LARGE-SCALE MAPPING AND GEOMORPHOMETRY OF UPLAND PERIGLACIAL LANDSCAPES IN EASTERN BERINGIA

By

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A THESIS

Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of

Geography – Master of Science

2018

ABSTRACT

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In subarctic and alpine regions, an altitudinal and latitudinal zone exists between the treeline and glaciers in which a distinct set of periglacial landforms and processes dominated. Several prominent periglacial geomorphologists have recently questioned whether periglacial processes can give rise to a “characteristic periglacial landscape.” This thesis tests the hypothesis that such landscapes do indeed exist in upland, cold, nonglacial environments. The landscape was examined through a multiscale approach using large-scale mapping and geomorphometry. Study sites were chosen from the largely unglaciated eastern Beringia, together forming a transect across this region. An additional site was mapped that represented a high alpine site, in which periglacial geomorphic processes are currently active. At each site, large-scale geomorphological maps of cryoplanation terraces (CTs) were generated using traditional field techniques and computer-generated mapping based on digital elevation models (DEMs).

Geomorphometric analysis was conducted at both the landform and landscape scales for sites in eastern Beringia. This analysis focused on the identification of CTs and the geomorphic “signature” of the landscape within the Yukon-Tanana Upland physiographic province. Results from these analyses indicate there is a distinct periglacial landscape, composed of an assemblage of interconnected forms. Cryoplanation landforms function as the foundation of this “periglacial landscape.”

ACKNOWLEDGEMENTS

I would like to express my sincere gratitude to all who helped make this thesis possible. It is appropriate to start by thanking all those involved with the Circumpolar Active Layer Monitoring (CALM) program for first introducing me to periglacial research and providing me with many subsequent opportunities. I would like to thank the United States Permafrost Association for funding this research. Funding from Michigan State University's Department of Geography and College of Social Science was essential in allowing me to travel to and conduct this research. Finally, I would like to extend my gratitude to Northern Michigan University for the use of equipment.

Dr. Ashton Shortridge of Michigan State University inspired me to pursue geomorphometry in this thesis. His inspiration and advice were invaluable. Dr. Shortridge's door was always open and he was very willing to take the time to help when difficulties arose.

I am indebted to Dr. Alan Arbogast of Michigan State University, who, not only served as an invaluable mentor while conducting this research but generously provided the opportunity to continue to expand my education beyond periglacial problems. Dr. Arbogast could always be counted on for good advice and an honest answer.

Dr. Frederick Nelson of Michigan State University first introduced me to the periglacial realm and fostered my interest in periglacial geomorphology. As an advisor and mentor, he provided the impetus for this research and continued support throughout the project. Dr. Nelson deserves special thanks for the many trips to East Lansing, Skype calls, and edits of papers. He went above and beyond to provide the opportunity to conduct this research and I could not have finished this work without his steadfast guidance and enthusiasm.

I would like to express my heartfelt gratitude to Kelsey Nyland for her mentorship and assistance in the field and through many aspects of this project. This work could not have been done without her support through many long hours of field and office work.

I would like to express my thanks to my parents for their support of my education and encouragement to obtain higher education and enriching experiences.

Finally, I would like to thank my wife, Katie, for her support of my graduate education and the pursuit of this project. I could not have gotten through this without the motivation and support she provided through the long hours of studying, writing, and through the many days spent apart.

Thank you!

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KEY TO ABBREVIATIONS

CT	Cryoplanation Terrace
CTAR	Cryoplanation Terrace semi-Automated Recognition
YTU	Yukon-Tanana Upland
DEM	Digital Elevation Model
DSM	Digital Surface Model
ERR	Elevation Relief Ratio
HI	Hypsometric Integral
SETSM	Surface Extraction from TIN-based Searchspace Minimalization
TIN	Triangular Irregular Network
USGS	United States Geological Survey

Chapter 1

Introduction

The concept of a "characteristic periglacial landscape" has been questioned in recent literature, spurring speculation about the importance of periglacial processes in landscape-scale geomorphology. This growing body of literature includes French (2016), who postulated that cold, nonglaciated upland landscapes in Yukon Territory may be composed of inherited features, and that periglacial processes may only be responsible for surficial forms. André (2003), another critic of the notion of a "characteristic periglacial landscape," questions the effectiveness of the mechanical weathering traditionally assumed to be associated with periglacial geomorphic activity. These critics based their claims on studies conducted on discrete periglacial landforms. However, few studies have focused on *assemblages* of features at varying scales and included landscape geometry in their analysis. This thesis seeks to resolve the question of the existence of a "characteristic periglacial landscape" through application of mapping, geomorphometric analysis, and spatial-analytic techniques to the unglaciated upland landscapes of Interior and western Alaska. An under investigated class of landforms known as *cryoplanation terraces* (CTs) abounds in this region. This thesis also examines the proposition that CTs form the foundational building blocks of periglacial assemblages.

1.1 The Concept of Landscape

Landscapes are "the unit concept of geography" (Sauer 1925), providing a defining principle for the discipline. Outside geography, the term *landscape* has often been used by artists, travelers, and members of the general public. Because of the many commonplace uses of this term, a definition of the term for use in scientific research is essential. With the central focus of this thesis being the periglacial landscape, an understanding of the term *landscape* is necessary.

1.1.1 History of the landscape concept: The concept of landscapes can be traced back to the middle ages, where the term *land* was introduced as a term for a physical location. The term *land* was originally used as a political construct that relates to the social structure of medieval Europe (Olwig 2002, p. xiii). In Germany, *land* was eventually expanded upon to became *landschaft*, a somewhat ambiguous term, which Hartshorne (1939) explained varied based on each individual's thoughts on the scope of geography. The ambiguous nature of landschaft in German, was not clarified in its translation to the English term *landscape*. This ambiguity led to a loss of meaning and a lack of definition in the field of geography (Hartshorne 1939). Early definitions of landscape and landschaft were based largely on the visual observation of the earth's surface (Penck 1927; Waibel 1933; Granö 1929 cf. Hartshorne 1939). Hartshorne (1939) expressed the need for a clearer term to describe the landscape. He reasoned that increased clarity was essential because the term was indistinguishable from the terms *region* and *area*. Based upon a review of the literature, Hartshorne (1939) was able to define *landscape* as "the external form of the earth's surface under the atmosphere." Hartshorne further clarified that the terms natural landscape and cultural landscape are actual landscape elements and not distinct types of landscape.

Since *landscape* was translated to English and dispersed through the field of geography in the early 20th century, there have been a series of refinements to the definition. As the term evolved over time, the focus of the geomorphic study of landscapes did as well. In the early 20th century, the Davisian landscape evolution theory of normal erosion (Davis 1909) dominated the study of geomorphic landscapes. Those who studied landscapes through Davisian theory, focused on visual observations of the structure, process, and stage of the landscape. Such visual observations relied on regional geography (e.g., Fenneman 1914) and the delineation of landscapes through regionalization of geomorphic processes and forms. Towards the middle of the 20^{th} century, the focus of landscapes shifted to one of the basic units of a landscape, landforms. The climatic origin of landforms, and subsequently landscapes, became a central focus of this era (e.g., Peltier 1950). This period was also the beginning of quantitative geomorphology (e.g., Strahler 1950). In the 1950s and the development of the quantitative revolution in geography, landscapes were described using quantitative measures that relate form to processes (e.g., Strahler 1952; Mark 1983). Today, studies of landscapes have expanded topically, with research investigating the paleoclimatic significance of the landscape, morphological studies of the landscape, and the sedimentary budgets of landscape elements (Haschenburger and Souch 2004). As the focus of landscape evolution changed, so did the definition. What started out as highly ambiguous and being defined by the field of view of an individual, became defined by the specific landforms making up a distinct area.

1.1.2 Landscape ecology: While the quantitative revolution was transforming the field of geomorphology, the increase in spatial analytical techniques filtered into ecology, sparking the subfield of landscape ecology. The primary goal of landscape ecology is to understand the spatial variation of ecological processes (Cain, Bowman, and Hacker 2011). This subfield provides a method for understanding landscape elements and their relation to ecology and the physical geography of a landscape. The field often focuses on patterns and spatial heterogeneity in the landscape (Turner 2005). Landscape ecology is necessary to this discussion, as the subdiscipline constitutes one of the major perspectives on the landscape (Higgins et al. 2012).

1.1.3 Definition of "landscape" for this work: For the purposes of this thesis, *landscape* is conceptualized geomorphologically: it consists of a complex of landforms that vary in size, composition, and morphology across space (Cain, Bowman, and Hacker 2011). More specifically, the landscape is an assemblage of landforms arranged on the land surface. This landscape assemblage may contain forms that are inherited or azonal in character (King 1950; Ambrose 1964; Twidale 1972; cf. Haschenburger and Souch 2004). In this thesis, analysis was conducted to understand the landscape at multiple scales. Mapping and geomorphometry were used to understand the basic units of the landscape, the landforms. At a broader scale, analysis was conducted across a periglacial region in an attempt to identify a distinct signature of periglacial environments.

1.1.4 Scale of the landscape: Scale is a central component in the study of geography, ecology, and many other disciplines. Without understanding the scale of a study incorrect conclusions may be drawn. In this work, the question of what the appropriate scale is to study the periglacial landscape is posed. A review of literatures related to defining the scale of landscapes shows that there is no clearly stated quantitative definition of landscape scale, although there is general agreement in the discussion of landscapes that they are scale dependent (e.g. Forman and Godron 1981; Withers and Meentemeyer 1999; Wu and Hobbs 2002; Higgins et al. 2012). One of the few studies to actually provide dimensions to landscape was Delcourt and Delcour (1988), who defined the scope of landscape ecology as covering those areas that are meso scale in nature, from 1 km to 100 km in width. Other more descriptive definitions have been proposed, such as Parker and Bendix (1996) who stated that landscape is intermediate between landforms and region. Forman and Godron (1981) provide both descriptive and quantitative bounds. When defining a landscape, they state that the landscape is geomorphically homogenous areas that vary in size but have distinct boundaries. Their discussion further defines the size as kilometers wide. While there appears to be some agreement that the size of landscapes fall into the meso scale range or that of tens of kilometers, this lack of a formal, agreed upon landscape scale must be addressed. Higgins et al. (2012) advocates that this sort of integrated landscape concept would be able to transcend disciplines. However, they also point out that there appears to be a degree of disagreement over how to define and view scale within and between disciplines, an issue that must be resolved.

1.2 Periglacial Geomorphology

The term *periglacial* was first defined by Lozinski (1909) "to designate the climate and climatically controlled features adjacent to the Pleistocene ice sheets" (cf. Washburn 1980). This first definition limited its utility in describing processes in regions such as Beringia, which were largely unglaciated during the Pleistocene. In the mid- 1900s the International Geographical Union (IGU) recognized the subdiscipline of periglacial geomorphology. During the same period, a published outlet for periglacial research, the journal *Biuletyn Peryglacjalny*, was introduced (1954). These events formalized and expanded the definition to include all cold-climate, non-glacial processes and landforms (French 2017). The broadening of the definition, which explicitly excludes proximity to glaciers as a criterion (Washburn 1980), allows for an increased range of study.

Although its existence is broadly accepted, a definition for the term "periglacial landscape" has been the subject of scholarly debates (e.g., André 2003; French and Thorn 2006; French 2016; French 2017). These discussions are exacerbated by the nebulous character of the term "landscape", and by the lack of precision in the definition of the periglacial zone. The term *zone*, as used here, follows climatic geomorphology's concept of the latitudinal and altitudinal zonation of landscapes. Tricart and Cailleux (1972) provided a detailed accounting of the zonation of landscapes and associated processes. A *zonal* process is one associated with a distinct climatic regime within which that process or landform can be found. Other processes are azonal, in that they are found across all climatic zones and lack a well-defined limit. Some scientists (e.g., Tricart 1967; Péwé 1969) provide evidence that the periglacial zone is linked with underlying permafrost and can thus be defined using the thermal properties of frozen ground, i.e., areas in which subsurface layers remain at or below 0^{o}C. However, this concept has been disregarded by most because not all landforms considered periglacial are associated with permafrost (French 2017).

Other attempts to create quantitative climatic boundaries for periglacial regions have been proposed. A few of those boundaries are: a mean annual air temperature of between -15^{o}C and -1^{o}C (Peltier 1950), -12^{o}C and 2^{o}C (Wilson 1968), and below 3^{o}C (French 2017). Although these "boundaries" may have merit, it is more common to encounter open-ended definitions that propose general criteria for the periglacial landscape, such as intense frost action and lack of perennial snow (i.e., Washburn 1980). Most definitions of periglacial zones describe them as being poleward of (or in alpine areas above) the tree line and excluding glacial processes. Given the prevalence of such unrestricted definitions, it is not surprising that some "periglacial landscapes" could be construed as inherited landscapes covered with "surface decorations" (Birot 1968). A holistic examination of the landscape that includes features involving entire slope sequences is necessary to better understand whether distinctively periglacial landscapes exist and what can or should be included in that conception.

1.3 Cryoplanation Terraces

1.3.1 Morphology: Cryoplanation terraces (CTs) are large periglacial landforms characterized by alternating treads and risers, giving the appearance of giant staircases (Figure 1.1). The risers (scarps) are typically covered with clastic rubble, while the nearly planar treads are a mosaic of vegetation, rock debris, and surficial periglacial landforms. One of most comprehensive examinations of cryoplanation terraces was conducted by Reger (1975), who mapped and classified 686 cryoplanation landforms across interior Alaska. Reger's terraces varied in size and morphology, with scarps ranging from 3 to 76 m in height and slopes of 9-32^{o}. Additionally, Reger found that treads range in length from as little as 5 m to hundreds of meters, and have considerably gentler slopes (Reger 1975). The overall size of these landforms can be anywhere from 3,000 to 845,000 m^2 (Reger 1975) and is such that they constitute entire slope sequences.

Although structural control has not been shown to be a dominant factor in cryoplanation terrace formation (Washburn 1980 p. 240), lithology has been suggested as important (French 2017), with numerous observations made regarding the geologic attributes of terraces. Eakin (1916), in his initial survey of terraces in the Yukon-Koyukuk Region, found that they are best developed in areas of Mesozoic rock composed of granite, greenstone, and quartzite schist. Reger (1975) added to Eakin's lithological observations by including volcanic rock as a common bedrock type in which cryoplanation terraces are formed. Reger also found that well-developed terraces were not common on fine- to medium-grained sedimentary rocks, an observation that appears consistent with other work (Demek 1969).

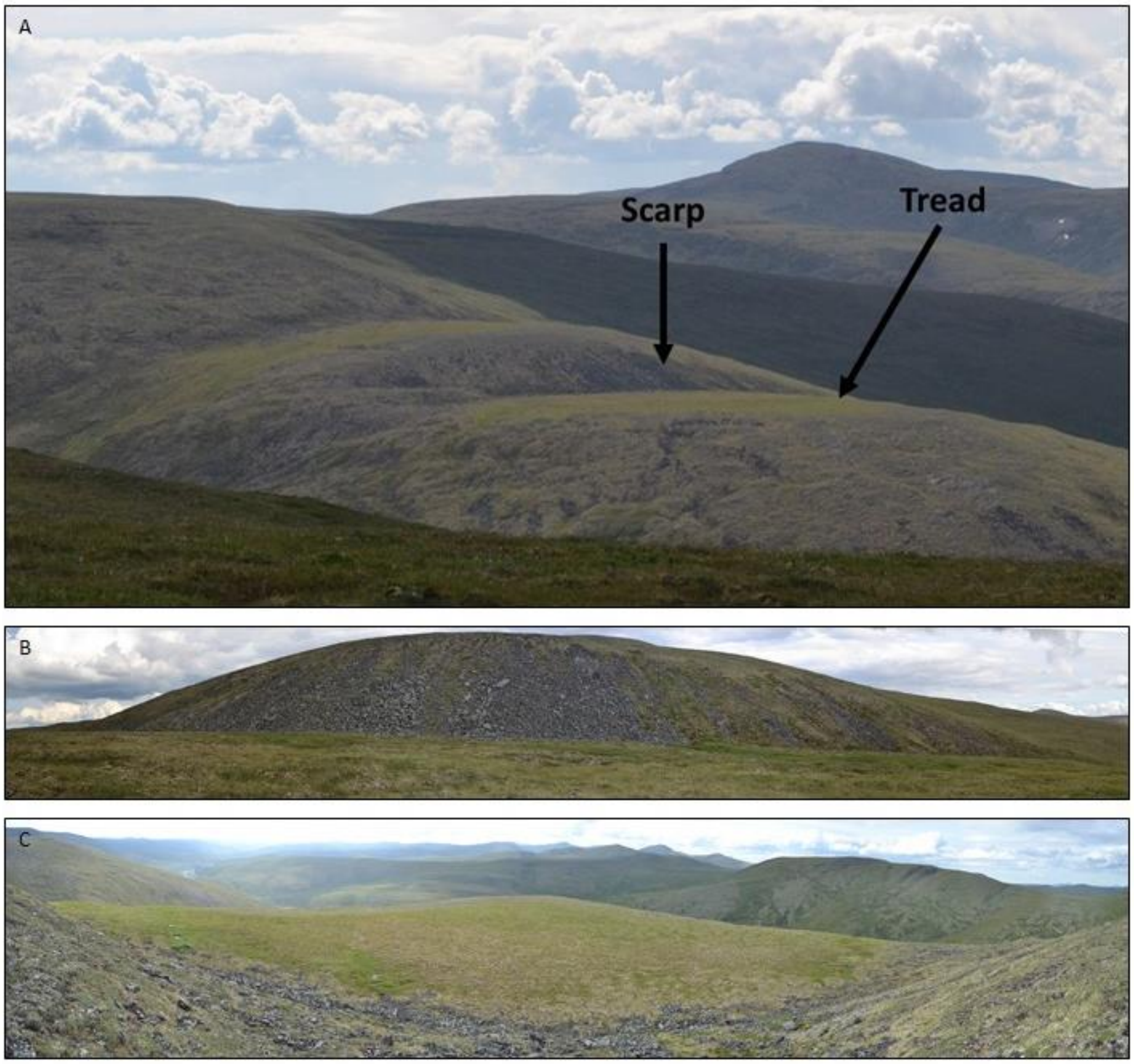

***Figure 1.1**. **Photos of cryoplanation terraces at Eagle Summit, AK:** A) series of cryoplanation terraces. The tread and riser (scarp) are highlighted to indicate the various components of the cryoplanation system. The tread is 200 m long and the scarp is 25 m in height. B) scarp of cryoplanation terrace, view to east. C) tread of cryoplanation terrace in part A, view to west. Note the rubble at the base of scarp and patterned ground beyond.*

1.3.2 History: Geologic observations of a general nature were common among early 20th century U.S. Geological Survey (USGS) scientists operating in Alaska (e.g., Moffit 1905; Prindle 1905; Mertie 1937) and provided a baseline for geomorphic research across Alaska. These studies were necessarily of a general nature and lacked in-depth investigations of landforms such as cryoplanation terraces. Additionally, in the intervening years the paradigm of landscape creation has shifted away from the Davisian model that influenced these pioneers. Today, those hundred-year old studies provide concise descriptions and powerful insights and form a useful basis for contemporary investigations into periglacial landscapes.

Currently, the predominant hypotheses regarding the origin of CTs holds that they form through a climatically controlled suite of processes (*nivation*) involving intensified weathering and sediment transport in the vicinity of late-lying snowbanks (Cairnes 1912). Proponents of this hypothesis cite research showing that cryoplanation terraces exhibit altitudinal similarities with glacial cirques (Nelson 1989; Nelson and Nyland 2017) and display poleward orientation similar to that of glacial cirques, also indicating a climatic origin (Nelson 1998). Others state that cryoplanation terraces are related to permafrost and other periglacial processes such as solifluction (Reger and Péwé 1976). Critics of the climatic-origin hypothesis of CT development raise several issues. French (2016) questioned the moisture regime available in periglacial regions, pointing out that many landforms found in periglacial regions show similarities to those in arid regions. Washburn (1980 p. 240) cited the presence of patterned ground on terrace treads as evidence that material transport on the terraces is too weak to remove material from terrace treads. As Thorn and Hall (2002) point out, however, little field-based research focusing on CTs has been undertaken in recent years.

1.3.3 Nivation: Weathering and transportation processes associated with late-lying snow patches, termed *nivation* by Matthes (1900), has been cited as being responsible for the formation of CTs. Matthes postulated that mechanical weathering and mass wasting are intensified in the vicinity of snowbanks. Since Matthes first proposed the idea, process-oriented nivation studies (e.g., Thorn 1976; Berrisford 1991) have increased understanding about how snow patches enlarge initial topographic irregularities on slopes, and the specific mechanisms involved. Thorn (1976) calculated long-term erosion rates in the Colorado Front Range and stressed the importance of both chemical and mechanical weathering for the creation of nivation hollows. He concluded that the nivation process suite is not effective enough to support long-held notions about the existence of a form continuum extending from nivation hollows through to glacial cirques. Nivation research has been expanded by others, including Ballantyne (1978), who investigated the hydrologic significance of the nivation system. Hall (1993) studied the breakdown of bedrock under the influence of late-lying snow, and Caine (1992) studied the sediment loads of snowpatches. Kňažkovà et al. (2018) calculated a long-term erosion rate of 0.77±0.12 mm/yr in a nivation hollow on James Ross Island near the northeastern tip of the Antarctic Peninsula. The aforementioned studies are just a few that have continued to refine the understanding of localized erosion associated with late-lying snow.

Cairnes (1912), although not widely credited, was the first to suggest that the nivation suite of geomorphic processes is responsible for development of cryoplanation landforms. While this interpretation has been accepted by many (e.g., Demek 1969; Reger 1975), recent literature (i.e., Thorn and Hall 2002; French 2017) points out the lack of field-based process investigation, highlighting the need for research that would lead to detailed understanding of the dynamics responsible for the formation of cryoplanation landforms.

1.4 Periglacial Assemblages

Earth's periglacial regions are often discussed using the term the *periglacial realm*. This term encompasses all areas that are very cold, but not glacial. Many of those areas have only recently become periglacial by virtue of deglaciation. Because much of the periglacial realm has not been operated on by periglacial processes for long enough, only a relatively small subset of the periglacial realm could feasibly have formed a periglacial landscape. This thesis proposes that the periglacial landscape is, in turn, made up of an assemblage of various landforms (Figure 1.3).

In the German periglacial literature, this periglacial landscape is described as a series of "form communities" reflective of the processes that formed them (e.g., Poser 1976). Much of the research in periglacial geomorphology has been focused on small features such as sorted patterned ground and solifluction lobes (e.g., Troll 1944; Furrer and Dorigo 1972; Graf 1973; Rudberg 1977) that constitute the components of form communities. Birot (1968, 125) considered such forms to be mere surface "decorations" that are insignificant in terms of slope evolution. The concept of a periglacial assemblage advanced in this thesis extends over a wide range of landform size, including small "microforms" (e.g., sorted patterned ground), meso-forms (e.g., solifluction lobes and terraces) and macro-forms (landscape-scale features such as cryoplanation terraces and cryopediments). Although this array of landforms may seem to be a chaotic mixture, the various forms are closely related through a common origin: freezing and thawing of earth materials in the presence of water.

The periglacial assemblage is composed of variously sized features that, considered as a unit, create a distinctive pattern extending across a broad spectrum of geographical scale. This concept was introduced indirectly in an unpublished report by Brunnschweiler (1965) and is illustrated in Figure 1.2 as the "altiplanorium." This thesis follows Brunnschweiler's concept, conceptualizing the periglacial assemblage in the context of cryoplanation (altiplanation) terraces, large periglacial landforms that remain inadequately studied from process-based and geomorphometric perspectives.

A potentially useful approach to the periglacial landscape problem is through the concept of *facies*, units of rock or sediment formed in distinct environments and recognizably distinct from adjacent units. The facies concept can be utilized in understanding and creating a general framework for the environments in which periglacial features form. The concept was developed by Madole (1972), who investigated the spatial distribution of Neoglacial facies in the Colorado Front Range. His hypothesis was that if the spatial arrangement of facies could be linked to their genesis then they could be significant indicators of past depositional environments at the local scale. Morris and Olyphant (1990) furthered Madole's (1972) work by creating a physical model for facies deposition. This model incorporated topoclimate and geology to predict the type of lithofacies that would form under various environmental conditions. A similar model, as proposed in Figure 1.4, would be useful in understanding and expanding on the concept of *periglacial facies*.

