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The development of the first legend for geomorphologic mapping of high mountain environments in the United Sates

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THE DEVELOPMENT OF THE FIRST LEGEND FOR GEOMORPHOLOGIC MAPPING OF HIGH MOUNTAIN ENVIRONMENTS IN THE UNITED STATES

By

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Geomorphological mapping is the attempt to depict the physical setting of the surface of the earth by mapping the landforms present and the processes responsible for their appearance, and is method that is practiced worldwide. Currently, there is no universally accepted legend for mapping the geomorphological features of all environments, though there have been several attempts made to develop such a legend. Instead, many different European nations have developed their own geomorphologic mapping legends for mapping the landscapes that exist within their national boundaries. In addition, certain countries have even developed highly specific geomorphologic mapping legends for specific geomorphologic environments. The United States has neither a geomorphological mapping legend suitable for mapping the entirety of landscapes that exist within the United States' boundaries, nor geomorphologic mapping legends suitable for mapping specific environments. This thesis was an attempt to develop the first geomorphologic legend for mapping the geomorphologic setting of high mountain environments in the United States.

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1. INTRODUCTION

Landforms are ubiquitous elements existing on the surface of the earth. The shape and appearance of each landform is generally unique to the environment in which it exists and the processes that are responsible for creating it. From the Himalayas of Asia to the Sahara desert of Northern Africa, and from the limestone cliffs off the coast of Greece to the great plains of North America, landforms of all different shapes and sizes can be observed.

Geomorphological mapping is the attempt to depict the physical setting of the surface of the earth by mapping the landforms present and the processes responsible for their appearance. Currently, geomorphological mapping is an approach within the sub-discipline of geomorphology that is practiced worldwide. However, there is no universally accepted system for mapping the geomorphological features of all environments, though there have been several attempts made to develop such a system. Instead, many different geomorphologic mapping legends have been developed by European countries such as Germany, France, Austria, and Switzerland, which have been used for mapping the landscapes that exist within their national boundaries. In addition, certain countries have even developed highly specific geomorphologic mapping legends for specific geomorphologic environments. For example, Kneisel et al. (1998) introduced a German geomorphologic mapping system for high mountains to be used by researchers from Austria, Germany, and Switzerland.

Historically, the agencies within the United States government, such as the United States Geologic Survey (USGS) and the Federal Geographic Data Committee (FGDC), have had little interest or input in the development of geomorphological mapping as an emerging field. As a result of this, the United States has neither a general geomorphologic mapping system, like those used by European countries for nationwide geomorphologic mapping, nor specific geomorphological mapping systems, like that used by Kneisel et al. (1998) for mapping high mountain environments. With the unique variety of landscapes that exist within the United States, from coasts to plains, to mountains and deserts, the development of a nationally unified series of geomorphological mapping systems for mapping specific environments, each capable of mapping large- to medium-scale areas, is necessary for the production of a nationwide geomorphological map.

This thesis was an attempt to answer the question, how does one effectively represent geomorphological features that exist within high mountain environments in the United States? Though there are legends in existence that may be used for mapping the geomorphology of these environments, such as the highly detailed legend developed by Kneisel et al. (1998) specifically for high mountain environments, or the legend developed by Pavlopoulos et al. (2009) for general geomorphological mapping of all environments, they are not entirely appropriate for reasons such as complex symbology that is often difficult to differentiate, or a legend that lacks the ability to represent certain features on the surface.

This thesis had two objectives: 1) to develop a legend specifically for mapping the geomorphology of high mountain environments in the United States, and 2) to produce multiple geomorphological maps at different scales using this legend to demonstrate its ability to effectively represent these environments. To accomplish this, extensive research was performed regarding different aspects of geomorphological mapping as well as principles of visual design. Fieldwork was then performed in a designated study area in the Rocky Mountain National Park in the summer of 2012; the case study is used to provide an example of the capability of the newly developed legend for representing geomorphological landforms and processes. The result of the thesis is the first geomorphological mapping system specifically for mapping high mountain environments in the United States.

2. BACKGROUND

2.1 The History of the Study of Geomorphology

Geomorphology is described as "the scientific investigation of landscapes, the processes that have formed them over time, the materials which they are composed of, the individual elements that combine to create them, and the way they will evolve through time" (Griffiths et al., 2011: 3), or simply the scientific investigation of landforms and the processes that shape them over time. The term geomorphology, first used in the late 1880s, is comprised of three Greek terms, *ge* meaning "earth," *morphe* meaning "form," and *logos* meaning "to write about," thus literally meaning to write about the form of the earth.

Though the discipline geomorphology is a seemingly young science, emerging in the late 19th century, people have long thought about the landscapes that surround them and the processes responsible for their physical appearance. "s landforms are the most widespread geologic phenomena, speculation as to their origin has gone on since the days of the ancient philosophers" (1969: 2). Some of the earliest writings concerning the surface of the earth and the processes that have formed it date back to ancient Greece and Rome. Xenophanes of Colophon (c. 580-480 BC) hypothesized that the earth's surface had risen and fallen throughout history, as there were seashells that existed on mountaintops (Huggett, 2011). Herodotus (c. 484-425 BC) considered the formation of the Nile delta, believing it to have formed due to the deposition of the mud from the Nile in the Mediterranean Sea (Martin, 2005). Aristotle (c. 384-322 BC) believed that both land and sea exchanged places over time (Hugget, 2011). Strabo (c. 54 BC – 25 AD) concluded that the origin of Mt. Vesuvius was caused by volcanic activity because of the nature of its summit. Seneca (c.? BC - 65 AD) recognized that rivers and streams were responsible for creating the valleys which they lied in.

Following this period of substantial thought concerning the physical world around us, many centuries passed having with little to no scientific thinking in Europe. In fact, Thornbury (1969: 4) stated, "so little progress was made in Europe from the days of the first century AD until the opening of the sixteenth century that little need to be said about it." Leonardo da Vinci (1452 – 1519) would break this stalemate of scientific thought, as he came to recognize that valleys were formed by fluvial incision and that the rivers and streams that lie in them were responsible for transporting and depositing eroded material elsewhere. Buffon (1707 – 1788) recognized the ability for rivers and streams to alter the landscape due of their erosive ability (Thornbury, 1969). Horace Bénédict de Saussure, from Switzerland (1740 – 1799), was one of the first true mountain geomorphologists, though technically a geologist. Saussure recognized the ability for streams and glaciers to sculpt mountains (Thornbury, 1969).

Concepts of modern geomorphology began to evolve at the end of the 18th century with the work of James Hutton (1726 – 1797). Of Hutton's many contributions to the discipline of geomorphology, it was his explanation of the concept, "the present is the key to the past" (in his work *Theory of Earth, with Proofs and Illustrations* in 1795), that was most notable. Hutton's work would have a profound impact on the discipline of geomorphology as many of the basic concepts of modern geomorphology can be found in his theory (Thornbury, 1969). The ideas and conclusions presented by Hutton had a profound impact on Charles Lyell (c. 1797 – 1875), who "became the great exponent of uniformitarianism…and probably did more to advance this principle and geologic knowledge in general than any other man" (Thornbury, 1969: 8). Lyell's greatest contribution to geology and geomorphology was his book, the *Principles of Geology*.

Thornbury (1969: 10) referred to the period between 1875 and 1900 as the "heroic age in American geomorphology." Thornbury (1969) stated that three individuals were largely responsible for laying the framework from which modern geomorphology would ultimately be built upon: John Wesley Powell (1834 – 1902), Grove Karl Gilbert (1843 – 1918), and Clarence Edward Dutton (1841 – 1912). Powell's most notable contribution to geology and geomorphology was the concept of a base level, or the lowest level that the land surface can be reduced to. "rove Karl Gilbert merits the recognition as the first true geomorphologist produced in this country [United States]…to him we are indebted for a keen analysis of the processes of subaerial [above sea level] erosion and the many modifications which valleys undergo as streams erode the land" (1969: 11). Dutton is probably most known for his analysis of individual landforms and his work regarding "the great denudation" (Thornbury, 1969). The work of these three individuals effectively initiated the development of geomorphology into its modern state.

It is unlikely that any other individual in the history of the discipline of geomorphology has had a more profound effect than William Morris Davis (1850 – 1934) (Thornbury, 1969). Of his many contributions to the discipline, his most notable was his theory of landscape evolution, which he referred to as the "geographic cycle." Most importantly, Davis was responsible for systematizing, or bringing together, the work of those before him (Engeln, 1942).

Up until this point, the discipline of geomorphology had been largely a descriptive or qualitative science, primarily concerned with understanding the history of the landscape and the landforms that comprise it. However, it was in the middle of the 20th century that the discipline of geomorphology became more quantitative, being concerned primarily with the processes responsible for the development of landforms within the landscape. This came to be known as *Process Geomorphology*.

Process geomorphology was established largely by Arthur N. Strahler in 1952 with his publication of the *Dynamic Basis of Geomorphology*. In it, he "proposed a system of geomorphology grounded in basic principles of mechanics and fluid dynamics that he hoped would enable geomorphic processes to be treated as manifestations of various types of shear stresses, both gravitational and molecular acting upon any type of earth material to produce varieties of strain, or failure, which we recognize as the manifold processes of weathering, erosion, transportation, and deposition" (Hugget, 2011: 12). Strahler, among others such as Luna B. Leopold and M. Gordon Wolman, were fundamental in the development of geomorphology as an empirically based and driven science.

The latter half of the 20th century gave rise to the further quantification of the geomorphologic discipline. Detailed field measurements and the use of mathematical and statistical models became prominent in the 1970s and 1980s. One of the most important contributions in this era of geomorphologic thought was the introduction of the concept of geomorphologic thresholds from Stanley A. Schumm. This concept holds that, "episodes of abrupt change can occur in geomorphic systems as thresholds are transcended" (Rhoads and Thorn, 2011: 69).

Contemporary geomorphological studies have been witnessed several trends. These are, " (1) an increasing concern with complexity and nonlinear dynamics, (2) rapid advances in measurement technology, (3) increasing computation and information-processing capabilities, (4) enhanced collaborations with other disciplines, especially engineering and the life sciences, (5) interest in philosophical issues, (6) concern about practical aspects of human impacts of geomorphological systems, and (7) a renewed focus on landform development over geological time scales" (Rhoads and Thorn, 2011: 70).

2.2 Geomorphological Mapping

Geomorphology is a science that is concerned with the landforms existing on the surface of the earth and the processes that are responsible for their formation. According to Hugget, "form, process, and the interrelationships between them are central to understanding the origin and development of landforms" (2011: 3). *Form* refers to the shape, or appearance of a landform, also known as a geomorphological unit, in the landscape. *Process* is defined as the "action involved when a force induces a change, either chemical or physical, in the materials or forms at Earth's surface" (Ritter et al., 2002: 2). Geomorphological mapping is the process of attempting to map earth's landforms and the processes that are responsible for their appearance.

Paron and Claessens state, "geomorphology is a young discipline compared to geology and soil science emerging from earth science and geography, and systematic geomorphological mapping is even younger" (2011: 75). Geomorphological mapping as we know it today dates back to the early 20th century when, in 1914, Siegfried Passarge (1866-1958) published what is considered to be the first detailed geomorphological map in a *morphological atlas*, which included eight separate maps describing "describing topography/vegetation, slope gradients (in five classes), valley forms, stratigraphy, physical resistance, chemical resistance, petrography and relief development" (Gustavsson, 2005: 9). However, the history of mapping the physical environment dates back far beyond the beginning of the 20th century, because, as Smith states, "mapping of landforms is probably as old as the making of maps" (Smith and Pain, 2011: 142).

Many of the earliest known maps contain information related to the topography of the earth. Early Babylonian maps produced c. 4500 years ago depicted the physical landscape using different symbolic elements, such as mounds representing mountain ranges or lines representing hydrographic elements (Gustavsson, 2005). Though these early maps were not scientific in nature, they still provided information regarding the physical landscape.

Over time, the way in which people have represented the physical landscape has evolved. As stated earlier, the first maps produced used the mound method to represent topography. This technique eventually gave way to the hachure method. The hachure method was adopted in the 18th century (Gustavsson, 2005); it depicts relief using parallel lines, in which the relative distance between the lines represents the steepness of the slope. In the 19th century, the hachure method was replaced by the use of contour lines and shaded relief maps to represent topography. Though contour lines and shaded relief maps can be used for the basic interpretation of the physical landscape, they fail to provide detailed information regarding the geomorphology of a landscape.

Modern geomorphological mapping is rooted in the physiographic descriptions and illustrations of the late 19th century. Pavlopoulos et al. state, "throughout the 19th century and into the early years of the 20th century, the principal method for studying landforms was through static descriptive physiography" (2009: 7). Descriptive physiographical research consisted of written descriptions of the geomorphological processes at work in a landscape and was often accompanied by illustrations such as sketches or block diagrams. Though many of these artistic renditions of the landscape and the geomorphological units and processes acting within it were excellent illustrations, they tended to be primarily pieces of art, offering qualitative descriptions rather than quantitative information (Pavlopoulos et al., 2009).

Physiographical descriptions and illustrations of a region's geomorphology gave way to early geomorphological maps at the beginning of the 20th century. Geomorphological maps published at this time, such as Passarge's from 1914, were very basic, depicting only specific or selected geomorphologic features or processes (Gustavsson et al., 2008). Geomorphological mapping would remain stagnant from this point, changing little, until after World War II. It was in the 1950s that the concepts of geomorphological mapping would begin to evolve into their current state.

According to Pavlopoulos et al., "in the 1950s and 1960s, the science of geomorphology developed into analytic physiography of the Earth's surface and the detailed geomorphological map became the research tool in geomorphology" (2009: 8). Technological advancements in remote sensing which were brought about due of the "very dynamic warfare style of World War II" changed the way in which geomorphological research was conducted. Remote sensing is defined as the "science and art of acquiring information about an object or phenomena without physically coming in contact with it" (Rao, 2002: 2), and it provides specific advantages for geomorphologic studies: multi temporal capabilities, multispectral capabilities, multi spatial capabilities, and the capability for remote sensors to obtain elevation data (Rao, 2002). Though the technological advancements of remote sensing greatly affected the ways in which geomorphological research was conducted, it was in the 1950s and 1960s that geomorphological mapping experienced its most notable development.

In 1956, M. Klimaszewski initiated a countrywide effort to map the geomorphology of the entirety of Poland at the 1:50,000 scale (Verstappen, 2011). This was the first effort to systematically survey the geomorphology of a country at such a large scale. Following shortly after, several other European countries developed similar geomorphological maps, such as France, Denmark, Germany, and Switzerland (Embleton and Verstappen, 1988; Verstapppen, 2011). As many European countries began to produce large-scale (detailed) geomorphological maps, a great variety of different geomorphological mapping systems were developed. Because of the many different geomorphological mapping systems that existed, several attempts were made in the 1960s by the International Geographic Union (IGU) and its Working Group on Geomorphological Survey and Mapping to develop an international standard system for geomorphological mapping (Embleton and Verstappen, 1988).

