the canyon walls in the Uncompahgre Valley in between Ouray and Ridgway, Colorado (Moore, 2005).

Above the Morrison Formation is the Dakota Formation, which unconformably overlies the underlying Morrison Formation and is Cretaceous. The Dakota Formation is the first formation deposited during the Cretaceous in the Ouray area. The Dakota ranges in thickness from ~12- 53 m (~40-175 ft) and can be seen in the valley walls above the slopes of the Morrison Formation (Moore, 2005). The Dakota Formation is a sandstone that was deposited in a shallow marine environment, such as a shoreline or beach, as the sea transgressed across the Morrison land surface (Moore, 2005). The Dakota Formation is conformably overlain by the Mancos Formation.

The Mancos Formation ranges in thickness, but is no more than 304.8 m (1000 ft) thick and can be found in the Uncompahgre Valley between Ouray and Ridgway (Moore, 2005). It is mid-Cretaceous and originally blanketed the entire area, but was truncated by erosion towards the end of the Cretaceous (Moore, 2005). The Mancos Formation is dominantly a gray-to-black shale with thin, buff-to-white sandstone and limestone lenses at the base. The Mancos Formation was deposited in a marine environment and is locally fossiliferous (Moore, 2005).

Other formations, such as the Mesaverde group and younger Cretaceous rocks, are not present in the area, but conformably overlie the Dakota Formation in surrounding areas (Moore, 2005). Toward the end of the Cretaceous time period, monzonite porphyry stocks and laccoliths were deposited along the Laramide-age Colorado Mineral belt.

The Ouray Stock, which is best exposed in the “Blowout” located on the northeast side of Ouray, Colorado is an example of deposit made by the Colorado Mineral Belt (Luedke and Burbank, 1962). The Blowout is associated with the Laramide Orogeny in the late Cretaceous to early Tertiary. This feature is comprised of altered Paleozoic and Mesozoic sedimentary rocks that are surrounded by an igneous intrusion (Luedke and Burbank, 1962). The Blowout (Figure 5) is recognized by its light-tan-to-yellow colors and contains quality ore deposits (Luedke and Burbank, 1962).

During the early Tertiary, after the San Juan dome had formed, many of the sedimentary and igneous bodies were eroded and subsequently overlain by the Telluride Conglomerate of the Eocene age (Moore, 2005). After deposition of the Telluride Conglomerate, the area experienced several episodes of volcanic activity during the Oligocene and Miocene (Moore, 2005). During this time, the volcanoes deposited thick accumulations of volcanic sediments, tuffaceous conglomerates, and mud-flow breccias, which are represented by the San Juan Tuff Formation (Lipman et. al, 1978).

The San Juan Tuff Formation has a maximum thickness >914 m (3,000 ft) over an area of ~731 km^2 (~2,400 mi^2) (Moore, 2004). The San Juan Tuff was deposited as a series of mudflows and water-laid volcaniclastic sedimentary rocks that originated as aprons around the vent facies accumulations of the surrounding volcanoes (Lipman et. al, 1978). The San Juan Tuff consists predominantly of rhyodacitic tuff breccia with minor amounts of volcanic conglomerates, air-fall tuffs, and welded ash-flow tuffs.

The aforementioned formations and respective general geologic descriptions provide a large-scale overview of the geology in the Ouray, Colorado area. A majority of the geologic units visible in the cliff sides and river and stream gorges are a result of multiple mountain-building events, massive erosional events, and a multitude of geomorphological processes. Geomorphological processes are defined as natural mechanisms of weathering and erosion that result in the modification of the surficial materials and landforms at the surface of Earth (https://www.for.gov.bc.ca/hts/risc/pubs/teecolo/terclass/geo.htm.). The general mechanisms associated with geomorphological processes are a product of the forces of nature in concert with gravity. Glacial, periglacial, mass movement, and fluvial geomorphologic processes are largely responsible for the landforms in the Ouray area.

Figure 6: Photograph of “The Blowout" from the Perimeter Trail. (Photo by author: 2016)

During the Pleistocene, the area was glaciated as a result of an icehouse paleoclimate regime. The most recent studies indicate that the last landscape-impacting Glacier in this area was Carbon-14 dated to ~14,000 years before present (Skinner and Porter, 1987). The glaciers formed during the Pleistocene are responsible for creating the deep gorges and valleys surrounding the area. Two common features in the area that are indicative of glacial activity are glacial cirques and U-shaped valleys. The largest glacial cirque that can be seen from the Perimeter Trail is known as The Amphitheater (Figure 6). The Amphitheater is believed to have formed during the Pleistocene (Reed, 2013).