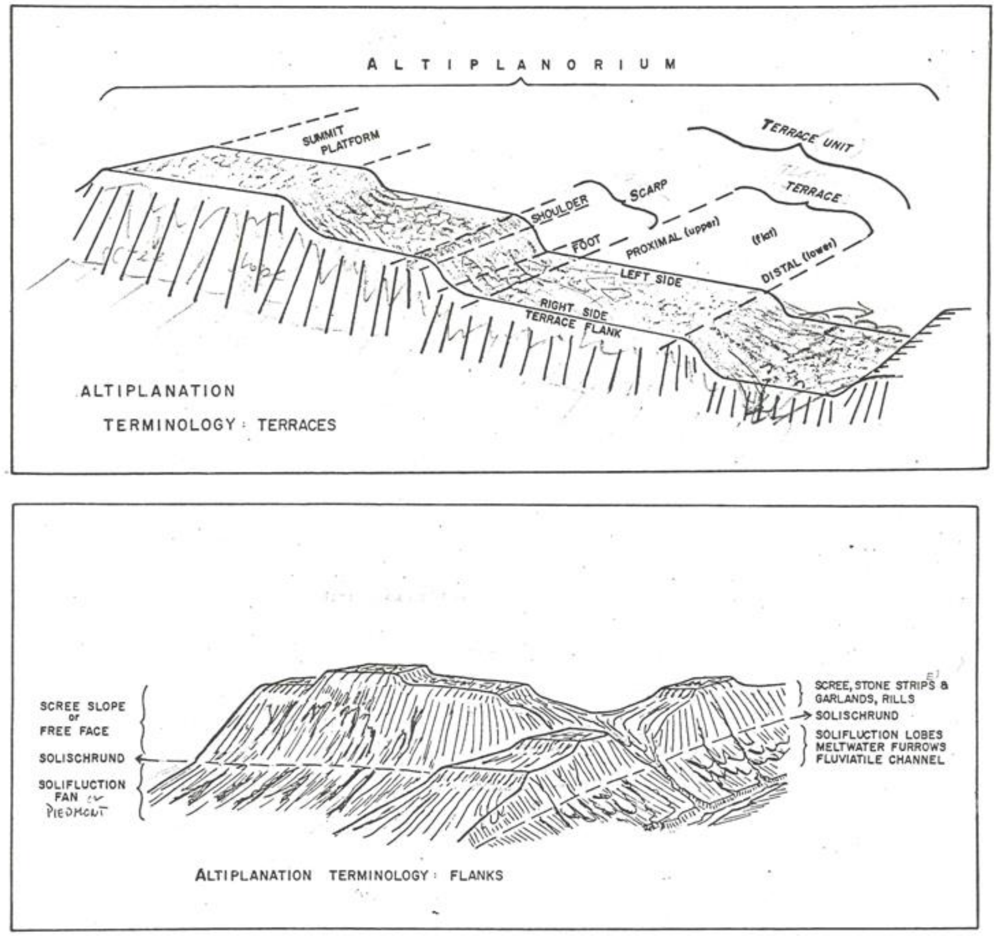

Figure 1.2. The "altiplanorium": *The altiplanorium is an integrating concept based on assemblages of minor periglacial features superimposed on much larger erosional periglacial landforms (altiplanation [cryoplanation] terraces). Figure from Brunnschweiler (1965).*

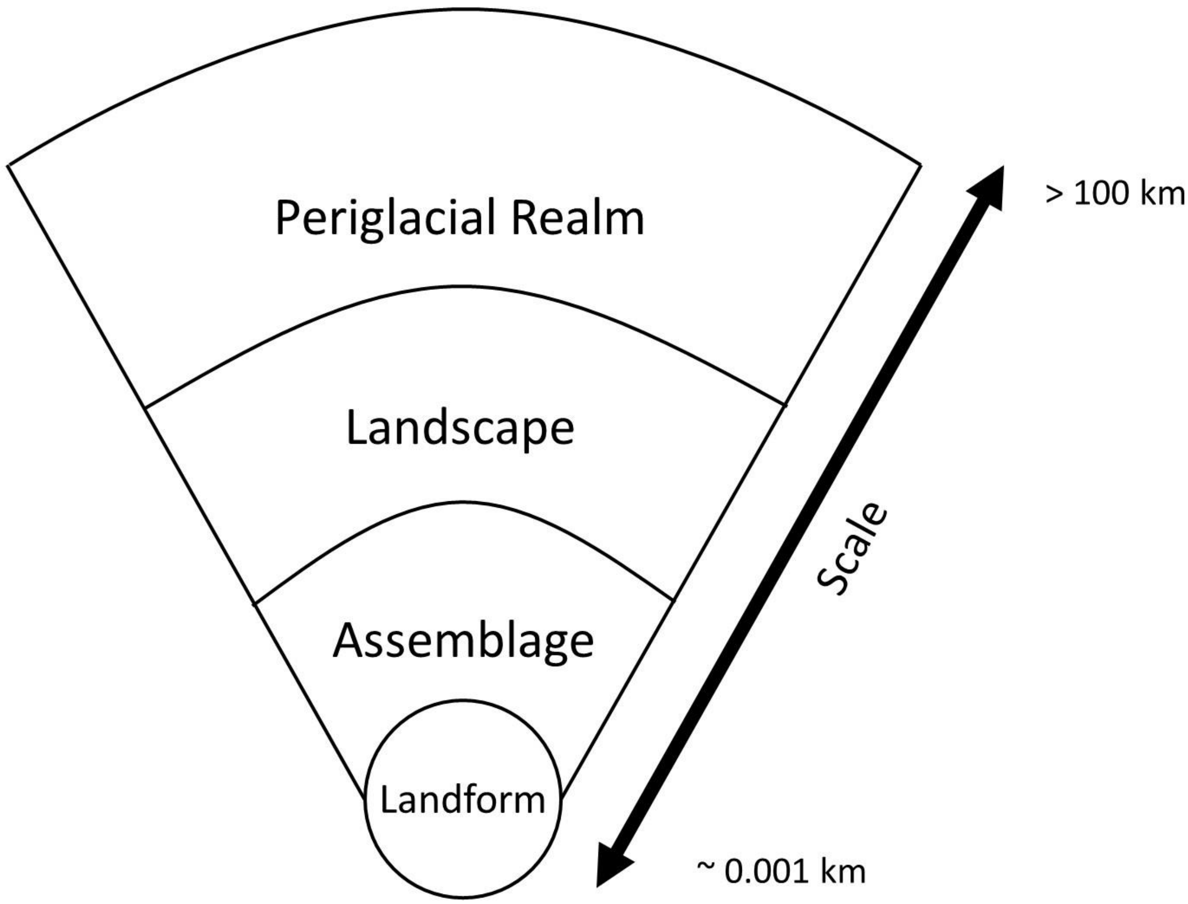

Figure 1.3. A conceptual diagram of the periglacial landscape: *This diagram shows how the periglacial landscape is made up of an assemblage of individual landforms. Landforms are the most basic unit of this study. A repeating series of these landforms is an assemblage, which in turn makes up the periglacial landscape. The periglacial realm consists of all these elements and all other periglacial features. This graphic illustrates how the landscape scales from the individual periglacial landforms to an assemblage, which in turn creates a landscape. The periglacial landscape, assemblage, and landforms all fall into the periglacial realm. Scale indicated is non-linear and numbers are an approximation.*

In establishing a model for periglacial facies, certain morphologic and climatic factors were accounted for. Because of their relatively large size and dominance on the periglacial landscape, CTs are the logical basis for this model. A review of the literature indicates that potential factors influencing the formation of cryoplanation terraces include climate (Reger and Péwé 1976; Nelson 1998; Nelson and Nyland 2017), bedrock type and structure (Reger 1975; French 2017), and topography (Nelson 1979b, 1989). The concept of periglacial facies, which is closely related to the assemblages discussed above, will facilitate understanding about the interplay between environmental parameters and how they are incorporated into periglacial landscape development.

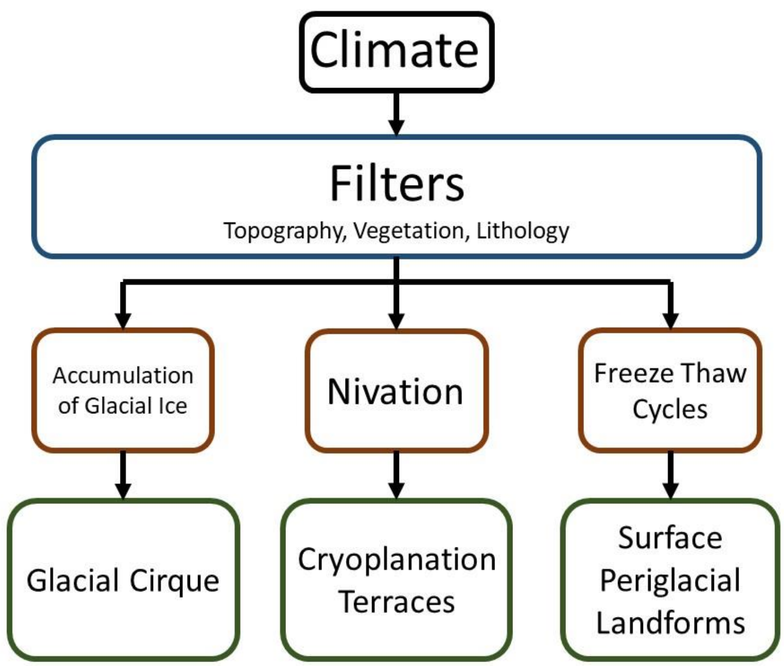

Figure 1.4. Proposed topoclimatic model for periglacial facies: *A proposed model for the development of a periglacial landscape and associated landforms (green bubbles) based on a series of filters (blue bubble) and processes (brown bubbles). The model assumes that climate is the driving force behind periglacial environments.*

1.5 Study Area – Beringian Uplands

Beringia (Figure 1.5) is the landmass north of 55° N extending roughly from the Lena River in eastern Siberia to the Mackenzie River in western Canada. Beringia is composed of three subregions: (a) eastern Beringia, the area between the former Bering Land Bridge and the Mackenzie River; (b) central Beringia, the former Bering Land Bridge (now the Bering Strait and islands within); and (c) western Beringia, extending west from the land bridge to the Lena River in Central Siberia.

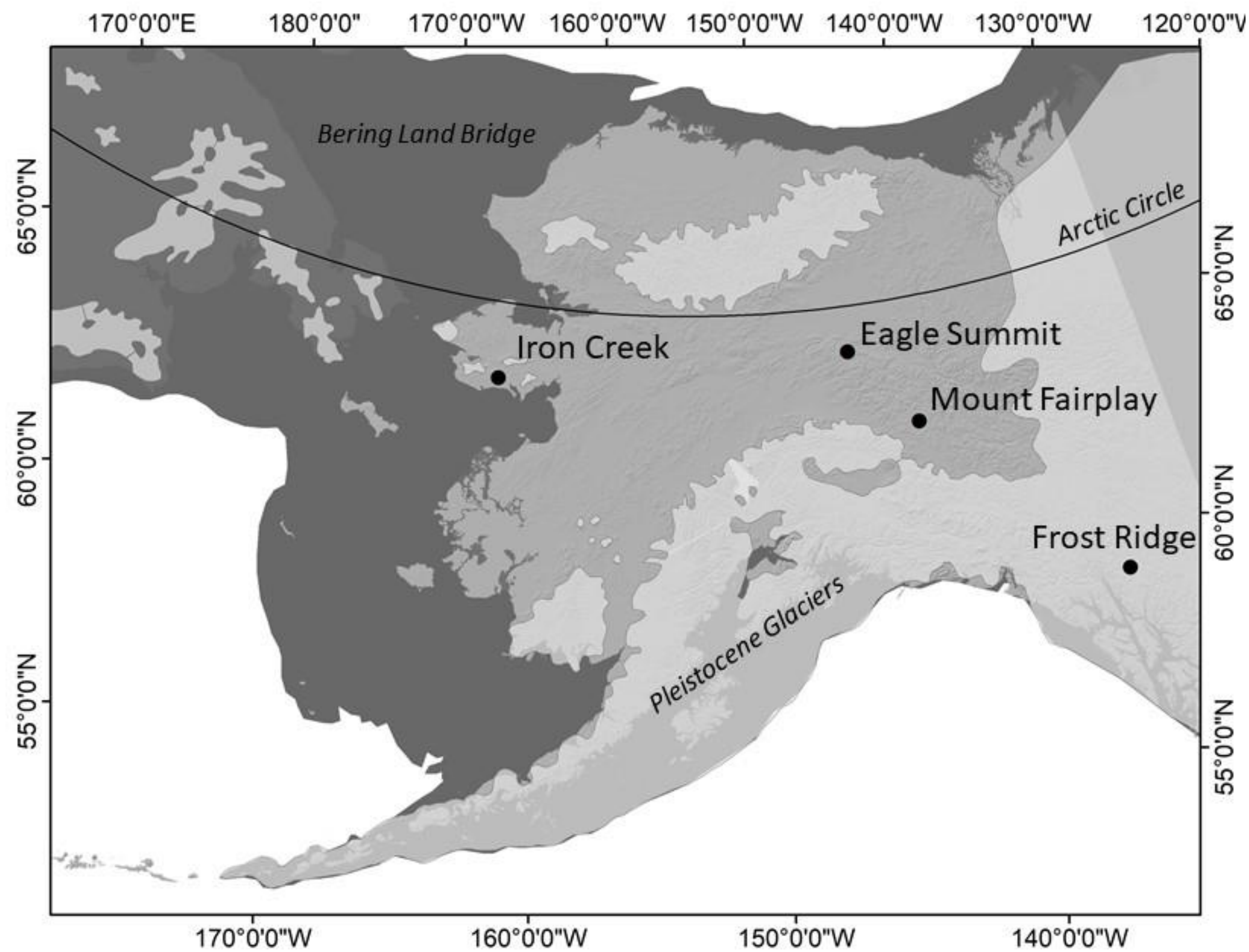

***Figure 1.5. Study sites in eastern Beringia:** The Bering Land Bridge (dark grey) and Pleistocene glaciers (light grey) are delineated to provide context. Study sites across Alaska and in British Columbia are indicated by black dots. Map adapted from Brubaker et al. (2005).*

1.5.1 Glacial and environmental history: During the last glacial maximum (LGM) Beringia remained largely unglaciated, with only scattered mountain glaciers existing at higher elevations of the generally "ice-free corridor" between the Alaska and Brooks Ranges. The southern and eastern boundaries of Beringia were defined by the large ice sheets. The Cordilleran Ice Sheet coalesced with mountain glaciers in the Alaska Range at the southeastern edge of Beringia. On the eastern edge of Beringia, the Laurentide Ice Sheet met with the Cordilleran, cutting off this ice-free region from the rest of North America (Brigham-Grette 2001). During the LGM, the climate in eastern Beringia was highly continental, owing to the physical barriers to the Arctic and Pacific Oceans created by the Brooks and Alaska Ranges. Because of its proximity to the ocean, central Beringia experienced a more marine climate with milder temperatures and a mesic environment. At higher elevations in eastern Beringia mean annual temperatures and precipitation decreased, leading to a cold, semi-arid environment (Hopkins et al. 1982; Elias 2001).

Vegetation in central Beringia was mesic tundra dominated by moisture-loving plants (Elias et al. 1997). Eastern Beringia was dominated by steppe tundra, a biome that is non-existent today, although the region was dominated by tundra plants that could survive with little moisture (Guthrie 1982). Paleoecologists disagree about whether Beringia was an arboreal refugium, but nonetheless it is unlikely that trees were present in upland areas of eastern Beringia (Hopkins, Smith, and Matthews 1981; Brubaker et al. 2005).

Around 18,000 years ago, two concurrent events changed the nature of the Beringian landscape: (1) the ice sheets began to retreat; and (2) the Bering Land Bridge became inundated with water as sea level rose (Brubaker et al. 2005). Subsequent changes in the environment resulted in a decrease in continentality in eastern Beringia. Nelson and Nyland (2017) computed Conrad's continentality index from climate data from across Alaska and found that contemporary eastern Beringia is still experiencing a pronounced continentality gradient that increases with distance from the Bering Sea. The opening of a corridor between the Laurentide and Cordilleran Ice Sheets allowed trees to migrate north and vegetation to transition to the tundra vegetation observed today (Brubaker et al. 2005).

1.5.2 Periglacial studies in Beringia: Although periglacial studies have been numerous in eastern Beringia, much of the research is fragmented and focused on discreet (specific) landforms, including patterned ground (e.g., Church, Péwé, and Andersen 1965), rock glaciers (e.g., Wahrhaftig and Cox 1959), frost mounds (e.g., Mackay 1986), and solifluction (e.g., Hanson 1950; Millar 2005). Curiously, only a few published studies have been devoted specifically to cryoplanation landforms in Beringia (Cairnes 1912; Eakin 1916; Obruchov 1937; Chaiko 1988; Péwé 1970; Reger and Péwé 1976). The dissertation by Reger (1975), although qualitative, stands out conceptually as the most comprehensive work ever produced about cryoplanation terraces in eastern Beringia. Moreover, the thesis contains the most comprehensive CT data set ever assembled. Unfortunately, with the exception of one short paper (Reger and Péwé 1976), most of the material in Reger's (1975) dissertation has not been published in the open literature. Several derivative studies used Reger's (1975) data set to demonstrate similarities in the geographic distribution (Nelson 1989), elevation trends (Nelson and Nyland 2017), and orientation (Nelson 1998) of CTs and glacial cirques. However, no major work has been conducted that focuses on periglacial assemblages in the Beringian landscape, Brunnschweiler's (1965) unpublished report being the sole exception.

1.6 Statement of Problem

Beringia should provide an ideal example of an upland periglacial landscape. Owing to ultracontintental climatic conditions during Pleistocene cold intervals, most of Beringia remained unglaciated during the entire Quaternary Period (Figure 1.5). Periglacial processes have, theoretically, operated over extended periods, possibly in nearly continuous fashion, throughout much of this vast area over the past 1.8 Ma. According to the tenets of climatic geomorphology (e.g., Birot 1968; Tricart and Cailleux 1972; Büdel 1977), this largely unbroken period of cold nonglacial conditions should, in principle, have resulted in a vast region in which the imprint of periglacial conditions prevails in the form of characteristic landform assemblages (cf. André 2003; French 2016).

Periglacial landforms have been documented in a variety of sizes throughout Beringia, from small (needle ice forms and patterned ground) and medium-sized constructional features (pingos and solifluction sheets) to large erosional forms encompassing entire slope sequences (cryoplanation terraces and cryopediments). Together, these landforms can be viewed as constituting a "periglacial form community" (see Poser 1976; Karte 1979), spanning a wide spectrum of geographical scale. To date, however, this concept has not been applied in unglaciated Beringia, which ironically is one of the very few extensive regions on earth in which periglacial processes have operated continuously over an extended period of geological time.

Spatially oriented analytic and statistical methods can be applied to periglacial assemblages in much the same way that they are applied to ecological associations in landscape ecology (see review by Turner 2005). Progress has been achieved along these lines in the periglacial realm (see work by Hjort et al. 2007, 2010, and references therein), but most such studies have been concerned with features in the smaller part of the periglacial landform scale continuum, and usually in polygenetic landscapes.

This thesis applies the form community concept in the periglacial realm to answer the question: *is there a characteristic periglacial landscape?* This question has been gaining prominence in periglacial geomorphology (André 2003; French and Thorn 2006; French 2015; French 2017). Beginning with André (2003), who asked: “do periglacial landscapes evolve under periglacial conditions?” Her study resulted in increased skepticism about the existence of a “characteristic periglacial landscape.” French (2016) questioned whether landscapes having a dominantly periglacial character exist and suggested that cryoplanation features may be inherited from past warm intervals. However, these studies focused on a single scale, and a holistic analysis utilizing a multi-scale approach has not been undertaken. This thesis explores the concept of “characteristic periglacial landscapes” through (a) application of contemporary mapping and spatial-analytic techniques to assemblages of periglacial landforms; and (b) use of geomorphometric procedures to identify cryoplanation landforms and to ascertain whether the topography of eastern Beringia exhibits distinctive and characteristic geometric and hypsometric signatures. This topical approach is highly unusual because it extends across a wide spectrum of geographical scale, is focused on a cold region that remained largely unglaciated throughout the Quaternary and considers both constructional and erosional periglacial landforms.

1.7 Hypothesis

This thesis tests the hypothesis that, a characteristic periglacial landscape does exist. Evidence for this assertion will be found in the existence of a repeating mosaic of periglacial assemblages over a continuum of spatial scale and in the distinctive geomorphometric properties ("signature") of upland Beringian topography. The thesis will evaluate this hypothesis through two related methodologies: (1) documentation, primarily through mapping, of the existence of repeating sedimentological and periglacial landform assemblages, extending across multiple spatial scales; and (2) analysis of periglacial landforms and Beringian terrain, using both specific and general geomorphometric tools. These methodologies are described below.

1.8 Methods

Study locations were determined in conjunction with a larger project investigating cryoplanation terraces on a transect across eastern Beringia. Alaskan study sites include cryoplanation landforms near Iron Creek (Seward Peninsula), Eagle Summit (interior Alaska), and Mount Fairplay (near the Alaska-Canada border). Together, these sites extend through terrain rising from 300 m above sea level in the west to over 1400 m in the east. A site at Frost Ridge in the Cathedral Massif near Atlin, British Columbia was chosen because the suite of periglacial processes collectively known as *nivation* were demonstrably active during the mid-1970s (Nelson, personal communication 2017).

1.8.1 Geomorphologic analysis and periglacial assemblages: Geomorphological mapping is the cartographic expression of geomorphic processes and landforms. It is often an integrated representation of climate, soils, landforms, topography, geology, and other factors (Smith, Paron, and Griffiths 2011) and "involves the partitioning of terrain into conceptual spatial units" (Bishop et al. 2012 pp. 5).

Distinctly geomorphological mapping methods can be traced back over 100 years to Passarge (1914), who is often credited with creating the first geomorphological map (Smith, Paron, and Griffiths 2011). The basis for modern geomorphological mapping in the United States goes back to the late 1800s, however, when regional geomorphology was standard practice for geomorphologists. Mapping at that time was at small spatial scales (i.e., involving large areas) and often focused on specific themes (Thornbury 1965). Powell (1895), while operating under the regionalist viewpoint, mapped the physiographic regions of the United States. This map definitively separated the United States into regions and spurred further work in the coming era. A shift in thought with regard to geomorphological mapping began after Powell's (1895) monograph. This shift saw scholars adding process to existing geologic maps, creating the geomorphologic maps of today. A revision of Powell's physiographic regions by Fenneman (1917) created a standardized process for descriptive physiographic mapping. By the 1950s the geomorphologic paradigm had shifted away from the Davisian idea of landscape genesis, changing the nature of geomorphology and its influence on geomorphologic mapping (Bishop et al. 2012) to a more process-oriented focus that necessarily changed the spatial scale at which investigation could take place. While geomorphological mapping in the United States (e.g., Thornbury 1965) and Canada (Bostock 1970) was focused on regional aspects, much of the scholarly progress in the subject at more local scales came from Europe.

In Europe, the precursors to geomorphologic mapping were mostly descriptive, with cartographic representation of terrain being dominant (Smith, Paron, and Griffiths 2011). Passarge (1914) is considered to be the first to publish a geomorphologic map, with only sporadic geomorphic maps following until after World War II. With the war necessitating a better understanding of terrain, cartography and mapping became a priority in Europe. After World War II, geomorphological mapping became more commonplace, with countries such as France, Czechoslovakia, and Hungary focused on mapping based on lithologic units, while Germany, Poland, and the Soviet Union considered landform-creating processes (Bishop et al. 2012). Small-scale mapping was also practiced widely in the Soviet Union (Smith, Paron, and Griffiths 2011). Countrywide geomorphological mapping became common practice in Europe, after Klimaszewski (1956, 1963) and Galon (1962) mapped Poland and Annaheim (1956) mapped Switzerland. In the latter half of the 20th century, European geomorphological mapping focused on applications such as engineering, environmental science, natural resource management, and related fields. Because of the high level of interest in applied geomorphologic mapping, Europeans have contributed significantly to the standardization of mapping symbols and legends (Demek 1972; Demek and Embleton 1976).

With the Cold War and subsequent advances in aerial imagery and satellite technology, digital image analysis became standard practice in geomorphological mapping. Advances in digital technology, specifically remote sensing, greatly increased the scale and breadth of geomorphological mapping (Smith, Paron, and Griffiths 2011). Today, the use of remotely sensed imagery is combined with digital elevation models (DEMs) to create large-scale representations of geomorphic processes. In hard-to-reach locations such as the Arctic, digital technology is fast becoming the standard (Evans 2012). Given the large expense of conducting research in the Arctic, using DEMs and other remotely sensed information can save time and money. Advances in technology have led to increased spatial resolution, making more geomorphic information available (Evans 2012).

While geomorphological mapping is often focused on terrain under temperate and alpine climates, some studies have applied the concept to periglacial features. Caine (1972), Rudberg (1972), Graf (1973), Åkerman (1980), Hjort et al. (2007, 2010), and several of the authors in the edited volume by Poser (1976), for example, have focused on periglacial geomorphological mapping and other forms of spatial analysis. Karte (1979, 1982, 1983) provided an overview of the German literature focused on periglacial "form communities" and mapping of periglacial phenomena.

For the purposes of this project, large-scale (e.g., 1: 10,000) geomorphologic maps will depict aspects of geology, general and periglacial geomorphology, and vegetation at the study sites. The surficial geology of the study areas has been documented by previous researchers (i.e., Foster 1967) and will be compiled via literature review.

Collection of mapping data was accomplished through a combination of general field survey techniques and acquisition of digital elevation models (DEMs). Sampling of terrace geomorphology involved collecting an extensive group of photos of periglacial features, identification and classification of surface geomorphic features, identification of vegetation, and the spatial zonation of these features. Identification in the field was followed with laboratory review using photographs. Surveys of terrace profiles were conducted during the summers of 2016 and 2017. At each site a general survey was undertaken that incorporated the entire terrace and was used to inform decisions in the field. Base maps were obtained using the 2 m resolution Arctic DEM (Polar Geospatial Center 2017), as well as maps created by Reger (1975). The mapping phase of this work was concluded in the lab by combining data into a GIS using ArcGIS and other geospatial software. Mapping symbols were modified from Demek (1972) and Gustavsson et al. (2006).

1.8.2 Periglacial geomorphometry: Geomorphometry is the quantitative study of the land surface (Pike, Evans, and Hengl 2009) and lies at the intersection of mathematics, geosciences, and computer science. Evans (1972, 1987) divided the study of geomorphometry into two distinct categories: *specific* and *general* geomorphometry. Specific geomorphometry is the study of individual (discreet) landforms of specific origin or morphological characteristics, while general geomorphometry investigates the continuous land surface (Pike, Evans, and Hengl 2009). In the context of this thesis, specific geomorphometry will focus on the cryoplanation landforms themselves and general geomorphometry will focus on extensive tracts of unglaciated uplands in eastern Beringia.

Geomorphometry has been studied since the late 1700s, but its origin dates to the beginning of human attempts to understand the shape of the earth through mathematics and visualization. Much of the evolution in the discipline of geomorphometry took place in Germany and Austria, where the subject has evolved with earth science, especially geography (Pike, Evans, and Hengl 2009). Today, the study of topography through contour maps and drawings (e.g., Clarke 1966) has been largely replaced with digital technology and computer algorithms. With the new generations of space satellites and a variety of new types of airborne sensors, the resolution of digital information has increased rapidly. Now, with LiDAR (Light Detection And Ranging) and radar applications, the resolution of digital mapping has even become an issue, with too much information available, creating problems related to storage and analysis (Evans 2012).

Applications of geomorphometry in the periglacial realm have been few (e.g., Nelson 1998). Most geomorphometric studies have focused on fluvial and glacial landscapes (e.g., Mark 1975; Evans 2009). Conspicuously absent is a periglacial "position paper" of a nature similar to that provided by King (1982) for glacial geomorphometry, which has since developed into a mature subject making extensive use of contemporary technology and tectonic theory (e.g., Mitchell and Montgomery 2006; Sternai et al. 2011). Chapters 3 and 4 constitute an initial attempt at developing a new field of study, tentatively named *periglacial geomorphometry.* This is accomplished in the context of cryoplanation landforms as a method for recognizing and analyzing periglacial landscapes. Application of the tools of specific and general geomorphometry to digital representations of topography will help to assess the validity of concerns raised by French (2016) and others skeptical about the validity of the cryoplanation concept, as well as the notion of a "characteristic periglacial landscape." Two general goals are involved: (1) identification of discreet cryoplanation landforms through manipulation of digital elevation models; and (2) derivation of the "signature" of a periglacial landscape through regional-scale analysis of the geometric and hypsometric properties of the topography.

1.8.3 Specific geomorphometry: To achieve the goals laid out above, specific criteria for the identification of CTs have been developed. It was anticipated that the characteristic sharp topographic break at CT scarp-tread junctions, together with adjacent flats (treads) will constitute the primary pattern-recognition tool for identifying the locations of individual CTs. Using the Alaska 2 m DEM (Polar Geospatial Center, 2017), these inflections should be recognizable through a kernel operator(moving window operation) (Clarke 1995 pp. 55) searching for minima and maxima in the derivatives of altitude. Remotely sensed imagery, Reger's (1975) data set, and a large-scale map of the Indian Mountain area (Péwé and Reger 1969) will be used to verify the procedure's effectiveness.