In 1962, representatives from fifteen different countries gathered in Krakow, Poland with the specific task of establishing certain guidelines for the production of geomorphological mapping. The guidelines, as described by Pavlopoulos et al., 2009, stated that:

- fieldwork, in conjunction with the use of aerial photo interpretation, is a basic necessity;
- maps produced should be in at a scale between 1:10,000 and 1:100,000;
- maps should contain information regarding morphography, morphometry, morphogenesis, and morphochronology "in order to study relief's past, present, and future development" (Pavlopoulos et al., 2009: 10);
- color and symbols should both be used for cartographic representation;
- the chronological order of landform development should be apparent;
- lithological data should be included;
- the legend should be arranged in a genetic-chronological order

In 1968, the IGU Working Group on Geomorphological Survey and Mapping, headed by J. Demek, presented the IGU Unified Key in the Manual of Detailed Geomorphological Mapping (Gustavsson, 2005). Shortly after, the Working Group developed similar versions of the original IGU Unified Key for medium- and small-scale geomorphological mapping. At the same time, the International Institute for Aerial Survey and Earth Sciences (ITC) was also developing a comprehensive system for geomorphological mapping at all scales. These two systems were the first attempts at the development of an international standard system for geomorphological mapping; however, since then, "the number of legends, representing different approaches and methodologies, has proliferated" (Pavlopoulos et al., 2009: 10).

Since the 1970s, development in the field of geomorphological mapping has primarily been because of technological advancements. As Smith and Pain (2011: 144) stated, "the biggest driver of geomorphic mapping has been technology: the availability of new data sources has allowed new insights and rapid mapping to be performed, organized under within the framework of a GIS [Geographic Information System]". Advances in remote sensing, aerial photography, radar imagery, and computer science are having a profound impact on geomorphological mapping. "Satellite imagery remains an important ongoing data source with an increasing trend towards longer archives, higher spatial resolution and greater data volumes; however, it has been the DEM [Digital Elevation Model] that has been at the forefront of much recent research" (Smith and Pain, 2011: 144). Contemporary geomorphological studies have been primarily concerned with methodological refinement. Many studies that have been recently conducted have attempted to reduce, or even remove, the subjective element of geomorphological mapping: human interpretation of landforms within the landscape. There has been a considerable amount of research conducted concerning automated and semi-automated techniques for identifying and delineating landforms using remotely sensed data.

2.3 Geomorphological Map Content

The content depicted in geomorphological maps provide the reader with information related to five fundamental landform concepts; these concepts are *morphology*, *morphometry*, *morphogenesis*, *morphochronology*, and *morphodynamics* (Pavlopoulos et al., 2009). *Morphology* refers to the appearance and or shape of the landscape. *Morphometry* is a concept regarding the geometric measurements of a landscape, such as slope, elevation, or curvature. The concept of *morphogenesis* refers to the origin or formation of a landform or landscape. *Morphochronology* is a concept dealing with the absolute or relative age of the landscape or landforms in the landscape. *Morphodynamics* refers to the current geomorphologic processes that are influencing the shape of the landscape and the landforms within it.

Dramis et al. (2011) stated that there are two different categories of geomorphological maps: *basic geomorphologic maps*, and *derivative geomorphological maps*. *Basic geomorphological maps*, also known as analytical maps, are geomorphological maps created using data collected directly from fieldwork, aerial photograph interpretation, or existing geologic, soil, vegetation, or land use maps. Basic geomorphological maps can be produced from two different perspectives. They may be made from a *morpho-evolution* perspective, or a *morphodynamic* perspective.

Morpho-evolution geomorphological maps are "concerned with the evolution of the landscape over geological timescales" (Dramis et al., 2011: 41). These maps are generally produced at smaller scales and provide a more general view of the geomorphology of a landscape. "Morpho-evolution maps represent Earth surface evolution in relation to endogenous agents (such as large-scale crustal vertical movements, surface tectonics and volcanism) and exogenous processes connected with past to modern climates" (Dramis et al., 2011: 41).

Morphodynamic geomorphological maps are concerned with the present geomorphology of Earth's surface. Morphodynamic maps are generally produced at larger scales and, hence, attempt to depict all landforms, surficial deposits, and processes related to the geomorphology in the landscape. In addition, morphodynamic geomorphological maps also may include non-geomorphological elements of the landscape, such as soils, landcover, hydrology, or landuse.

According to Dramis et al., "*derivative geomorphological maps* are obtained through selection, generalization and reuse of data reported in basic maps with the purpose of zoning the spatial/temporal distribution of significant geomorphological processes" (2011: 42). Derivative geomorphological maps, also known as *pragmatic geomorphological maps*, are more easily readable than basic geomorphological maps, thus making them capable of being read by specialists and non-specialists alike. Derivative geomorphological maps are often used by engineers, planners, and decision makers (Dramis et al., 2011).

2.4 The Uses of Geomorphological Maps

Dramis et al. claim that, "geomorphological maps are amongst the best tools for understanding the physical context of the Earth's surface" (2011: 39). As stated earlier, geomorphological maps provide detailed information regarding the landforms existing on the surface of the earth and the physical processes responsible for creating them. They are currently used in many different applications, and it can be assumed that in the future, the number and importance of these applications will only increase (Smith and Pain, 2011).

Paron and Claessons (2011) stated that the makers and users of geomorphological maps can generally be placed into categories: national departments, private companies, and research and development institutions.

Since the 1950s, many different countries, predominantly European, have produced nationwide geomorphological maps. The purpose of an extensive nationwide map, such as the *Geomorphological Atlas of the People's Republic of China*, is to attempt to document all aspects of a region's geomorphological setting, and thus is incredibly complex. Nationwide geomorphological maps are not produced with the intention of answering specific questions, as are geomorphological maps produced by private companies and research and development institutions.

Geomorphological maps produced by private companies and research and development institutions are produced to answer specific questions. These kinds of geomorphological maps are often much simpler in their presentation than nationwide geomorphological maps, as they need only to present information directly related to the questions they are attempting to answer, such as "which area is most prone to flooding," or "where is there the greatest risk of landslide activity?" Private companies that often make and use geomorphological maps are insurance companies, engineering firms, and environmental agencies.

In addition to these three broad categories, it is necessary to describe a fourth maker and user of geomorphological maps: academics. Academic geomorphologists often produce geomorphological maps for the purposes of scientific inquiry, or for the advancement of the field through methodological refinement or technological improvement. For example, Seong et al. (2009) published results concerning the geomorphological setting of the Skardu, Shigar, and Braldu Valleys in the Central Karakoram, Pakistan; several geomorphological maps were included in the publication to provide a visual aid for understanding the geomorphological setting of the region. Geomorphological maps are also often produced in order to demonstrate the use of a new method or technique for geomorphological mapping. For example, research was conducted on the expert-driven semi-automated geomorphological mapping of mountain environments (Asselen and Seijmonsbergen, 2006).

2.5 Elements in Geomorphological Map Design

In 2011, Jan-Christoph Otto, Marcus Gustavsson, and Martin Geilhausen published the article, *Cartography: Design, symbolization and visualization of geomorphologic maps* in the journal, Developments in Earth Surface Processes. This article provides detailed information regarding the theory of cartographic design in relation to geomorphological mapping and was used as the basis for the theoretical background of cartographic design. According to Otto et al., “geomorphological maps are highly complex thematic maps depicting the composition of the Earth’s surface and the processes working there” (2011: 254). As the surface of Earth is highly complex and extremely dynamic, it should be the goal of the cartographer to depict this environment in a way that is detailed enough to “reduce subjective impressions” (Gustavsson et al., 2006: 92), yet maintains an element of easy readability. Unfortunately, it is not uncommon for geomorphological maps to be so detailed and complex that they lose their ability to convey relevant information to the reader, essentially rendering them useless. It is the holistic design of the map, including the layout and different components, which affect its ability to communicate information effectively. Elements in cartographic design include basic design principles, symbolization, and map layout and organization.

2.5.1 Basic Design Principles

There are four basic principles of cartographic design: *legibility*, *visual contrast*, *figure-ground perception*, and *hierarchical organization*. These design principles affect the overall readability of a map, which ultimately affect how effectively the content of the map is communicated.

Legibility, as described by the *New Oxford American Dictionary* (2013), is the quality of being clear enough to read. It is arguably the most important of the basic principles of cartographic design. The legibility of a map determines its effectiveness at communicating information. Geomorphological maps are especially prone to becoming illegible, as they attempt to depict highly complex environments using a great number of different symbols. The readability of a geomorphological map is largely affected by symbol size and density. Symbol size and density are determined by the scale of the mapped area and the actual size (or the physical dimensions) of the map.

Otto et al. state that, "[*visual*] *contrast* is the basis of vision" (2011: 259). Contrast is defined as the state of being strikingly different from something else (New Oxford American Dictionary, 2013). Visual contrast, in the context of cartography, is referring to the ability for map users to differentiate objects in the map from one another; it can be achieved by implementing visual variation in the map.

Figure-ground perception, as described by Otto et al., is "a person's ability to distinguish between an object and its surrounding" (2011: 259). The "figure" refers to a specific object, while the "ground" refers to the background. Figure-ground perception helps to convey the relative importance of mapped information. In the context of geomorphological mapping, "figures" are the objects of interest, or the geomorphological units or landforms, while the "ground" is the landscape. Geomorphological units are the more important objects in this scenario, and thus need to draw the reader's attention.

Differences, inter-relationships, and hierarchies that exist between objects are often depicted using *hierarchical organization*. This principle of design is used only marginally in geomorphological mapping. Hierarchical organization comes from the concept of visual hierarchy. According to Hashimoto and Clayton, "When a design consists of many different areas of emphasis, the concept of hierarchy must be introduced. The idea of visual hierarchy is to organize each area of emphasis so that it does not conflict or take away attention from another area of emphasis" (2009: 48).

2.5.2 Symbology

Brewer states that, "the subtlest of details can determine how map data is read and interpreted. The shape of a marker, the width of a line, the arrangement of a pattern – each conveys specific information" (2005: 143). Cartographic representation is achieved by the use of three basic feature types: *points*, *lines*, and *areas*. Otto et al. claim, "a differentiation of these basic representations, to express relationships among or differences between the data, can be achieved by variations of the basic visual variables: *shape*, *size, orientation, texture, or color*" (2011: 255).

A *point* is the most basic feature class that can be used to represent data. Points are typically used in cartography to represent the geographic location of an object; however, they are not limited just to representing feature locations on a map. The scale of a map will determine whether a point will be used to represent the specific geographic location of an object, or an area. Point symbols variations can be created using the visual variables size, shape, orientation, and color.

Lines are another basic feature class that is used to represent data on a map. Lines are used in cartography to represent long, linear features, such as streams, rivers, or roads. Once again, map scale also determines whether a feature will be represented in a map using a line or a polygon. A common example of the importance of scale can be observed when attempting to represent a river or stream in a map. At a smaller scale, a river or stream is most effectively depicted using simple lines. However, at larger scales, it may be more appropriate to represent the river or stream using an area, or polygon. Variations in linear symbols can be achieved using size, shape, orientation, texture, and color.

Areas, or polygons, are the third kind of basic feature class that can be used to represent geographic data on a map. "Polygons on a map enclose areas that represent the shape and location of homogeneous areas, such as lakes, forest stands, and soil types" (Zeiler and Murphy, 2010: 51). Variation in polygon design can be accomplished using size, shape, orientation, texture, and color.

Shape refers to the form, or appearance, of a symbol. According to Otto et al., "shape variation…is the most commonly applied visual variable in geomorphological maps because of the great number of different symbols for different landforms" (2011: 257). Symbol shapes used for representing data can be simple, such as circles, squares, or triangles, or they can be complex. *Size* refers to the geometric dimensions of a symbol. Specifically, it refers to the symbol's length, width, or area, and not the actual size of the object it represents. The size of a symbol can be used to portray variations in the physical size of an object, or the relative importance of the object. *Orientation* refers to the relative position of an object in relation to others. It is most commonly used to symbolize the direction of flow of an object, such as a debris flow or a rock fall. *Texture* is a visual variable that affects the appearance of areal and linear objects. It refers to the "shape, orientation or the spacing of components that generates a pattern" (Otto et al., 2011: 256). Textures can be randomly or systematically ordered.

Gustavsson et al. states, "*color* is the most eye-catching graphic variable" (Gustavsson et al., 2006: 92). Because of this, it is the most powerful way to differentiate objects from one another (Otto et al., 2011). There are three characteristics of color that can be manipulated to create differences and relationships in cartographic representation, these are: hue, value (or lightness), and chroma (or saturation). *Hue* refers to the pure color that we associate with color names, such as red or blue. In actuality, hue refers to the dominant wavelength of the electromagnetic spectrum emitted from an object that is sensed by the human eye. Hue, when used in different kinds of thematic mapping, is most often used to indicate or differentiate features (Brewer, 94). *Value* is the inherent "lightness" or "darkness" of a hue. Variations in the value, or lightness, of mapped data is usually used to represent a hierarchy or ranking within the data. A hue's value can be manipulated by adjusting its tint or shade. Tint is affected by adding white to a hue; this causes the hue to appear lighter. Shade is affected by adding black to a hue, causing the hue to appear darker. *Chroma*, or saturation, is the "colorfulness" of a hue. Cynthia Brewer described it as "a measure of the vividness of a color" (Brewer, 2005: 96). Chroma is the amount of color in proportion to the amount of grey. A completely saturated hue is one that contains no proportion of grey within it. As the proportion of grey is increased within the hue, it becomes desaturated. Desaturated hues are greyer than saturated hues, and thus more neutral.

2.5.3 Map Layout and Organization

According to Otto et al., "graphic communication, like maps, delivers all information at once. This means information is not perceived sequentially, but instantaneously with respect to the location and relative position on the map sheet or screen. Thus, the appearance and composition of graphical elements should be considered thoughtfully" (2011: 263). In order for a map to be most effective in communicating information, it must be designed in a way that exploits human perception. Maps contain a series of components that give it context and provide the user with important information regarding the mapped data, the orientation of the map, and the relative location of the mapped data. These components commonly include the legend, inset map, north arrow, coordinate grid, scale bar or text, information regarding the coordinate system and map projection, the map author, the date of production, and any other additional information. According to Otto et al., "map components have to by systematically arranged to generate visual harmony and balance and to deliver the message of the map" (2011: 262).

"Map layout," according to Otto et al., "consists of the arrangement of the map components into a functional composition and a meaningful and aesthetically pleasing design to facilitate the visual communication" (2011: 262). In order to organize the final map document in a way that is not only effective at communicating important information, but also aesthetically pleasing, concepts of *planar organization* must be adhered to. Planar organization consists of three distinct concepts: *focus, balance, and internal organization*.