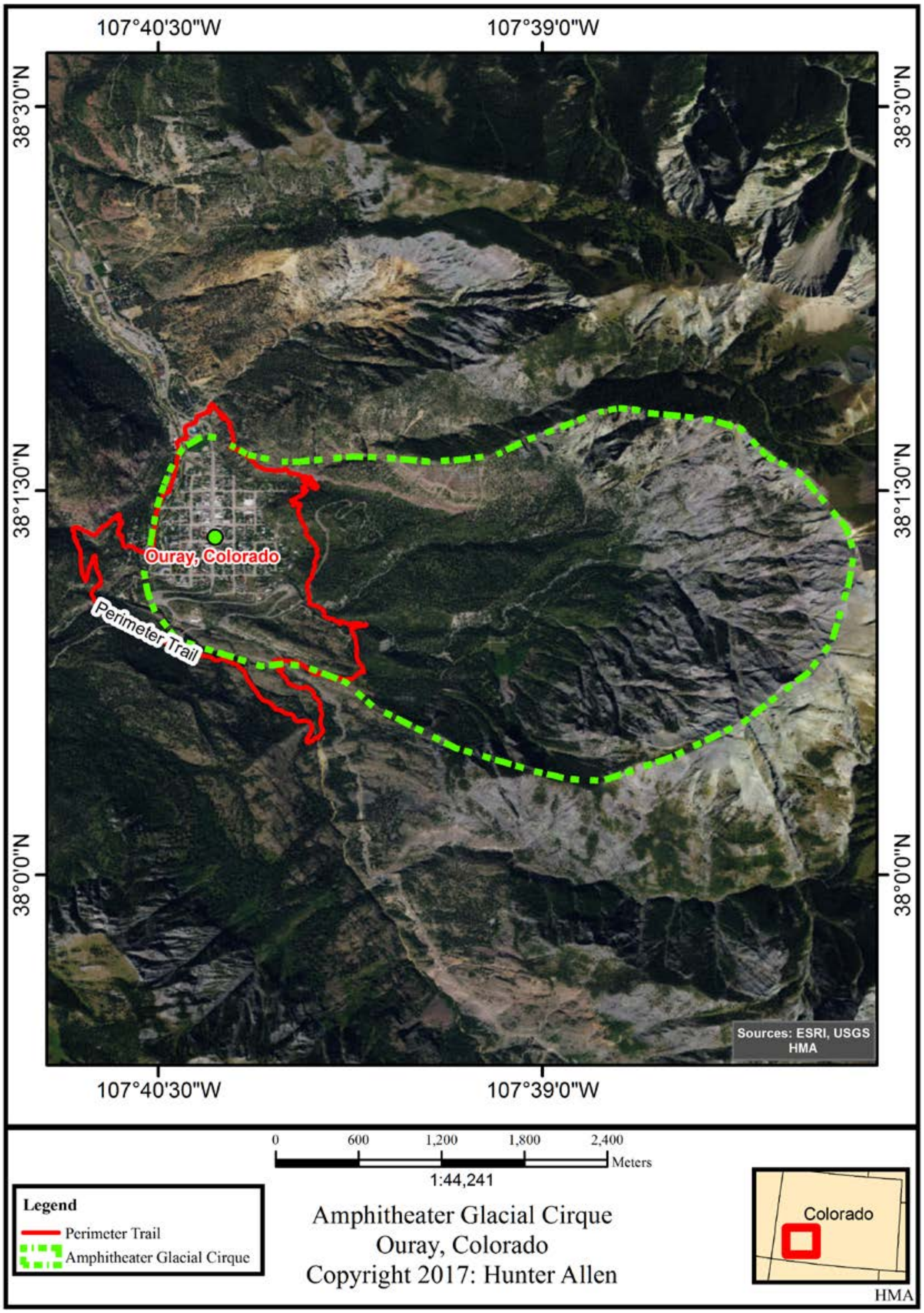

Figure 7: Amphitheater Glacial Cirque Outline.

Mass movement is another geomorphological process that has also largely impacted the landscapes surrounding Ouray. Mass movements include: landslides, debris flows, mud-flows, avalanches, etc. These events are dependent on the two key factors: gravity and angle of repose. In the area surrounding Ouray, over-steepened slopes and cliff ledges have the potential to exceed the angle of repose and cause a mass movement. The most significant mass movement to date is the Ouray Amphitheater landslide (Figure 7). The Ouray Amphitheater landslide occurred during the last glacial stage during the Pleistocene and covers a surface area of ~7,602,661 m^2 (~81,834,372 ft^2) (Reed, 2013). This massive landslide likely resulted from an over-steepening of the valley walls in combination with post glacial erosion and is composed of San Juan Tuff intermingled with glacial deposits (Reed, 2013). A mass movement in the Ouray area has the potential to be destructive and deadly. In an attempt to advise the public, Ouray County developed a Multi-Hazard Mitigation Plan designed to reduce long-term risk to people and property from natural hazards (e.g. mass movements and flash floods.) (Ouray County Multi-Hazard Mitigation Plan, 2008)

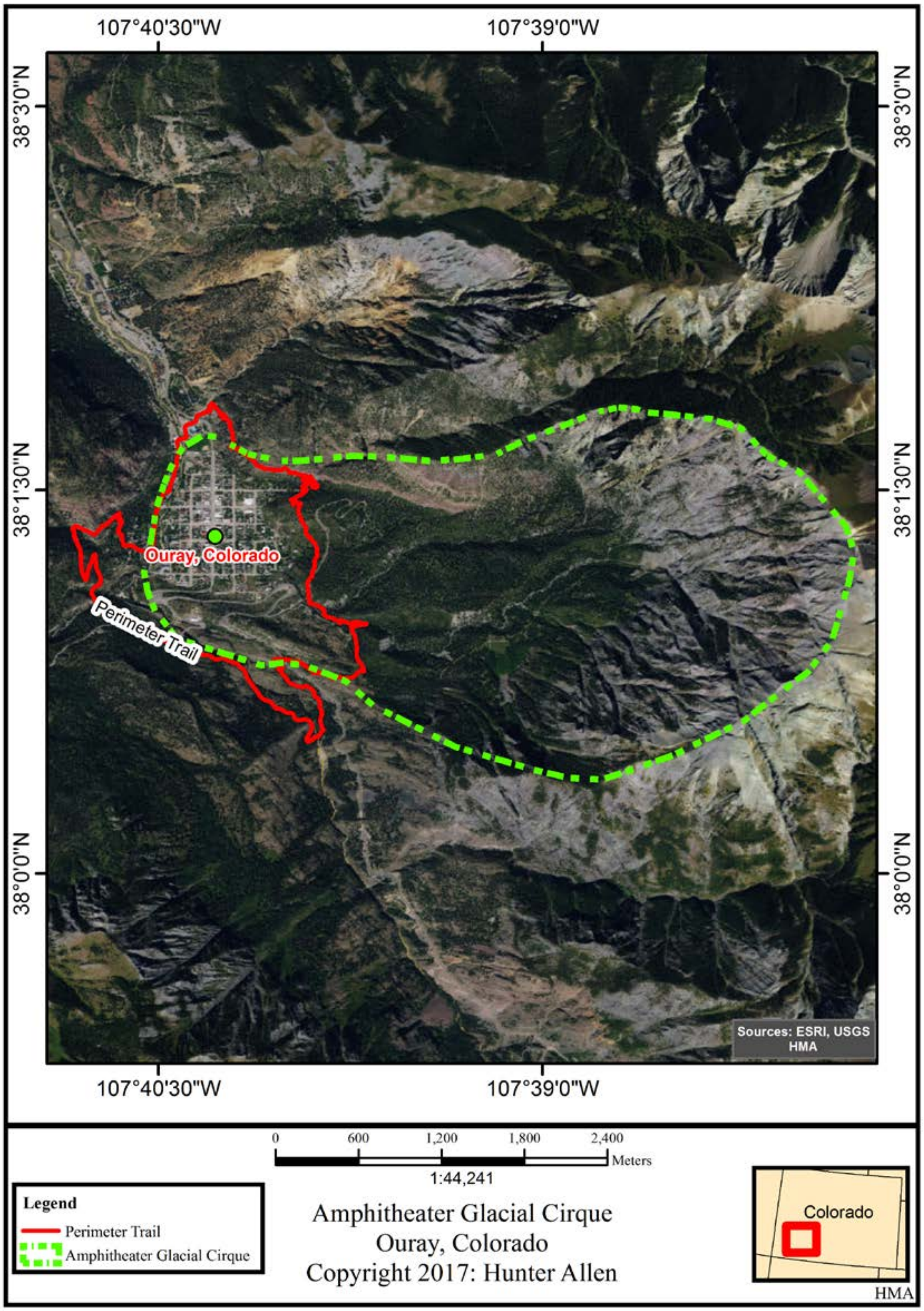

Figure 8: Outline of the Ouray Landslide.

In addition to the glacial and mass-movement processes, fluvial processes have significantly impacted the landscapes in the Ouray area. The Uncompahgre River Gorge was formed by erosive action of the Pleistocene glaciers (Blair, 1996). Glaciers initiated the formation of the Uncompahgre Gorge by eroding the Precambrian quartzites and slates of the Uncompahgre Formation (Blair, 1996). As glaciers receded, large volumes of runoff formed the Uncompahgre River gorge. The river continued to erode the Uncompahgre Formation for thousands of years, forming the gorge seen today. An additional geomorphic feature formed from fluvial processes are the “baby bathtubs” (Figure 8). These step pool features can be seen along Portland Creek on the east side of Ouray and have been formed from years of fluvial erosion.