1.8.4 General geomorphometry: General geomorphometric tools involve *hypsometric analysis*, which treats the distribution of the ground surface area of a landmass with respect to altitude. The procedure used in this thesis is based on Strahler's (1952) *hypsometric integral*, a measure of actual landmass volume with respect to a reference solid with the same basal (map-view) configuration. This section of the thesis will employ the *elevation-relief ratio,* a measure of the ratio of upland to lowland (Pike and Wilson, 1971) proposed by Wood and Snell (1960). The elevation-relief ratio was mathematically proven by Pike and Wilson (1971) to be equivalent to the hypsometric integral proposed by Strahler (1952), but easily computed from DEMs.

Nelson (1979b) conducted preliminary analysis indicating that the hypsometric integral may be a valuable tool for identifying a periglacial "signature" in the landscape. Owing to the unusual preponderance of flat-topped ridges and summits in "cryoplanated terrain," the hypsometric integral should show increasingly higher values with increased terrain "maturity," which is the opposite of what studies in areas of fluvial erosion conclude. The corresponding hypsometric curve may be unusually convex, showing a large proportion of the land area at relatively high elevation, and thus providing a signature of terrain developed under periglacial conditions. This analysis expands upon Nelson's inference by using the elevation-relief ratio to conduct a multi-scale analysis of watersheds across the Yukon-Tanana Upland (Wahrhaftig 1965).

The methods and analyses proposed above will help to quantitatively address concerns in recent literature (e.g., André 2003; French 2016) regarding the existence of a characteristic periglacial landscape. By identifying periglacial landscapes in the context of cryoplanation terraces links will be established, across a range of spatial scales, between landform assemblages, terrain geometry, and periglacial conditions.

Chapter 2

Mapping and Multiscale Analysis of Periglacial Assemblages

"Great things are done by a series of small things brought together."
--V. Van Gogh

"Visually, one of the most distinguishing characteristics of the Arctic is the abundance and arrangement of a number of small, relatively uniform, features such as oriented lakes, drumlins, meander scars, ice-wedge polygons, string bogs, solifluction stripes, and block fields. Indeed, the repetitive nature over large areas of such forms has prompted many visitors to use the term "monotonous" in their descriptions of the Arctic."

– H. J. Walker 1983

Walker (1983), in a book chapter titled "E Pluribis Unum" (*out of many, one*), created the perfect literary image of the assemblage that forms Arctic and sub-Arctic periglacial landscapes. The concept of a periglacial assemblage is simple; there exists a series of periglacial features that merge and superimpose, forming an assemblage.

2.1 Background

Geocryology consists of two closely interrelated areas of scientific inquiry: the study of permafrost (including engineering) and of relatively small and discreet surficial landforms. *Permafrost*, earth material continuously at or below 0^o C for two or more years (Washburn 1980), is unquestionably important in the periglacial realm. Permafrost is a central focus of geocryology and is necessary for numerous periglacial landforms such as pingos, ice-wedge polygons, and gelifluction terraces (French 2017). However, by most definitions, permafrost is not necessary for landforms to be classified as periglacial (Washburn 1980). Landforms frequently referred to as periglacial may be formed through polyzonal or azonal processes that are not reliant on permafrost. For example, frost shattering of rock clasts and bedrock due to freeze-thaw cycles is distinctly periglacial. Some features, such as cryoplanation terraces, have not been studied enough to fully understand their relation to permafrost (French 2017). Although some writers have asserted a strict relationship between CTs and permafrost, (Reger and Péwé 1976) most (e.g., Demek 1969; French 2017; Ballantyne 2018) state that it is not necessary for CT formation.

Small (cm to 1 m) and medium (meter to decameter) sized periglacial landforms have been the subject of much study in periglacial geomorphology. Beginning with early exploratory expeditions to the Arctic and Antarctic in the 1800s (French 2017), qualitative observations of these landforms were common. In the early 1900s, quantitative study began to supplement the qualitative observations by prospectors and explorers in the Arctic and Antarctic regions. With a few exceptions (Lozinski 1909, 1912; Andersson 1906) it was not until the mid-20th century that process-based scientific understanding of periglacial landforms really developed. Lozinski (1909, 1912) is widely credited with coining the term *periglacial* and Andersson (1906), with his studies on solifluction, was one of the early pioneers of the subject. Studies of solifluction (e.g., Benedict 1970; Price 1974; Matsuoka 2001) have shown it to be an effective mass movement process involving the transport of material downslope in periglacial areas. Gelifluction, a closely related process, relies on material flowing slowly over permafrost. In this thesis, the term *solifluction* will be retained because it is more general and because the presence of permafrost at all locations has not been confirmed.

Patterned ground features, which Ballantyne (2018, pp. 148) described as “nature’s embroidery,” are another type of periglacial feature that has been studied extensively. Troll (1944) was among the first investigators to undertake comprehensive, worldwide study of the morphology and genesis of patterned ground. Many studies followed that served to better understand how these features formed (e.g., Washburn 1956; Goldthwaite 1976; Ballantyne 1996; Kling 1997; Boelhouwers et al. 2003). Similarly, frost boils are of considerable interest in periglacial studies (e.g., Mackay 1980; Walker et al. 2004). The study of clastic fragments and how they react to periglacial processes (e.g., Corte 1963), is closely related to patterned ground. Frost jacking (Dyke 1984; Anderson 1988) is commonly observed in periglacial areas, as are blockfields (Rapp 1967; French 1987). Blockfields have also been used to identify past periglacial landscapes (Park Nelson, Nelson, and Walegur 2007). Although the list of studies conducted on small landforms is long and comprehensive, there have been few English-language studies that provide a link between these features and *assemblages* of periglacial landforms, illustrating that national "schools" of periglacial geomorphology have long existed. Curiously, with the exception of a few in-depth publications (e.g., Demek 1969; Reger and Péwé 1976; Nelson 1989; Thorn and Hall 2002), little attention has been given to the foundational building blocks of the periglacial assemblage: cryoplanation terraces.

2.1.1 Periglacial form communities: Beginning with Troll's (1944) survey of the periglacial realm, German-language literature is in sharp contrast to the focus on singular types of periglacial feature that has dominated Anglophone periglacial science. Karte (1979) reviewed the concept of "periglacial form communities," widely investigated in German-language literature, in his discussion of periglacial zonation. This concept is similar to the ecological concept of *community*. In ecology, a community is defined as "a group of interacting species that occur together at the same place and time" (Cain, Bowman, and Hacker 2011). The form community concept applies the ecological definition to periglacial forms. The periglacial form community concept can thus be expressed as *a group of periglacial forms that interact with each other in the same geographic space.* This concept establishes a link between the individual forms, the processes that form them, and the surrounding forms (Kelletat 1970; Garleff 1970; Karte 1979). By allowing features to interact over multiple scales, knowledge of each individual and its formation helps to explain the geographic location of other, similar features, thereby forming an assemblage. This concept of an assemblage of periglacial features standing as a distinct landscape is in direct opposition to the views of André (2003) and French (2016).

2.1.2 Periglacial assemblage: Based on the periglacial form communities discussed in the German-language literature (e.g., Karte 1979) and the qualitative observations of various authors, the periglacial assemblage could be viewed as the core of the periglacial landscape, with cryoplanation terraces and cryopediments functioning as the foundational building blocks. The periglacial assemblage is defined formally in this thesis but has been conceptualized previously in figures and diagrams by multiple authors. Brunnschweiler (1965) created a schematic of a periglacial assemblage in what he termed the *altiplanorium.* Brunnschweiler's term was based on his observations and detailed sketches (Figure 1.2) of altiplanation terraces (now known as cryoplanation terraces). The term was derived as an analog for the long-existing geological features *anticlinorium* and *synclinorium*, large structural features on which minor folds are superimposed. In Europe, Karte (1979, 146-147) expressed the periglacial assemblage as a series of landforms from small, patterned ground features and frost-jacked clasts to cryoplanation terraces and cryopediments (Figure 2.1). Karte's (1979) representation is a graphical expression of the periglacial form community concept. Åkerman (1980) provided a similar graphic based on empirical data from West Spitsbergen. Reger (1975) described the periglacial assemblage in an idealized diagram of a system of cryoplanation terraces (Figure 2.2). In his figure, Reger illustrates cryoplanation terraces as having a series of smaller, surficial periglacial features inscribed on them, an observation consistent with those presented in subsequent paragraphs of this thesis. These detailed descriptions of the interrelationship between small features, CTs, and the periglacial landscape reinforce the concept of the periglacial assemblage. Not only do they support Walker's (1983) construct of a singular landscape integrating numerous, small landforms, they also indicate that this is indeed a visually distinctive landscape, created by the effects of periodic freezing and thawing, and is composed of distinctly periglacial features.

2.2 Geomorphological Mapping in Alaska and British Columbia

Geomorphological mapping is the cartographic representation of climate, soils, landforms, topography, geology, and other environmental factors (Smith et al. 2011). It is a representation of the terrain surface and environmental factors that define the geomorphologic processes shaping it. Conceptually, geomorphological mapping partitions terrain into distinct spatial units (Bishop et al. 2012). In this study, geomorphological mapping focuses on presenting field-collected data to show the individual forms that make up the periglacial assemblage.

2.2.1 Study sites: Mapping and analysis for this chapter was conducted at the four sites shown in Figure 1.5. Three sites were chosen to represent landforms along an east-west transect across Alaska. The transect (Nelson and Nyland's "Transect 1") corresponds to the gradient of mean annual air temperature and continentality along the same path, (Nelson and Nyland 2017, Figure 3). The terrain at each of the sites is relatively similar, with flat-topped ridges and steep-sided valleys. Ridges are festooned with small periglacial features. Hillslopes are in almost all cases slopes of transportation, and valley bottoms connect with fluvial networks. The fourth study site (Frost Ridge) is located in the Cathedral Massif near Atlin, British Columbia (Figure 2.3C). In the 1970s Frost Ridge was described as a site of active nivation and other periglacial processes in a thesis by Nelson (1979a). Further study at this location allows for a comparison between this site, where active nivation processes are ongoing, and the dormant cryoplanation terrace sites in Alaska (Figures 2.2 A and B).

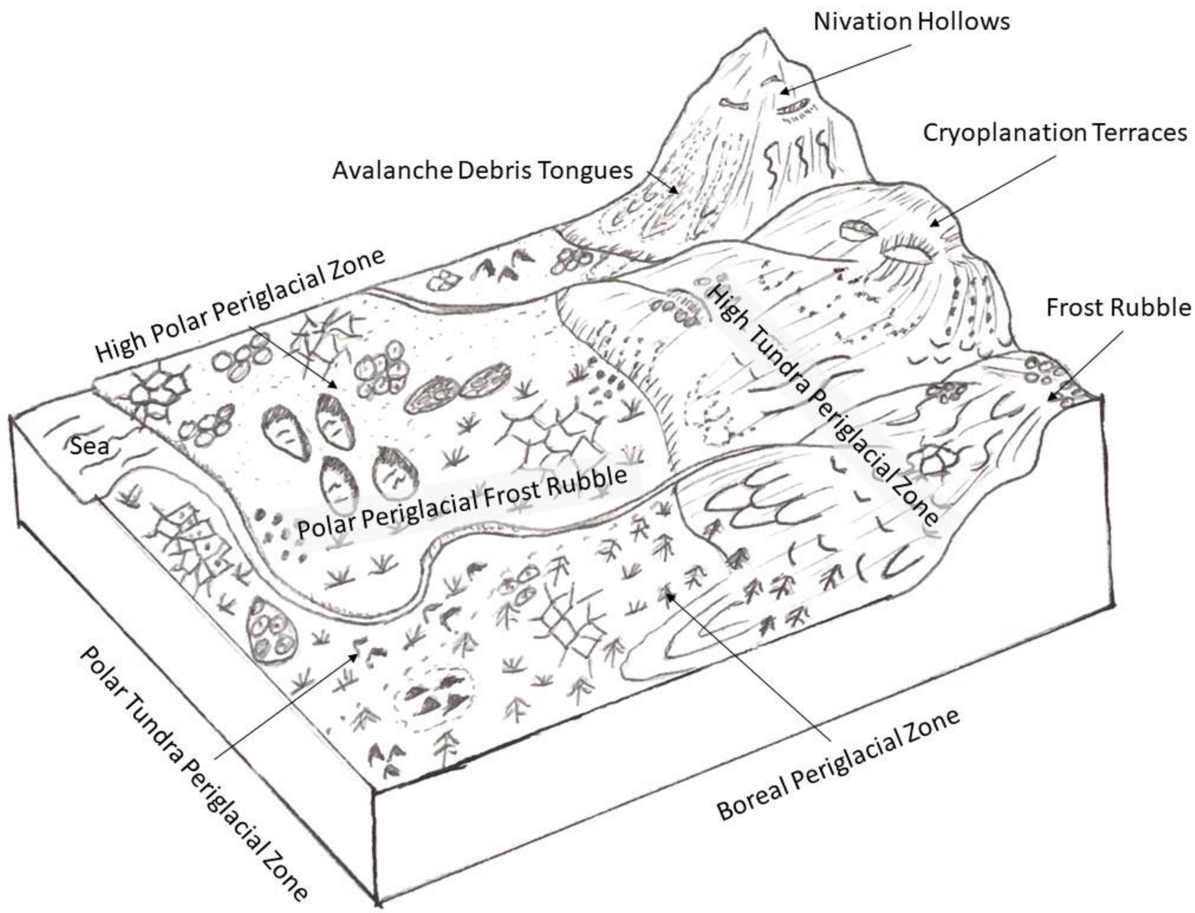

Figure 2.1. Illustration of the periglacial assemblage: *This figure represents the idealized the periglacial landscape and is redrawn from a diagram by Karte (1979) in his discussion of periglacial form communities.*

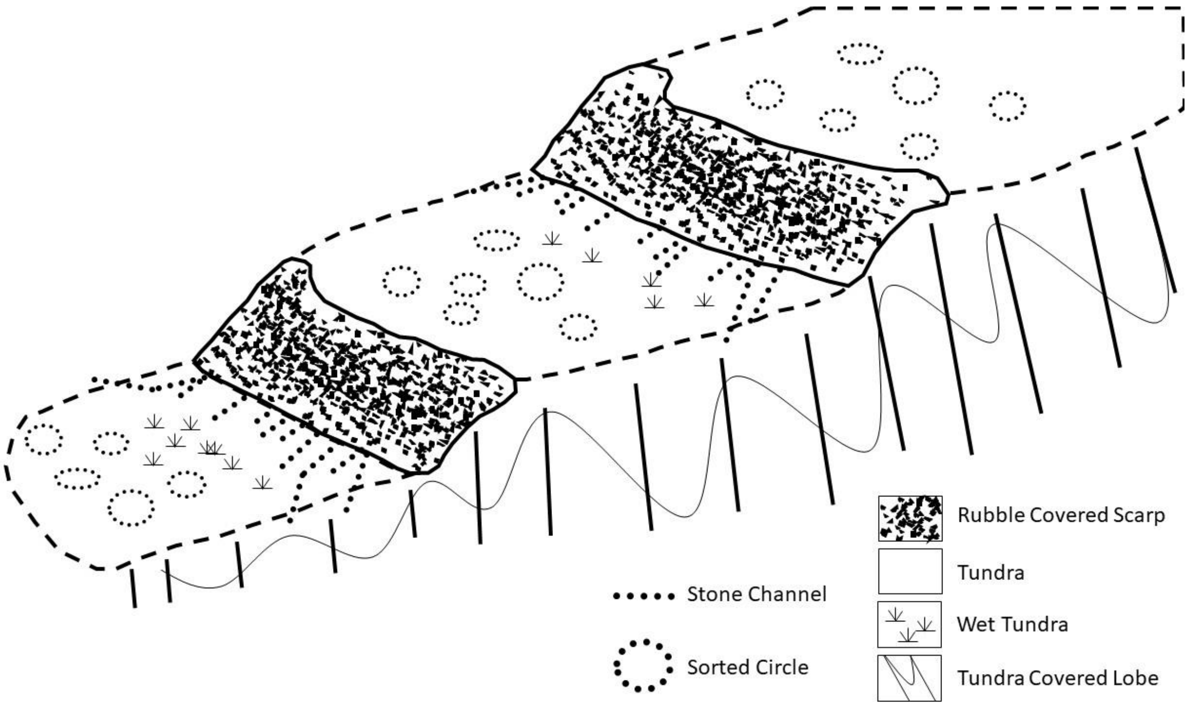

Figure 2.2. Idealized sketch of cryoplanation terraces: *The terrace figure (redrawn from Reger 1975 fig. 17 p. 47) is a less detailed expression of the periglacial assemblage shown by Brunnschweiler (1965) and Karte (1979), but serves to show that this idea, while not specifically expressed, has been pervasive in the literature.*

Table 2.1. Relative sizes, elevation, and orientations of terraces at study sites

Site	Terrace Size (ha)	Elevation (m.a.s.l.)	Orientation
Iron Creek	0.23-0.96	600	East
Eagle Summit	0.77-8.86	1,113	West
Mount Fairplay	3.01-3.98	1,689	North
Frost Ridge	5.12	1,676	Predominantly North

At each of the three sites in Alaska, cryoplanation terraces and smaller features are present, although the relative sizes of features and terraces vary between sites (Table 2.1). A wealth of periglacial features exists at the Iron Creek site and provides an excellent example of the ubiquity of small features in the periglacial landscape. At Eagle Summit, periglacial features are abundant, although an extensive mat of tundra vegetation obscures much of the terrace treads. In the higher elevations at Mount Fairplay, multiple periglacial features not present at the other sites are found, such as tors and talus slopes. In contrast, at high elevation, on the lee side of the coastal mountain range east of Juneau, Alaska, Frost Ridge is a is home to active periglacial processes and landforms. Numerous periglacial features, active nivation hollows, and late-lying snowbanks can be found at this site. The similarities between Iron Creek and Frost Ridge are worth further exploration due to the climatic gradient and elevation difference.

Terraces surveyed in this study ranged in orientation across the north, west, and east directions. Nelson (1998) performed directional statistical analysis of terraces identified by Reger (1975) and found they were predominately located in the northwest and northeast quadrants in interior Alaska. Orientation was more diffuse in western Alaska, possibly in response to a dominance of cloudy conditions near the Bering Land Bridge coast (Reger 1975; Guthrie 1982).

2.2.2 Mapping methods: Geomorphological mapping was conducted through both field-based procedures and digital terrain analysis. Field-based mapping was accomplished using traditional mapping and surveying methods. At all study sites, initial topographic surveys were conducted with a hand level and stadia rod. The topographic profiles were used to identify the locations of terraces, based on morphologic characteristics. Once identified, the terrace area was surveyed with handheld GPS. Scarp and tread lengths and angles were measured using a laser range finder and clinometer. Surface periglacial forms were identified, located with GPS, and dimensions were measured. A series of form communities was delineated on at least one terrace tread at each study site. Also noted were areas where debris was likely to flow off the edge of treads, or topographic depressions in terrace sides. Several solifluction features on the side slopes were measured and geolocated.

Figure 2.3. Panoramic photos of study sites: *A) Eagle Summit Terrace 10, looking west. Terrace tread is roughly 4 hectares. B) Mount Fairplay Terrace 25 and 24 looking north. The total area occupied by the terraces at Mount Fairplay is roughly 14 ha. C) Frost Ridge looking northeast. The tread at Frost Ridge is roughly 5 ha. Treads at Eagle Summit and Mount Fairplay are vegetated, but contain scattered periglacial features, namely sorted stripes and nets. Frost Ridge is largely devoid of vegetation, except in the greenish-toned area in the upper left of the photo. Numerous sorted stripes follow the fall line across the tread.*

Snow surveys were conducted at Frost Ridge, where snowbanks remained on the landscape at the time of the study (late July, 2017). Snowbank perimeter and surface were surveyed with GPS and hand surveying methods (Figure 2.4D). Ground penetrating radar (GPR) was run along a north-south transect across the snowbank surface (Figure 2.4A) to obtain a subsurface topographic profile. At three locations on each snowbank snow pits were dug to check the accuracy of the GPR and to study the stratigraphy of the snowbank (Figure 2.4B).

Data were compiled from multiple literature sources. Base maps showing surficial and bedrock geology were digitized from Wiltse et al. (1995) for Eagle Summit, Foster (1967) for Mount Fairplay, and Till et al., (2010) for Iron Creek. Geologic maps were superimposed with terraces and periglacial features. The ArcticDEM used in this analysis was obtained from the Polar Geospatial Center at the University of Minnesota (Polar Geospatial Center 2017).

Digital mapping was conducted using basic digital terrain analysis in ArcGIS and GRASS geospatial software. GIS mapping at the Alaskan study sites was done using the Arctic DEM, a freely available two-meter resolution DEM derived from optical satellite imagery (Polar Geospatial Center 2017). Due to a crosshatch artifact in the ArcticDEM and the high variability of this 2-meter resolution product, a 9x9 neighborhood low-pass filter was applied to the DEM before calculating the terrain derivatives of slope and aspect. Surface flow accumulation was also calculated on the DEM to identify topographic depressions and areas where material is likely to flow off terrace treads. No high-resolution DEM exists for the Frost Ridge study site, so a map by Cialek (1977) was used to provide elevation and topographic information.

The final maps were compiled in ArcGIS using both field-collected and DEM-derived data. Map symbols were modified from Demek (1972). This modification of symbols is reflective of the large scale (1:10,000) of the map, which is at the extreme end of Demek's (1972) range for large-scale mapping. Additionally, Demek's symbols have not been updated and are not reflective of current science. One attempt has been made at updating symbols for geomorphological mapping (Gustavsson et al. 2006), but the periglacial symbols were secondary to that project and are not visually appealing. Additionally, the traditional method of geomorphological mapping created maps that were difficult to interpret, so maps in this thesis were created as a series that reflects the various elements (topography, geology, and landforms) of a geomorphological map.

2.2.3 Mapping results: Results from the geomorphological mappings indicate that there is both diversity and similarity in features between sites. Across all of the sites in Alaska the general topography remained relatively constant, with the landscape dominated by flat-topped ridges. Generally, the terraces surveyed in this thesis were ridgetop terraces (Reger 1975) that descend from a flat summit down into a valley. At Eagle Summit (Figure 2.5a), a series of five terraces were surveyed, from the summit to the lowest terrace, 100 meters below. At Mount Fairplay (Figure 2.6a), the terraces were separated by a large slope that divided the terrace series. No terrace existed on the summit of the mountain, but numerous terraces were identified on all ridge spurs from the summit. On the Seward Peninsula, Iron Creek, (Figure 2.6a), the terraces are ill formed, with a summit type terrace, followed by two terraces on a ridge. The valleys on either side of the ridge at Iron Creek are steep sided, all with running water at the base. The side-slope topography at Frost Ridge (Figure 2.8) appears to have been affected by a valley glacier during the Wisconsin glacial period (Slupetzky and Krisai 2009 and references therein), although the top of Frost Ridge does have a large terrace, indicating a periglacial environment that exists in close proximity to glacial landscapes. On the north side of the Frost Ridge study site, terraces are smaller, with snowbanks obscuring much of the terrace. Topographic profiles done with GPR (Figure 2.10) indicate that nivation hollows are forming under the snowbanks, incising themselves into the hillslope and creating terraced forms that extend longitudinally across the slope subparallel to the contour. Nelson (personal communication, 2017) found cold (subzero) multi-year ice containing sediment bands in these snowbank positions in the mid-1970s, implying geomorphic quiescence at that time, and indicating that periglacial processes have become more active under recent climate warming.

Figure 2.4. Study methods at Frost Ridge, BC: *A) GPR survey of snowbanks. B) Measurements of snow temperature and density. C) Collection of suspended sediment at the downslope edge of a snowbank. D) Survey of snowbanks, surrounding topographic depressions, and periglacial features.*

Geology varied between the sites. Observations of terraces from Eakin (1916), Mertie (1937), and Reger (1975) show that cryoplanation terraces are found on many bedrock types. Data collected verify those observations. In the east, at Mount Fairplay, the bedrock was primarily volcanic (Figure 2.6b), being dominated by mafic and felsic volcanic rock. At the Eagle

Summit study area in the central Yukon-Tanana Upland, bedrock is primarily quartzite (Figure 2.5b). At the westernmost site (Iron Creek), bedrock is Ordovician schist (Figure 2.7b).

Across the study sites, mapping of the periglacial assemblage showed the presence of many similar features, summarized in Table 2.2. Sorted stripes are important features appearing at all sites, in varying sizes. At Eagle Summit (Figure 2.5c and 2.5d), Mount Fairplay (Figure 2.6c and 2.6d), and Iron Creek (Figure 2.6c and 2.6d), sorted stripes can be found running from the scarp toward the edge and sides of the tread. At Frost Ridge, those stripes are observed at the base of snowbanks, with water moving through them. These stripes channelize the water away from the scarp, moving material with it and progressively eroding the base of the scarp. The stone stripes channelize suspended sediment over the sides through "spillways." These spillways have solifluction lobes immediately downslope in almost all cases. The few cases where this is not true are where the spillway enters another stone stripe. Using a surface flow accumulation algorithm derived from the ArcticDEM, the movement of water and suspended sediment across terrace treads was modeled. While there are limitations to the specific terrain modeling performed, it does help confirm field observations that indicate areas where material is transported off terrace treads.