Focus refers to the location on a map that focuses the users attention. This is sometimes called the *focus of attention*. A map's design must be arranged in such a way that it guides the attention of the reader towards the focus of the map, as in the main map rather than the components that give context to the main map. Otto et al. claim, "the map reader tends to focus on the visual center, implying that the most important information should be positioned here" (2011: 262). The visual center of the map is not the geometric center of the map; rather it lies slightly above the geometric center.

Hashimoto and Clayton state that, "the visual principle that a design is weighted equally is called balance" (2009: 49). Balance, in the context of cartography, refers to the perceived visual weight of elements in the final map. Visual weight is ability of an object or element in a graphic composition to draw the focus of the reader to itself. The visual weight of an object depends on several properties: *position*, *size*, *shape*, and *color*; however, the most important of these properties determining the visual weight of objects concerning the layout and design of a map are position and size. *Position* refers to the location of an object. In the same way that one reads a book, maps are read in a particular direction. The human eye will traverse an imaginary line that goes from the top left corner to the bottom right corner of a graphic composition. Objects that are positioned in the upper left portion of this composition are "heavier" than those in the lower left portion. Objects that are positioned in the center of a composition also have a lesser weight than those that are lying away from the center, as a component's weight increases proportionally to its distance from the center (Otto et al., 2011: 263). The placement of the different components within a map should be arranged in a way that emphasizes the items importance.

Size refers to the geometric dimensions of an object. Objects that have a greater size have a greater visual weight than smaller objects. Thus, larger objects will tend to draw the readers attention more than smaller objects. In regards to the layout and design of a map, the components that are more important for effectively communicating the map's content should be greater in size than those that have lesser importance. For example, the main map should be the largest item on the map. The inset map that gives context to the main map should never hold a greater visual weight than the main map itself, as it is of less importance to the reader. The size of the map components should be determined by their relative importance.

Shape and color also affect the visual weight of an object in a map. These variables are only used marginally in the design and layout of a geomorphological map and are more important regarding the design of a symbol, however they are important to consider in this process. *Shape* refers to the form or appearance of an object. Objects that have a regular or uniform shape have a lesser visual weight than objects that have irregular shape. Regarding the design and layout of a geomorphological map, this variable is mainly applicable to the border of elements contained within the map, such as the main map or the inset map. Applying borders to other map elements, such as the legend or scale bar "should be avoided as it borders separate objects and interrupt the flow of visual perception" (Otto et al., 2011: 263).

Color also can affect an object's visual weight as well. Though this is more important regarding symbol design, it is useful to consider when designing the layout or organization of the final map. Otto et al. state, "colors draw the viewer's attention strongly to certain areas…[they] should be used for the most important information" (2011, 263). In a geomorphological map, the most important information is the main map and the legend, as they constitute the purpose of the map. These are the only components in the map that should have color. Applying color to other, less important, components within the map can cause them to draw the reader's attention.

Internal organization is the third element of planar organization that affects the functionality and aesthetics of a map. Internal organization refers to the underlying structure of the map. A map's structure provides it with a sense of visual order and generates harmony between the different components that create the whole. Internal organization is mostly achieved through the alignment of the components of a map in relation to one another. A common way to generate internal organization in a map is to use an imaginary grid for the positioning of different map components. According to Otto et al., "the grid subdivides the map sheet into horizontal and vertical paces and generates sight-lines that create stability of the layout" (2011, 263).

2.6 Issues in Contemporary Geomorphological Mapping

The purpose of geomorphological mapping is to produce a generalized and easily understandable visual representation of the physical setting of an area. Today, geomorphological mapping is practiced worldwide, and thus there are a great variety of different geomorphological mapping systems in existence. Because of this, the appearance and content of many geomorphological mapping systems varies.

2.6.1 The Lack of a Universally Adopted Geomorphological Mapping System

Currently, there is no universally accepted system for geomorphological mapping in existence. Though there have been numerous attempts since the 1960s to create and adopt a standard system for the geomorphological mapping of every environment at every scale, no such system is universally accepted.

2.6.2 Diversity of Legends

Though the overarching purpose of geomorphological maps and geomorphological mapping in general is to depict the physical surface of the earth, they often appear radically different. Otto et al. state, “maps covering the same area but mapped by different geomorphologists using different mapping systems can…give completely different impressions, depending on whether the emphasis is on morphometry/morphography, chronology, lithology, or genesis/processes” (2011: 267). Since the development of the comprehensive geomorphological mapping systems (the *IGU Unified Key* and the *ITC Geomorphological System*), the pursuit of a universal system for geomorphological mapping has largely been abandoned (with certain exceptions, such as the system developed by Pavlopoulos et al., 2009) as it lacks practicality (Verstappen, 2011). Instead, there have been many efforts to develop standard geomorphological mapping systems at the national level. Many countries, predominantly European, have developed systems specifically for the geomorphological mapping of their own environments, such as Germany, Spain, Switzerland, Sweden, and China among others (Otto et al., 2011).

In addition to the development of standard geomorphological mapping systems for national use, some countries have even developed standard systems for mapping specific environments, for example, high mountain environments.

2.7 Geomorphologic Legend by Pavlopoulos et al. (2009)

In 2009, Kosmas Pavlopoulos et al. published *Mapping Geomorphological Environments*, a highly descriptive textbook covering many different aspects of geomorphological mapping, including techniques, applications, and workflows. In addition, Pavlopoulos et al. also developed an extensive general geomorphological mapping system legend containing two hundred and thirteen different symbols, capable of mapping all types of geomorphological environments in all scales. This legend is owned and copyrighted by the academic journal publishing company Springer, which must be contacted in order to obtain permission to use the legend.

The system uses the three basic feature types: points, lines, and areas (or polygons). Though originally black and white, the authors demonstrate that the symbols can be modified in order to enhance their visual variance by applying color to them; this was demonstrated in five different case studies included in the text.

The system is subdivided into eight different categories: 1) fluvial; 2) coastal; 3) lacustrine; 4) glacial; 5) karstic; 6) volcanic; 7) aeolian; and 8) surface landforms, topography, lithology and tectonics. Each category contains symbols to represent what the authors consider "main" geomorphologic landforms. Though the system is seemingly comprehensive, as it contains symbols for each major geomorphological environment, it is lacking in is ability to represent the complete geomorphic environment. For example, the glacial environment category contains thirty-six different symbols. Several of the symbols included in the glacial environment category, which are considered by the authors to be main geomorphologic landforms in glacial environments, are not included in other geomorphologic mapping systems specific to high mountain environments, where alpine glaciation is highly prevalent. Symbols included in Pavlopoulos et al.'s (2009) system that are frequently not included in other geomorphologic mapping systems, such as Kneisel et al.'s geomorphologic legend for high mountain environments (1998), include crevasses, cryoturbation, fjord, gelifluxion, gelivation, glacial striations, kames, loess, pinko (polygons made of stones), and seracs.

Though the system developed by Pavlopoulos et al. is capable of mapping many different types of geomorphological environments, it is likely that it is not the most appropriate legend that can be used for the task of mapping high mountain environments due to its inherent lack of the ability to represent the geomorphological features that are present in high mountain environments. However, the system does provide a good example of a complete and unified geomorphological mapping system that could be used for the production of a nation-wide geomorphological map.

2.8 Geomorphologic Legend for High Mountains by Kneisel et al. (1998)

In 1998, a working group of German geomorphologists, under the direction of M. Richter, developed a standard legend specifically for geomorphological mapping of high mountain environments (Kneisel et al., 1998). This legend differs greatly from the system developed by Pavlopoulos et al. (2009), as it is highly specific, capable only of representing geomorphologic units features and processes that exist within high mountain environments. It is comprised of a total of fifty-five different symbols, and also uses the three basic feature types: points, lines, and areas (polygons).

The legend developed by Kneisel et al. (1998) is divided into eight different categories which contain symbols relating to each category; these are: 1) fluvial forming areas, 2) periglacial-nivation forming areas, 3) glacial forming areas, 4) geomorphic processes, 5) hydrology, 5) permafrost, 6) bedrock/sediment sizes, 7) dating of forming elements, and 8) edges, steps, and other forms.

A major difference between this legend and the legend developed by Pavlopoulos et al. (2009) is that it does not use color, with the exception of the use of the hue blue for representing rivers, streams, and lakes.

As mentioned above, the legend developed by Kneisel et al. (1998) is highly specific and focuses on geomorphological landforms, dynamics, and processes that exist and occur within high mountain environments. Symbols included in this legend are very descriptive and allow the user to obtain a great deal of information regarding the geomorphologic features and processes present in the environment. For example, the system includes three different symbols for representing rock glaciers. Each of the three symbols represents the state of the rock glacier, whether active, inactive, or historic, and only marginally differs in appearance. Another example of the highly specific nature of this system can be observed in the two different symbols used to represent precipices based on relative elevation differences. Once again, the appearance between the symbols only differs marginally.

As the system developed by Kneisel et al. (1998) is so specific, it is well suited for the geomorphological mapping of large and very large-scale environments. However, it is limited to a single environment that it is capable of representing.

3. PROJECT OBJECTIVES

Historically, geomorphological mapping has been predominantly a European tradition, with little involvement from the United States in the development of the field. While many western European countries have developed standard geomorphological mapping systems for their environments, such as Germany and Greece, government agencies within the United States, such as the USGS, have made no attempt to develop a standard system for mapping general geomorphological environments, let alone specific geomorphological environments, such as high mountain environments or coastal environments.

While the United States currently lacks its own geomorphological mapping system, it does possess a standard geologic mapping system. The Federal Geographic Data Committee (FGDC) and United States Geologic Survey (USGS) have comprised an extensive collection of cartographic symbols for use in mapping geologic environments. Geologic maps are designed to provide "complex information regarding the geology of an area, such as composition, age, genesis, and extent of an area's geologic materials, as well as the geometry, orientation, and character of the geologic structures that have deformed them" (FGDC, 2006: 11). The symbology used for producing geologic maps presents a significant problem for accurately representing the geomorphological aspects of a landscape. For example, Kellerlynn (2004) conducted a Geologic Resource Evaluation for Rocky Mountain National Park, Colorado. In her report Kellerlynn (2004: 14) stated, "Rocky Mountain National Park abounds in geologic features that may be of concern for park planning, public safety, or resource protection. Geologic features (or landforms) and processes have scientific and aesthetic significance, as well as continually affecting human beings and other living things. These features and processes may not be readily apparent on the park's geologic map".

3.1 Project Objectives

The primary objective of this project was the development a geomorphological mapping legend for use in high mountain environments in the United States. The legend developed in this thesis was specifically developed for representing the landforms and processes existing in the high mountain environments of the United States, though it is likely to be appropriate for use in other countries that contain similar topography. The legend will be based on two existing geomorphological mapping legends: the legend developed by Kneisel et al. (1998) and the legend developed by Pavlopoulos et al. (2009), which are not entirely appropriate for mapping the geomorphological features present in high mountain environments in the United States. These legends were selected as they present two different approaches to geomorphological mapping: the legend by Kneisel et al. (1998) is highly detailed and was developed specifically for high mountain environments, while the legend by Pavlopoulos et al. (2009) is much more generalized and was developed for geomorphological mapping of all environments.

In addition, the project aimed to test the ability of the newly developed legend to depict the geomorphological setting of a high mountain environment in the United States by producing multiple geomorphological maps using the newly developed legend. While the accuracy of the created geomorphological map is of obvious important, it is not the objective of the project to create a completely accurate geomorphological map of the study area; rather it was to develop a legend for the geomorphological mapping of high mountain environments in the United States and to test its ability to effectively communicate information related to the geomorphological features within a landscape.

3.2 High Mountain Environments

Currently, there is no international standard definition for a high mountain environment, or *Hochgebirge*. Barsch and Caine (1984: 288) stated that there are four fundamental characteristics of mountain terrain: "elevation; steep, even precipitous, gradients; rocky terrain; and the presence of snow and ice". Carl Troll (1899 – 1975) proposed that mountains can also be characterized by "vegetative-climatic zones; high potential energy for sediment movement; evidence of Quaternary glaciation; and tectonic activity and instability" (in Owens and Slaymaker, 2004: 4). For this project, a high mountain environment will be defined using characteristics from both, Barsch and Caine (1984) and Troll (in Owens and Slaymaker, 2004).

4. STUDY AREA

The study area, Glacier Creek watershed, is located within Rocky Mountain National Park, 70 miles northwest of Denver, Colorado. Rocky Mountain National Park straddles the Continental Divide and is located at the junction of four different counties in Colorado: Boulder, Grand, Jackson, and Larimer. The park contains an area of approximately 416 square miles with elevations ranging from 7,800 feet above sea level (a.s.l.) to the summit of Longs Peak, the tallest peak in the Colorado Front Range, at 14,255 feet a.s.l. Rocky Mountain National Park was selected because all forms of geomorphological landforms and processes related to high mountain geomorphology exist within the park: glacial, fluvial, eolian, and those related to mass movements.

The Glacier Creek watershed has an area of approximately 12.9 $miles^2$ and lies in the southeastern region of the park and is comprised of a series of glacially carved valleys extending eastward from the Continental Divide. The Glacier Creek watershed was selected as the study area as it was contained all of the characteristics of a "high mountain environment," as defined by both, Barsch and Caine (1984) and Troll (in Owens and Slaymaker, 2004). In addition, this region of Rocky Mountain National Park is highly accessible, which allowed for easy and efficient access to different geomorphological units in the field.