The aforementioned natural mechanisms of geomorphologic processes have largely sculpted the Ouray area, but the landscapes have also undergone change that is anthropogenic in nature. Landscapes in the Ouray area have been affected by dams, gabions, concrete drainage systems, home development, trails, roads, etc.

Figure 9: Baby Bathtub features along Portland Creek. (Photo by author: 2016)

To stabilize road cuts and prevent erosion of existing roads, gabions are common in the area. Gabions (Figure 9), stemming from the Latin word *cavea*, which means “a cage,” are constructed from welded wire in a gridded pattern and are subsequently filled with rocks, concrete or other material designed to stabilize and slow erosion (Hilfiker, 1991). An additional anthropogenic feature encountered in the area are concrete drainage systems. At the base of the Cascade Falls, a concrete drainage system can be found that re-directs the water from Cascade Creek. These concrete drainage systems change the natural route of the river.

Figure 10: Gabions protecting existing road. (Photo by author: 2016)

3.2 Climate and Vegetation

Generally, the San Juans are semiarid. Depending on the time of year, weather patterns can widely vary (Blair, 1996). The average maximum temperature and average minimum temperature in Ouray is 15.5 degrees Celsius (60 degrees Fahrenheit) and -3.8 degrees Celsius (25.3 degrees Fahrenheit), respectively (Western Regional Climate Center, 2006). On average, temperatures drop roughly -15.5 degrees Celsius (4 degrees Fahrenheit) for every ~304.8 m (~1,000 ft) of elevation gained (Blair, 1996). Ouray receives precipitation in the form of water, snow, and ice yearly with a combined average of 34.0 cm (13.4 in) of precipitation per month (Figure 10). Vegetation in the area varies based on elevation and location. Generally, Quercus ilicifolia (scrub oaks) and Juniperus (junipers) are common on the lower slopes, and Populus (cottonwoods) and Quercus phellos (willow oaks) are present along the waterways. In higher elevations, Populus tremuloides (aspen), Pinus (pine), Abies (fir), and Picea (spruce) can be found in large numbers (Burbank et al. 1984). The average limit for the alpine level in the Ouray area is ~3,500 m (~11,500 ft) (Burbank et al. 1984).

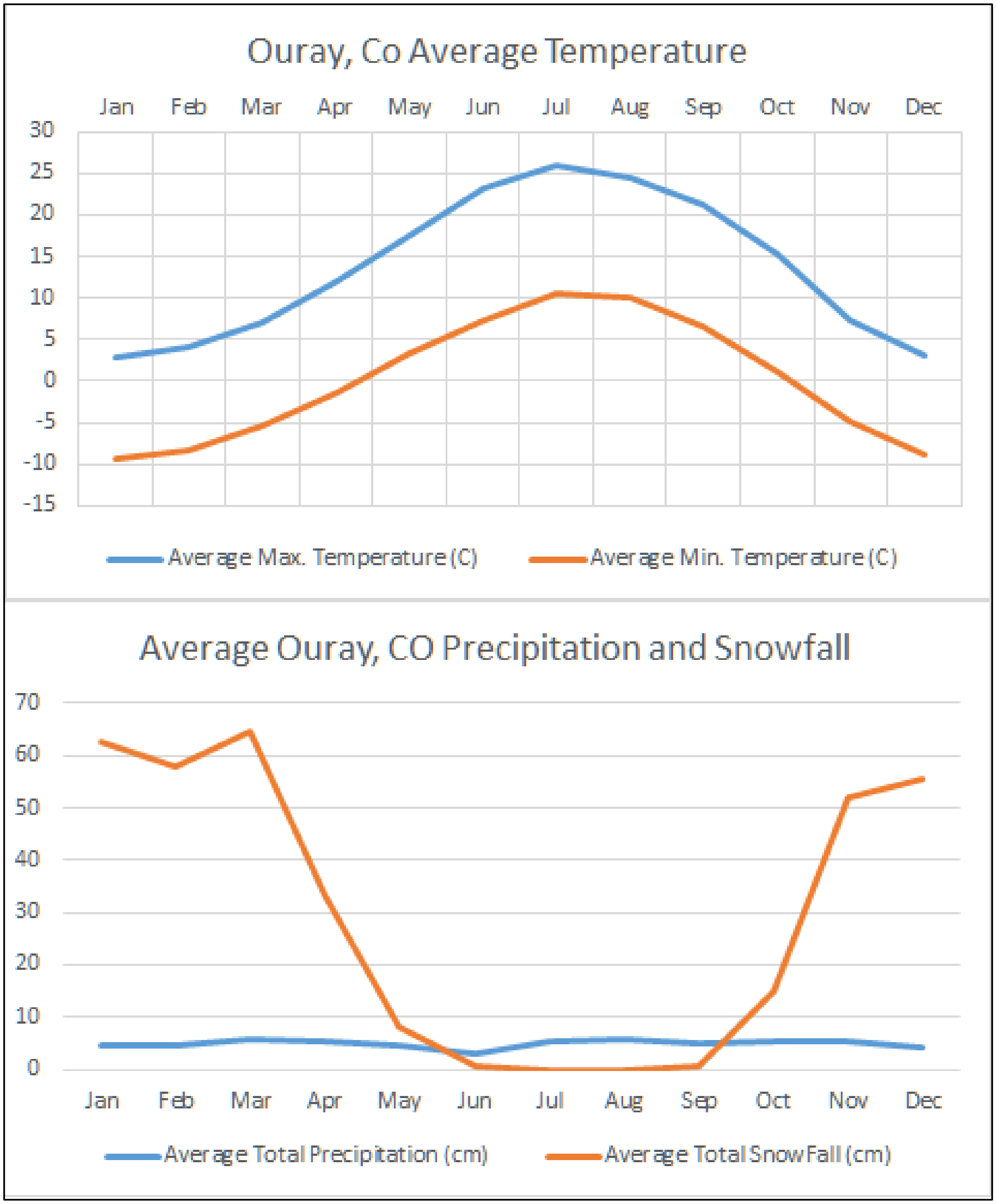

Figure 11: Ouray Climagraph. (NOAA).

During spring (March, April, May), Ouray has an average maximum temperature of 12.2 degrees Celsius (54 degrees Fahrenheit) and an average minimum temperature of -1.1 degrees Celsius (30 degrees Fahrenheit) (Western Regional Climate Center, 2006). Although March and April are designated as spring months, winter-like conditions are still very much present in the Ouray area. The average snowfall and precipitation during spring is ~40 cm (~16 in) (Western Regional Climate Center, 2006). The flora during the spring are abundant in number and type and continue to bloom throughout most of the summer months.