Table 2.2. Periglacial features found at study sites: *Sites are arranged from west to east. An X represents the feature present at the site. This list is not necessarily comprehensive and is based on qualitative observation of features.*

Feature	**Iron Creek**	**Eagle Summit**	**Mount Fairplay**	**Frost Ridge**
Sorted stripes	X	X	X	X
Frost Jacked Rocks	X	X		
Sorted Patterned Ground	X	X	X	X
Frost Boils		X	X	
Rubble covered Scarps	X	X	X	X
Solifluction Lobes	X	X	X	X
Needle Ice Creep				X
Nivation Hollow	X	X	X	X
Exposed Bedrock	X	X	X	?
Solifluction Terrace	X			

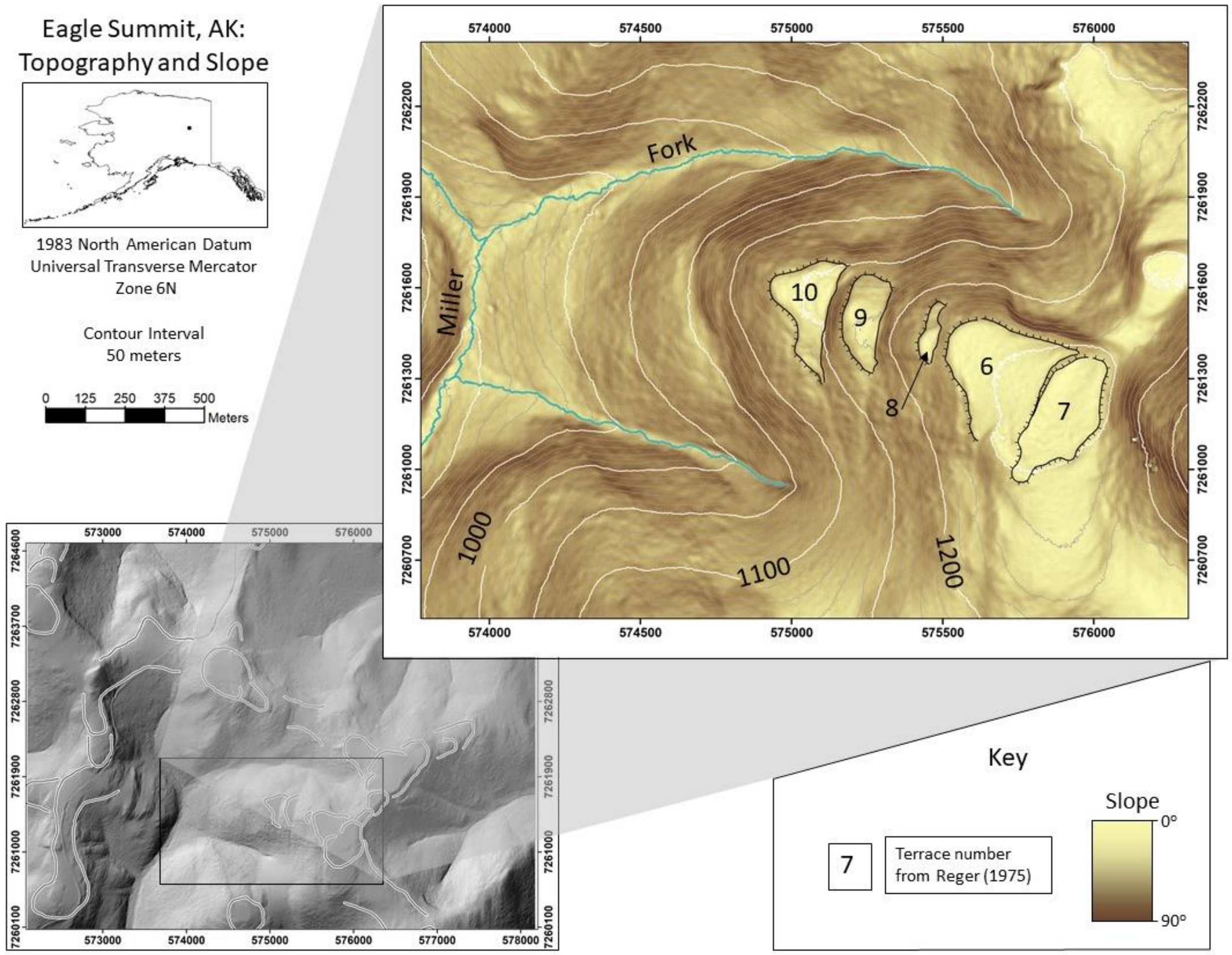

Figure 2.5a. Topography of Eagle Summit, AK: *Inset map in lower left shows the larger area around the Eagle Summit study site, with areas where Reger (1975) delineated terraces outlined in black and white. The larger map in the upper right give topographic contours derived from the Arctic DEM (Polar Geospatial Center 2017). The background color is an indication of the degree of slope. From this image, cryoplanation terraces can easily be seen based on the slope, with low angle slopes representing treads and subsequent high angle slopes representing the scarps.*

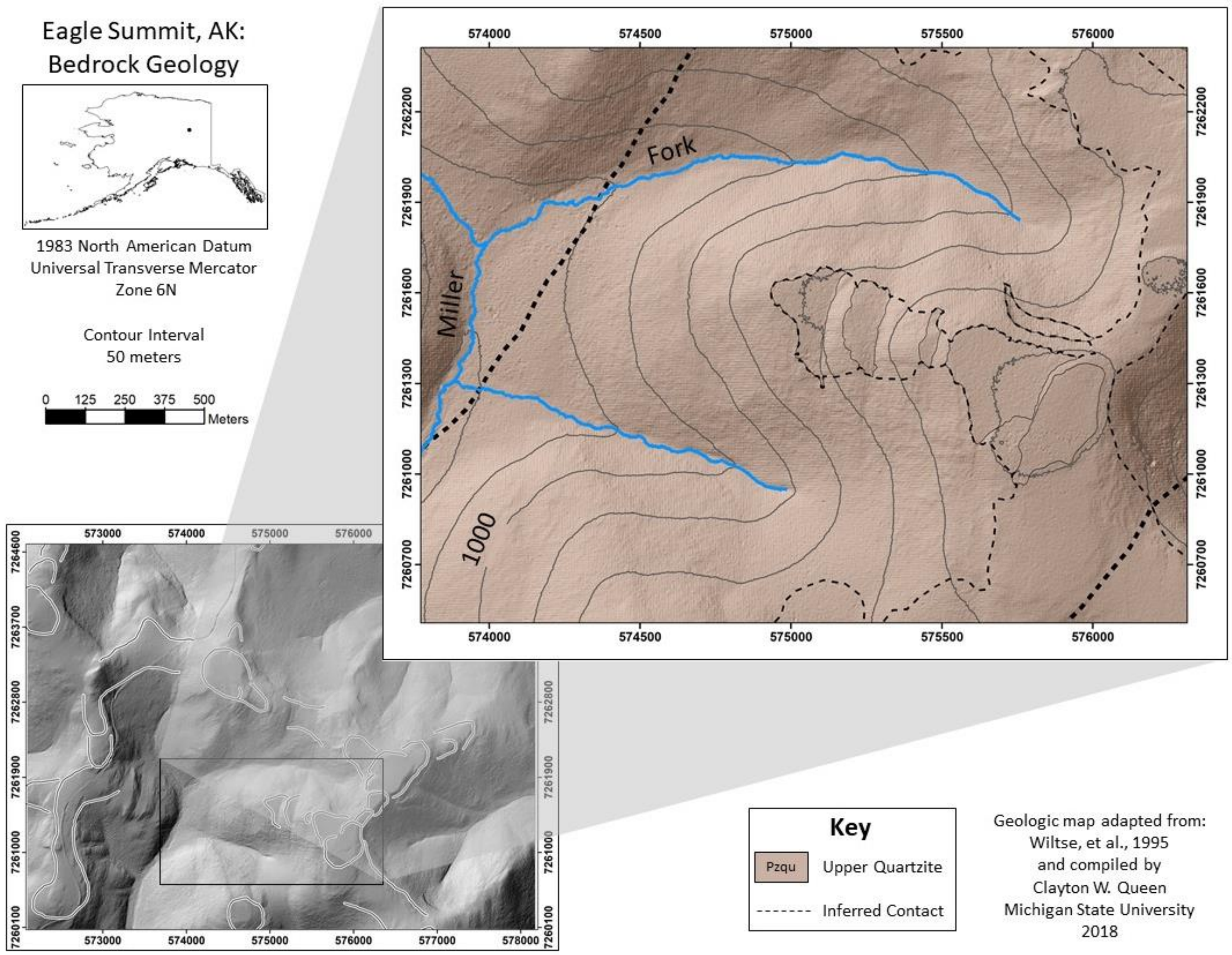

Figure 2.5b. Bedrock geology of Eagle Summit, AK: *Adapted from Wiltse et al. 1995, this map shows uniform quartzite throughout the study site, however, consistent with observations by Reger (1975) the underlying geology varies between the sites described in this chapter.*

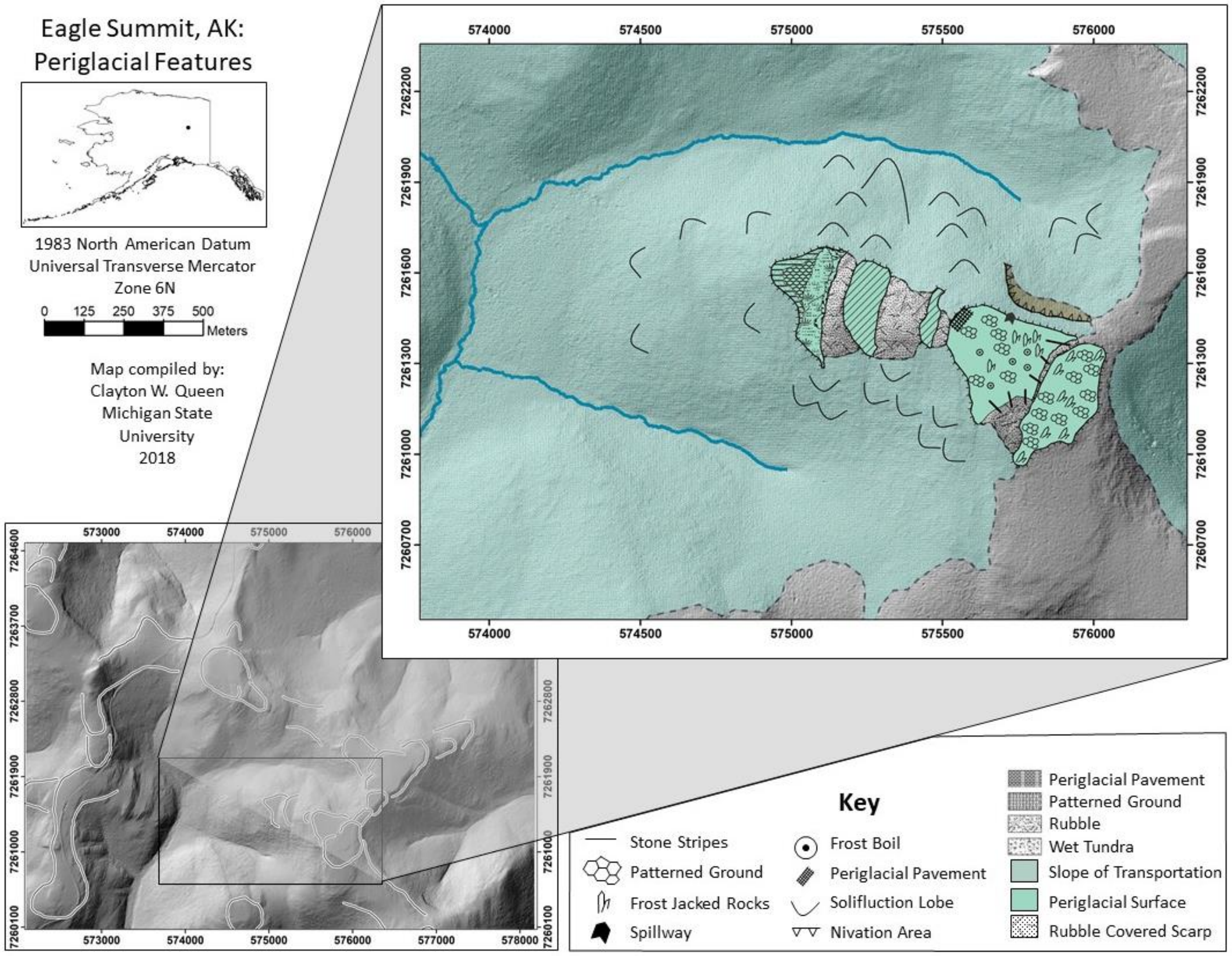

Figure 2.5c. Periglacial features at Eagle Summit, AK: *The map in the lower left corner indicates locations of terraces mapped by Reger (1975), showing that in the general area there are numerous CTs. In the upper right map, cryoplanation terraces and other periglacial features have been identified and delineated. . On the lowest terrace, the tread was subdivided into a series of zones where similar periglacial features were found in high density. The upper treads show the locations of various periglacial features. Downslope from the CTs, the hillside is covered in solifluction features. Grey areas are continuations of the flat-topped ridges and are covered with small periglacial features similar to those mapped on terraces.*

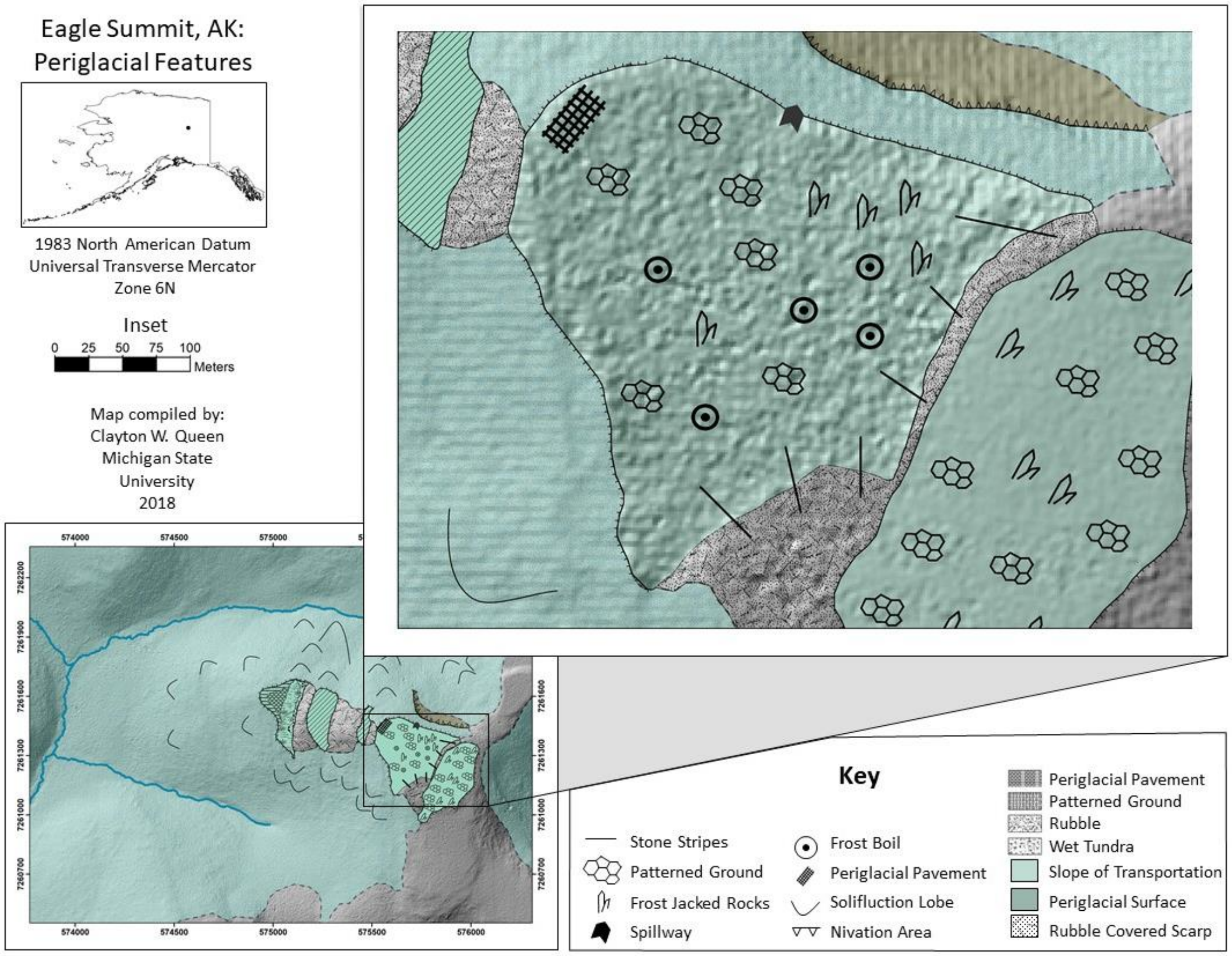

Figure 2.5d. Subset of terraces at Eagle Summit, AK: *Large-scale map of terraces 7 and 6 at the Eagle Summit study site. This view of the terraces allows for closer inspection of the mapped periglacial features. A pattern begins to emerge on this terrace. Sorted stripes are apparent at the scarp-tread junction. With distance from the scarp, however, other patterned ground features become more prominent, especially sorted circles and nets.*

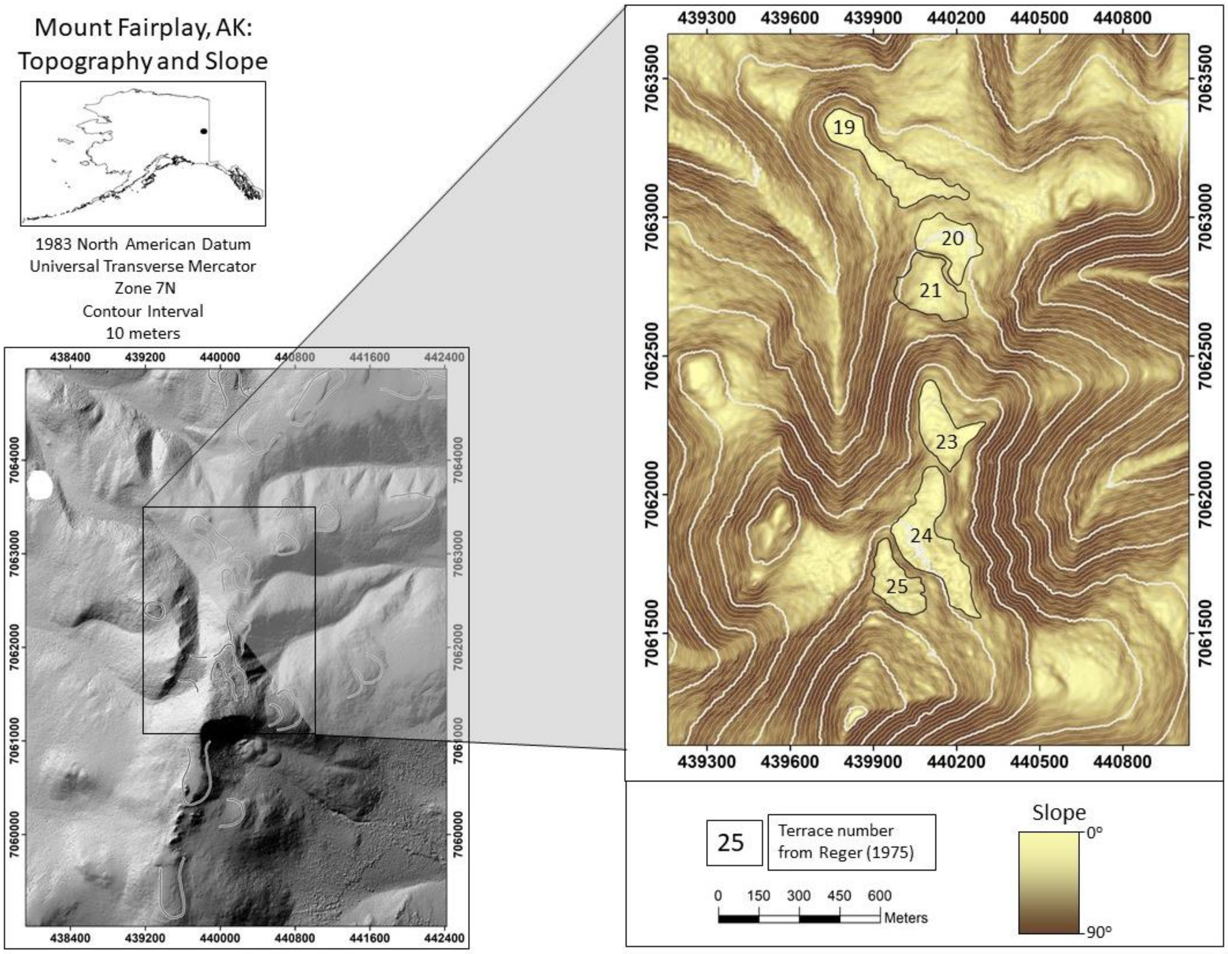

Figure 2.6a. Topography of Mount Fairplay, AK: *Inset map in lower left shows the larger area around the Mount Fairplay study site, with areas where Reger (1975) delineated terraces outlined in black and white. The larger map in the upper right give topographic contours derived from the Arctic DEM (Polar Geospatial Center 2017). The background color is an indication of the degree of slope. From this image, cryoplanation terraces can easily be seen based on the slope, with low angle slopes representing treads and subsequent high angle slopes representing the scarps*

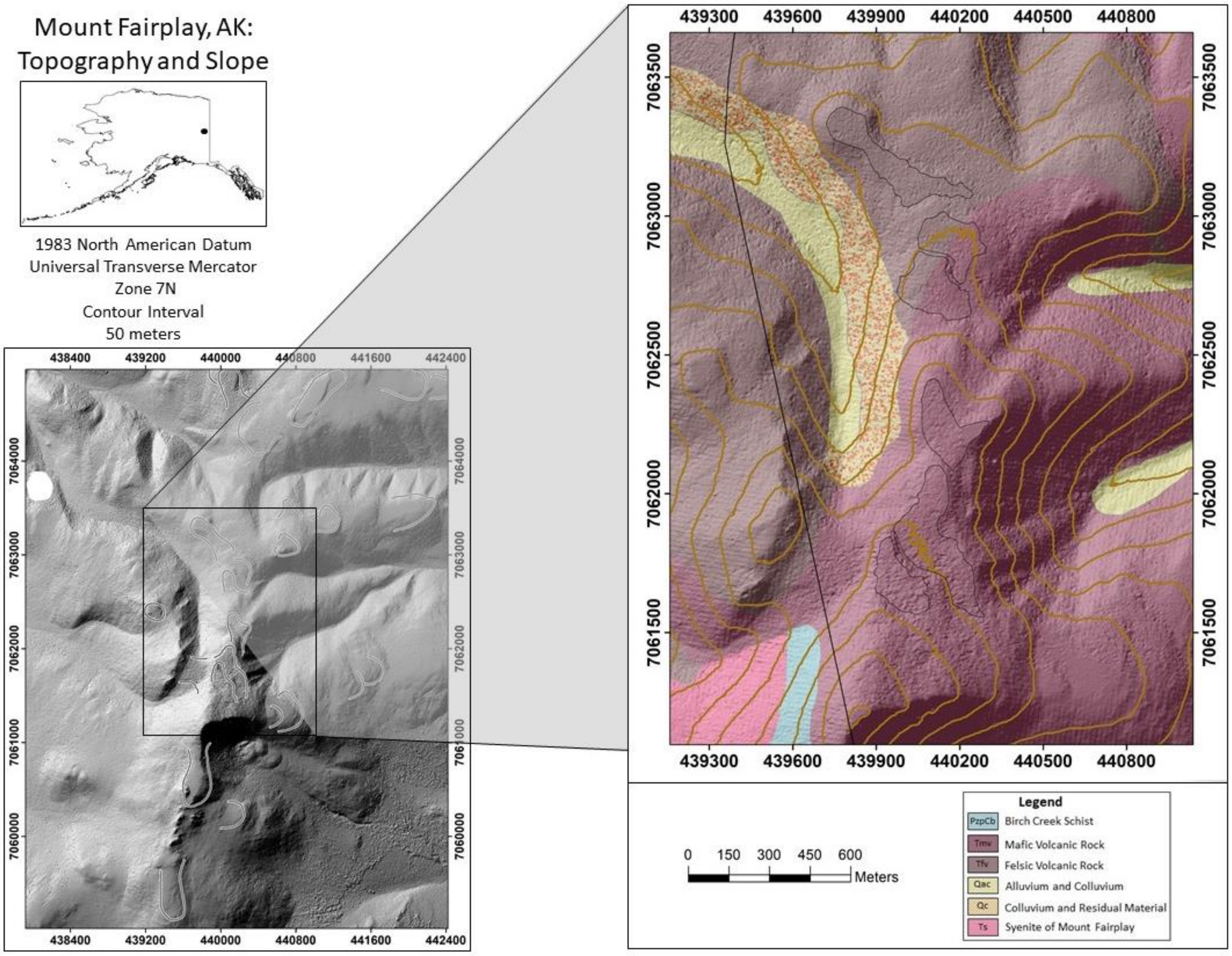

Figure 2.6b. Bedrock geology of Mount Fairplay, AK: *Adapted from Foster (1963), this map shows that bedrock at this site is mostly volcanic, with Quaternary sediment in the valleys, indicating the location of eroded debris. The terraces identified and discussed in this section are found on mafic and felsic volcanic rock.*

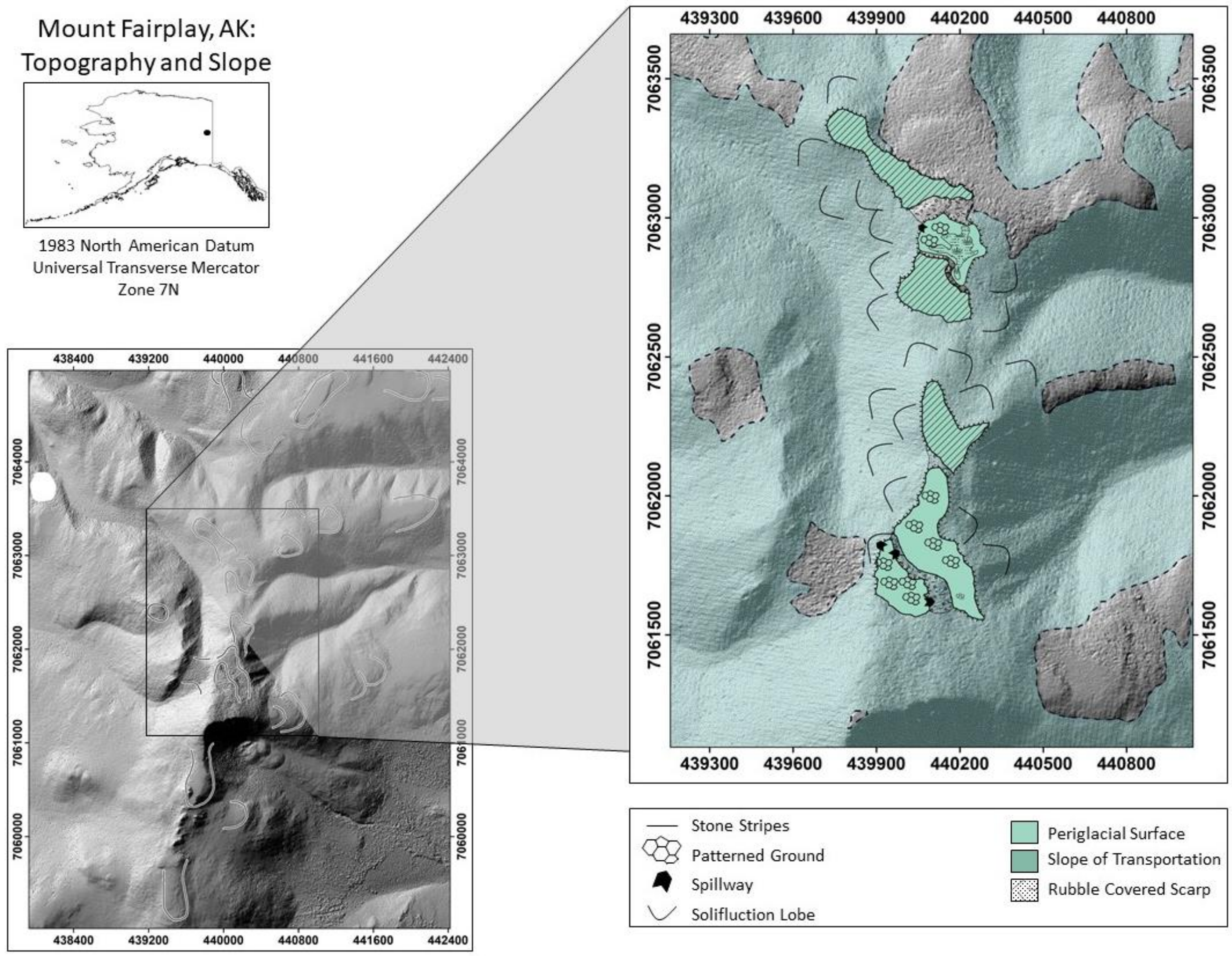

Figure 2.6c. Periglacial features at Mount Fairplay, AK: *The map in the lower left corner indicates locations of terraces mapped by Reger (1975), showing that in the general area there are numerous CTs. In the upper right map, cryoplanation terraces and other periglacial features have been identified and delineated. On one of the lower terraces, the tread was subdivided into a series of zones where similar periglacial features were found in high density. The upper treads show the location of various periglacial features. Downslope from the CTs, the hillside is covered in solifluction features. Grey areas are continuations of the flat-topped ridges and are covered with small periglacial features similar to those mapped on terraces.*