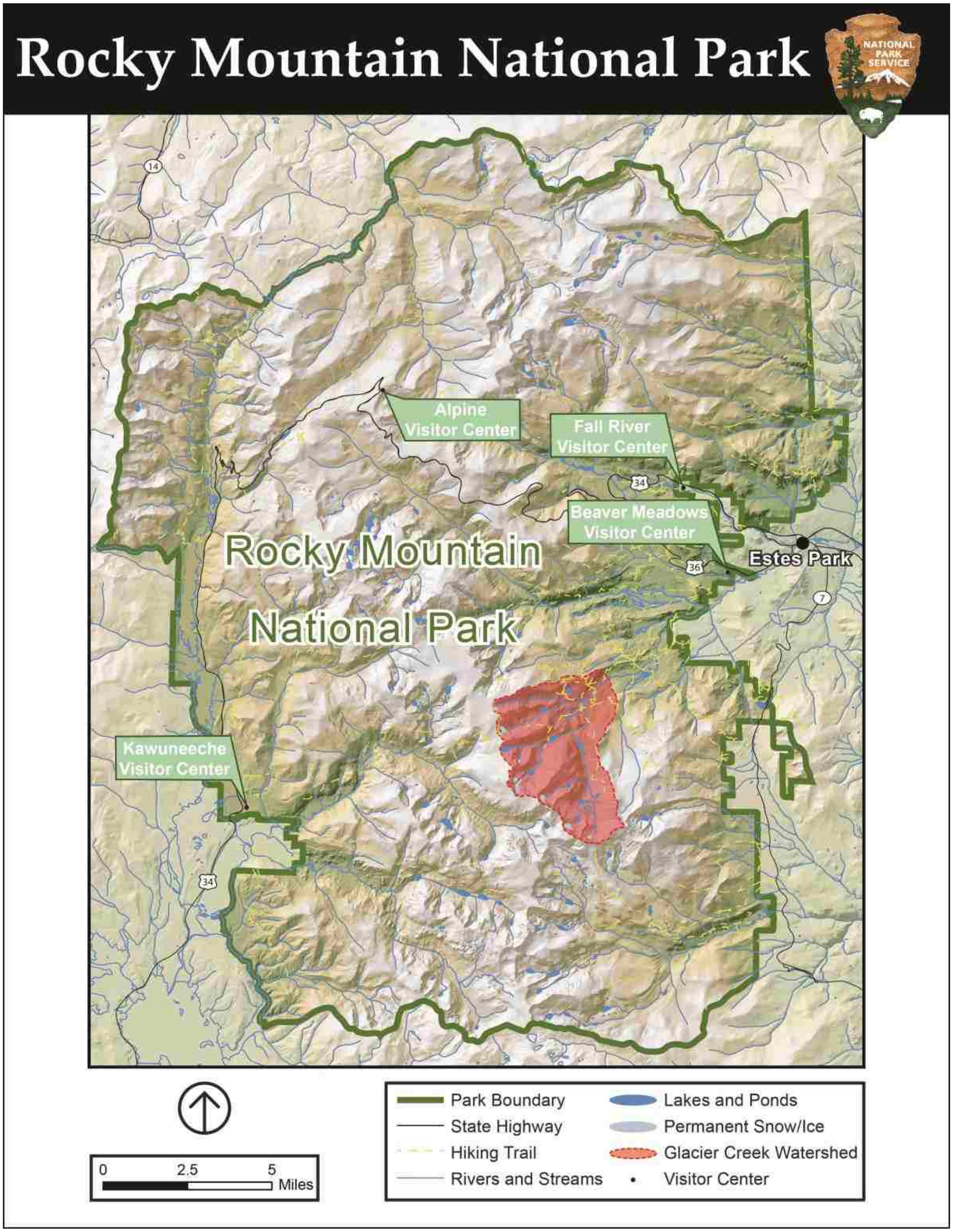


Figure 1: Map displaying the study area relative to Rocky Mountain National Park

4.1 Geology

Rocky Mountain National Park is located in the Front Range, a mountain range rising west of Denver, Colorado. The Front Range is longitudinally oriented and extends from the Arkansas River in Colorado to the Northern extent of the Laramie Range in Southern Wyoming.

The geologic setting of Rocky Mountain National Park can be divided into three different periods spanning nearly 2 billion years (Kellerlynn, 2004). In this span of time, Rocky Mountain National Park has undergone significant and dramatic geologic change, as "it has had a long history of tectonic activity indicated by the elevation of the basement rocks – the Precambrian gneisses, schists, and granites – that are now exposed in the Front Range" (Harris and Tuttle, 1990: 265). Of the three periods, only the most recent will be discussed here, as it is responsible for the current state of the Rocky Mountain region. A detailed geologic history of Rocky Mountain National Park can be found in *Geology of the National Parks* (Harris and Tuttle, 1990).

The third and most recent period of major tectonic uplift in the Rocky Mountain region occurred in the beginning of the Cenozoic Era. Fault-blocks, composed of Precambrian basement rock, experienced uplift and were brought to the surface by the Laramide Orogeny at the beginning of the Tertiary Period (Harris and Tuttle, 1990). These fault-blocks gradually became exposed as the shale beds left after the disappearance of the shallow seas were worn down due to ongoing weathering and erosion. During this time, the region also experienced widespread volcanism in the Oligocene Epoch, roughly 36 to 24 million years ago (Kellerlynn, 2004). "In late

Tertiary time, successive uplifts that were part of a broad regional uparching" (Harris and Tuttle, 1990: 272) occurred and caused the Rocky Mountains to be uplifted to their current height.

4.2 Geomorphology

The Rocky Mountain region has undergone significant geomorphologic change throughout its history. Glaciers that once existed within the boundaries of Rocky Mountain National Park are primarily responsible for the dramatic scenery that can be seen today. "At their maximum extent, the glaciers of the Front Range coalesced to form a small ice cap with the high peaks jutting up through the perennial snowfields and glacial ice" (Harris and Tuttle, 1990: 267). It was these glaciers that "did the major shaping of the alpine scenery that we see in Rocky Mountain National Park today" (Harris and Tuttle, 1990: 267).

Rocky Mountain National Park experienced numerous periods of glaciation throughout the Quaternary Period that can be divided into four major episodes: early glaciation, Bull Lake glaciations, Pinedale glaciations, and Neoglaciation.

The earliest glaciation, referred to as the Pre-Bull Lake glaciation (Kellerlynn, 2004), to affect the region surrounding Rocky Mountain National Park occurred ~1.5 million years ago. This episode involved at least two major glacial advances; however, nearly all evidence of the Pre-Bull Lake glaciers existing within the park boundaries has been destroyed by later glaciations (Harris and Tuttle, 1990).

The next episode was the Bull Lake glaciation between 500,000 and 80,000 years ago. It "deepened the same cirque basins, enlarged canyons, joined together tributary glaciers, and left prominent end moraines" (Harris and Tuttle, 1990: 274).

The Pinedale glaciation began ~30,000 years ago and experienced its maximum between 23,500 and 21,000 years ago, before deglaciation occurred ~15,000 years ago (Kellerlynn, 2004). It was this Pinedale glaciation that was most responsible for shaping the alpine landscape that exists within Rocky Mountain National Park today. "Evidence of these glacial episodes can be seen in the steep cirque headwalls along the continental divide" (Harris and Tuttle, 1990: 275).

Finally, the neoglaciation occurred ~3,800 years ago (Harris and Tuttle, 1990); however, the glaciers that existed at this time were confined within the cirques that were already present.

4.3 Climate

The climate of Rocky Mountain National Park is variable, depending on elevation, slope, and aspect (National Parks Service, 2013) The annual average temperature for the region ranges from 35°F to 45°F, and is primarily influenced by the prevailing westerly winds and the north-south orientation of the Rocky Mountains. The climate can be separated into two distinct climate patterns caused by the presence of the Continental Divide, which determines the amount of incoming solar radiation and precipitation.

During the winter months, from December to March, the difference between the different halves of Rock Mountain National Park can be easily observed. At this time, the eastern half of the park will experience warmer temperatures and lower amounts of snowfall than its western counterpart. The eastern side of the park has an average low temperature of 18°F and will receive, on average, 6 inches of snow per month. This is significantly different from the western side of the park, which has an average low temperature of 7°F and receives on average 24 inches of snow per month.

Springtime, occurring during the months of April and May, is marked predominantly by unpredictable weather patterns that cause large variations in both temperature and precipitation. Average temperatures in the eastern portion of the park at this time lie around 44°F, while the western portion experiences average temperatures of 39°F. Snow is still common in both portions of the park at this time.

Summer months, from June to August, are typically moderate in temperature, with average high temperatures in the eastern portion at 76°F and average high temperatures in the western portion of the park at 73°F. Afternoon thunderstorms and high winds in the upper elevations are common occurrences.

Fall months, September through November, are typically drier and cooler. At this time temperatures begin their slow descent into the lower registers of the thermometer. Snowstorms potentially may occur as early as September during a typical fall.

4.4 Vegetation

Rocky Mountain National Park lies within the Colorado Rockies forest ecoregion and is characterized by "dramatic vertical zonation" (World Wildlife Foundation, 2013). This is caused by the abrupt gradient, which occurs as elevation increases from flatlands to mountain environments. There are three distinct zones that exist within the park, each containing its unique vegetation: the montane, subalpine, and alpine tundra zones.

Below the montane zone, between 5,600 and 9,500 feet a.s.l. (National Park Service, 2012), lies the montane zone. The montane zone harbors a warm, dry climate that allows for diverse vegetation to exist (Alberts, 1963). Here, Ponderosa pine (*Pinus ponderosa*), Lodgepole pine (*Pinus contorta*), Douglas fir (*Pseudotsuga*), and aspen (*Populus tremuloides*) (Daubenmire, 1943) are common. The montane zone also provides an ideal climate for various forms of shrubs; some commonly observed shrubs are Antelope Bitterbrush (Purshia tridentate), Raspberry (Rubus strigosus), and Wax Currant (Ribes cereum) (Alberts, 1963).

The subalpine zone exists between 9,000 and 11,000 feet a.s.l. (National Park Service, 2012) and is dominated by subalpine fir (*Abies lasiocarpa*), and Engelmann spruce (*Picea engelmanni*). This zone is characterized by much higher moisture content than the montane zone, as it receives approximately double the amount of precipitation (Alberts, 1963).

Located in the higher elevations above 11,000 feet a.s.l. (National Park Service, 2012), is the alpine tundra zone. This zone is characterized predominantly by barren, rocky landscapes; however, "vast expanses of it are covered with a cold, wet soil mantle (Alberts, 1963: 21). Vegetation that exists in the alpine tundra zone consists mainly of grasses, sedges, herbs, shrubs, and perennials.

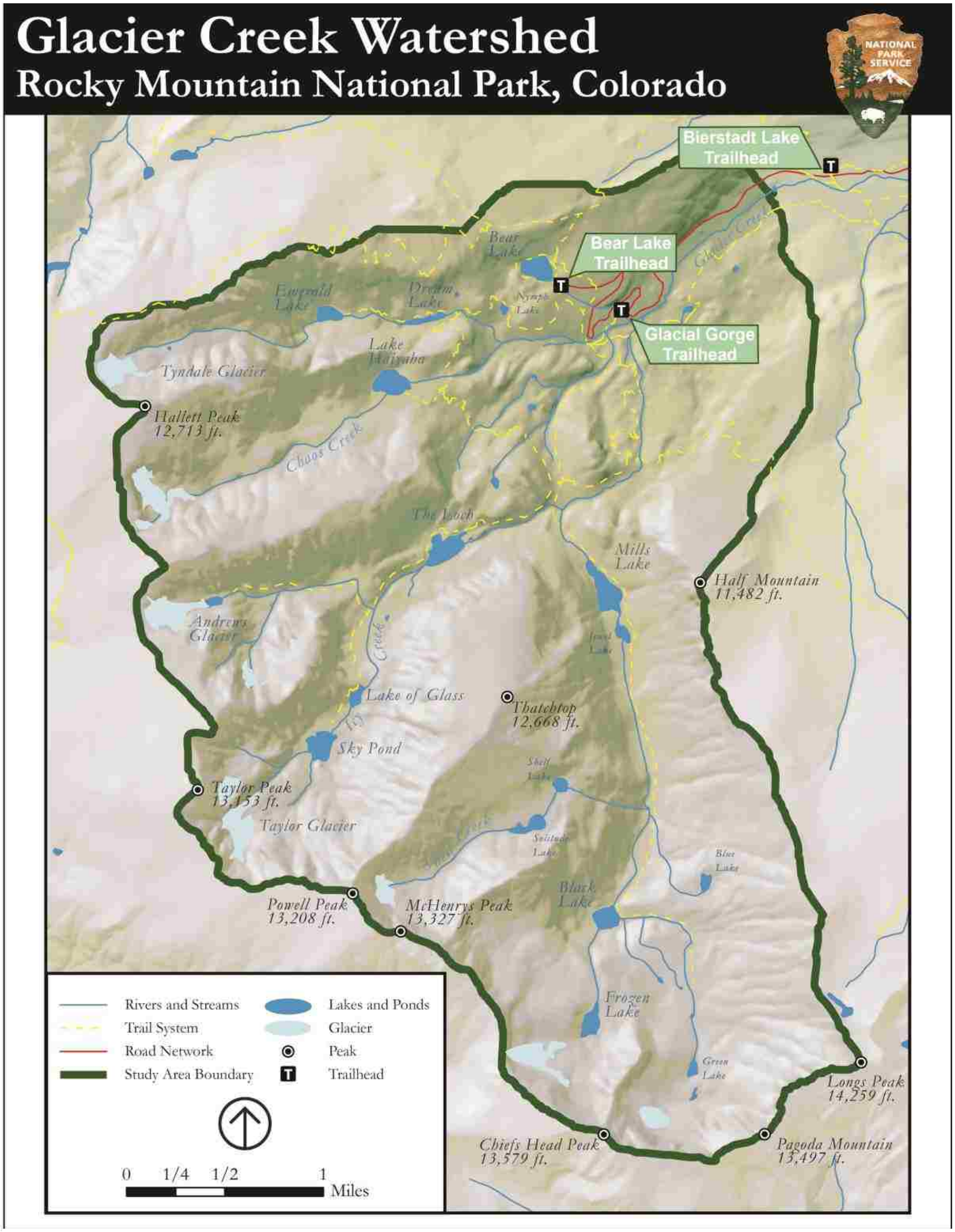


Figure 2: Map displaying the study area, the Glacier Creek watershed in Rocky Mountain National Park

5. METHODS

5.1 Data Acquisition and Geodatabase Generation

Using ArcGIS 10, a geodatabase, containing both raster and vector data, was created that to store all geographic data that would be involved in the analysis. Each dataset contained in the geodatabase was originally projected in, or reprojected to, the North American Datum 1983 (NAD83) Universal Transverse Mercator (UTM) Zone 13 projection.

Vector data were stored in three different feature datasets: Census, RMNP (Rocky Mountain National Park) Logistics, and Geomorphologic Units. Feature classes stored in the Census feature dataset included roads, linear water features, and areal water features for each of the four Colorado counties that the park was located in. Railroads, county boundaries, and state boundaries were also stored in the Census feature dataset. These datasets were obtained from the U.S. Census Bureau's TIGER database (http://www.census.gov/geo/maps-data/data/tiger.html), an extensive online database that contains geographic datasets created and maintained by the U.S. Census Bureau. The RMNP Logistics feature dataset contained trails, trailheads, and the park boundary feature classes. These were obtained from the National Park Service Data and Information Clearinghouse (http://www.nps.gov/gis/data_info). The Geomorphologic Units feature dataset contained a single point feature class, Geomorphologic Units, which would be used to store locational data recorded in the field. Data sources for these feature datasets can be observed in *Table 1*.