During the summer months (June, July, August), the average maximum temperature is 25 degrees Celsius (78 degrees Fahrenheit) and the average minimum temperature is 11.6 degrees Celsius (53 degrees Fahrenheit) (Western Regional Climate Center, 2006).The average precipitation during summer is approximately 4.8 cm (1.9 in) (Western Regional Climate Center, 2006). June receives the most sun and is the driest month of the year in Ouray (Blair, 1996). On average, the town receives sunlight for 12.4 hours a day and only receives rainfall four out of the thirty days in June (Blair, 1996).

During July, Ouray often experiences a monsoon-like weather pattern, which in some cases, produce high winds, hail, lightning, and torrential downpours. These thunderstorms are associated with the flow of humid air from the tropical Pacific that travels into the southwestern United States resulting in more prevalent thunderstorms (Blair, 1996). As the monsoon weather patterns diminish in September, the air becomes cooler and more dry (Blair, 1996).

During the fall, Ouray experiences an average maximum temperature of 14 degrees Celsius (58 degrees Fahrenheit) and an average minimum of 0.5 degrees Celsius (33 degrees Fahrenheit) (Western Regional Climate Center, 2006). The fall season receives on average 27.4 cm (10.8 in) of precipitation. Most of the precipitation during the fall is in the form of snow during the month of November. On average, 51.8 cm (20.4 in) of snowfall can be expected. The fall season is a desired time for tourists to visit due to the changing of the leaves. As winter approaches, plummeting temperatures and frequent snow storms become regular.

Winters in Ouray have an average maximum temperature of 2.7 degrees Celsius (37 degrees Fahrenheit) and an average minimum temperature of -8.0 degrees Celsius (16 degrees Fahrenheit) (Western Regional Climate Center, 2006). The winters are known for their heavy snow falls that average 60.9 cm (24 in) per month.

4. APPLICATION DEVELOPMENT METHODS

Various methods were used to acquire, analyze, and compile data into a smartphone application. The initial step was the compilation of a literature review of the Ouray, Colorado area, to become familiar with the general geology and geomorphology. By reviewing various topographic, geologic, and soils maps I began to effectively compile a list of what should be seen in field studies (Burbank et al., 2008; Moore, 2004; Blair, 1996). Upon completion of a literature review, a plan for field work was designed and executed.

In the field, various tools and techniques were utilized to collect the necessary data to accomplish the objectives for this thesis. FieldMove Clino®, an application developed by Midland Valley, was used to compile field notes, measurements, and photographs.

In addition to the FieldMove Clino® application, a Garmin® GPSmap 60Cx handheld Geographic Positioning System (GPS) was used to record accurate readings of pertinent waypoints to be included in the smartphone application. The Garmin® GPSmap 60Cx hand-held GPS uses multiple satellites to triangulate the user's position to within 5 m (16.4 ft) ("What is GPS?," 2016). The handheld GPS was also used to precisely record the route of the Perimeter Trail.

The Gigapan Epic Pro®, in concert with a Nikon DSLR Camera, was used to acquire extremely high-resolution panoramic photographs containing billions of pixels ("About Us," 2017). The Gigapan Epic Pro® was used to take high-resolution photographs of Ouray’s eastern and western facades and may be accessed *via* the links in the appendix. In addition to the literature review, considerable time and effort was dedicated to researching the most effective way to present the data in the form of a functioning application.

When developing an application, several questions must be taken into consideration. For example, can the application properly function on varying screen sizes, and operating systems? The fundamental goal was to find a platform that would host this application on any smartphone, tablet, or computer, regardless of the manufacturer or operating system.

Initially, Apple's® Xcode software and the innovative programming language “Swift,” was considered for the development of the application. Xcode is an open source software program developed by Apple®. This software program is an integrated suite of tools designed for developing software for devices running an Apple® operating system. Having no extensive background in computer programming, I sought out an intensive training course to learn the Swift programming language so that I could understand what was required to develop a mobile application of this nature. The decision to forego the use of Apple’s® Xcode was ultimately made because using Swift would only allow users with Apple® products to access it.

Argon Augmented Reality Web Browser was an additional potential candidate considered to host the application. Argon is a project created by the Augmented Environments Lab at Georgia Tech. Developed by Blair MacIntryre and colleagues in 2009, Argon was intended to create a platform that allows people to develop and experience mobile augmented reality using the same technologies that are used to develop websites and software applications (MacIntryre, 2011). This platform allows for the users to access the camera in the smartphone. Wherever the user points the camera, respective information is displayed to the user (MacIntyre, 2011). This platform would have been a great choice for this project, but I was unable to use this software and platform because of the costs associated with the development.

Additional options were considered, such as getting an outside professional application developer to assist with development and Google Earth Trekker®, but the cost and timelines associated with these options were insurmountable. The final platform that was chosen to host the smartphone application was the ESRI ArcGIS®' online Story Maps program.

The decision to host the application using the ArcGIS® Story Map Template was made primarily because ArcGIS® Story Maps Applications can be viewed on any computer, tablet, or smartphone, using any operating system. Additionally, this choice leads to the use of the application for several years without constant updates. When creating and maintaining software applications, developers are required to continuously alter, tweak, and debug the source code as new operating systems are released. Several issues can be expected during the process of writing and developing the source code, which requires a considerable amount of time and effort to develop an application that runs smoothly and effectively. Choosing to use ArcGIS®' Story Maps template eliminates a majority of the laborious efforts associated with developing and maintaining an application while preserving its long-term use.

ESRI (Environmental Systems Research) company was founded in 1969 and is dedicated to making the world a better place by developing Geographic Information Software Systems ("We pioneer problem solving using GIS," 2017). In doing so, ESRI has developed a host of various technologies that allow geographic information to be displayed in an effective manner. The development of ArcGIS® Online has opened an avenue for people to create and share powerful geographic data that can be viewed by anyone with a computer or smartphone. Recently, Story Map Builder, which is a Geo Apps extension of ArcGIS® Online, allows developers and non-developers the ability to build easy-to-use, functional applications.

A choice from 10 Story Map Templates can be made depending on what kind of story the developer wants to tell. The *Map Tour* template is designed to present a set of specific geographic waypoints that include annotated photographs, videos, and descriptions and are linked to an interactive base map. This template is ideal for walking tours and provides an attractive, user-friendly template that allows the developer to present a number of waypoints on a map in a desired sequential order through, which a user can browse. The most beneficial and noteworthy aspect to the ArcGIS® Story Map template is that it is designed to be used in any web browser, on any device, including smartphones, tablets, or computers.

Hosting the data on this platform allowed the development of an application that offers hikers the ability to learn about the geologic and geomorphic features associated with the Perimeter Trail. Additionally, the application will help them stay safe by posting the user’s location on the trail. Once the necessary data were collected, the data were compiled into a functioning smartphone application using Flickr®, ESRI ArcGIS®, and Story Map builder.