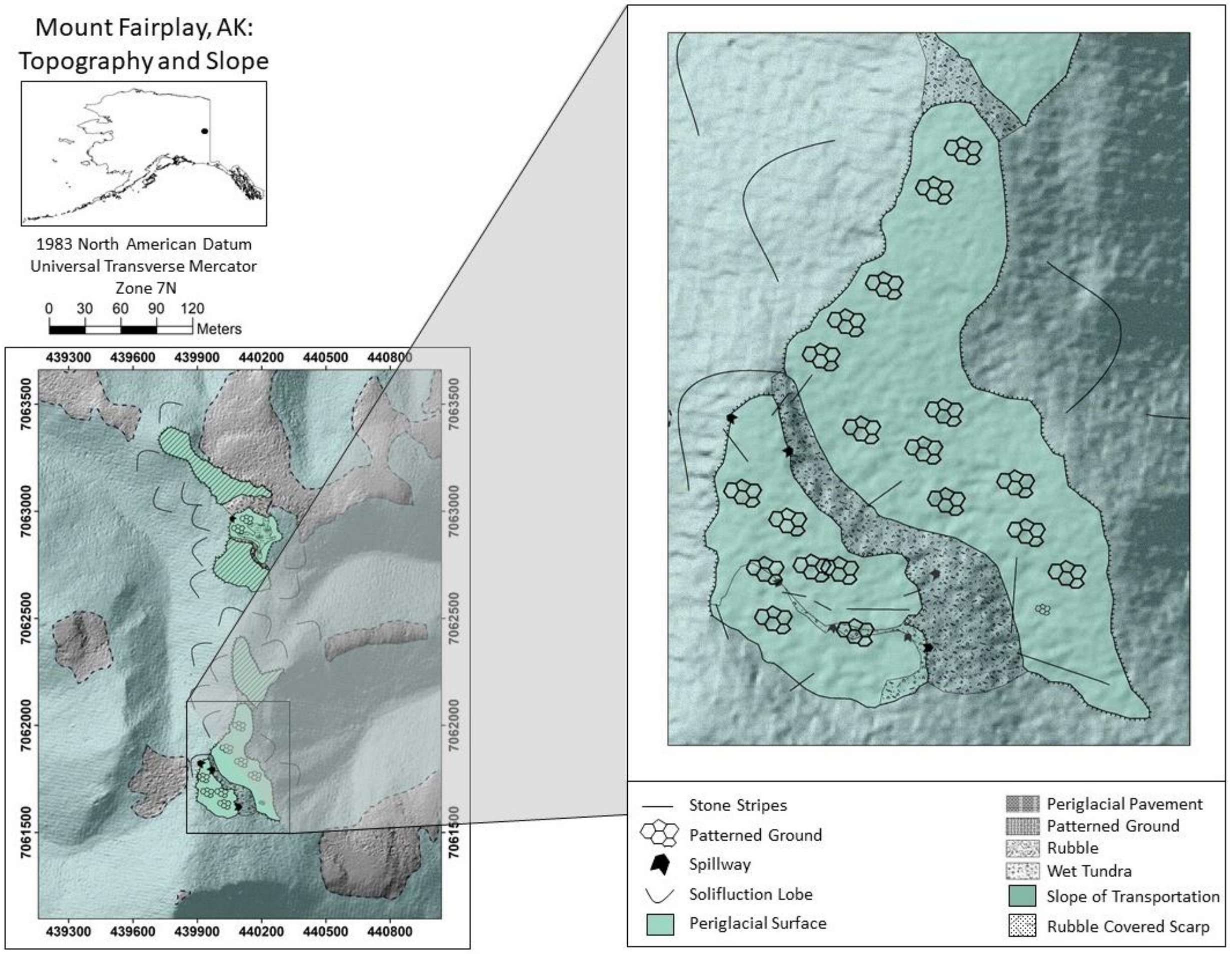

Figure 2.6d. Subset of terraces at Mount Fairplay, AK: *Large-scale map of terraces 24 and 25 at the Mount Fairplay study site. This view of the terraces allows for closer inspection of the mapped periglacial features. A similar pattern to the one observed at Eagle Summit can be seen here, with sorted stripes at the scarp tread junction and other patterned ground features (sorted circles and nets) farther out.*

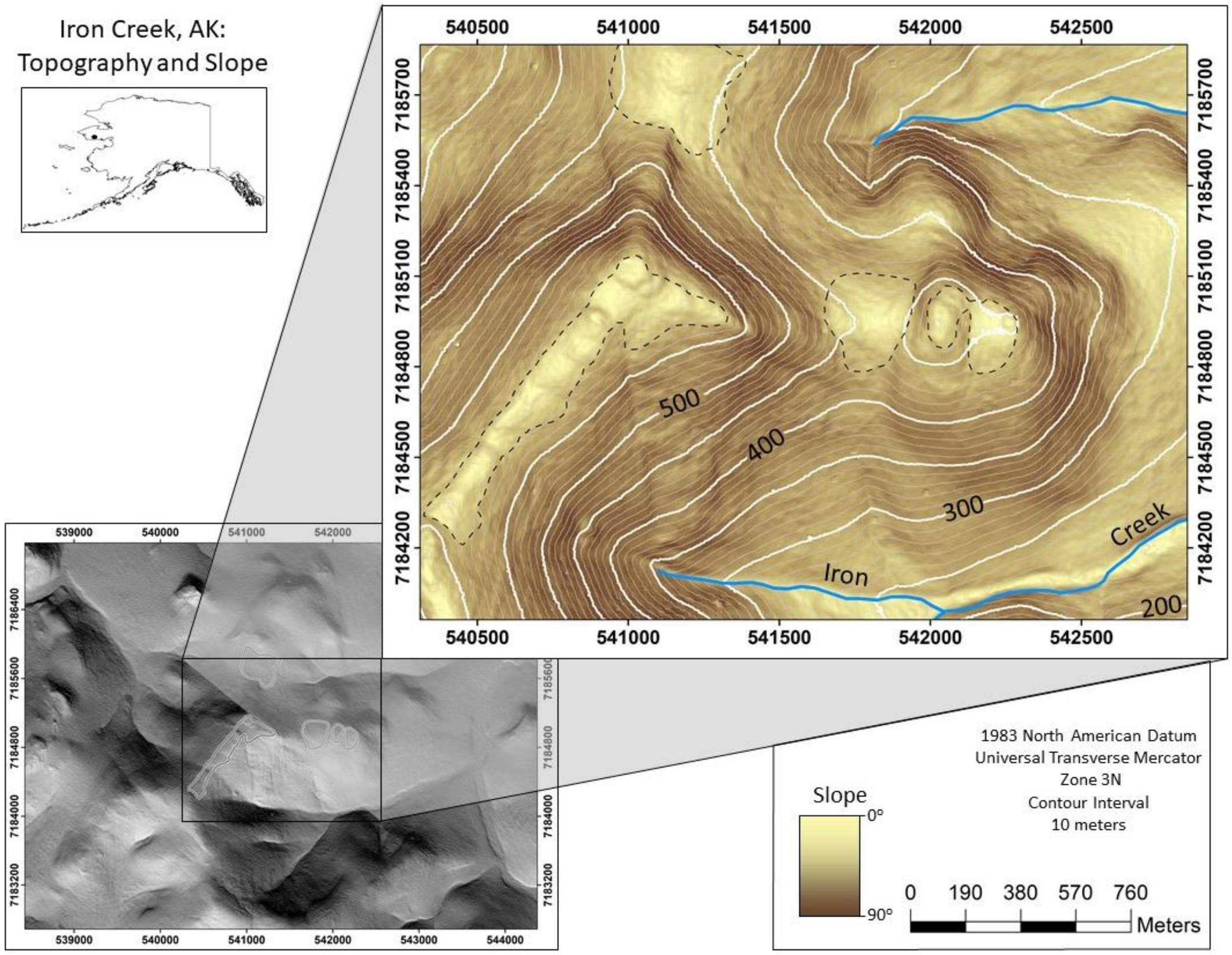

Figure 2.7a. Topography of Iron Creek, AK: *Inset map in lower left shows the larger area around the Iron Creek with delineated terraces outlined in black and white. The larger map in the upper right displays topographic contours derived from the Arctic DEM (Polar Geospatial Center 2017). The background color is an indication of the degree of slope. From this image, cryoplanation terraces can easily be seen based on the slope, with low angle slopes representing treads and subsequent high angle slopes representing the scarps.*

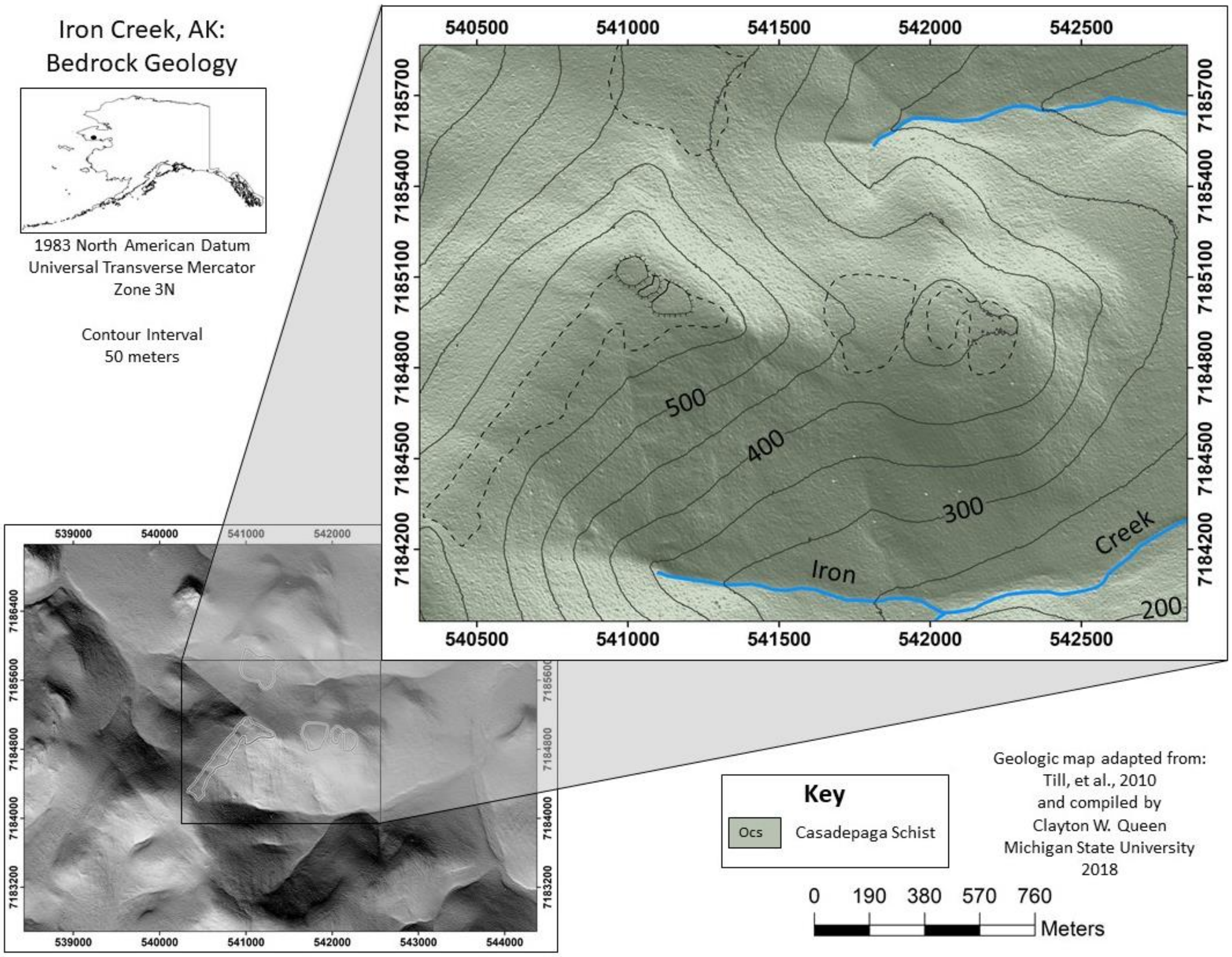

Figure 2.7b. Surficial geology of Iron Creek area, AK: *The map is adapted from Till et al. (2011). Bedrock at this site is uniformly schist.*

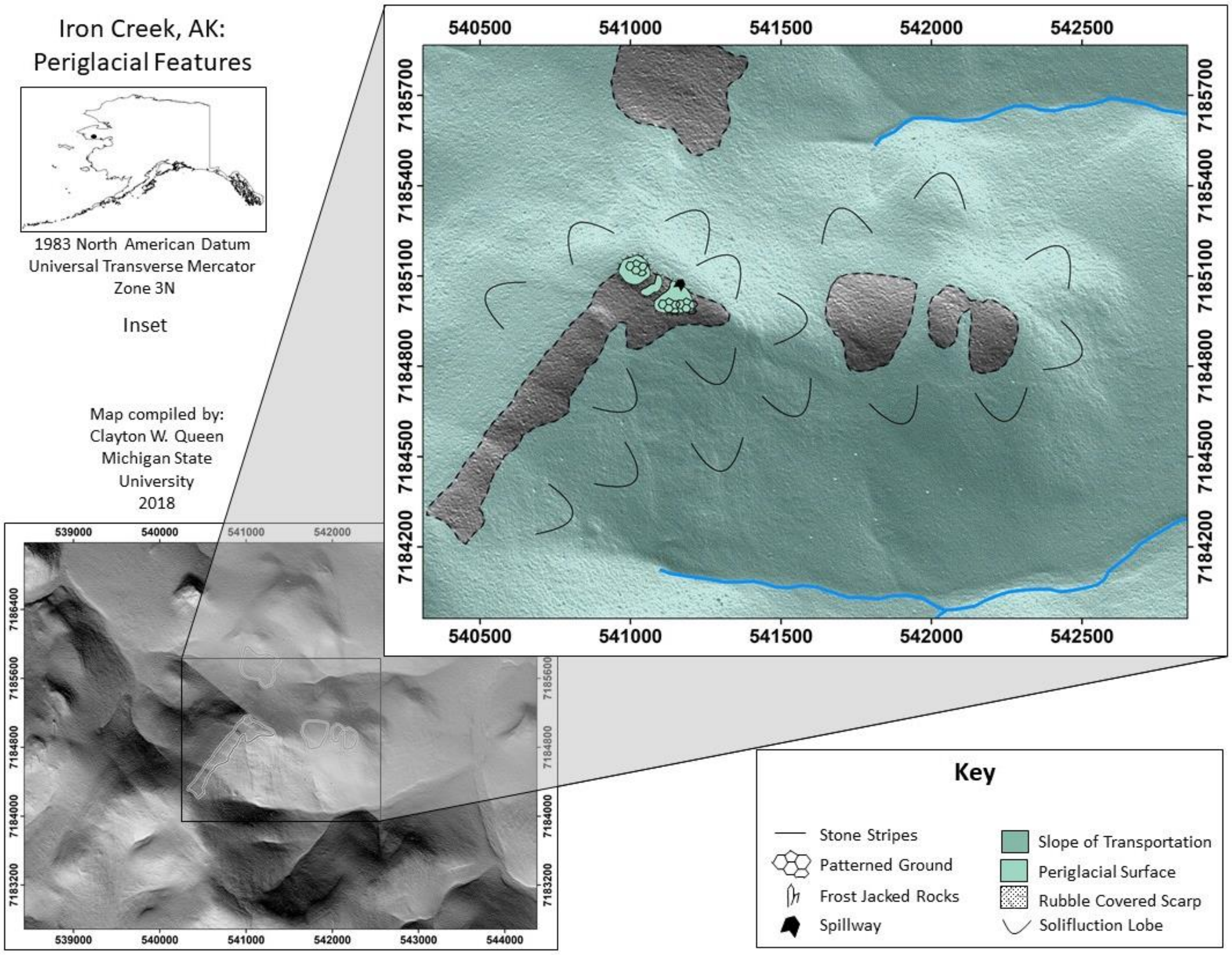

Figure 2.7c. Periglacial features at Iron Creek, AK: *Cryoplanation terraces are outlined with individual features noted on terrace surface. Side slopes are covered in solifluction features. Grey areas are continuations of the flat-topped ridges and are covered with small periglacial features similar to those mapped on terraces.*

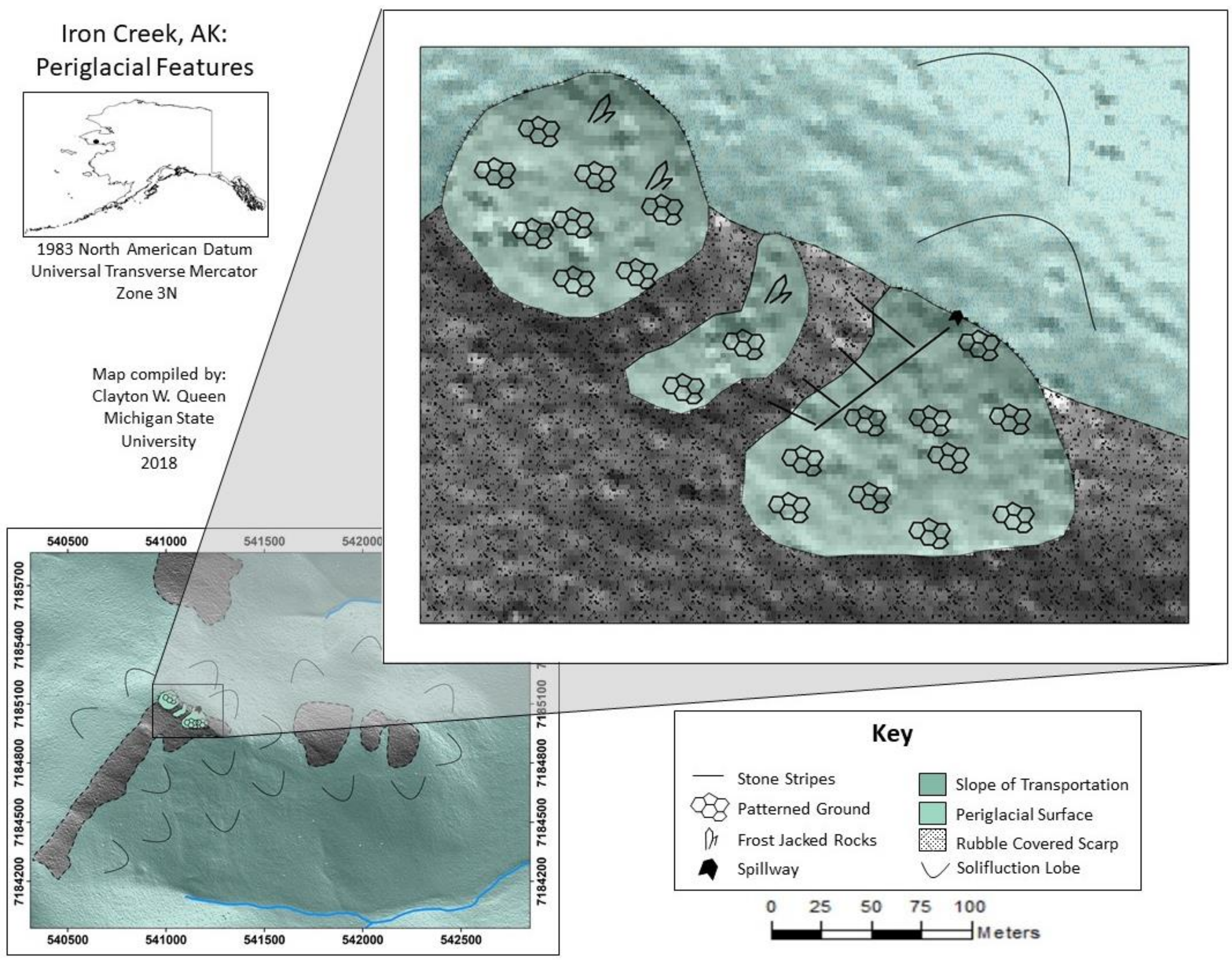

Figure 2.7d. Subset of terraces at Iron Creek, AK: *This view of the terraces allows for closer inspection of the mapped periglacial features. The same pattern observed at Mount Fairplay and Eagle Summit was observed at Iron Creek, with sorted stripes at the scarp-tread junction and other patterned ground features (sorted circles and nets) away from the scarp.*

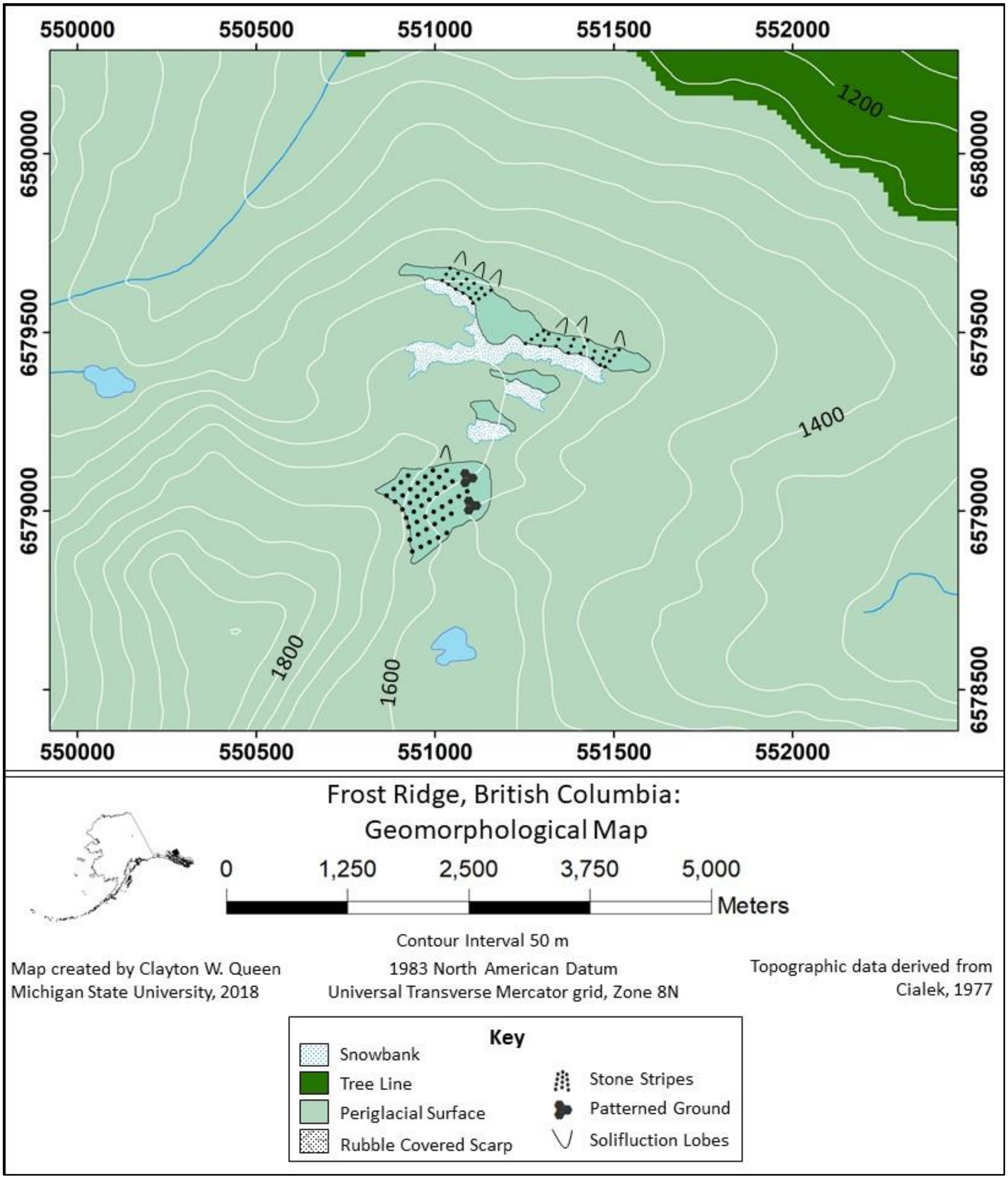

Figure 2.8. Geomorphological map of Frost Ridge, BC: *One terrace has been delineated on top of the ridge, with incipient terraces and late lying snowbanks have been noted. The ridge is a periglacial site between two glacial valleys. The numbers next to snow banks correspond with GPR profiles in Figure 2.8.*

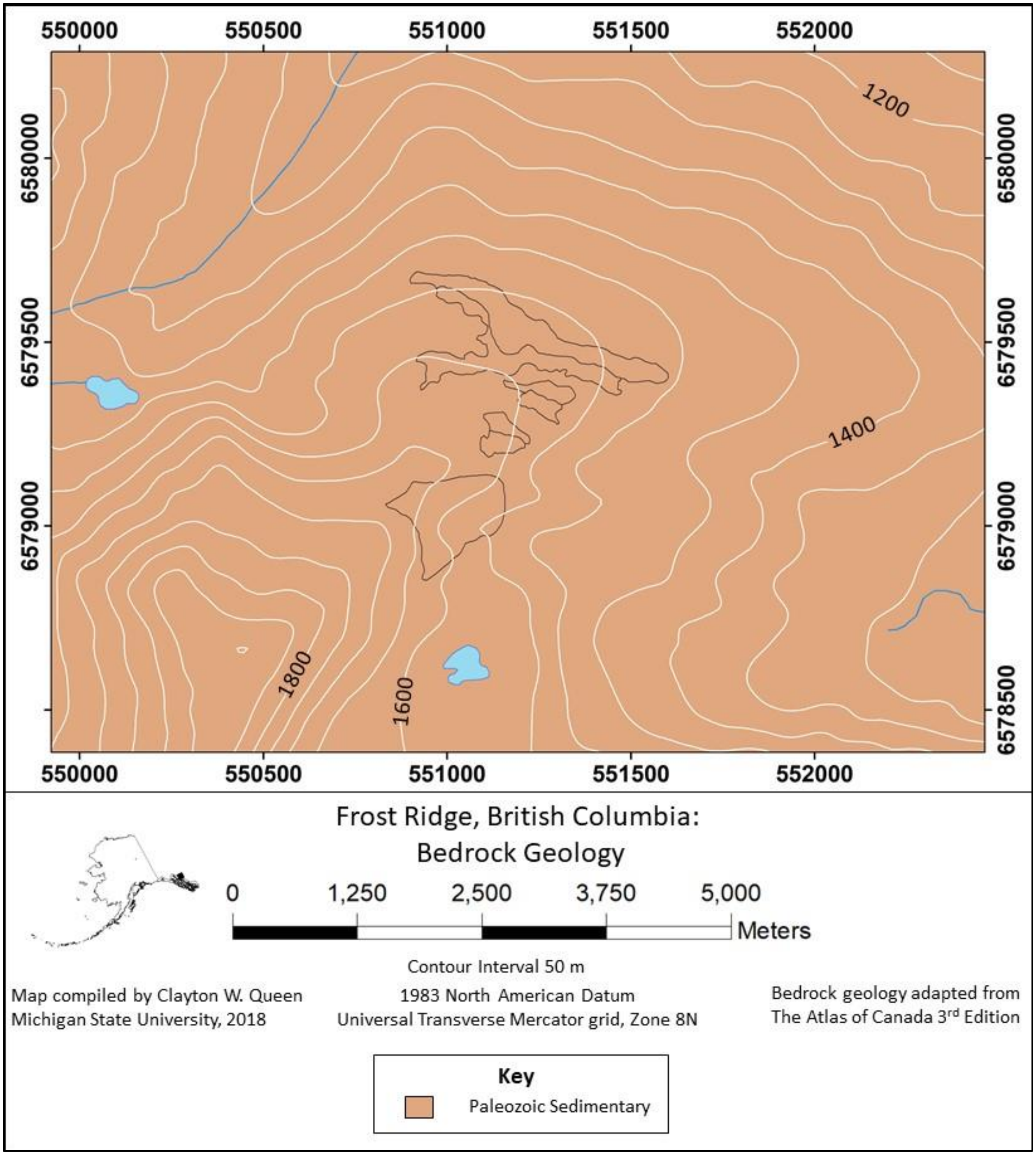

Figure 2.9. Bedrock geology of Frost Ridge, BC: *The study areas is uniformly sedimentary rock. Geologic data adapted from the Atlas of Canada (1958).*

Measurements of sorted stripes were undertaken at Frost Ridge, Eagle Summit, and Mount Fairplay. Table 2.3 shows the results of these measurements, allowing for comparison of the stripe widths. As the slope leveled out, the stripes give way to other forms of sorted patterned ground, primarily circles and nets. A calculation of slopes from the ArcticDEM on terrace treads at Eagle Summit and Mount Fairplay show a series of circular shapes that are interpreted to be sorted patterned ground (Figure 2.11). Soil pits dug across the terrace treads provide further evidence for the interpretation that patterned ground features exist across the terrace. Clasts exhibiting varying degrees of weathering were found in the majority of soil pits. Together, these findings make the case that the terraces have been forming for long periods of time and help to link terraces in Alaska with those studied at the more active Frost Ridge site.