Geodatabase	Feature Dataset	Dataset	Source
RMNP_Geodatabase	Census	BoulderCo_ArealWaterFeatures	http://www.census.gov/geo/maps-data/data/tiger.html
		BoulderCo_LinearWaterFeatures	http://www.census.gov/geo/maps-data/data/tiger.html
		BoulderCo_Roads	http://www.census.gov/geo/maps-data/data/tiger.html
		GrandCo_ArealWaterFeatures	http://www.census.gov/geo/maps-data/data/tiger.html
		GrandCo_LinearWaterFeatures	http://www.census.gov/geo/maps-data/data/tiger.html
		GrandCo_Roads	http://www.census.gov/geo/maps-data/data/tiger.html
		JacksonCo_ArealWaterFeatures	http://www.census.gov/geo/maps-data/data/tiger.html
		JacksonCo_LinearWaterFeatures	http://www.census.gov/geo/maps-data/data/tiger.html
		JacksonCo_Roads	http://www.census.gov/geo/maps-data/data/tiger.html
		LarimerCo_ArealWaterFeatures	http://www.census.gov/geo/maps-data/data/tiger.html
		LarimerCo_LinearWaterFeatures	http://www.census.gov/geo/maps-data/data/tiger.html
		LarimerCo_Roads	http://www.census.gov/geo/maps-data/data/tiger.html
		Railroads	http://www.census.gov/geo/maps-data/data/tiger.html
		CountyBoundaries	http://www.census.gov/geo/maps-data/data/tiger.html
		StateBoundaries	http://www.census.gov/geo/maps-data/data/tiger.html
	RMNP_Logistics	Trails	http://www.nps.gov/gis/data_info
		Trailheads	http://www.nps.gov/gis/data_info
		ParkBoundaries	http://www.nps.gov/gis/data_info
	GeomorphologicUnits	GeomorphologicUnits	User Created

Table 1: Table displaying geodatabase structure and data sources.

Raster datasets used in the analysis consisted of two forms of remotely sensed imagery that were obtained from the United States Department of Agriculture (USDA) Geospatial Data Gateway, located at the Natural Resources Conservation Service (http://datagateway.nrcs.usda.gov). Four different imagery datasets provided by the National Agricultural Imagery Program (NAIP) were obtained, one for each of the four Colorado counties that the park boundary overlaps. These datasets were high spatial resolution (1 m) true color aerial photographs (red, green, and blue bands), which were acquired in the summer of 2011 by aircraft mounted with passive remote sensors. In addition, twenty-five digital elevation models (DEMs) were also obtained from the USDA. A DEM provides the average elevation for each cell in raster dataset, dependent on the spatial resolution of the dataset; the DEM datasets used in the analysis had a spatial resolution of 10 m.

5.2 Initial Geoprocessing Workflow

Initial geoprocessing consisted of performing a series of steps using ArcGIS to create the framework with which the analysis would be later performed. The geoprocessing workflow included a series of steps designed to remove extraneous information from the vector data. These steps included appending corresponding vector datasets and clipping them to the Rocky Mountain National Park boundary. For example, the four different linear water feature datasets (one for each county that Rocky Mountain National Park intersects) were appended, or joined, together using the Append function in ArcGIS, creating a single dataset. This newly created dataset was then clipped to the Rocky Mountain National Park boundary using the Clip function in ArcGIS. When each of the vector datasets had been processed, the collected raster datasets were also put through a series of geoprocessing steps. First, the twenty-five individual DEM datasets were mosaicked together, creating a single seamless image. Using this newly created DEM mosaic, the study area boundaries were delineated using a series of tools in ArcGIS' Hydrology toolbox. Next, using the Surface Analyst toolbox in ArcGIS, a series of DEM derivatives were created from the DEM mosaic. This included maps displaying relief, slope, and curvature.

5.3 Legend Development

The framework, or what the legend would be capable of representing, was developed prior to conducting fieldwork. Because the purpose of the study was to produce a comprehensive legend for mapping the geomorphological features and processes in high mountain environments, multiple sources were utilized in order to compile a comprehensive legend.

The legend developed by Kneisel et al. (1998), which was developed by a group of experts in the field of mountain geomorphology, was primarily used as the framework that the new legend would be based upon. Of the fifty-five geomorphologic features and processes capable of being represented by the legend developed by Kneisel et al. (1998), a total of thirty-six were included in the new legend. However, certain features and processes included in their legend were omitted from the new legend on the basis of generalization. For example, the legend developed by Kneisel et al. (1998) contains three different symbols for representing rock glaciers, three different symbols for representing morainic ridges, and two different symbols for representing permafrost. The new legend includes a single symbolic element for each of these features, in order to reduce complexity.

The legend developed by Pavlopoulos et al. (2009) was also utilized in the process of determining the contents of the new legend. From this legend, twelve different symbolic elements for representing geomorphological features and processes were incorporated into the new legend. Features and processes from the legend developed by

Pavlopoulos et al. (2009) that were not included in the new legend were omitted on the basis of duplication, or because they do not occur in high mountain environments. For example, many features and processes (such as cirques, glaciers, and rock glaciers) included in the new legend were already incorporated into it from the system developed by Kneisel et al. (1998). Other landforms and processes were also omitted from the new legend because they result from continental ice sheets and ice caps, such as in the case of drumlins or eskers.

In addition, United States National Park Service *Geologic Resource Evaluation* for Glacier National Park, Rocky Mountain National Park, and Denali National Park were obtained. Geologic Resource Evaluations are peer-reviewed documents published by the National Park Service, which discuss the geologic history, geologic issues, and provide a written inventory of the geomorphologic features and processes that exist within its respective park. Denali National Park (Alaska, United States) and Glacier National Park (Montana, United States) were selected as they each contain high mountain environments and exhibit the geomorphological landforms and processes that are associated with them. The Geologic Resource Evaluations were used to augment the framework based upon the legends developed by Kneisel et al. (1998) and Pavlopoulos et al. (2009), by including six specific geomorphological features that were not included in either existing geomorphological mapping legend. For example, the legends developed by Kneisel et al. (1998) and Pavlopoulos et al. (2009) did not include a symbol for representing a hanging valley, a glacial landform that is included in each of the three Geologic Resource Evaluations consulted.

5.4 Fieldwork

During the summer of 2012, a total of eight days were spent conducting fieldwork in the study area within Rocky Mountain National Park. Fieldwork consisted of capturing digital images of different geomorphologic units existing in the landscape using a digital camera and plotting data points using a Global Positioning System (GPS) receiver. These images and data points collected would later be used as references for identifying and delineating geomorphologic units from the aerial photographs in the lab-based analysis. In addition, a large-scale (1:24,000) topographic map was carried into the field. A rough sketch was made of large geomorphologic units (such as cirques or hanging valleys, rather than erratic boulders) on the map and descriptive notes were recorded in a field book.

When a geomorphologic unit was located and identified in the field, an image was taken of it. Using a Trimble Juno 3 GPS receiver (sub-3 m horizontal accuracy) containing the Geomorphologic Units feature dataset, a data point was plotted. Points collected contained six attributes associated with the data point: the geographic coordinates (latitude and longitude) of the data point, the type of geomorphologic unit, the image number associated with the data point, the approximate bearing (or direction in reference to magnetic north) in which the image was taken, the photographer's initials, and the date. In total, 186 data points and 397 images were collected. A large disparity exists between the amount of data points and images collected because in many instances multiple images were taken of a geomorphologic unit in an attempt to collect the best possible image for visual reference. The approximate locations of the GPS points can be observed in Figure 3.

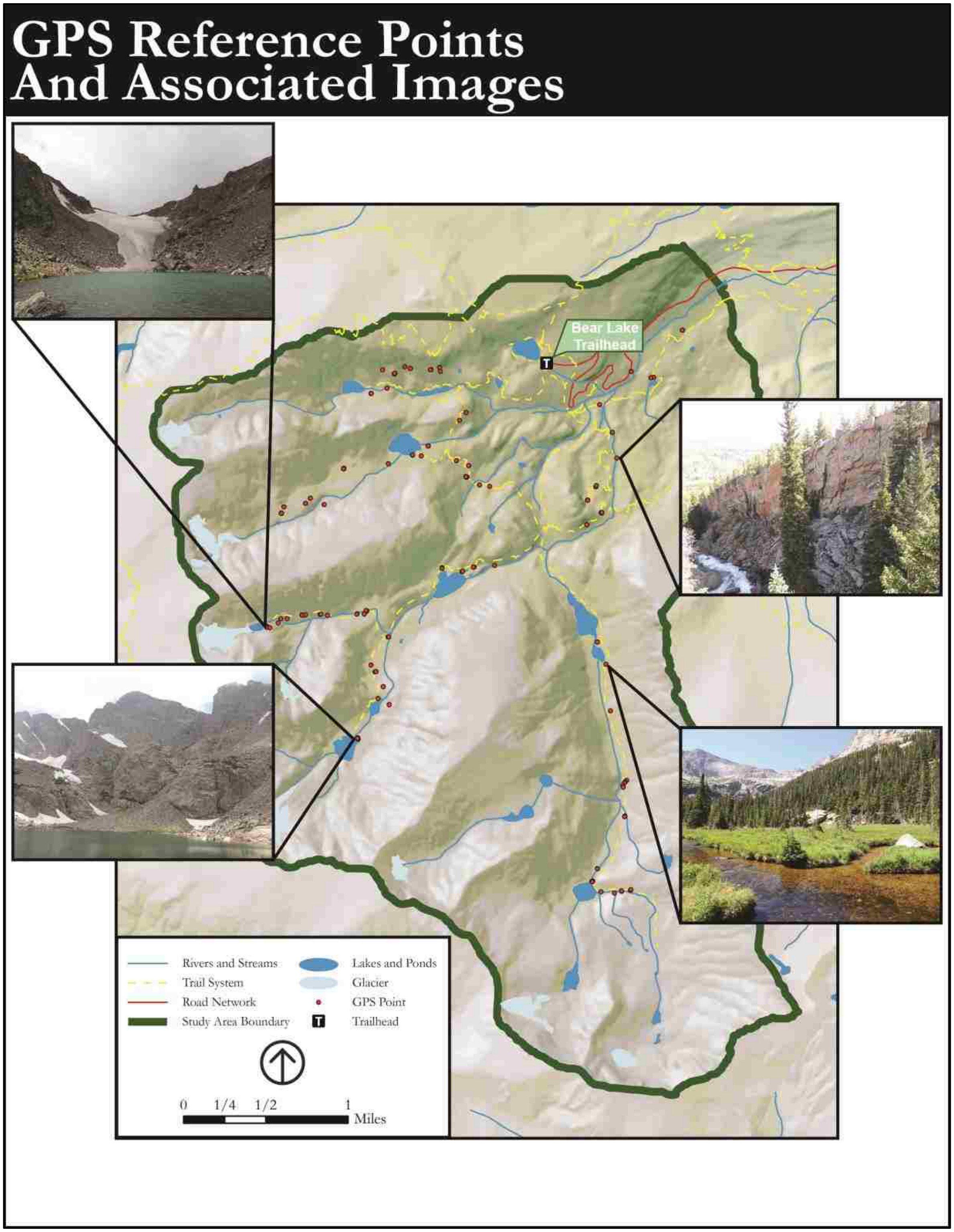


Figure 3: Approximate locations of the GPS points gathered and associated images

5.5 Digitization of Geomorphologic Units

Following the completion of the fieldwork in Rocky Mountain National Park, digitization, or drawing, of geomorphologic features began using ArcGIS 10. This was a process of creating a series of new feature classes (one for each geomorphologic unit identified in the landscape, such as a debris cone feature class and a alluvial plain feature class) within the Geomorphologic Units feature dataset. Using a combination of aerial images, DEMs, and the GPS data points along with their corresponding digital images, geomorphologic units identified on the landscape were manually delineated in ArcGIS and stored in each of their respective feature classes. When the digitization of the study area's geomorphological units was completed, objects were exported out of ArcGIS and into Adobe Illustrator for the production of the final map document.

5.6 Symbolic Representation and Design Development

Using Adobe Illustrator, a series of symbolic representations were designed to represent geomorphological landforms and processes. Adobe Illustrator is computer software developed specifically for creating and manipulating vector graphics. Variation between the symbolic representations created was achieved using the five visual variables: size, shape (or appearance), orientation, texture, and color.

The type of feature, whether point, line, or area (polygon), used to symbolize a geomorphologic unit was determined either logically, or through reviewing existing systems. Many geomorphologic landforms, such as cirques, glaciers, and glacial moraines are discrete objects on the landscape with defined boundaries or edges.

Landforms such as these can be effectively represented using any of the three basic feature types. Geomorphologic processes, however, are often less defined within the landscape; hence why both existing systems, Kneisel et al. (1998) and Pavlopoulos et al. (2009), use line feature types to represent them. Following the example of the pre-existing systems, geomorphologic processes were represented in the new system by linear features which indicated the direction of motion.

The appearances of symbols in the newly developed legend were based upon the appearances of symbols included in the pre-existing legends developed by Kneisel et al. (1998) and Pavlopoulos et al. (2009), with the exception of geomorphological features and processes that did not exist in either pre-existing legend. For these features and processes, the appearance of the symbol was original.

Table 2 displays a comparison of four different symbols for representing geomorphologic features and processes (cirques, debris cones, debris flows, glaciers), which are included in each legend.

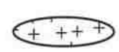
	Kneisel et al. (1998)	Fyock (2013)	Pavlopoulos et al. (2009)
Cirque			
Debris Flow			
Debris Cone			
Glacier			
Moraine			

Table 2: Comparison of symbol design from the existing legends by Kneisel et al. (1998) and Pavlopoulos et al. (2009), in addition to the newly developed legend.

Cirques, or bowl-like hollows formed at the source of a glacier, seem to have acquired a cartographic convention for their representation. This has taken the appearance of a series of short lines extending perpendicular from a primary line used to delineate the cirque wall, which can be observed in the legends developed by Kneisel et al. (1998) and Pavlopoulos et al. (2009). Because of this existing cartographic convention, the appearance of the symbol included in the new legend is only marginally different than the pre-existing geomorphological mapping legends; this is to promote continuity between the legends. The new legend represents cirques using two parallel lines, which delineate the cirque wall, with a series of short lines extending inward (toward the center of the cirque) perpendicular from the inner parallel line.