4.1 Development of the Story Map

The initial task when developing a Story Map is to create a base map using ArcGIS® online, or ArcGIS® desktop. For the base map of this Story Map, I chose to display satellite imagery. After choosing the style of base map, additional layers or shapefiles were developed to provide supplemental information. I uploaded the Perimeter Trail to ArcGIS®, which was recorded using the handheld GPS to ArcGIS®, and saved it as a shapefile. I then imported the shapefile into ArcGIS® online and added it to the existing satellite imagery base map. Once the supporting layers and shapefiles were uploaded to the base map, the next step was to determine the number of waypoints that were to be included in the application.

The following step was to annotate the photographs that would represent the respective waypoints. Annotating the photographs allows for viewers to have a better understanding of what the photograph is attempting to convey. Upon completion of annotating the waypoint photographs, the photographs needed to be uploaded to a photo/video sharing service (e.g. Flickr, Picasa, YouTube®, etc.), that is accepted by the ESRI's Story Map interface.

After consulting with the Story Map support team and testing the various image and video import services, Flickr® was used to import the annotated photographs into the Story Map. I used the online photo storage service, Flickr®, to store the annotated photographs because it offers the ability to store the photos in an album and subsequently add descriptions, and add latitude and longitude coordinates associated with the photographs. The developer has the ability to create the content for the Story Map waypoints using only the Flickr® photo storage website.

After the photos were edited, organized, described, geotagged, and uploaded to Flickr®, the next task was to choose from one of ten app-templates that best fits what I was trying to convey. I selected the *Map Tour* template because its primary function is to guide users through a sequence of places ("Story Maps," 2017). Once the *Map Tour* template was chosen, I was then prompted to choose how I wanted to upload the images or videos; Whether the images and videos were hosted online (such as through Flickr®, Picasa®, YouTube®) or if I wanted to upload the images to the Story Map using the ArcGIS® Map Tour layer.

Using the Flickr® import option within the Map Tour interface, the album created on the Flickr® photo storage website was imported to the Story Map. Importing photos to the Story Map using the Flickr® service allows for the respective descriptions, geographic locations, and sequential order of the photos to be converted into the format of the Story Map. The photos were brought in as sequentially ordered waypoints with matching descriptions, and specific geographic locations. Once the Flickr® album was uploaded, I began the task of quality checking and testing the application. The application was tested using multiple smartphones, tablets, and computers to ensure that the application functioned properly.

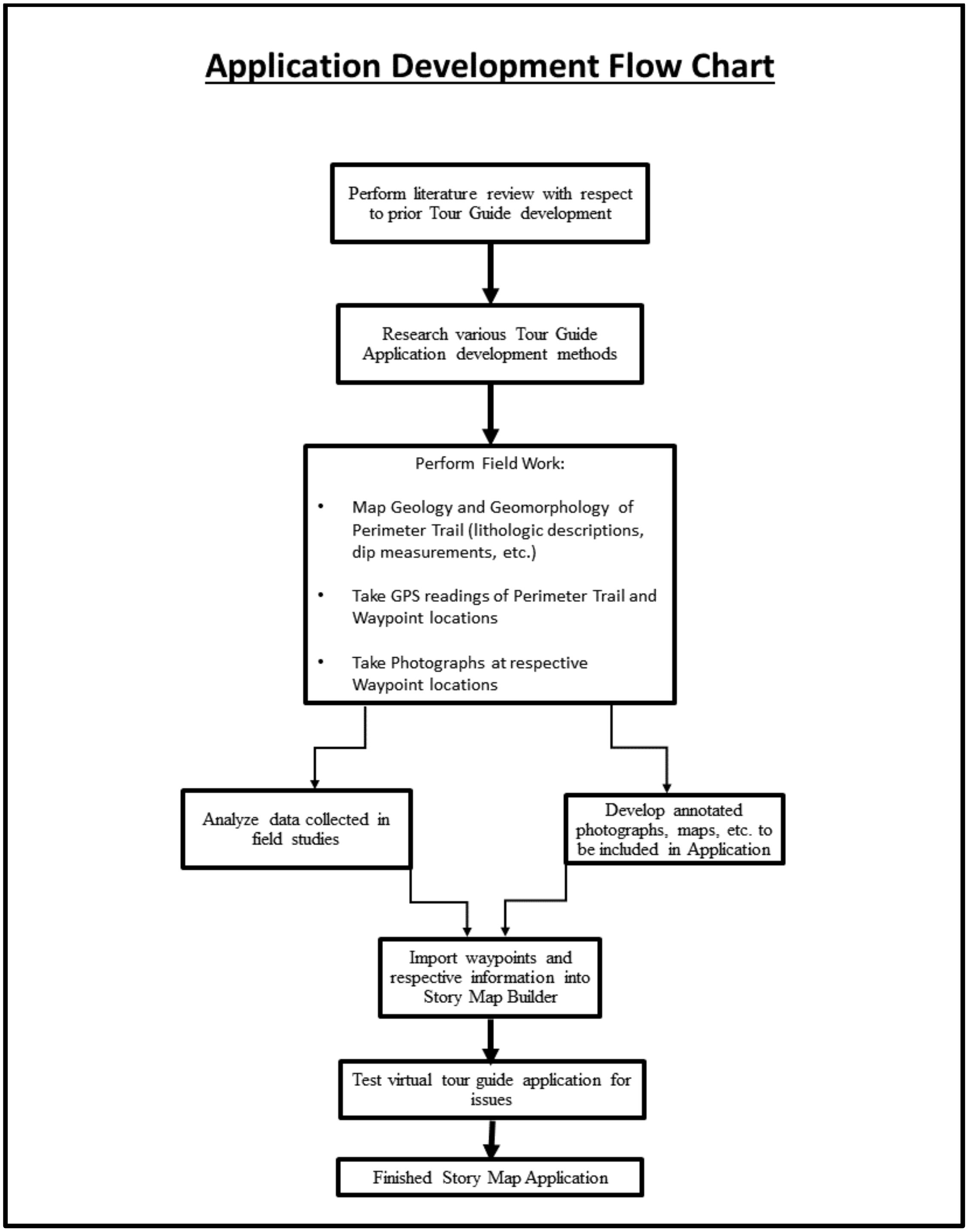

Figure 12: Flow chart showing general steps taken to achieve application development.

4.2 Perimeter Trail Description

The Perimeter Trail is ~9.3 km (~5.8 mi) and has been continuously developed since 2006 by the U.S. Forest Service in partnership with a nonprofit organization, The Ouray Trail Group, and the city of Ouray. Hiking the trail takes ~4 hours and is an easy-to-intermediate trail with a few moderately steep grades. The trail begins at an elevation of ~2,363 m (~7,753 ft) and reaches a maximum elevation of ~2,608 m (~8,557 ft), where hikers catch a glimpse of the town in the foreground and noteworthy San Juan Mountain peaks, such as Mount Hayden and Twin Peaks, in the background ("Hike the Ouray Perimeter Trail in Ouray, Colorado," 2015). The trail circumnavigates the city of Ouray and can be accessed from five locations around the town: The Visitors Center, Cascade Falls, Pinecrest Street, 5th Avenue, and Queen Street.