Table 2.3. Comparison of sorted stripes at Frost Ridge, Mount Fairplay, and Iron Creek: *All measurements are in meters. Stone stripes were not measured at Eagle Summit but appear to be of similar magnitude to those at Mount Fairplay.*

	Frost Ridge	Mount Fairplay	Iron Creek
Mean (m)	1.40	3.43	1.81
Min (m)	0.50	2.30	0.90
Max (m)	4.40	4.80	3.50

Between treads, some similar features were noted. All terrace scarps are covered with angular clastic rubble, apparently pieces of frost-shattered bedrock derived from bedrock outcrops. At the base of these scarps, where the slope is reduced, the rubble is in many places “channelized” into sorted stripes. In some places, the stripes grade into sorted nets and garlands. Farther from the scarps, where the slope is reduced even more, the sorted stripes become sorted polygons. Nelson (1979a) reported that on Frost Ridge water continued to flow through the coarse sections of sorted circles, probably continuing to carry sediment. In the middle of the terraces at Eagle Summit and Mount Fairplay, patterned ground gives way to wet tundra vegetation, at least at the surface. At the far side of the terrace, the wet tundra becomes smaller patterned ground features and then gravel pavement, which exists on the outer edge of the terrace treads. Surrounding the terraces on all sides, except those that lead to another terrace, are slopes of transportation with solifluction features extending to streams and then rivers in valley bottoms (Figure 2.5a, 2.6a, 2.7a). The middle sections of terraces exhibited differences, depending on the morphology and vegetation cover. Terraces at Mount Fairplay have frost boils and wet tundra areas in the mid-terrace region. At the Eagle Summit site, the center is a mosaic of tundra vegetation and sorted polygons. Both sites have areas of saturated peat with a high frost table (~30cm) in early July. The wetness of these peat areas is attributable to their occupation of low-lying areas on the terrace tread.

The periglacial features identified on the terraces are similar at the different sites (Table 2.2), although their morphology differs. Features at the Eagle Summit and Mount Fairplay sites appear to be dormant. Evidence for contemporary geomorphic dormancy includes the high percentage of clasts with nearly complete lichen cover (Figure 2.12A) and nearly complete vegetation cover on many terrace treads. These observations appear to be consistent with the literature (e.g., Reger 1975; Reger and Péwé 1976), although Reger (1975) and Reger and Péwé (1976) describe relict rather than dormant cryoplanation terraces in Alaska. However, contrary to the conclusions of Reger and Péwé (1976), these terraces are not relict, but in a semi-dormant state where the nivation processes are not as strong and the moisture supply is not as high as during the LGM. Cursory evidence does suggest that freeze-thaw related processes and landforms are still operating on the terraces. One metric indicating that there are still limited periglacial processes acting upon these sites can be indicated by counts of recent rock fracture. Counts of rock clasts at three sites indicate that roughly 2% of rocks were fractured. Frost boils are present and active at the Eagle Summit, Mount Fairplay, and Iron Creek sites. At Iron Creek, the features appear only slightly more active.

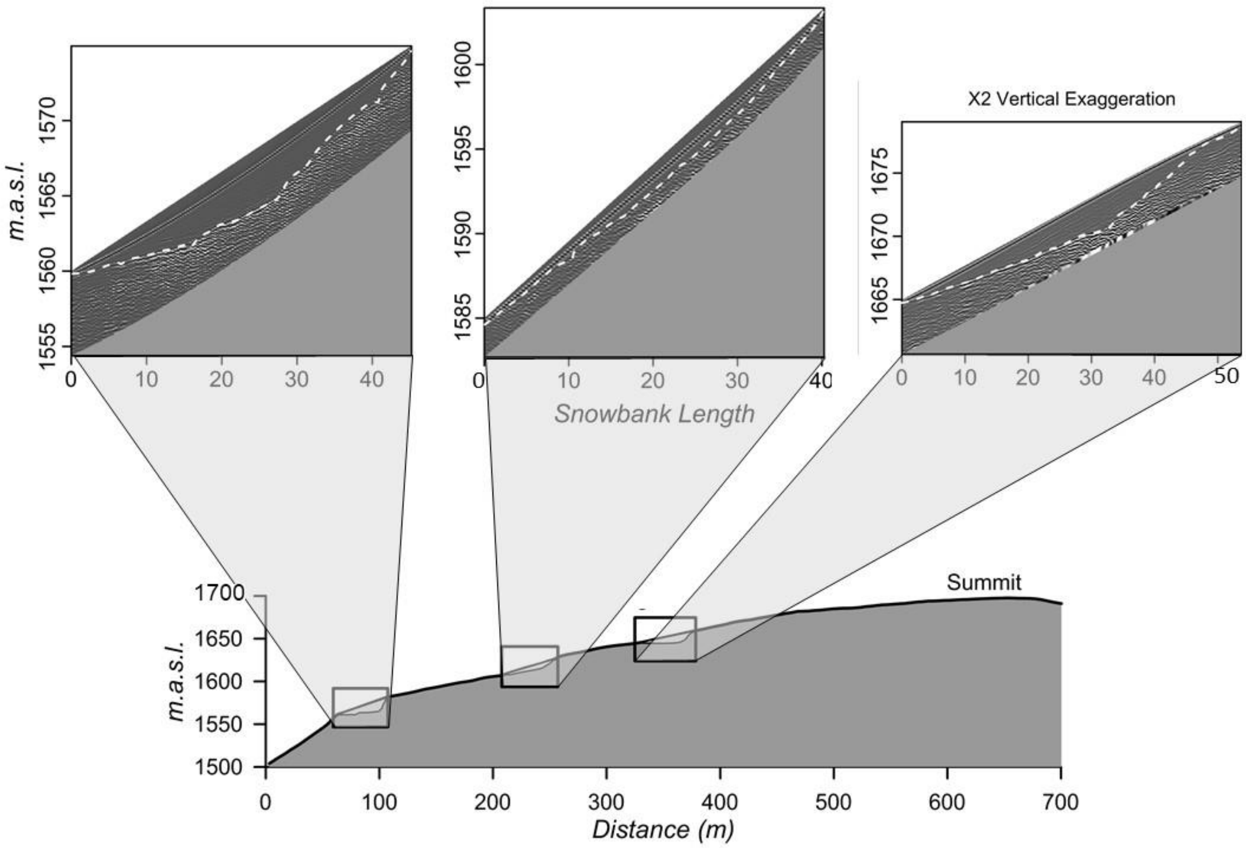

Figure 2.10. Profile of snowbanks at Frost Ridge, BC: *Positions of these snowbanks are indicated in Figure 2.8. The dark grey line is the surface of the snowbank, the dashed white line is the surface of the ground below the snowbank. The white line flattens out beneath the snowbank indicating these are actively eroding and have the potential to become terraces over time. Figure courtesy of K. Nyland 2017.*

Solifluction appears to be active at both the Eagle Summit and Mount Fairplay sites. Although this study did not include instrumental observations of solifluction movement, evidence of downslope movement of material was observed at the Mount Fairplay site and repeat observations at the Eagle Summit site show burst solifluction lobes that must have involved rapid movement of large volumes of sediment. At Mount Fairplay, evidence of moving water was seen at the scarp-tread junction and digital terrain analysis modeling of surface hydrologic flow on the tread agrees with field observations of water moving towards the sides of terraces and into solifluction lobes on the terrace sides. Clasts within nivation hollows near the Eagle Summit site, where snow remained into early July, had less lichen cover and the snow supplied moisture to the area. Nelson (personal communication, 2017) observed that snow remained well into August at these locations in the early 1980s. Similarly, at Frost Ridge, clasts and material in the sorted stripes were largely free from lichen (Figure 2.12b) and appeared to be subject to significant activity by periglacial processes, although the features have undergone some settlement since the mid-1970s (Nelson personal communication 2017). At Frost Ridge, the sorted stripes were observed through a crude sediment trap to be channeling water, a phenomenon also noted by Nelson (1979a) at the same location.

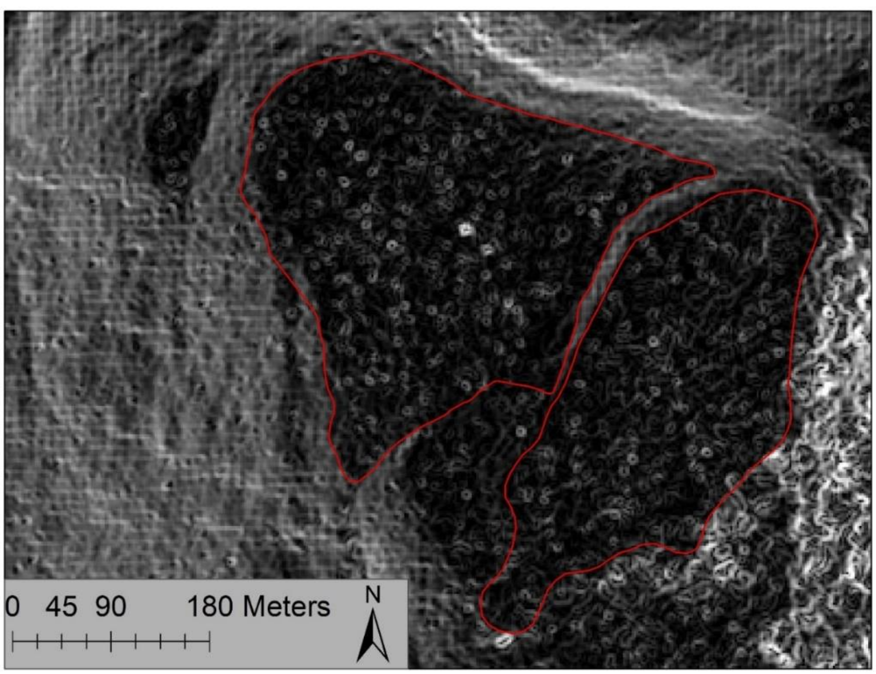

***Figure 2.11**. **Pattered ground from slope at Eagle Summit, AK:** The results of DEM (Arctic DEM) derived slope calculations at Eagle Summit study site, terraces 6 and 7 are outlined in red. The white is interpreted to be patterned ground features that have since been buried by vegetation.*

Figure 2.12*.*Comparison of geomorphically active and inactive rock clasts: *a) Lichen covered rock clasts in a stone stripe at the base of the scarp between Eagle Summit terrace 7 and terrace 6. b) lichen free sorted stripe at Frost Ridge. This sorted stripe appears to be active, with water running through its base.*

2.2.4 The facies concept and the periglacial landscape: The concept of periglacial facies is not new to the periglacial literature, having been initially proposed by Lozinski (1909) and recently mentioned by French (2017, pp. 3). A more extensive exploration can be found in Richmond (1962) and Morris (1981). However, it does appear that the linkage between the periglacial facies concept and the periglacial landscape has been extended only as far as block fields and rock glaciers. This thesis proposes expanding upon the facies concept to include periglacial forms that, pursuant to Madole (1972), can give indication of environmental conditions. Conversely, by pursuing an understanding of these facies and their depositional environments, the conditions necessary for the formation of periglacial landforms can be deduced.

Given what is known about cryoplanation terraces and the environment of Beringia during the Last Glacial Maximum, as well as the formation of small periglacial landforms, a conceptual representation of the periglacial landscape can be created. Morris and Olyphant (1990) conceptualized a physical model that relates topoclimatic factors to the deposition of facies. A similar model is appropriate here (Figure 1.4). This model would link the periglacial landscape to surface features by providing an understanding of the environmental factors necessary for the formation of various periglacial forms, including cryoplanation terraces. Climate is the driving force behind the periglacial environment (Washburn 1980, 2), but local factors play a major role in the manifestation of various landforms (Morris and Olyphant 1990). These local factors, or filters, include, topography, vegetation, and lithology. By providing minute adjustments to the climate, the filters will produce just enough variation to alter the physical manifestation of the landscape. In the model shown in Figure 1.4, the filters yield three possible forms, glaciers, cryoplanation terraces, and surface periglacial landforms. It has been shown that CTs occupy the same climate space as glacial cirques (Nelson 1989; Nelson and Nyland 2017) and thus some simple factors might affect the mass balance of snow and thereby cause the formation of vastly different landforms. If, for example, snowbank orientation is such that the snowbanks melt before the end of the year most years, nivation will occur and CTs will form. If snowbanks are not able to remain on the landscape for longer than in the immediate surroundings due to less favorable topographic position or a combination of aspect and lithology, smaller surface features will likely form instead. Evidence for this depositional model can be seen at Eagle Summit, within close proximity to the study site, CTs, a glacial cirque, and small features are all present. A map by Péwé, Burbank, and Mayo (1967) indicates that a glacial cirque is present on the east side of the study site ridge; if this interpretation is correct, its form has been modified significantly in postglacial time. On the west and north sides, cryoplanation terraces are found, and among both of these features surface periglacial features have been documented. The features likely formed after the others, owing to changes in environmental conditions.

2.3 Conclusion

This chapter examines the spatial location and arrangement of periglacial features on the Beringian landscape through detailed mapping. By formalizing the idea of form communities in the periglacial landscape, the patterns of observed features become a larger assemblage, rather than a series of small, essentially disconnected, features.

Large-scale mapping of periglacial sites across Alaska indicate that this landscape is indeed a system of interconnected parts that, together as a periglacial assemblage, constitutes a distinct landscape. At all sites, a series of form communities creates a repetitive pattern. The similarities between sites that range in elevation from 600 to 1600 m.a.s.l. and are separated by distances of over 1000 km show that this landscape is not unique to one site, but can be found in many Beringian uplands, which are in large part a periglacial domain. This pattern can be seen as a series of small, micro-forms that embroider the larger meso-scale features, CTs and cryopediments. The distinct nature of some of the micro-forms and the processes, which are connected to the formation of the larger forms, comprise a distinct and characteristic landscape.

The mapping efforts described above solidify the notion that cryoplanation terraces are the foundation of the periglacial landscape. It is through this large-scale mapping of terraces that the identification of the relationship between small- and large-scale periglacial features is shown. The identified relationship between the unquestionably periglacial features and larger slope-scale features provides a description of the periglacial landscape. This shift in thinking will allow for a critique of French (2016) and André (2003) that relies on the periglacial attributes of the small features at a landscape scale.

Owing to their relatively small size, the periglacial microforms (e.g., sorted patterned ground, frost boils, frost-jacked clasts) mapped in this study are difficult to discern on most air photographs. Field mapping is laborious and time-consuming, and only relatively small areas can be mapped without investment in a major field campaign. In some cases (e.g., Evans 2017), high-resolution air photos facilitate mapping of more extensive areas than those covered here. Progress in this area of research is most likely to come, however, from use of unmanned aerial vehicles or UASs (Whitehead and Hugenholtz 2014), and from small-satellite technology (Kulu 2018; Mascaro 2018), which can provide resolution of as little as 0.3 m.

Chapter 3
Specific Periglacial Geomorphometry

This chapter focuses primarily upon understanding the signature of periglacial processes on the landscape and predicting the locations of specific forms (CTs) using semi-automated methods. In the previous chapter, it was concluded that there is indeed a distinct landscape composed of a repeating series of interconnected forms and sediments, an *assemblage* of forms, that makes the periglacial landscape distinctive. This chapter uses specific geomorphometric methods to both *recognize* and *delineate cryoplanation* terraces and to demonstrate their ubiquity and distinctive imprint on the landscape. Through a multi-method and multi-scale approach, a semi-automated identification sequence will provide a method for distinguishing the periglacial landscape.

3.1 Review of Geomorphometry

Geomorphometry is the quantitative study of the landscape through the intersection of geomorphology, mathematics, and computer science (Pike et al.2009). By defining landscape attributes in a mathematical construct, the landscape is demarcated through a series of geometric shapes. Landforms have a specific geometry and the conglomeration of these landforms together creates a landscape that varies in geometry over space.

The study of geomorphometry has roots in basic cartographic and spatial analysis. However, the subject has increased in popularity with the availability of high-capacity computing and digital representations of earth's surface (Pike et al. 2009). Computer-aided spatial analytics has also greatly increased the speed and accuracy of applying geomorphometric methods, making this technique more commonplace. As the methods used in geomorphometry have evolved, the predominant use has been to analyze and understand fluvial landscapes. A smaller subsection of the literature on geomorphometry has been applied to glacial landscapes. Even less has been done to apply geomorphometric techniques to periglacial landscapes.

3.1.1 Evolution of geomorphometry: The study of geomorphometry is interwoven with the subjects of terrain analysis and terrain modeling (Pike 2002). Early studies in geomorphometry were conducted using terrain data collected by pioneers of geography, such as Alexander Von Humboldt (Pike 2002). Methods of analysis have evolved over time with the increased accuracy of topographic maps through to the use of computers to perform landscape analysis (Pike et al. 2009). As of 2002, over 4,000 publications related to geomorphometry had been written, beginning in the nineteenth century. These publications span many disciplines, demonstrating that the subject is of considerable importance to many scientists (Pike 2002).

With the quantitative revolution in geomorphology and its shift from primarily geography to geology (Church 2005), the nature of landforms became an important part of geomorphologic study. A review of “land form geography” (Zakrzewska 1967) built upon an earlier review of morphometric studies (Hammond 1964) to broaden the scope of inquiry from those of basic morphologic parameters such as slope, local relief, and texture. Through these basic parameters, various landscape indices were developed, forming the foundation of geomorphometry. Wood and Snell (1960) pioneered this landform analysis using their terrain index, which was furthered by Pike (1988), who identified a series of landscape parameters and used them to predict a geomorphic signature. Further work has sought to identify ways in which simple measures such as slope and relief can be put together in an automated procedure to classify landforms (Dikau et al. 1991, 1995). Together, the identification of landforms constitutes a primary subfield of geomorphometry.

A major shift in the field of geomorphometry came when Evans (1972, 1987) subdivided the subject further into *specific* and *general* geomorphometry. Specific geomorphometry is concerned with discreet or individual landforms, while general geomorphometry focuses on the geomorphic landscape, or continuous land surface. This subdivision of the two types of study allows for a multiscale approach to understanding the landscape.

Modern geomorphometry relies on digital elevation models (DEMs) for elevation information. DEMs are gridded matrices with each node (pixel) representing a specific elevation. Another version of an elevation model is a digital surface model (DSM). The primary difference between a DSM and a DEM is that a DSM represents the surface of the earth and will often include vegetation, buildings, or other surface covering, while DEMs are bare-earth models of the land surface (Bishop and Shroder 2004).

3.1.2 Terrain analysis: With the increased use of DEMs in geomorphometry, it is important to understand the limitations of DEMs. A DEM is a discrete dataset that segments the elevations of the study area into a regularly spaced series of nodes, the locations of which are arbitrary with respect to the topographic surface they represent (Mark 1975). The discrete division between neighboring pixels poses a problem in modeling the continuous land surface. To solve the problem of continuous data in a discrete space, several techniques have been proposed that allow for the derivation of landscape attributes from these discrete models. For example, slope, the first vertical derivative of terrain, can be linked with the concept that the landscape represents a function. The derivative of a function is its slope at a point (Sharpnack and Akin 1969). On a DEM, each grid node represents an elevation value, or point, and should have a corresponding slope value. The second vertical derivative of terrain, profile curvature, can again be traced to the mathematical relationship between a function and its second derivative, the rate of change of slope. Through consideration of terrain by these derivatives it can be computationally manipulated, allowing for highly sophisticated quantitative analysis and comparison.

3.2 Introduction to Periglacial Geomorphometry

Periglacial geomorphometry is proposed here as a subdiscipline of geomorphometry that has not been extensively explored in the literature. An extensive collection of work addressing geomorphometry in cold regions has focused on identifying glacial cirques (e.g., Eisank et al. 2010; Eisank, Smith, and Hiller 2014; Wagner 2018). Concepts related to periglacial geomorphometry were touched upon briefly in an unpublished study by Nelson (1979b), which provides a description of the need for such a subject, including an application to "cryoplanated terrain." Further research proposed by Nelson (1979b) relates to the periglacial landscape, particularly cryoplanated uplands, and states that these landscapes should have a distinct hypsometric signature that allows it to be distinguished from other landscapes, a topic featured prominently in Chapter 4 of this thesis.

Using data derived from Reger's extensive study, Nelson (1998) contributed to specific geomorphometric analysis of cryoplanation terraces (CTs) using directional statistics (e.g., Mardia 1972; Fisher 1993). This work was analogous to work in glacial geomorphometry pioneered by Evans (1977). Additional geomorphometric analysis by Nelson and Nyland (2017) demonstrated that cryoplanation terraces exhibit elevational trends similar to those of glacial cirques, indicating that cryoplanation terraces are climatically controlled and thus useful in understanding the origins of periglacial landscapes.

3.2.1 Periglacial geomorphometry applied to the Beringian landscape: This research applies the concepts and lessons from the broader subject of geomorphometry to the periglacial environment of eastern Beringia. The subdiscipline of periglacial geomorphometry will thus have the goal of understanding the periglacial landscape through analysis of the character and form of cold-climate, nonglacial landforms. Periglacial geomorphometry will be discussed in the context of cryoplanation terraces and how they form the fundamental underpinning of the upland periglacial landscape. The analysis undertaken in this thesis uses a multiscale approach that incorporates both specific (this chapter) and general (Chapter 4) geomorphometry.

3.3 Specific Periglacial Geomorphometry of Cryoplanation Terraces

Chapter 2 concluded that cryoplanation terraces can be regarded as the foundational building blocks of upland periglacial landscapes. It follows that no investigation into the geomorphometric signature of the upland periglacial landscape would be complete without specific geomorphometric analysis of cryoplanation terraces. This chapter discusses the application of multiple geomorphometric methods to individual and series of cryoplanation terraces at the previously discussed sites of Mount Fairplay and Eagle Summit (Figure 1.5) along with several sites mapped by Reger (1975) and previously glaciated sites mapped by Péwé, Burbank, and Mayo (1967).

It is well understood that defining a landform based on morphometric parameters cannot be done without some degree of subjectivity (Pike 2001). With respect to cold-climate landforms, Evans and Cox (1974) discussed the difficulties involved in achieving an operational definition for glacial cirques, a relatively simple geomorphic feature. Wide variation in cirque morphology occurs in glaciated uplands, and it is virtually impossible to avoid at least some subjectivity in conducting inventories of these features. Operational definitions of cryoplanation terraces face similar challenges. Despite a wide range of CT morphological attributes and size, the definition of a cryoplanation terrace has been addressed primarily through qualitative verbal description, sometimes augmented by semi-quantitative measures, such as ranges of scarp and tread dimensions, slope angles, and topographic position (e.g., Demek 1969; Reger 1975). Increasing availability of high-resolution representations of the land surface facilitates the creation of quantitative definitions of landforms. These, in turn, can be used through geomorphometric analysis to further the goals of geomorphology (Evans 2012). This chapter makes a first attempt at developing an objective, semi-automated method for recognizing and delimiting cryoplanation terraces using high-resolution digital elevation models.

A series of terrain attributes were calculated in an effort to identify which would be most effective for the detection of terraces. First, slope and aspect algorithms were applied to the study areas. Second, tangential and profile curvature were calculated for the study sites. Third, three low-pass filters were applied to the study sites and the previous two methods were applied to these smoothed DEMs. Fourth, the elevation-relief ratio (Pike and Wilson 1971) was calculated based on a grid over the study sites. Finally, all of these parameters were used collectively to create a semi-automated method for detecting the locations of CTs in the landscape.

3.*3.1 Slope and aspect calculations:* The calculation of slope and aspect from a DEM is common and many methods exist to determine these attributes. In a basic sense, slope is the rate of change in elevation from point A to point B and can be calculated by dividing rise by the run. Given a continuous function, slope becomes the first vertical derivative of that function. In a raster environment, such as a DEM, where data comprise a discrete grid of values, defining a continuous function is not possible. This means that the slope is dependent on the resolution of the DEM. To work around the lack of continuity, various algorithms have been developed, one of the more common being the Horn (1981) algorithm. Horn (1981) takes the eight cells surrounding the target raster cell and averages the east-west and north-south gradients (Equation 3.1). These averages are used to designate a value for each raster pixel that is indicative of the rate of change in elevation between the surrounding pixels.