Unlike cirques, there is no cartographic convention for representing debris cones; this can be observed from the pre-existing systems. The legend developed by Kneisel et al. (1998) depicts debris cones using a series of solid black lines extending from a point of origin. The assumed intent of these lines is to indicate the direction of flow of debris. In between these lines exist triangular shapes, which exhibit black boundary lines and white interiors. While effective in communicating the orientation and extent of debris cones, the symbol lends itself to over-complicating the geomorphological map by including too many visual objects in a single symbol. The legend developed by Pavlopoulos et al. (2009) represents debris cones in a much more simple manner. The symbol used in this legend depicts debris cones using dashed lines that also extend from a single point of origin. This is both effective in communicating information regarding the origin, orientation, and extent of the debris cone, while not over-complicating the map. The appearance of the symbol for representing debris cones in the new legend is based upon the appearance of the symbol included in the legend by Pavlopoulos et al. (2009). This symbol is depicted by a series of lines extending from a point of origin. The lines are dashed and increase in width with distance from the point of origin. The intent behind the increasing width of the line is to represent the outward flow exhibited by debris cones. The design of the symbol is effective in communicating information regarding origin, orientation, and extent of debris cones, all the while remaining different in appearance from the symbol included in the legend developed by Pavlopoulos et al. (2009) for legality issues regarding copyright.

Debris flows are similar to debris cones, regarding the fact that there is no standard cartographic convention for representing them. The legend developed by Kneisel et al. (1998) depicts debris flows with a series of wave-like curves with an arrow at the end. Once again, this is likely to indicate direction of flow. This symbol is effective in communicating information, as well as being relatively simple in nature. However, as it is black in appearance, it easily blends in to the geomorphologic map. The legend developed by Pavlopoulos et al. (2009) represents debris flows in an entirely different manner. Pavlopoulos et al. (2009) represent debris flows very similar to debris cones, as they use a single dashed black line for representing this geomorphologic process. This symbol is also effective at communicating information, however it is very similar in appearance to debris cones, potentially making the process of distinguishing the two difficult. The newly developed legend represents debris flows most similar to the legend developed by Kneisel et al. (1998). It uses a red tapering red line with an arrow at the end. Because mass-movements pose a particular threat "to communities and infrastructure" (Hearn and Hart, 2011), the color red was used for this symbol, along with other geomorphologic processes, because it is commonly associated with danger (Otto et al., 2011). The arrow at the end of the tapering line is meant to depict the direction of flow. This symbol is effective in communicating information regarding the location and flow direction of debris flows. In addition, the symbol is easy to differentiate from others because of its color.

Glacial ice is also a geomorphologic unit that lacks a standard cartographic convention for its representation. In the legend developed by Kneisel et al. (1998), glacial ice is represented with by a grey polygon with a solid black outline. While being effective in delineating the boundaries of the glacier, this symbol is lacking in the uniqueness of its appearance, which is quite similar to other symbols included in the legend, such as possible permafrost, probable permafrost, and dead ice, which all appear as polygons filled with marginally different grey hues. The legend developed by Pavlopoulos et al. (2009) represents glacial ice with a different approach. The symbol used by this legend appears as a solid white polygon with a dashed black line, which delineates the boundaries of the glacier. This is moderately ineffective in its ability to represent glaciers because there is little visual contrast in its design. The unobstructed white fill of the polygon coupled with the black dashed line produces little visual contrast between the object and the background, causing the object to blend into the geomorphologic map, becoming less noticeable. The newly developed legend depicts glaciers in a very different manner from both pre-existing legends, making it more effective in its ability to communicate relative information regarding glacial ice. The new legend represents glaciers with white fill that is obstructed by blue dashes and a blue boundary. Once again, color was used in the symbol design because it is the most "eye-catching" visual variable (Otto et al. (2011). The solid white background of the polygon is obstructed by blue dashes and is bounded by a solid blue line; this produces texture within the symbol, and thus enhances the visual contrast of the symbol making it more easily identifiable within the geomorphologic map.

5.7 Map Production

The last step was the production of multiple geomorphological maps using Adobe Illustrator. Two maps were produced: one fine scale map of the study area, and a second very-fine scale map of a small subset of the study area. To do this, the geomorphologic units digitized in ArcGIS were imported into the Adobe Illustrator interface. Complex objects, such as lines and polygons, which contained great amounts of data were generalized using a simplification function in Adobe Illustrator. Otto et al. state, "generalization is the abstraction of map objects aiming at a simplification of the map content in order to fit the scale or purpose of the map without significantly changing the map's message" (2011: 259). The simplification function used in Adobe Illustrator removed a user-defined percentage of nodes, or points connecting different lines. In doing this, the complex shape of certain objects was reduced, presenting a more easily readable map. Once the units were generalized, the appropriate symbols were applied to them.

Following the completion of the production of the two primary geomorphological maps, two additional geomorphological maps were generated. These maps were very-fine scale depictions of the study area subset. However, they were populated with recreations of the symbols from the legends developed by Kneisel et al. (1998) and Pavlopoulos et al. (2009). The purpose for creating these additional maps was to provide a visual comparison between the two existing legends and the newly developed legend.

6. RESULTS

6.1 The Development of the First Legend for Mapping Geomorphology in High Mountain Environments in the United States

The study resulted in the development and production of the first geomorphological mapping legend specifically for mapping high mountain environments in the United States. In total, it includes sixty different symbols for representing geomorphological landforms and processes in these environments (Figure 4). Visual variance between geomorphological units was achieved by utilizing size, shape (appearance), texture, orientation, and color. The legend is capable of representing these environments at scales between 1:10,000 and 1:50,000.

The appearance of most symbols included in the new legend was based upon the design of symbols included in the legends developed by Kneisel et al. (1998) and Pavlopoulos et al. (2009). However, as neither existing geomorphological mapping legend contained symbols for certain geomorphological features, their designs were original.

The legend is divided into eight categories: 1) geomorphologic features, 2) geomorphologic processes, 3) glaciology\hydrology; 4) edges and ridges, 5) valley shape, 6) topography, 7) surface material, and 8) other. The contents of each category were based upon the content of similar categories from the legend developed by Kneisel et al. (1998).

The geomorphologic feature category contains a total of thirty-two different symbols for represent geomorphological features related to glacial, fluvial, and hillslope geomorphological processes. Symbol designs were similar to those of the existing systems developed by Kneisel et al. (1998) and Pavlopoulos et al. (2009). Visual variance in this category was mainly achieved using shape or appearance, and texture. In addition, the colors black, white, the combination of both, and grey were also used.

The geomorphologic process category contained a total of five different symbols for representing geomorphologic processes related to hillslope geomorphology. Hillslope processes (such as debris flows and rockslides) "pose an ever increasing risk to communities and infrastructure" (Hearn and Hart, 2011: 107); because of this, they were assigned the color red, as red is commonly associated with "danger" (Otto et al. 2011). Symbols for geomorphologic processes appeared as variations of the "arrow" shape, so as to communicate the direction of flow for each process.

The glaciology/hydrology category was also based upon the similar category developed by Kneisel et al. (1998). It contained a total of eight different geomorphologic features. This category used shape or appearance, texture, and color to create visual variance between symbols. In order to maintain continuity with standard mapping conventions, the symbols for lakes and ponds, rivers and streams, perennial springs, and waterfalls were assigned the color blue. Glaciers and perennial snow used a combination of the colors blue and white. The symbols for flood plains and wetlands were assigned the color green, due to the presence of vegetation.

The edges and ridges category contained five different geomorphologic features. This category was also based upon a similar category from the legend developed by Kneisel et al. (1998). These symbols achieved visual variation through shape or appearance, and color. The only symbol in this category of the legend that had color assigned to it was the symbol for levees, which was assigned the color green to maintain continuity with the symbols for flood plains and wetlands.

The fifth category, valley shape, contains two symbols for representing the valley profile. The symbols, intended for representing the shape of a valley, either glacial or fluvial, were adopted and modified from the legend developed by Pavlopoulos et al. (2009). Both symbols appear black in color.

The topography category contains a single symbol for representing contour lines, for use as the base map. The contour interval used is dependent on several variables, such as the scale of the mapped area and the amount of relief within, and is ultimately the choice of the cartographer.

The surface material category, which contains six different symbols for representing surface material, was adopted and modified from the legend developed by Kneisel et al. (1998). Visual variance between the symbols was achieved by the use of color. The six symbols, for representing clay, silt, sand, pebbles, gravel, and boulders, appear as solid colors. The color for each symbol is a different tint of the color brown. As the grain size of the material increases, the color of the symbol becomes lighter. For example, clay, which has a very fine grain size, is the darkest hue, while boulders, which have a very coarse grain size, appear as a very light hue in comparison.

The final category of symbols, labeled as “other,” contains a single symbol for representing trails, either human or animal in origin. This appears as a yellow dashed line. Yellow was used because it is easily distinguishable within the map.

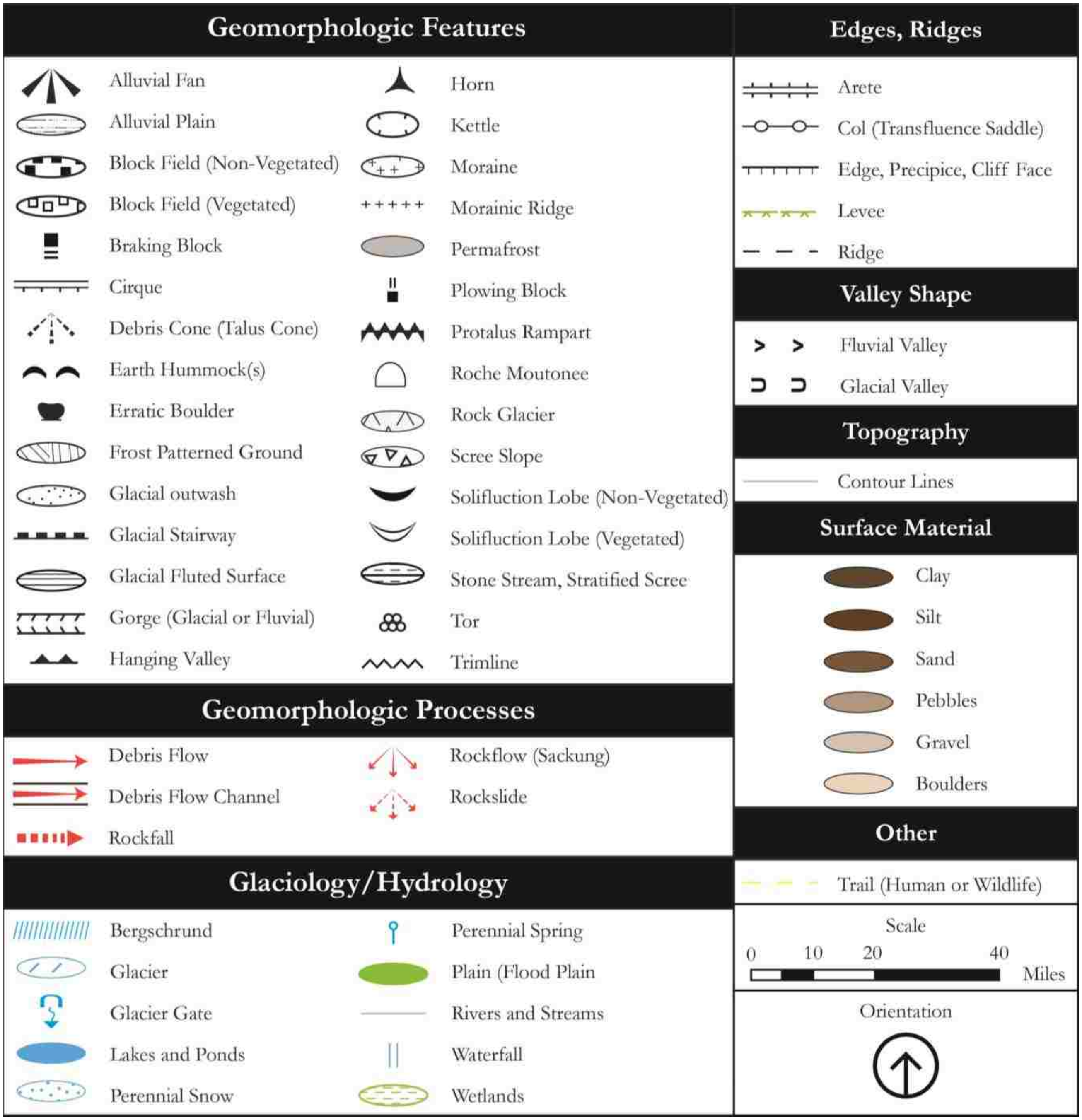


Figure 4: The legend for the newly developed system for geomorphological mapping of high mountain environments in the United States

The design of the map layout of the proposed system is similar to the basic design specified by Otto et al. (2011). The map layout was designed to follow the basic principle of visual balance. The visually heaviest object is the geomorphological map itself. As it is also the most important object in the map, it is important that it be placed in a location that emphasizes its importance; thus, the geomorphological map was placed in the upper left corner, where, in western culture, an individual looks to first. The geomorphological map should have a bounding rectangle, or neatline, surrounding it to emphasize importance and maintain neatness. This is the only object that should have a bounding rectangle so that other objects do not gain unwanted visual weight.

The legend of the geomorphological map is the second most important object in the map document. Because of this, it needs to maintain a visual weight that is less than the main geomorphological map, while being visually heavier than all other items. The most effective way to do this is to place it in the lower right corner of the document where the eye will travel to after leaving the main map. As the legend may potentially include geomorphologic units that are not found in the study area, should omit any symbols that are not present.

A reference map that depicts the location of the area of interest in reference to the surrounding area should also be included. The appearance of the reference map is left to the discretion of the cartographer. Common options for the appearance of the reference map are a basic shape, or a DEM derived shaded relief. Color can be used for either option; however, it is important that the reference map holds a lower visual weight than the main geomorphological map in order to not draw attention away from the most important objects in the document. The position of the reference map should be on the right side of the document, above the legend.

In addition, it is essential to include map elements that give the map-reader reference information. Otto et al. state, “geomorphological maps characteristically include the following map elements surrounding the main map: title, scale, directional indicator (north arrow), coordinate gird or border, information on coordinate system and map projection, and author information" (2011: 262-263). While most map elements listed here should be included in the final document, one is left to the cartographer's discretion: the incorporation of the coordinate grid. The purpose of a coordinate grid, created by lines of latitude and longitude, is to provide locational reference. While useful for small-scale geomorphological maps, large- and medium- scale geomorphological maps often are concerned with areas that are too small to necessitate the incorporation of a coordinate grid in the final document.

The placement of these objects also follows the outline described by Otto et al. (2011). The title, which provides the map-reader with a brief summary of the contents of the map, should be placed in the top-left corner, above the main geomorphological map. The scale bar should be either below the geomorphological map, or within the bounding rectangle surrounding the geomorphological map. This is left to the discretion of the cartographer. However, it is essential that a scale bar be used rather than a scale text (1inch = 10,000 inches) so that the scale of the map remains accurate if its physical size is altered. For example, if a map is produced at a certain scale on a specific map sheet (a scale of 1:20,000 on a 8.5" x 11" map sheet) and the physical size of the map sheet is altered, the scale text remains constant and is no longer accurate. A directional indicator or north arrow should be placed in the space below the main geomorphological map, or within the geomorphological map's bounding rectangle. Additional textual information, such as information concerning the coordinate system and projection that the map is displayed with or information regarding authorship of the map, should be placed below the main geomorphological map.