The first waypoint of the virtual tour guide application is the Visitors Center. The Visitors Center is the most common starting point for the trial and is located at 1230 Main St, Ouray, CO. It is recommended to hike the ~9.3 km (~5.8 mi) trail in a clockwise direction because that is the direction in which the trail signs face.

The trail begins on a wood-edged path in the parking lot behind Skyrocket Condos. Hikers make their way to a set of wooden stairs that leads up to the Cascade Mountain cliffs. The trail continues south and then east where hikers traverse over scree slopes comprised of Holocene talus deposits.

The second waypoint encountered on the trail is the Pistol Root Tree Waypoint (Figure 12). This waypoint shows a tree that is experiencing soil creep. Over the lifetime of the tree, the debris and soil on this steep slope are slowly shifting downslope, causing the base of the tree to continuously bend, in an attempt to stay upright. At this location, the geology is primarily talus slope deposits that are on a steep angle and are largely un-lithified causing instability on the slope face.

Figure 13: Pistol Root tree on Talus slope deposits. (Photo by author: 2016)

At ~0.5 miles after the start of the trail, the trail traverses across a cliff comprised of the Hermosa Formation. This site provides a great view of Mt. Abram and Hayden Mountain to the south. This site also provides a great example of preferential erosion. As hikers continue on the trail for ~1.1 km (~.7 mi), they will reach the Cascade Falls and Cascade Creek Bridge.

Cascade Falls is the third waypoint in the application and is ~36.5 m (~120 ft) waterfall of Cascade Creek, which heads near the peak of Cascade Mountain at an elevation of ~3,352.8 m (~11,000 ft). (This location may be used to shorten the hike and return to town by taking the Cascade Trail down to 8th Avenue) The Cascade Waterfall has created a large plunge pool at its base and also helped create the cascade creek.

The trail resumes across a bridge over Cascade Creek, and continues on the Lower Cascade Trail. After crossing the Cascade Bridge, the trail lithology transitions from talus slope deposits and Hermosa Formation deposits, to Amphitheater Landslide deposits. The Lower Cascade Trail continues for ~0.3 km (~0.2 mi) until it bifurcates where the Perimeter Trail turns south and the Lower Cascade Trail continues eastward.

The Perimeter Trail continues south for ~1.6 km (~1.0 mi) to the intersection of the 5th avenue trail and the Perimeter Trail. (This location may be used to shorten the hike and return to town by taking the 5th Avenue Trail back to town). This part of the trail is a particularly good area to look for wildflowers in the spring and summer time. The trail then continues for ~2.1 km (~1.3 mi), which will lead hikers to the Amphitheater Campground Road. The Amphitheater Campground road eventually leads to the bridge that crosses over Portland Creek. At this junction, hikers take the Baby Bathtubs Trail to the left of the Portland Creek bridge.

Along the Baby Bathtub Trail, the basement rocks have been eroded into small step-pools. At the Portland Creek Bridge, the trail turns right and continues for ~91.4 m (~300 ft) and then turns left and continues uphill to the Three Pines picnic area. The trail continues until it exits onto Portland Mine Road. Following the Portland Mine Road uphill and turning right, the trail opens up to the Potato Patch. This flat-lying field is comprised of undifferentiated Quaternary deposits and was once cultivated and farmed during the gold and silver rush. Crossing through the Potato Patch and continuing uphill for a short distance will the trail reaches the High-Point Waypoint of the Perimeter Trail, which is at an elevation of ~2,590 m (~8,500 ft). At this location, lithology transitions from the undifferentiated Quaternary deposits to the pre-Cambrian Uncompahgre Quartzite Formation. The trail continues for ~0.4 km (~0.25 mi) until it reaches the intersection of Highway 550 (Million Dollar Highway) and the Perimeter Trail. Crossing the highway, the trail continues south for ~0.8 km (~0.5 mi) and crosses the bridge over the Uncompahgre River. Just south of this location is the Hydroelectric Dam that Ouray uses as a source of energy. Shortly after crossing the bridge a stile is used to cross over the penstock used to regulate the flow of the Uncompahgre River. The trail continues north along the Uncompahgre River Gorge for ~0.9 km (~0.6 mi) until reaching the Ice Park Reservoir Waypoint (Figure 13). This reservoir is used by the town during the winter to create the ice climbing routes for the well-known Ice Climbing Park. From this waypoint, the trail continues ~0.32 km (~0.2 mi) until reaching the intersection of

CR361 and the Perimeter Trail. Hikers safely cross CR361 and continue on the Perimeter Trail until reaching the Box Canyon High Bridge. When crossing the High Bridge, a textbook angular unconformity can be seen looking southwest. In (Figure 14), the nearly vertical underlying rocks from the Uncompahgre Formation are overlain by flat-lying sedimentary Paleozoic rocks of the Elbert, Ouray Limestone, and Leadville Limestone Formations (Burbank and Luedke, 1984). This is indicative of the mountain building events that formed the San Juan Mountains.

Figure 14: Ice Park Reservoir waypoint. (Photo by author: 2016)

Figure 15: Angular unconformity between the underlying nearly vertical Proterozoic metamorphic rocks of the Uncompahgre Formation and the overlying nearly horizontal Paleozoic sedimentary rocks of the Elbert Formation, Ouray Limestone, and Leadville Limestone. (Photo by author: 2016)

After crossing the High Bridge and exiting the low-roof tunnel, the trail descends a staircase and leads to Pinecrest Road. (Hikers may exit the trail from this location by walking downhill on Pinecrest Road). The trail ascends uphill using Pinecrest Road and follows a switchback. At the end of Pinecrest Road, the trail continues into the forest until reaching the intersection of the Oak Creek Trail and the Perimeter Trail. The Oak Creek trail goes left while the Perimeter Trail descends into the rugged Oak Creek canyon. Hikers continue to descend into Oak Canyon until they reach the Oak Creek Bridge. After crossing the bridge, hikers ascend a short set of stairs to the intersection with the Old Twin Peaks Trail and turn right to exit the canyon at Henn’s overlook.

Henn’s overlook is a great location to see the Amphitheater and Amphitheater landslide deposits. From here, hikers follow the trail until they reach Queen Street, which may also be used as an access point to the trail. Hikers follow the Perimeter Trail for ~0.8 km (~0.5 mi) down to the Ouray Trails Park and then exit onto Oak Street. Hikers follow Oak Street north until they reach the Visitor Center, which completes the Perimeter Trail hike.

5. SUMMARY AND CONCLUSIONS

At the commencement of this research, the general public was unable to learn and understand the geology, geomorphology, and landscapes surrounding the Perimeter Trail without having an extensive geologic background, or personal tour guide. The completion of this thesis provides the general public with a functioning, user-friendly, and dependable application that may be accessed by any person with a smartphone, tablet, or computer. This application fulfills its main objective by serving as a virtual tour guide that provides the general public with location-specific geologic and geomorphologic descriptions.