Aspect (orientation) is, in the simplest terms, the direction faced by the slope. For a continuous function, aspect is the first horizontal derivative of elevation. The calculation of aspect commonly uses the same eight neighboring cells used in calculating slope. In this case, the algorithm identifies the change in both the horizontal and vertical directions. A straightforward method for calculating aspect is given in Equation 3.2 (Olaya 2009, 146).

Using the algorithms discussed above and the Arctic DEM (Polar Geospatial Center 2017), slope (Figure 2.4a; 2.12a) and aspect maps were calculated for each of the study sites. A visual inspection of these maps shows significant areas of nearly flat (<5°) slopes. These flat areas are primarily cryoplanation terrace treads or river valley bottoms. Owing to irregularities in the DEM and the fine resolution of the data, slope maps at 2 m resolution are too variable for this analysis, and a different method for performing these calculations was developed, as described below.

Equation 3.1.

$$Change\ in\ Horizontal\ Slope = \frac{(Za + 2Zd + Zg) - (Zc + 2Zf + Zi)}{8 * Cell\ Res.}$$

$$Change\ in\ Vertical\ Slope = \frac{(Za + 2Zb + Zg) - (Zc + 2Zh + Zi)}{8 * Cell\ Res.}$$

A	*B*	*C*
D	*E*	*F*
G	*H*	*I*

Equation 3.2.

$$Aspect = 180 - \arctan\left(\frac{dz/dx}{dz/dy}\right) + 90 * \frac{dz/dx}{|dz/dx|}$$

3.3.2 Tangential and profile curvature calculations: Curvature is the second derivative of elevation, or the rate of change of slope. Slopes can be flat, concave, or convex. To calculate curvature, it is necessary to specify the direction for this calculation. Profile curvature is the rate of change from the bottom to the top of the slope (Equation 3.3). Tangential curvature is equivalent to plan curvature, except in that it adds a slope as a factor. It has been shown that tangential curvature is a better measure in specific geomorphometry (Olaya 2009). Tangential (plan) curvature is simply the rate of change from side to side (Equation 3.4). Following Olaya (2009), the equations used in a GIS environment to calculate profile and tangential curvature are shown in Equations 3.3 and 3.4 respectively.

Equation 3.3.

$$Profile\ Curvature = \frac{\left(\frac{dz}{dx}\right)^2 * \left(\frac{d^2z}{dx^2}\right) + 2 * \left(\frac{dz}{dx}\right) * \left(\frac{dz}{dy}\right) * \left(\frac{d^2z}{dx^2}\right) * \left(\frac{d^2z}{dxdy}\right) + \left(\frac{dy}{dz}\right)^2 * \left(\frac{d^2z}{dy^2}\right)}{\left(\left(\frac{dz}{dx}\right)^2 + \left(\frac{dz}{dy}\right)^2\right) * \sqrt{\left(1 + \left(\frac{dz}{dx}\right)^2 + \left(\frac{dz}{dy}\right)^2\right)^3}}$$

Equation 3.4.

$$Tangential\ Curvature = \frac{\left(\frac{dz}{dy}\right)^2 * \left(\frac{d^2z}{dx^2}\right) - 2 * \left(\frac{dz}{dx}\right) * \left(\frac{dz}{dy}\right) * \left(\frac{d^2z}{dxdy}\right) + \left(\frac{dz}{dx}\right)^2 * \left(\frac{d^{2z}}{dy^2}\right)}{\left(\left(\frac{dz}{dx}\right)^2 + \left(\frac{dz}{dy}\right)^2\right) * \sqrt{1 + \left(\frac{dz}{dx}\right)^2 + \left(\frac{dz}{dy}\right)^2}}$$

As with slope, the use of profile and tangential curvature was limited when applied to the 2-meter Arctic DEM, as curvature is highly variable. Inspection of the curvature maps reveals that they indicate locations of cryoplanation terraces. However, analysis of these locations proved to be unnecessarily complicated.

3.3.3 Low-pass filters: The Arctic DEM was created using automated photogrammetry software, the Surface Extraction from TIN -based Searchspace Minimalization (SETSM) (Polar Geospatial Center 2017). The SETSM software extracts information from optical satellite imagery. Although the software provides a visually appealing product, a series of crosshatch artifacts appear in the data. Noh and Howat (2015) demonstrated that the SETSM algorithm was highly accurate in both horizontal and vertical directions, although they failed to recognize the artifacts produced by this method. The crosshatch artifact visible in the ArcticDEM (Polar Geospatial Center 2017) inhibits certain geomorphometric calculations, including the accurate identification of cryoplanation terraces.

To reduce the artifact, a low-pass filter was run on the DEM. A low-pass filter is a neighborhood (kernel) operation that takes the average of neighboring cells to fill in the target cell. For example, using a 3 X 3 neighborhood, the filter would take the three neighboring cells in either direction and average them to replace the target cell value. For this project, 3 X 3, 9 X 9, 21 X 21, and 75 X 75 neighborhoods were used. Some filters were applied to excessively smooth out the data for a specific purpose (i.e., the 75 X 75 filter), others were compared for optimal smoothing to remove artifacts and variability. Once low-pass filters were applied to the DEM, slope and aspect algorithms were run on the smoothed DEM. From these new slope maps various geomorphometric analyses were conducted.

3.3.4 Elevation-relief ratio: Strahler (1952) developed the hypsometric integral (HI) as a method to classify and compare landscapes. Although an extremely useful measure, Strahler's method of calculation involves planimetry from maps, and is both laborious and time-consuming. Wood and Snell (1960) furthered Strahler's idea by developing a mathematically identical measure, the elevation-relief ratio (ERR) (Equation 3.5), which is simple to calculate on DEMs (Pike and Wilson 1971). With advances in computer-aided analysis, the ERR has been used frequently in geomorphology and allows for comparison of landscapes, often at a watershed scale. This method extends beyond the comparison of watersheds and can be used to predict features on the landscape. Pérez-Peña et al. (2009) developed a method that used the ERR to predict the location of fault scarps. By resampling the DEM and applying the ERR to each grid node, the location of steep scarps becomes apparent. A similar method was applied to study sites in this chapter as a means to identify the locations of terrace scarps.

Equation 3.5.

$$ERR = \frac{Mean\ Elevation - Minimum\ Elevation}{Maximum\ Elevation - Minimum\ Elevation}$$

3.3.5 Semi-automated identification of cryoplanation terraces (CTAR): Descriptive studies of cryoplanation terraces have identified basic characteristics of terraces that can provide a baseline for their identification. Demek (1969) and Reger (1975), the two major reviews of the cryoplanation landform literature, are in agreement that terrace treads range in slope from 0^{o} to 5^{o}. Adjacent to terrace treads, scarps rise at angles of 9 to 32^{o}, providing a distinct contrast between low- and high-angle slopes. This morphological description creates the primary parameters for CT recognition (identification). Using rasters derived from the ArcticDEM and described in the preceding sections, this semi-automated method (CTAR) is shown as a flow diagram in Figure 3.1. The procedure uses both a 75 x 75 neighbor average kernel and a 21 x 21 neighbor average kernel to create low-pass filters in GRASS GIS (GRASS Development Team 2018). The 75 x 75 filtered DEM is then used to calculate flow accumulation using the GRASS r.watershed command (Gruber and Peckham 2009). The absolute value of the output flow accumulation is taken and accumulations of more than 100 pixels are filtered out. By filtering out the higher flow accumulations, only the ridges are being used in subsequent calculations.

To address the high variability of the Arctic DEM (Polar Geospatial Center 2017), slope was calculated on the 21 x 21 neighborhood raster, which greatly reduced variation in the DEM. The slope raster was then combined in an if-then statement with the flow accumulation raster to recognize CTs. In this study, a threshold value of 5° slopes, based on the observations of Demek (1969) and Reger (1975), was used to recognize the CTs at Reger's Eagle Summit, Mount Fairplay, Indian Mountain, Kwethluk River, and Sittookooyook River study sites, each of which contains numerous CTs (Figure 3.2).

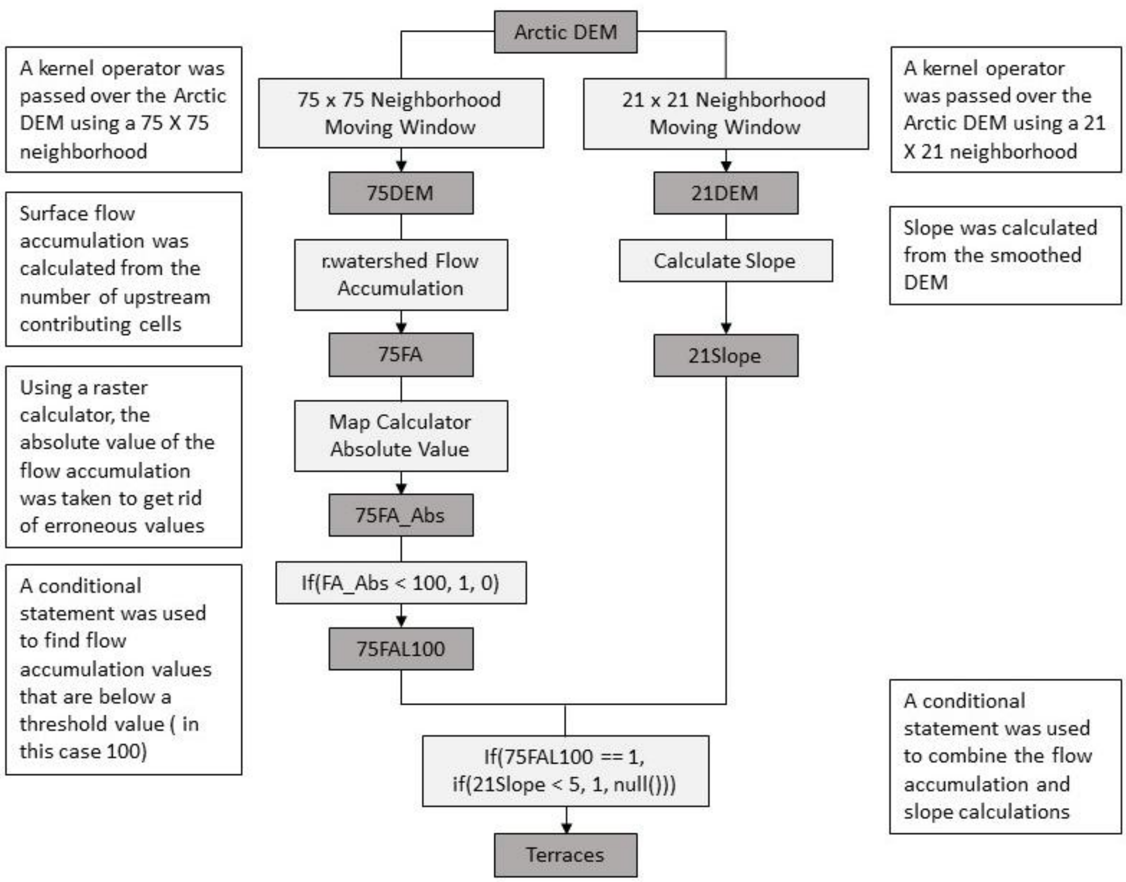

Figure 3.1. Flow diagram of the methods for the Semi-Automated Identification of CTs: *Darker boxes are output rasters, lighter boxes are the operations performed, and descriptions of these operations can be seen on the sides. The use of 75 x 75 and 21 x 21 low pass filters was chosen because they provide the optimal resolutions to perform the various methods outlined here. The procedure was created and run in GRASS GIS software.*

3.4 Results from Semi-automated Identification of Cryoplanation Terraces

In the initial exploratory analysis of cryoplanation terraces various terrain parameters were calculated and filtered out to find the most appropriate measure. The calculation of slope allowed for visual identification of cryoplanation terraces (Figure 3.3). Gentler slopes are associated with valley bottoms, summit flats, and cryoplanation terraces. The steeper slopes coincided with valley walls and terrace scarps. CTs were easily recognized on the low-angle slopes and were used in subsequent calculations. The calculation of aspect, however, did not provide any additional information on the location of cryoplanation terraces and was not used for identification.

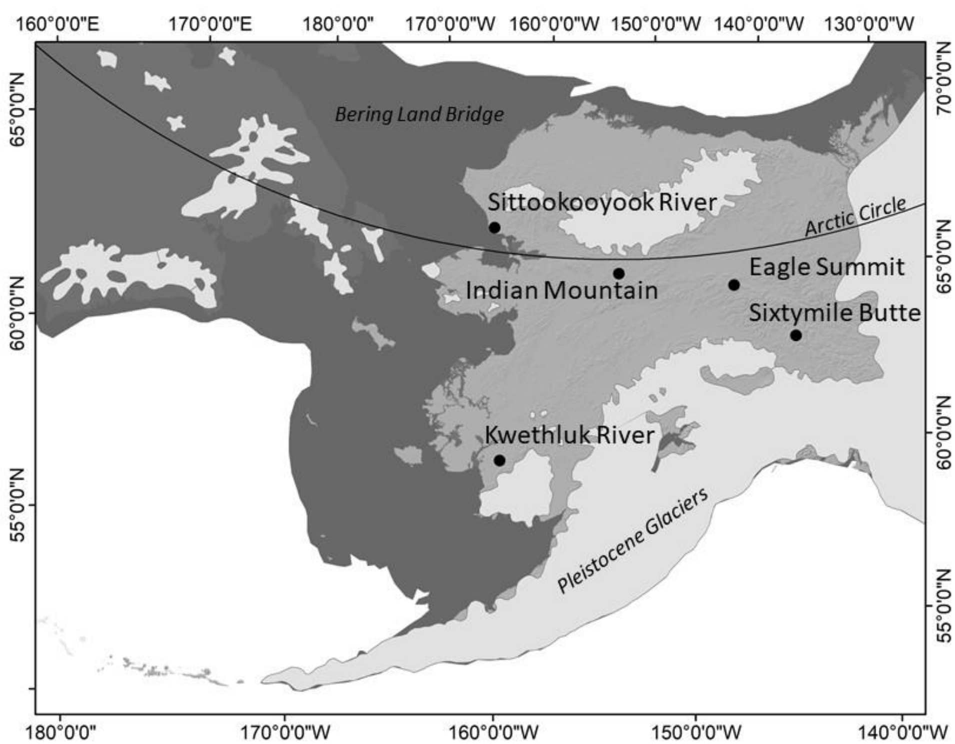

Figure 3.2. Map of sites where the CTAR was tested: *Each site was previously mapped by Reger (1975) and used to test the accuracy of the identification sequence. Also noted on the map is the extent of Pleistocene Glaciers (light grey) and the Bering Land Bridge (dark grey) adapted from Brubaker et al. (2005).*

When the terrain derivative of curvature was calculated, visual identification of terraces was possible in both the profile and tangential curvature maps. Profile curvature resulted in the identification of scarps (Figure 3.4), while tangential curvature showed the nearly flat treads of the terraces (Figure 3.5). CTs were easily recognized, but also misidentified other landforms (i.e., solifluction lobes and nivation hollows) when curvature was used in the semi-automated method for CT identification.

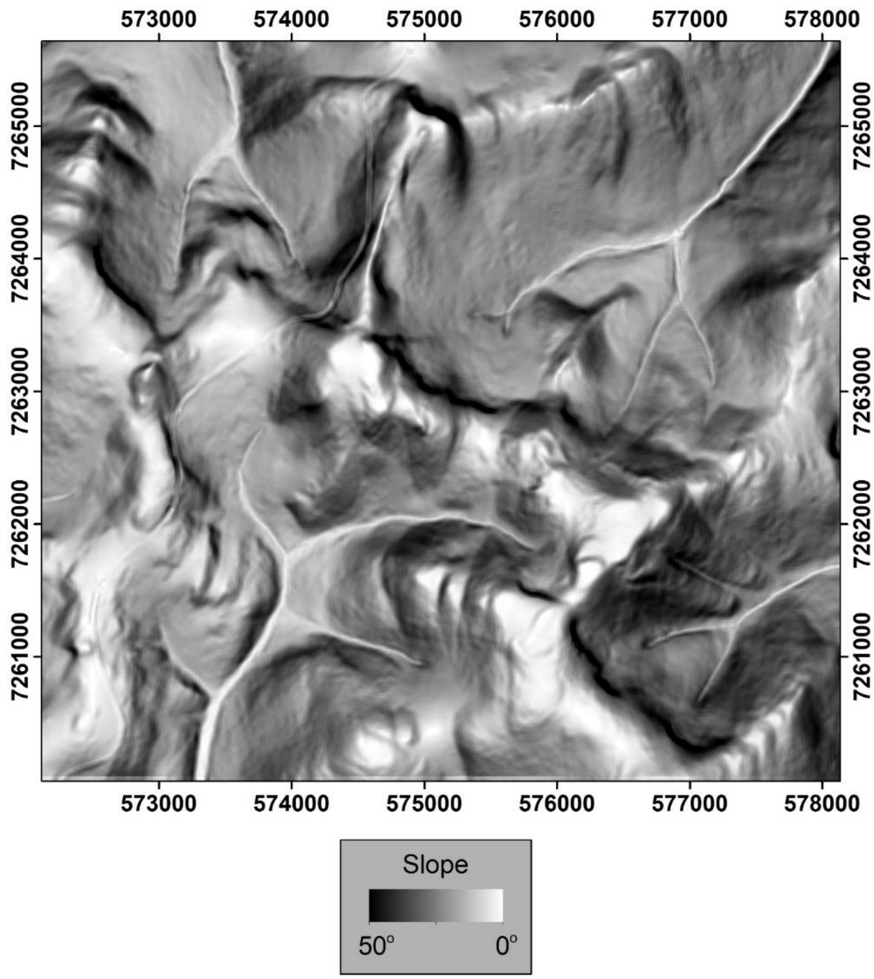

***Figure 3.3*. Map of slopes at Eagle Summit, AK:** *Computation of slope provides an example the visual impression given by the slope maps created for both Eagle Summit and Mount Fairplay. Flat-topped ridges and terraces are highlighted in lighter tones; scarps and valley walls are darker. Coordinates for this map are UTM Zone 6N.*

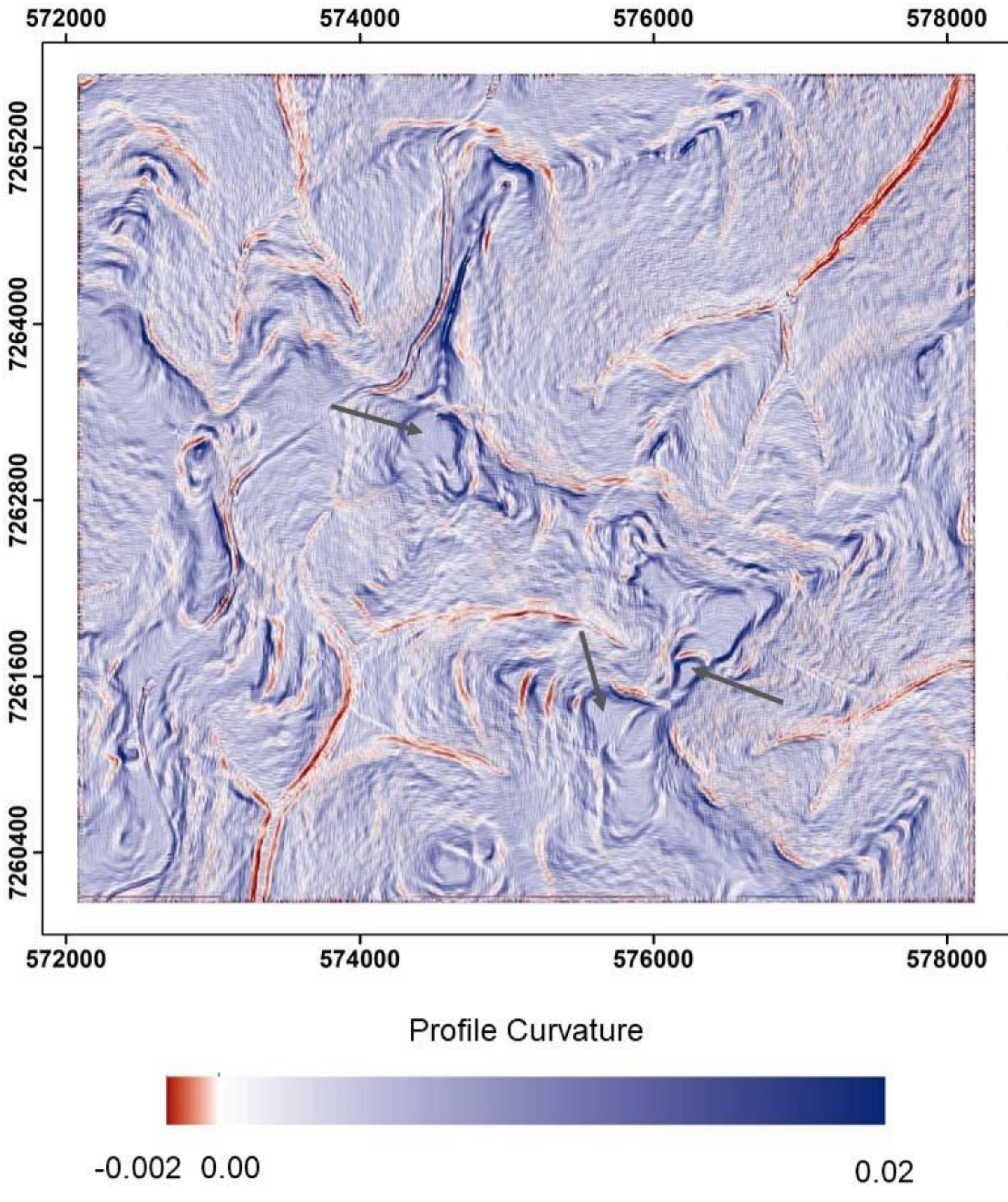

Figure 3.4. Profile curvature map of Eagle Summit, AK: *Red values are concave, blue values are convex. Terraces and summit flats (indicated by grey arrows) are immediately apparent in this image as lighter blues with scarps visible as dark blues and reds. Coordinates on this map are given as UTM Zone 6N.*

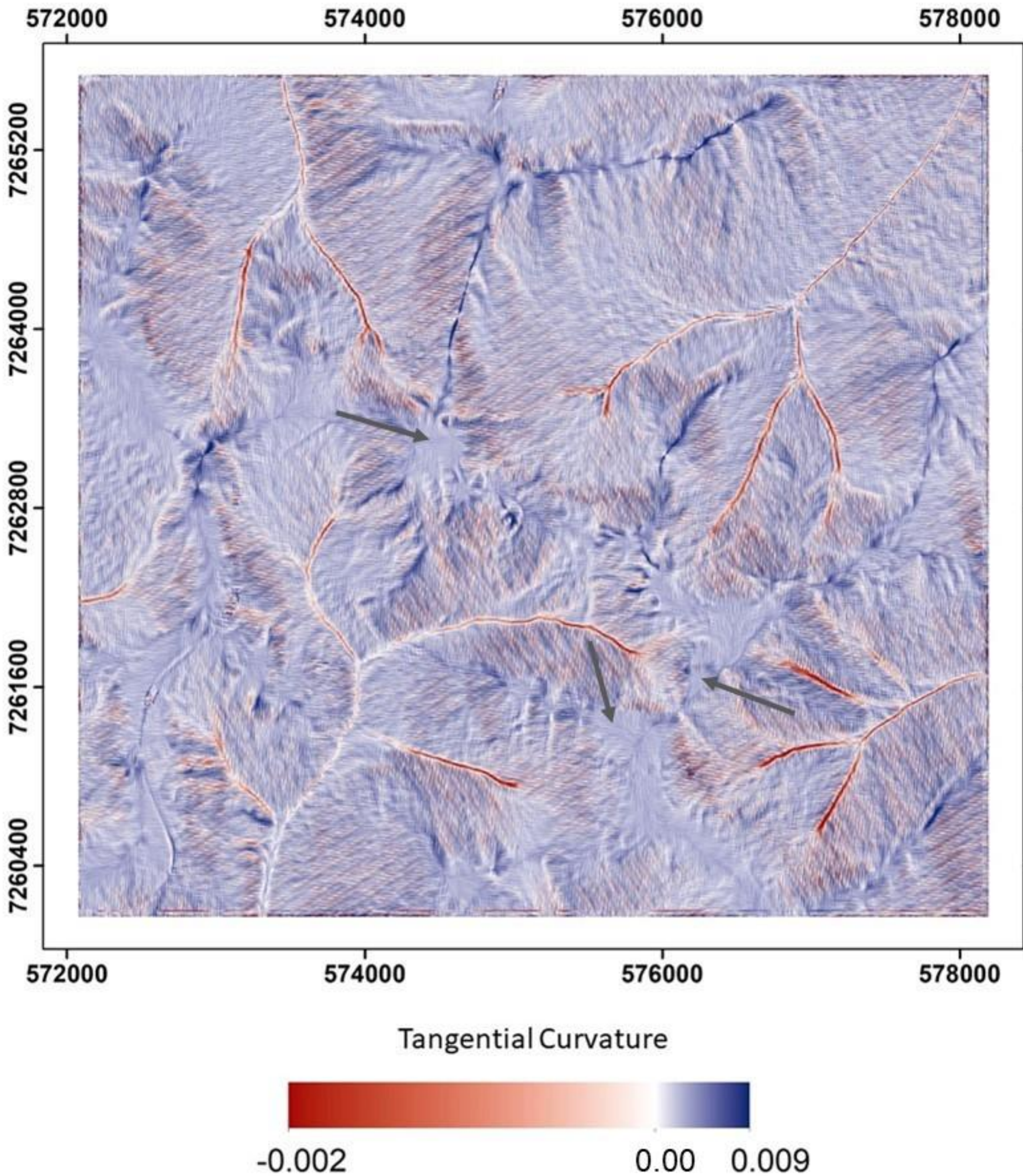

Figure 3.5. Tangential curvature map of Eagle Summit, AK: *Red values are concave, blue values are convex. Terraces and summit flats (indicated by grey arrows) are immediately apparent in this image because of the clustering of flat to slightly convex slopes (light blue tints). Coordinates on this map are given as UTM Zone 6N.*

Smoothing the DEM before performing calculations allowed for better generalization of terrain derivatives. This generalization helped to visualize the terrain and to perform terrain analysis. An optimal neighborhood size was identified from five different resolution filters by performing the identification sequence with each one and comparing the result. The optimal resolution varied depending on the calculation performed. Slope was calculated using a 21 x 21 low-pass filter and the watershed analysis was done using a 75 x 75 low-pass filter.

Computation of the ERR using a gridded approach helped to identify terrace scarps (Figure 3.6), although mathematically it was not ideal for identification of terraces. The large variation caused by the scale of the grid and the scale of the DEM inhibited the utility of this method. While performing additional analysis on the ERR raster would likely have yielded a favorable result, this method was more complicated than was deemed necessary.