In order to provide the most complete depiction of a landscape, it is necessary to include as much information as possible. Similar to Passarge's *Morphological Atlas* (1914), a geomorphological map produced using the newly developed system is intended to be supplemented by the inclusion of additional information. A modern geomorphological study should include much more than simply a single geomorphological map. With the availability of great amounts of spatial data in the United States, much of it for free, those performing a geomorphological study have the capability to include multiple kinds of spatial information, allowing for a holistic depiction of the landscape, and might include one, or more of the following:

- Reference map(s)
- Geological map
- Morphometry map(s) – elevation, slope, surface curvature profile, etc.
- Aerial photography/satellite imagery
- Landcover map(s)
- Additional textual information

6.2 Geomorphological Map of the Glacier Creek Watershed, Rocky Mountain National Park, Colorado

In addition to the development of a new legend for mapping geomorphological environments of high mountain environments in the United States, the project also produced a large-scale geomorphological map of the Glacier Creek watershed in Rocky

Mountain National Park, Colorado as a test case. This can be observed in Figure 5. A second geomorphological map was also produced using the new legend. This map was produced at a very large scale (~1:12,000 inches) of a small subset of the Glacier Creek watershed (Figure 8). It is important to state, however, that the geomorphological map produced for the study area within Rocky Mountain National Park may not be a completely accurate representation of the geomorphological setting of the Glacier Creek watershed, as this was not the objective of the project. The purpose of this geomorphological map was to provide an example of the capability of the newly developed legend to represent the geomorphological landforms and processes that exist within high mountain environments in the United State.

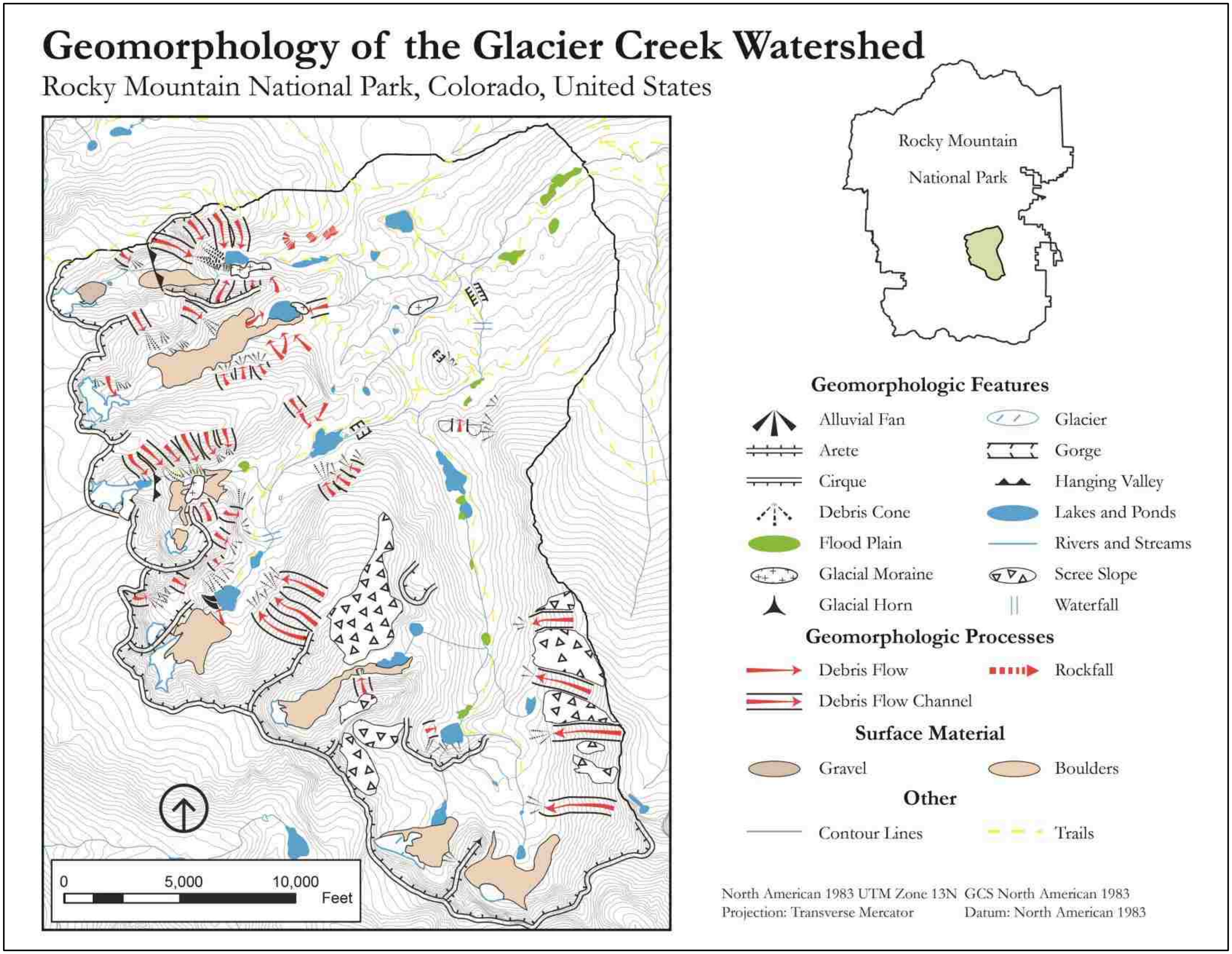


Figure 5: The final geomorphological map produced for the Glacier Creek watershed

The final map produced of the Glacier Creek watershed depicts the dynamic geomorphological setting of the study area. Twenty-one different geomorphological units were identified; these were primarily of glacial origin. Glacial troughs, or "U" shaped valleys, extend eastward from the continental divide. The glaciers that once existed within these valleys have all but disappeared completely, leaving behind small glaciers and perennial snow masses. Cirques carved into the bedrock by glacial ice depict the extent of the glaciers that once existed within Rocky Mountain National Park. Arêtes, or the thin ridge that exists between parallel glacial troughs, also exist. A glacial horn, or a peak resulting from the headward erosion of multiple glaciers converging at a central point, was identified as well. Multiple hanging valleys were also identified, providing evidence of multiple glaciation events. Tarns, paternoster lakes, and glacial debris currently reside in the valley floors. Two Roche Moutonees were also identified in the lower elevations. Talus cones were found at the base of the valley headwalls and sidewalls.

To a lesser extent, fluvial and hillslope processes have also played an active role in the evolution of the landscape. Landforms resulting from hillslope processes, such as rockfalls, rockslides, and debris flows were found in various locations throughout the study area. Debris flow channels were commonly found above talus cones. Scree slopes were found to exist on shallow slopes above treeline. The many streams running along the valley floors have resulted in landforms specific to fluvial processes, such as alluvial fans, alluvial plains, gorges, and waterfalls, which were also identified in the Glacier Creek watershed.

All of the above landforms and processes, glacial, hillslope, and fluvial, can be located and identified on the final geomorphological map, which uses 50ft contour lines derived from a DEM for the background. The geomorphological map itself has been placed in a bounding rectangle, to promote a neat and clean appearance, in the upper left corner of the map sheet, adhering to the principles of visual hierarchy and weight. A north arrow to provide orientation and scale bar have been placed below the geomorphological map in the lower left corner of the bounding rectangle that houses the geomorphological map, so as not to draw the users attention away from the map itself. In the lower left corner of the map sheet lays the legend. Symbols for geomorphologic units that were not present in the study were omitted from the legend, as they were unnecessary and utilized much needed space. Above the legend in the upper right corner of the map sheet lays a reference map that depicts the location of the study area in relation to the rest of Rocky Mountain National Park. The title and subtitle of the map are located in the top left corner of the map, as this is pertinent information to the user in regards to understanding what is depicted within the map. Textual information regarding the projection of the geomorphologic map is located in the bottom right corner of the map sheet.

7. DISCUSSION

The newly developed system is the optimal choice for the production of geomorphological maps of high mountain environments in the United States. While other geomorphological mapping systems may be used, such as the system developed by Kneisel et al. (1998) and Pavlopoulos et al. (2009), the new system is the only geomorphological mapping system in existence that has been developed specifically for mapping the geomorphologic setting of high mountain environments in the United States.

Of the two existing systems tested for their ability to effectively represent the geomorphologic features and processes that exist within these environments, the legend developed by Kneisel et al. (1998) is the stronger choice.

This system's greatest strength lies in its ability to represent a great amount of different geomorphological features and processes that exist within high mountain environments, which can be seen in Figure 6. As it was developed in Germany by a group of collaborating geomorphologists, it contains an extensive inventory of symbols for representing features and processes that are specific to high mountain environments. While it is missing certain geomorphological features that were explicitly included in the Geologic Resource Evaluations for Denali National Park, Glacier National Park, and Rocky Mountain National Park, such as erratic boulders, horns, cols, glacial outwash deposits, glacial stairways, and hanging valleys, the system could be augmented by adding symbols to represent these features, thus making it capable of more completely representing these environments.

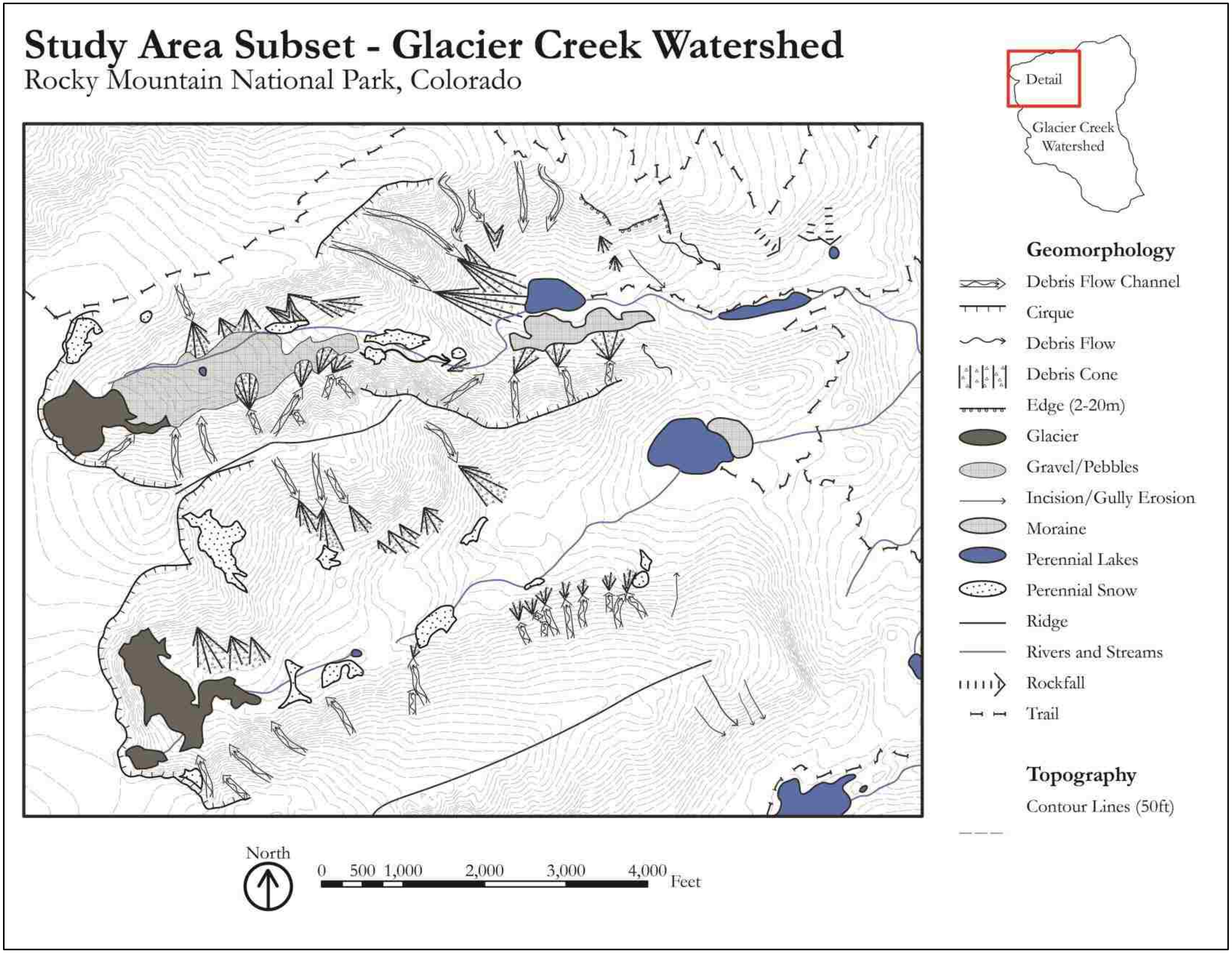


Figure 6: Geomorphological map of a subset of the Glacier Creek watershed produced using the legend developed by Kneisel et al. (1998)

It is not uncommon for geomorphological maps to be overly complex causing illegibility. This can be caused not only by their highly detailed nature, but also by symbolic design. Though the legend developed by Kneisel et al. (1998) is capable of representing a great amount of geomorphologic features and processes that exist within high mountain environments, the ability for it to effectively communicate information regarding these features and processes is hindered by the design of the symbols.

The primary weakness of the system developed by Kneisel et al. (1998) lies in its cartographic representation of geomorphologic features and processes. Because the authors avoided the use of color, choosing only to use black and white, to create visual variation between symbols (with the exception of the color blue for rivers, streams, and lakes), variation between different geomorphologic features and processes is dependent entirely on symbol size, shape (appearance), orientation, and texture.

Symbols within this legend primarily use its shape, or appearance, to create visual variation between different geomorphologic forms and processes. This is most often effective for creating visual variance between symbols in the legend. However, there are specific cases when the appearance of certain symbols only differ slightly, which can potentially cause confusion for the user. A specific example lies in the symbols for representing incisions (or gully erosion) and debris flows (Table 3).

Debris Flow	Incision (Gully Erosion)
	

Table 3: A comparison of two different symbols included in the legend developed by Kneisel et al. (1998).

Incisions are represented by a straight line with an arrow on the end used to depict direction of travel. The appearance of the symbol for debris flows, however, is only marginally different: it's represented by a wave-like line that has an arrow on the end, used to depict direction of travel. In other cases, visual variation is attempted through the use of size. This can be seen in the symbols used to depict moraines and gravel/pebble plains. Both symbols appear to be nearly identical, with the same texture composed of a very tight grid of black lines. The only difference between the two symbols is the outer boundary line, which is roughly double in thickness for the moraine as it is for the gravel/pebbles plain, causing the two units to easily be confused with one another. As color is the most eye-catching of the visual variables, it would have been advantageous for the system developed by Kneisel et al. (1998) to incorporate it into its symbolic design.