The utilization for a thesis of this style is wide-reaching. Additional Story Map Applications can be developed to target specific interests and audiences. For example, Story Maps could be developed that focus on the flora and fauna of the region, or a purely historical Story Map that provides users with historical information regarding the mining operations and abandoned mine shafts that are located in the area surrounding the Perimeter Trail. The development of Story Maps of this nature can provide students the opportunity to gather research for their respective studies to develop a thesis while having an opportunity to deliver a long lasting, impactful, and educational Story Map to the public. Another potential next step could be the development of a paper brochure of the Perimeter Trail, which has not yet been produced because of the newness of the trail. The Perimeter Trail could be displayed on an 11x17 inch brochure. Details of the

Perimeter Trail could be displayed on the reverse side of the map with annotated photographs, descriptions, and respective GPS locations.

This thesis has the potential to impact the way students choose to conduct their respective work. It was the goal of this thesis to contribute to the body of knowledge in the community of academia for its geologic and geomorphologic efforts, but more importantly, I wanted the application to give the general public a way to further their education. The justification for the development of the application is that all too many graduate and PhD students spend several years researching a specific topic just to have it read a few times by their committee and then archived. I aim to change this cycle by developing a research-based thesis that can also be utilized by the general public.

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APPENDIX A: TRAIL WAYPOINTS

A-1. **Visitors Center-** Welcome to the start of The Perimeter Trail!! Please make your way across Main Street and head toward the wooden edged path behind the Skyrocket Condos! Enjoy your time!

Latitude: 38° 1'46.32"N

Longitude: 107°40'22.03"W

A-2. **Pistol Root Trees-** Be on the lookout for trees with their trunks bent like this! This is indicative of "soil creep", where the soil has slowly shifted down-slope over time do to gravity and the angle of repose.

Latitude: 38° 1'47.42"N

Longitude: 107°40'15.35"W

A-3. Hermosa Cliff Preferential Erosion- Notice how there is an overhanging ledge above you and an indentation of the rocks where you are walking. This is known as preferential erosion. This occurs when weaker, less stable rocks are eroded quicker than more competent rocks.

Latitude: 38° 1'34.03"N

Longitude: 107°40'1.85"W

A-4. **Cascade Falls-** This waterfall is ~120 ft in height and is formed from the Cascade Creek which starts ~2000 ft above where you are standing near the peak of Cascade Mountain!

Latitude: 38° 1'30.71"N

Longitude: 107°39'55.23"W

A-5. ***Calcochortus gunnisonii* (Sego Lily, Gunnison’s Liliaceae)-** This Wildflower can be seen in Subalpine, Montane, and Subalpine zones during the months of June to August.

Latitude: 38° 1'46.32"N

Longitude: 107°40'22.03"W

A-6. **Violet Aster:** Be on the lookout for these beautiful little flowers in the summer time.

Latitude: 38° 1'19.08"N

Longitude: 107°39'54.86"W

A-7. **Erosion Protection Wall (Gabions)-** These walls have been placed here to prevent the overlying soil deposits from washing down-slope from when they excavated this area for the now existing road.

Latitude: 38° 1'5.87"N

Longitude: 107°39'54.82"W

A-8. Baby Bathtubs (Little Portland Creek)- The Uncompahgre Formation at this location has been eroded over time by the Little Portland Creek. During the summer, this creek typically does not have the water power to erode the bedrock, but snowmelt during the spring significantly increases the volume of water.

Latitude: 38° 1'2.72"N

Longitude: 107°39'52.28"W

A-9. **Potato Patch-** This field was used for planting potatoes during the gold and silver rush. This area is on the edges of the amphitheater landslide, which you will learn about later on the trail!

Latitude: 38° 0'47.05"N

Longitude: 107°39'43.50"W

A-10. High Point Lookout: Great job! You have reached the highest elevation of the Perimeter Trail at approximately 8500 ft. This lookout is a great spot to view Whitehouse Mountain (13,492 ft.) and Twin Peaks. (10,500 ft.)

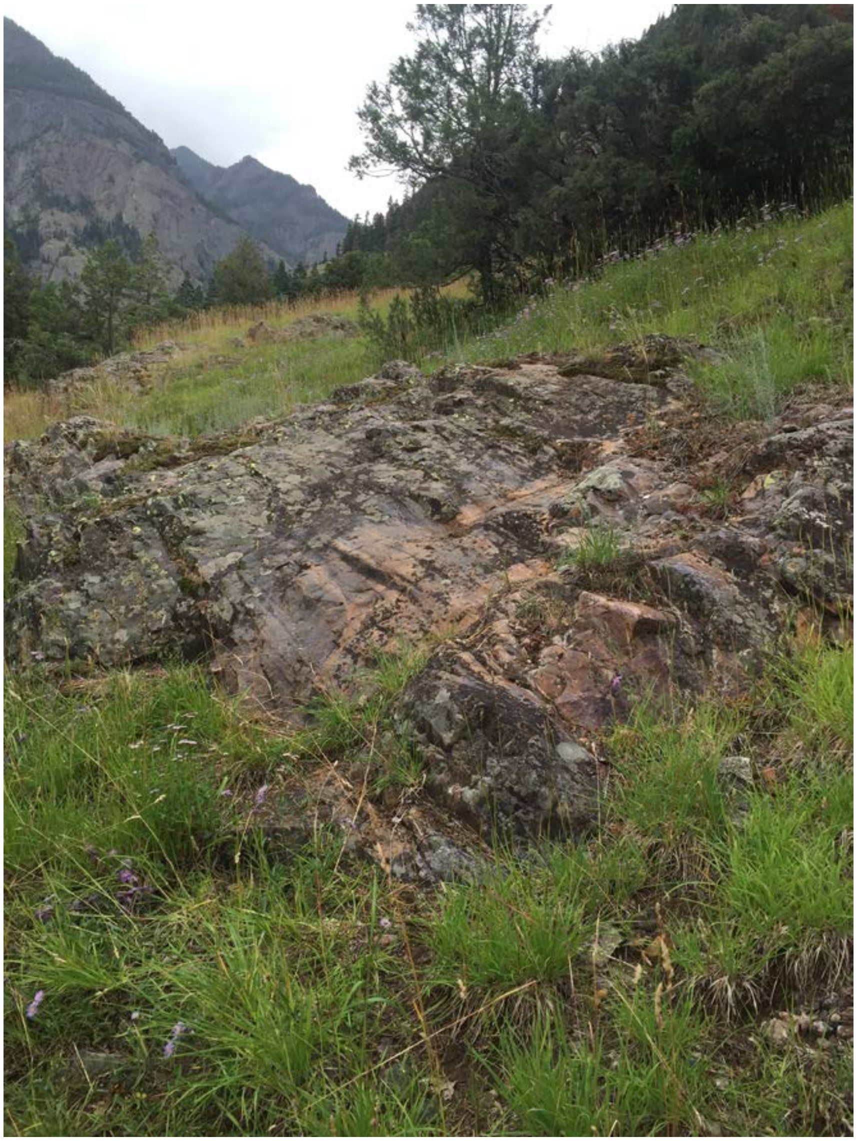
Latitude: 38° 0'46.16"N

Longitude: 107°39'47.48"W

A-11. **Roche Mountonée-** At this location, notice how the Uncompahgre Formation appears to have smooth linear striations. This was caused by immense pressure and movement from glaciers that were present here during the Pleistocene time period.