The legend developed by Pavlopoulos et al. (2009), while still capable of representing certain aspects of the geomorphologic setting of high mountain environments in the United States, is the weaker of the two legends tested in the study area.

The greatest strength of legend developed by Pavlopoulos et al. (2009) lies in its symbolic design. Unlike the legend developed by Kneisel et al. (2009), Pavlopoulos et al. (2009) take full advantage of the five visual variables (size, shape or appearance, orientation, texture, and color) to create visual variation between symbols used to represent geomorphologic features and processes. Of these, the most effective way in which the authors create visual variation between symbolic elements is through the use of color. While this is an obvious strength, given that color is the most eye-catching of the visual variables, it also lends itself to a particular flaw in the legend developed by Pavlopoulos et al. (2009)

Pavlopoulos et al. (2009) do not designate which color should be applied to which feature or process, leaving this choice to the cartographer. While this allows for a certain amount of artistic freedom for the cartographer, it does provide a standard to be used for the production of different geomorphological maps. In the work published by Pavlopoulos et al. (2009), *Mapping Geomorphological Environments*, the authors demonstrate the effective use of color in five different geomorphological environments; the authors also demonstrate that, by not designating a standard color scheme to be used, geomorphological maps displaying similar information can appear vastly different.

The primary weakness in the legend developed by Pavlopoulos et al. (2009) lies in its inability to represent the complete geomorphological setting of high mountain environments. Though it is capable of mapping certain aspects of the physical environment, it is incapable of representing the complete environment, as it lacks symbols for represent significant geomorphological features and processes that are included in other, more specialized, geomorphological mapping systems, such as the system developed by Kneisel et al. (1998). This can be observed in Figure 7. Because this legend lacks symbols necessary to represent the complete geomorphological environment of high mountain environments, it should be avoided for producing geomorphological maps of these environments.

The newly developed legend is the first geomorphological mapping system developed specifically for high mountain environments in the United States. It is the optimal choice for geomorphological mapping of these environments, as it was designed using based upon the strengths of the two legends developed by Kneisel et al. (1998) and by Pavlopoulos et al. (2009). The new legend is capable of providing a more comprehensive representation of the geomorphological environment, as well as being more effective in communicating information by taking advantage of the five visual variables.

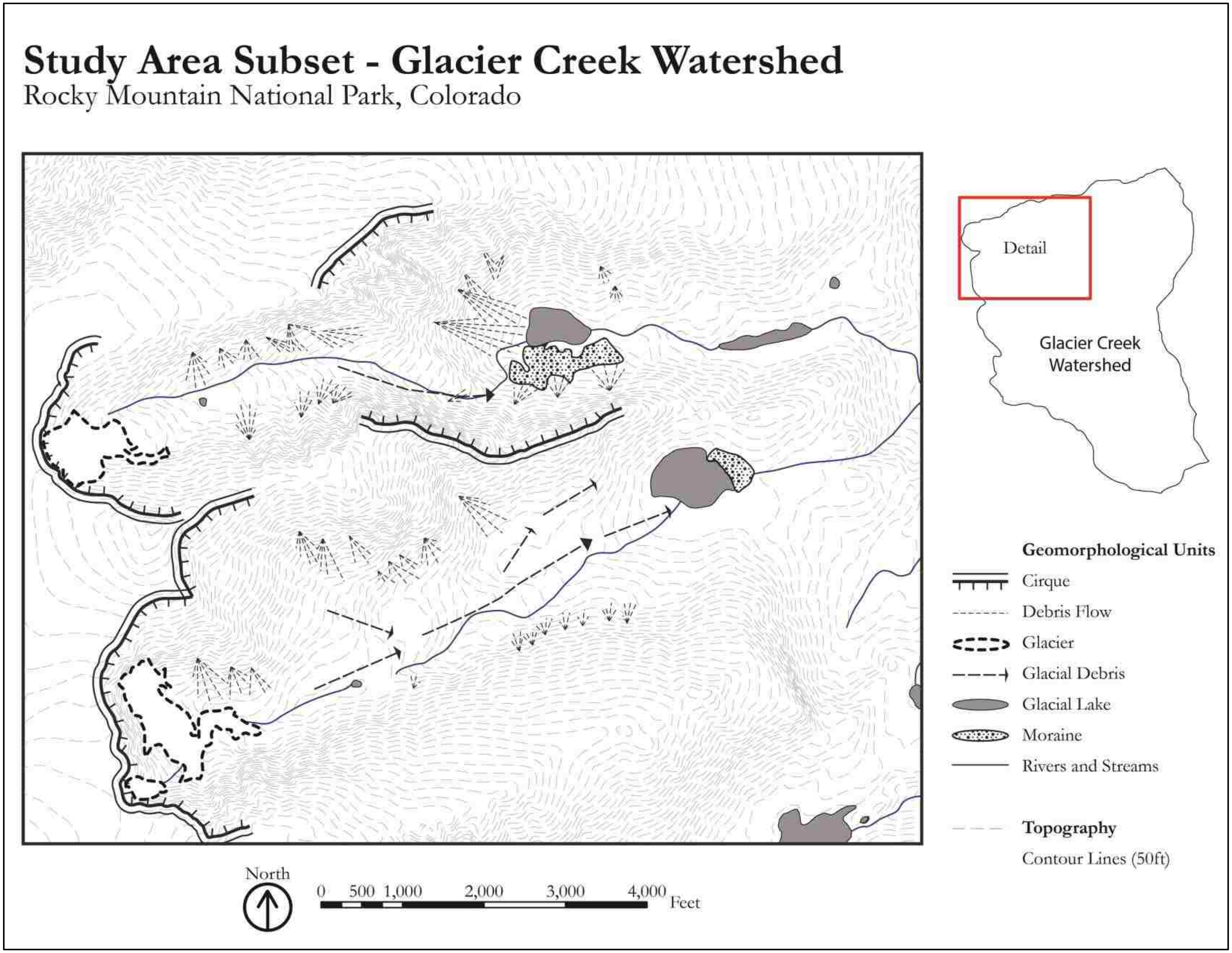


Figure 7: Geomorphological map of a subset of the Glacier Creek watershed produced using the legend developed by Pavlopoulos et al. (2009)

The new legend, as it was based upon the legend developed by Kneisel et al. (1998), is comprehensive in nature. The new legend contains a series of symbols capable of representing fifty four different geomorphologic features and processes, and was compiled using five different sources in order provide the most comprehensive legend. It contains forty-one symbols for geomorphologic features and processes identified within the legend developed by Kneisel et al. (1998). The new legend does not include the entire collection of symbols contained within the legend developed by Kneisel et al. (1998) in an attempt to reduce complexity. For example, the legend developed by Kneisel et al. (1998) contains three symbols, whose appearance only differs marginally, for representing rock glaciers in the landscape. In order to generalize, or reduce complexity, the new legend contains a single symbol for representing rock glaciers. Similarly, the legend developed by Kneisel et al. (1998) also contains three symbols, which also only differ marginally in appearance, for representing morainic ridges in the landscape. Once again, in an attempt to generalize, the new legend contains a single symbol for morainic ridges.

The new legend also contains a series of symbols for landforms and processes that were not included in the legend developed by Kneisel et al. (1998). Certain symbols for geomorphologic landforms and processes were adopted from the system developed by Pavlopoulos et al. (1998), such as glacial erratics, glacial debris, and glacial horns. Items included in the legend developed by Pavlopoulos et al. (2009) that were not included in the new legend were symbols for representing geomorphologic landforms and processes associated with ice sheets and ice caps, as the new legend is intended for high mountain environments that have been affected by alpine glaciation. For example, some of the symbols included in the legend that were developed by Pavlopoulos et al. (2009) that were omitted from the new system include drumlins, fields of drumlins, and eskers, among others. Other symbols that were omitted from the new legend were also done so in the interest of generalization. For example, the legend developed by Pavlopoulos et al. (2009) has a series of symbols for representing different aspects of glaciers, such as glacial ice, the glacier border, and the glacier tongue. The new legend contains a single symbol for representing the whole of the glacier.

In addition to the legends developed by Kneisel et al. (1998) and Pavlopoulos et al. (2009), the new legend contains symbols for geomorphologic units and processes that were not included in these legends, but included in documented scientific literature. Items included in the Geologic Resource Evaluations for Rocky Mountain National Park, as well as Denali National Park and Glacier National Park, were also included in the new legend in order to make it more comprehensive than existing geomorphological mapping systems.

Not only is the new system more comprehensive than existing systems, it is also more effective in communicating information regarding the geomorphological features and processes than the existing legends developed by Kneisel et al. (1998) and Pavlopoulos et al. (2009). This can be observed in Figure **8**. Contrary to the legend

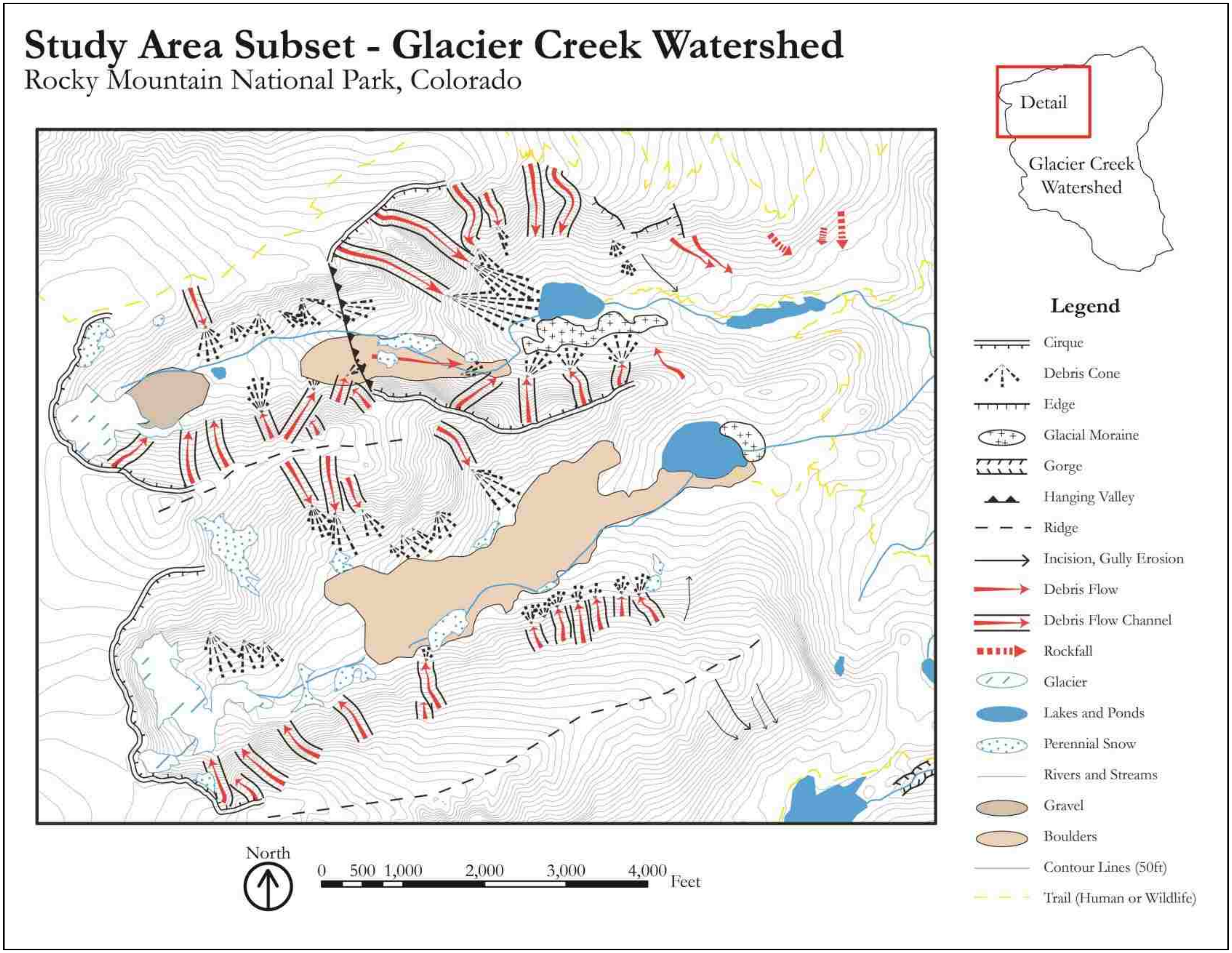


Figure 8: Geomorphological map of a subset of the Glacier Creek watershed produced using the newly developed legend

developed by Kneisel et al. (1998), the new legend takes full advantage of the use of color, the most eye-catching visual variable. For example, the new legend uses the hue cyan for hydrologic features, red for mass movements, and the combination of cyan and white for glaciers and perennial snow. By using color, visual contrast is generated, increasing readability of the geomorphological map. While the legend developed by Pavlopoulos et al. (2009) also uses color, the authors did not designate which colors should be applied to which symbol, which results in a lack of continuity amongst different geomorphological maps. The new legend, however, designates which colors to be used. This ensures that geomorphological maps produced by different authors will appear similar.

However, the new legend does have certain limitations. Just as the systems developed by Kneisel et al. (1998) and Pavlopoulos et al. (2009) were not without flaws, the new system has potential for improvement. The new legend is potentially incomplete. It is possible that the new legend is incapable of representing the complete geomorphologic setting of a high mountain environment on the grounds that certain geomorphologic features and processes are not included in the final legend.

A potential way to mitigate this problem is for the development of a unified definition of high mountain environments. By defining what a high mountain environment is, and what geomorphologic features and processes can potentially exist within these environments, a comprehensive inventory can be developed. Once an inventory has been developed, an existing legend may be augmented, or a new legend may be created.

8. CONCLUSION

This thesis project was successful in completing its primary objective: the development of a legend for mapping the geomorphological setting of high mountain environments in the United States. In addition, multiple geomorphological maps of a designated study area were also successfully produced to provide examples of the capability for the newly developed system to represent geomorphological landforms and processes that exist in high mountain environments.

The development of a legend for geomorphological mapping of high mountain environments existing in the United States is an effort towards joining other countries around the globe that are attempting to represent the physical surface of the earth. Prior to this study, the United States has made little, if any, efforts towards the unification and standardization of geomorphological mapping systems, relying instead on the USGS standard geologic mapping system to represent all environments. By attempting to develop a legend specifically for mapping geomorphological environments, rather than geologic, a step toward a national standard has been made.

High mountain environments are only one of the many different landscapes that exist within the United States' boundaries. Further research must be performed concerning the development of geomorphological mapping systems for each of these different landscapes. Through increased interest in the field of geomorphological mapping and collaboration between geomorphologists, the task of developing an extensive nationally unified key, although great, is certainly possible.

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