Latitude: 38° 0'58.93"N

Longitude: 107°40'34.64"W



A-12. **Ice Park Reservoir:** The Ice Park Reservoir was developed by the town of Ouray to assist with creating the ice climbing routes for the famous Ice Park in the Uncompahgre River gorge.

Latitude: 38° 0'51.27"N

Longitude: 107°40'20.73"W

A-13. **Uncompahgre Quartzite-** Here is another example of Roche Mountonée. Notice how the Uncompahgre Quartzite formation looks to have been polished smooth. This happened in response to many years of glaciers sliding over this surface.

Latitude: 38° 1'3.60"N

Longitude: 107°40'44.39"W

A-14. **High Bridge Angular Unconformity**- This Angular Unconformity was formed over hundreds of millions of years. The Uncompahgre Formation was deposited as flat lying sedimentary rocks and were later tilted almost 90 degrees by a tectonic event. At a later point in geologic history, a large portion of the Uncompahgre Formation was eroded and truncated by the flat-lying rocks of the Elbert Formation.

Latitude- 38° 1'3.46"N

Longitude- 107°40'43.26"W

A-15. **Calcite Vein-** Notice the white vein of crystalline calcite. This was likely formed from hydrothermal alteration where mineral rich fluids under high temperature and pressures work their way through cracks in the rocks. This is an example of how the rich ore deposits were created in the area.

Latitude- 38° 1'7.14"N

Longitude- 107°40'44.79"W

A-16. The Blowout- Notice the yellow to gray appearance of this mountain side. This area was subjected to a volcanic blowout in the Tertiary geologic time period. This event is believed to have happened roughly 50 million years before present. The center of the blowout is located at:

Latitude- 38° 2'22.31"N

Longitude- 107°40'1.76"W

The blowout can be seen on the trail from several different locations, but can best be seen from the Blowout waypoint located at:

Latitude: 38° 1'14.62"N

Longitude: 107°40'44.80"W

A-17. Oak Creek Bridge Troll- Don't forget to check for the troll under the bridge that crosses over Oak Creek! *Disclaimer- Do not climb!!!

Latitude: 38° 1'21.09"N

Longitude: 107°40'49.95"W

A-18. Amphitheater Landslide: The Amphitheater Landslide is outlined in red in this photo. This landslide was likely caused after the glaciers receded during the Pleistocene time period leaving behind over-steepened slopes. A mixture of deposits overcame the angle of repose and slid down slope. This landslide covers an area of ~81,834,372 square feet!!

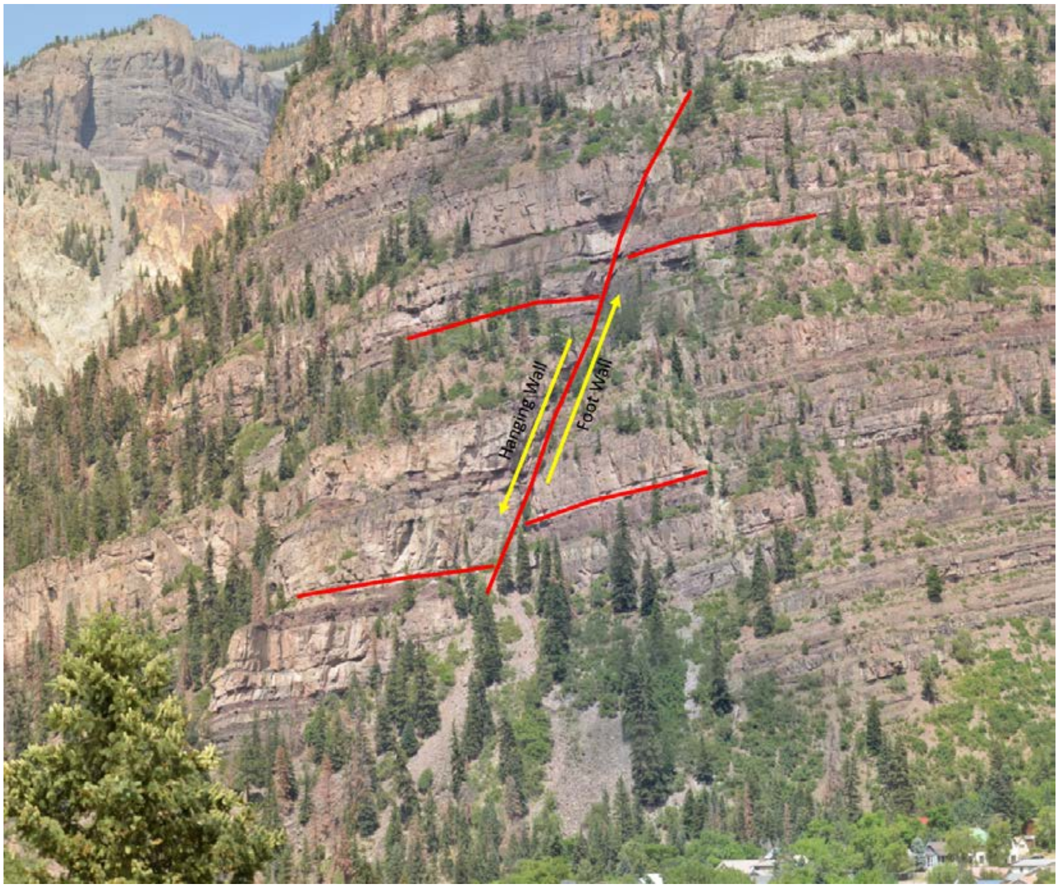
Latitude: 38° 1'19.57"N

Longitude: 107°40'44.97"W

A-19. Normal Fault Example- This is a great example of a Normal Fault caused from domal uplift. Normal Faults are oriented with the hanging wall being down thrown relative to the footwall. These faults are generally formed in an extensional stress regime.

Latitude: 38° 1'19.57"N

Longitude: 107°40'44.97"W



A-20. Amphitheater Lookout: At this location, be sure to observe the bowl-like shape of the mountain face and u-shaped valley. This is referred to as a glacial cirque. Glaciers during covered this part of the San Juan Mountains and really helped shape the landscapes you see today!

Latitude: 38° 1'19.57"N

Longitude: 107°40'44.97"W

APPENDIX B: GIGAPAN PHOTO LINKS

B-1. Eastern Facade view of Ouray: http://gigapan.com/gigapans/191345

B-2. Western Facade view of Ouray:

http://gigapan.com/gigapans/7e0cd8965e6b380bfe16e3b0d6544f7f

APPENDIX C: PERIMETER TRAIL APPLICATION ACCESS

The Perimeter Trail Story map may be accessed *via* the link below.

-http://arcg.is/2jlw3Ke