The goal of this analysis is to provide a method that can be applied to a DEM and will identify the locations of CTs. This identification/recognition procedure (CTAR) was applied to sites identified by Reger (1975): Eagle Summit, Mount Fairplay, Indian Mountain, Kwethluk River, and Sittookooyook River (Figure 3.1). The first two locations were visited in the field and large-scale mapping was conducted on terraces in that location (Chapter 2).

All of the sites named in the previous paragraph were originally mapped by Reger (1975), who used 1:63,360 scale USGS topographic quads to discern areas in which CTs may be common. Reger, who is a highly accomplished photo interpreter (e.g., Krieg and Reger 1976, 1982) then used the best available imagery to delineate individual terraces on the quadrangles. The fact that CTs are recognizable on such low-resolution maps demonstrates their prominence in the Beringian landscape.

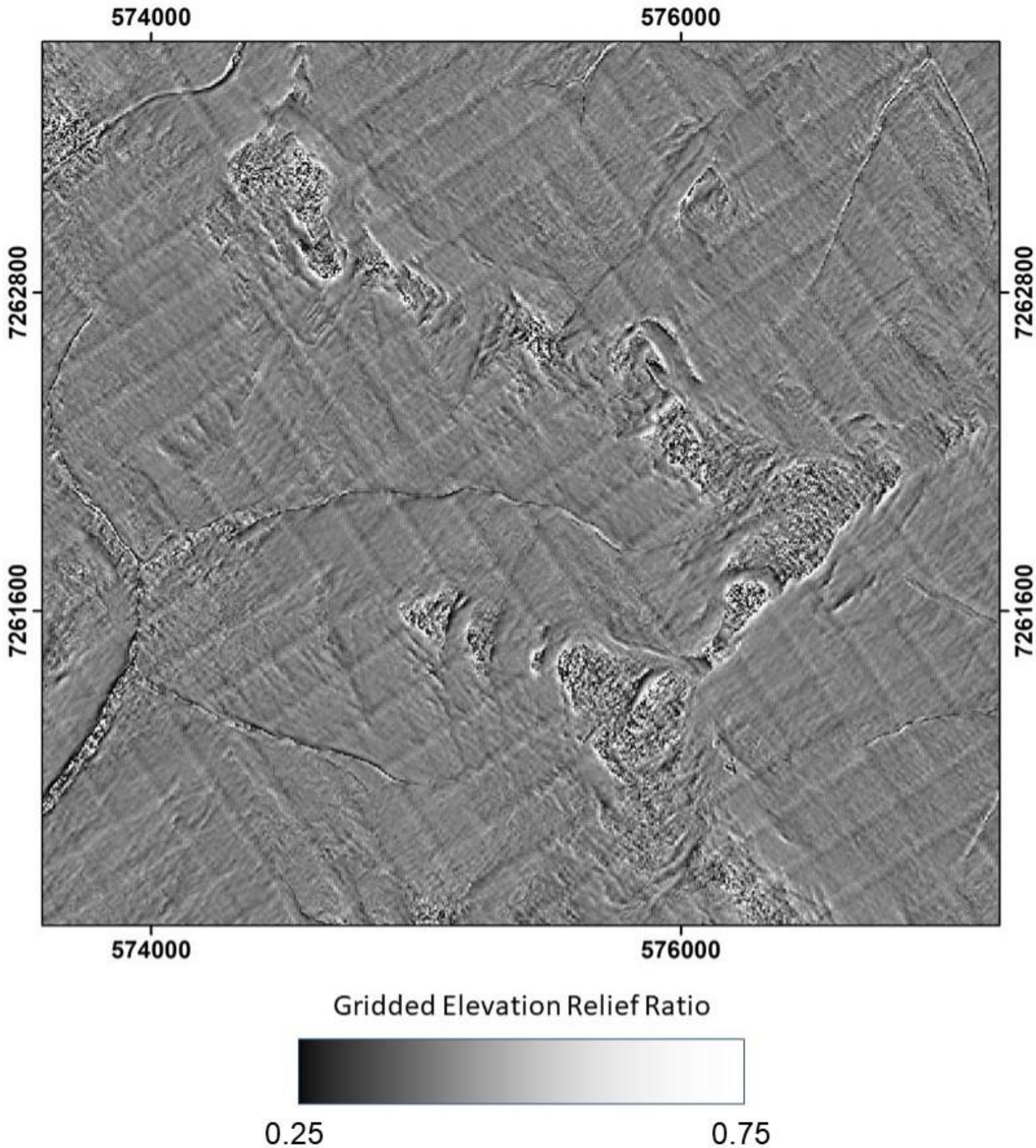

Figure 3.6*. *Map of ERR at Eagle Summit, AK: *This map shows the elevation relief ratio calculated from a 5 m grid. Lighter areas have a higher ERR, dark areas have a lower ERR. Cryoplanation terraces can be seen as areas of non-uniform ERR values. Coordinates around ERR map are from UTM Zone 6N.*

The scale used by Reger was much coarser than that used in the present study. Indian Mountain is the only exception to this scale restriction, as Reger extensively mapped terraces in the field at that site, using a topographic base map prepared exclusively for his project. As expected, more terraces were identified using CTAR than were mapped by Reger (1975) (Table 3.1). It is important to note that the semi-automated method, while performing well in most cases, did misidentify terraces in some locations, particularly at the Sittookooyook River site. The high degree of error seen at the Sittookooyook site could be an artifact of holes in the DEM at that location. Because of the data gap, the low-pass filter values may be artificially lower and flow accumulation will not have the upstream contributing area necessary for proper analysis. In addition, the nature of the terrain at this site, which contains relatively large low-lying areas, creates false positives.

Comparison of results from the CTAR method with Reger's (1975) site maps provided a means to check the effectiveness of the new method. Table 3.1 summarizes the accuracy of this method by comparing how many of Reger's (1975) CTs were identified and how many new CTs were found. The method for identifying CTs worked well at Eagle Summit and Mount Fairplay. At Sittookooyook River, Indian Mountain, and Kwethluk River, the sequence had to be adjusted slightly. Due to large low-lying areas adjacent to the study sites, an additional filter was necessary. At these sites, all areas that were less than the mean elevation were filtered out to exclude the flat, low-lying regions.

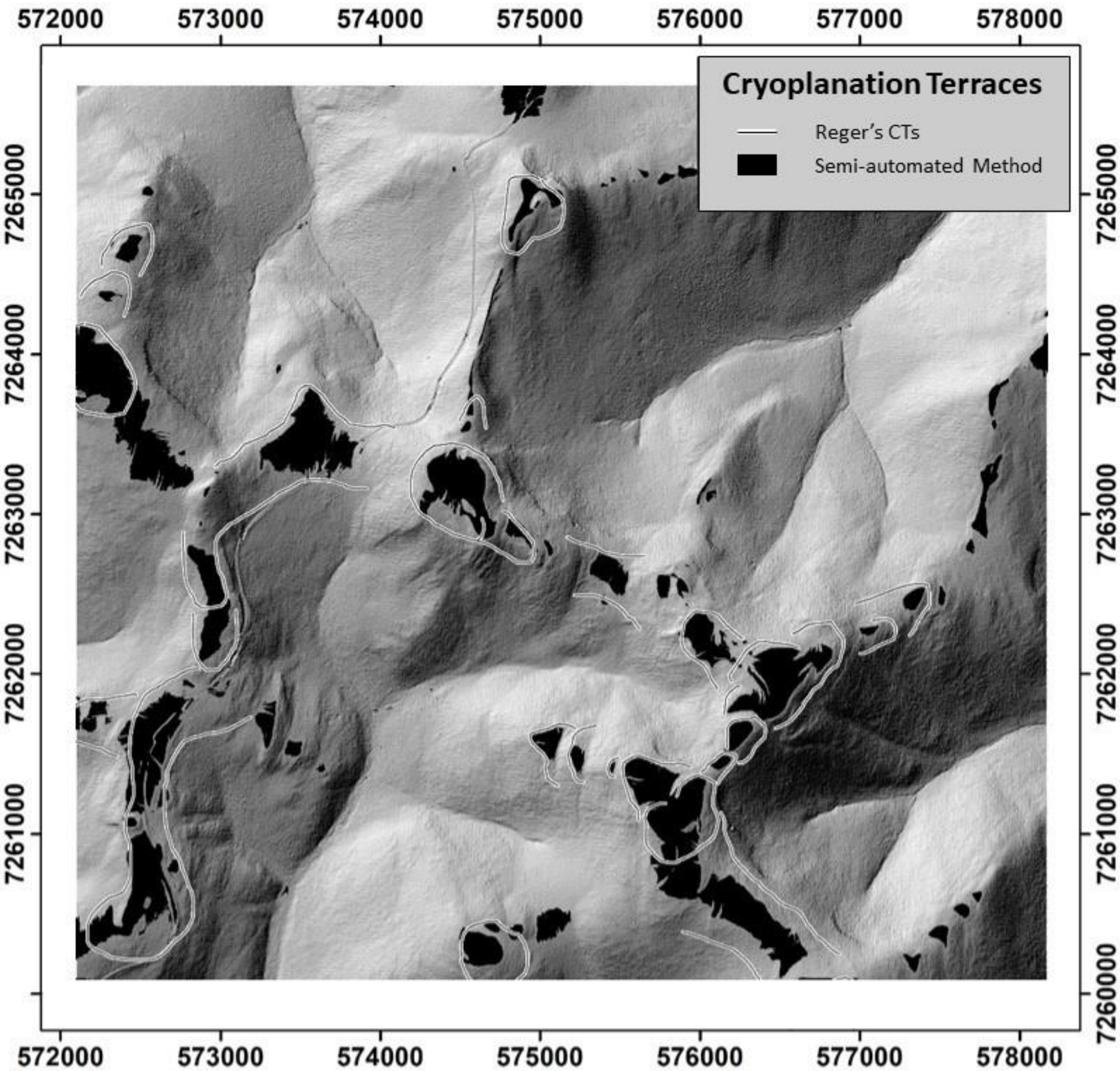

Figure 3.7*. *CTAR accuracy assessment at Eagle Summit, AK: *Comparison of the semi-automated identification of cryoplanation terraces developed in this study to the terraces identified by Reger (1975) at Eagle Summit. Coordinates in this map are measured in meters from UTM Zone 6N. Note that terraces identified by CTAR consistently fall within the bounds of CTs delineated by Reger (1975).*

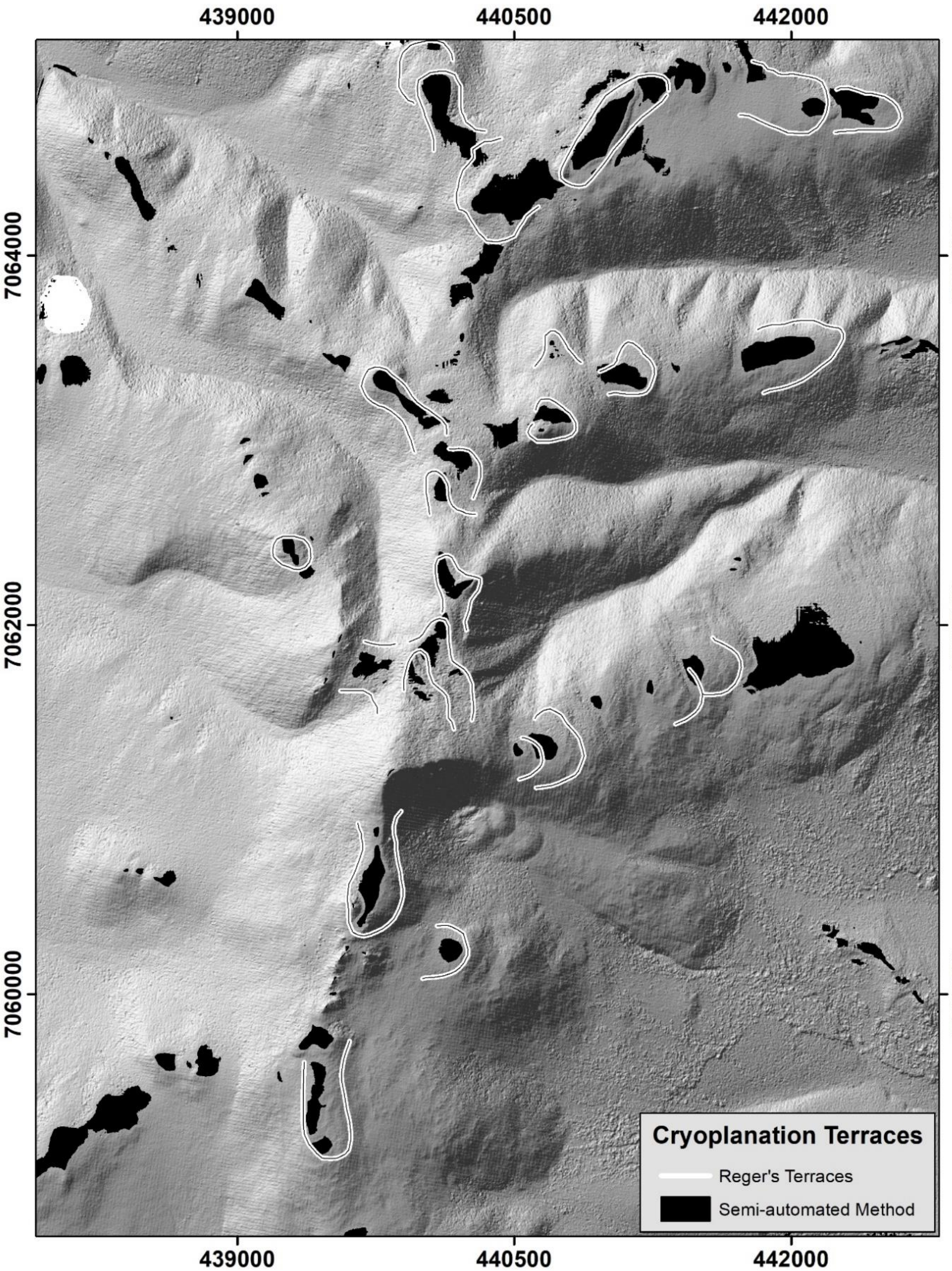

Figure 3.8. CTAR accuracy assessment at Mount Fairplay, AK: *Comparison of semi-automated method developed in this study to the cryoplanation terraces identified by Reger (1975) at Mount Fairplay. Coordinates are UTM Zone 7N.*

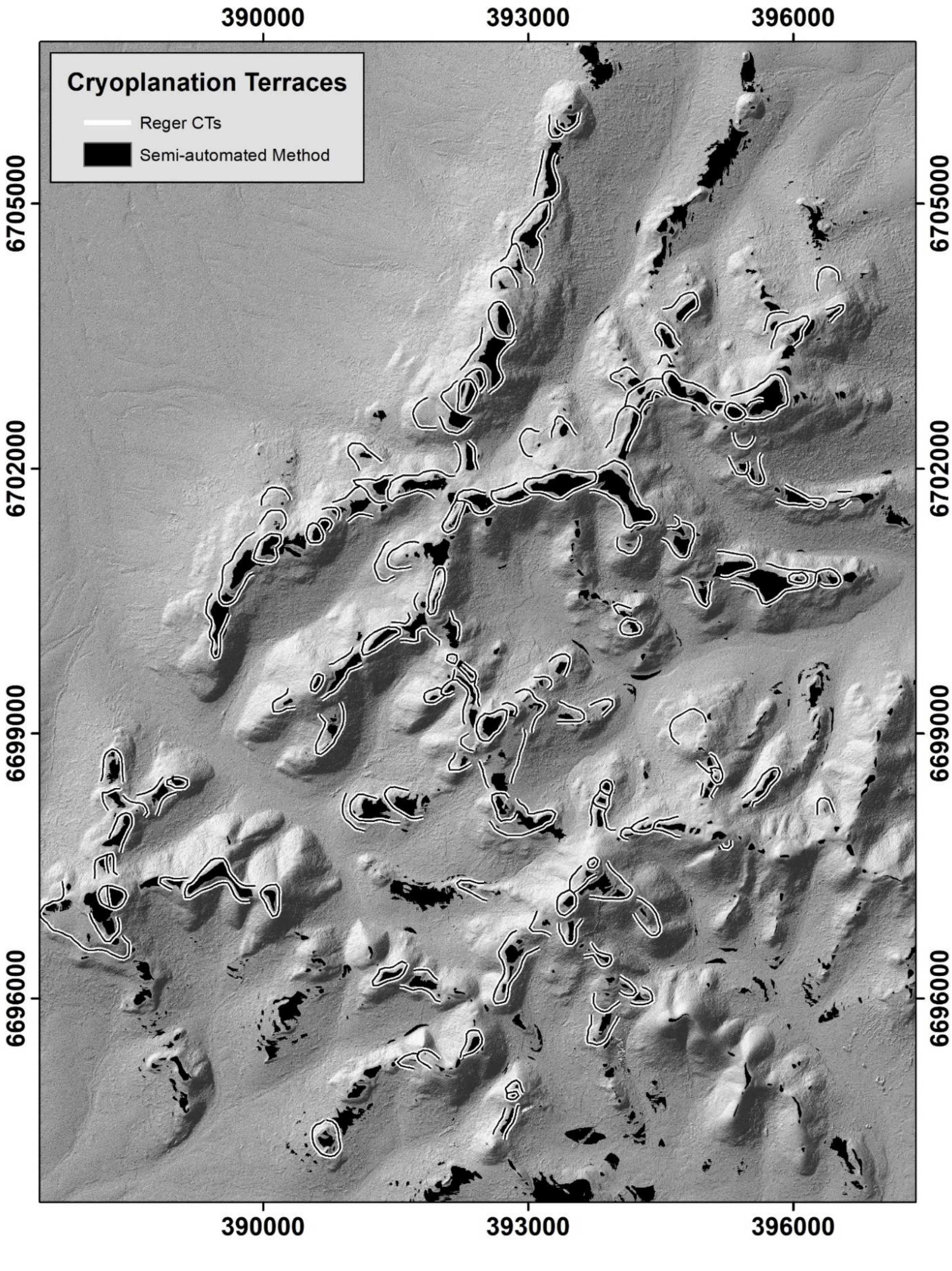

Figure 3.9. CTAR accuracy assessment at Kwethluk River, AK: *Comparison of CTs at Kwethluk River identified using the semi-automated approach developed in this study compared with those mapped by Reger (1975). Coordinates are in UTM Zone 4N.*

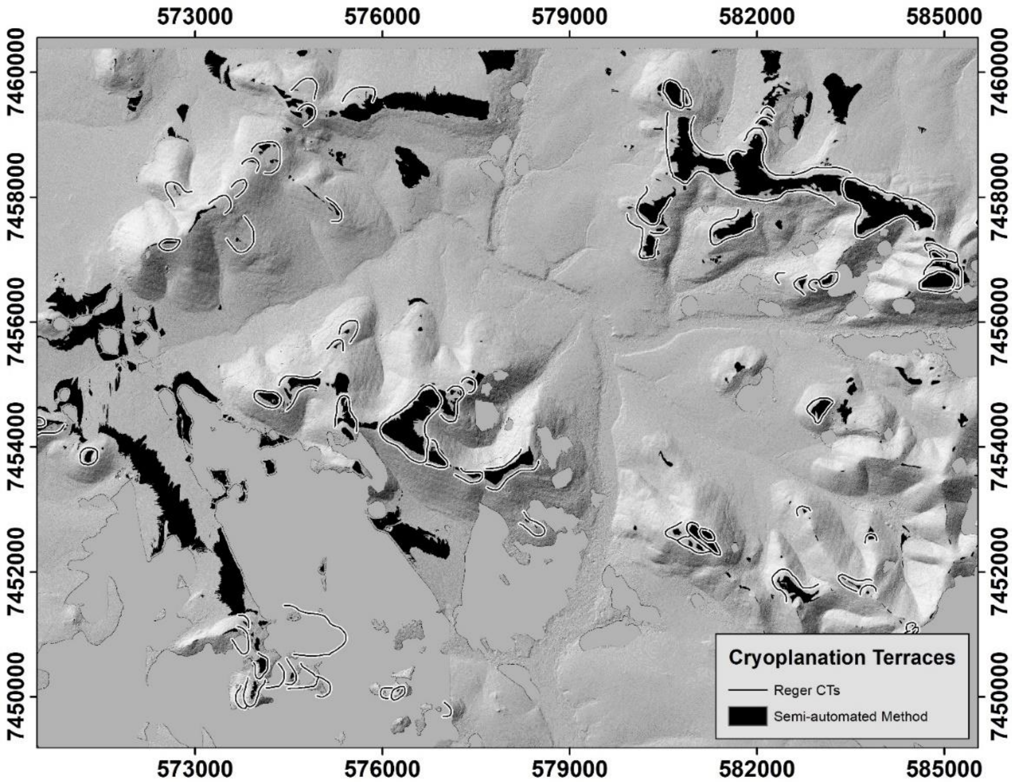

Figure 3.10. CTAR accuracy assessment at Sittookooyook River, AK: *Comparison of CTs at Sittookooyook River identified using the semi-automated approach developed in this study compared to those mapped by Reger (1975). The semi-automated approach to finding CTs was less accurate than expected at this site, with relatively large, low, flat areas identified and large holes in the data. Coordinates are UTM Zone 3N.*

Table 3.1. ***Summary of accuracy assessment for CTAR:*** *The number of terraces identified by the algorithm compared to the number of terraces identified by Reger (1975). The CTAR identified more terraces than Reger, again underscoring the ubiquity of these features.*

Site Name	Total Number of Terraces Identified	Number of Terraces Identified by Reger	Number of Reger's Terraces Identified	Percentage Identified
Eagle Summit	47	29	29*	100
Mount Fairplay	50	25	25*	100
Kwethluk River	166	146	131	90
Sittookooyook River	86	71	58	82
Indian Mountain	74	88	66	75

* Size of these sites is smaller than the area mapped by Reger (1975) due to lack of full coverage by the Arctic DEM.

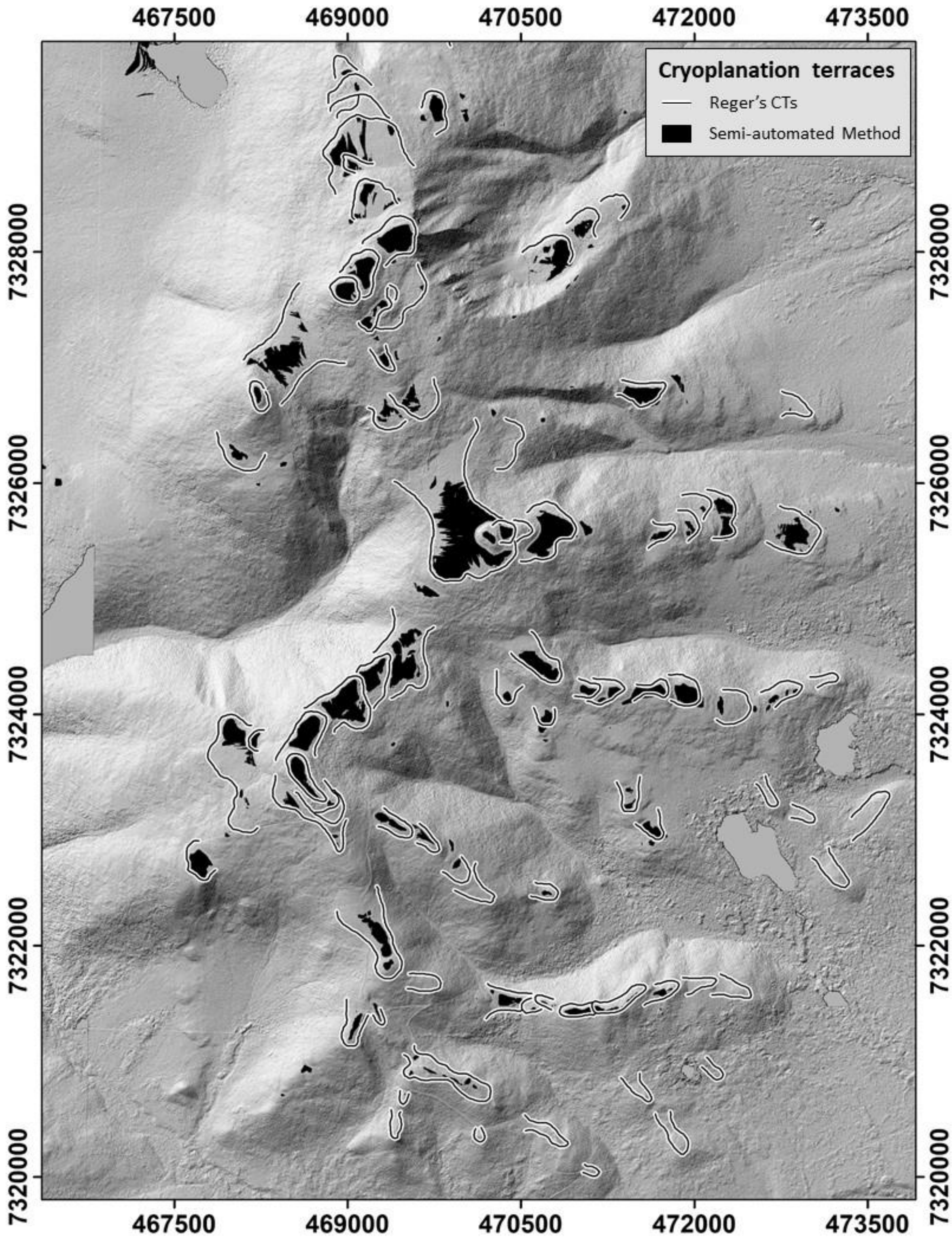

Figure 3.11. CTAR accuracy assessment at Indian Mountain, AK: *Comparison of CTs at Indian Mountain identified using the semi-automated approach developed in this study compared to those mapped by Reger (1975). The high resolution base map used by Reger (1975) at this site makes it an important test site for the CTAR method. Coordinates are UTM Zone 5N.*

3.5 Conclusion

The Semi-Automated Identification of CTs (CTAR) uses basic terrain parameters to identify the location of cryoplanation terraces on the landscape. In a multistep process whereby, certain areas are identified based on morphological characteristics, the CTAR filters out areas that are in valleys and only searches ridgetops or mountain summits for flat areas, i.e., areas with slopes less than 5°. Because CTs are found in upland periglacial environments, some locations require that low-lying areas be filtered out. To assess accuracy, CTAR was tested at five sites identified by Reger (1975), distributed across eastern Beringia. Overall, the CTAR performed well, with almost 90 percent accuracy. In addition to identifying nearly all of Reger's (1975) CTs, the CTAR was able to identify potential terraces that had not been mapped previously. Overall, CTAR constitutes a substantial methodological advance for the delineation of CTs. The ability to identify CTs based on a DEM provides a useful tool for recognition of upland periglacial environments.

The application of geomorphometry to periglacial geomorphology provides a fresh analytical technique for scientists who work on periglacial problems. With high-quality DEMs and the increased processing power of contemporary computers, periglacial geomorphometry has potential to provide a less expensive alternative to many forms of field-based work in periglacial regions. This chapter provides one example of the application of periglacial geomorphometry to answer the research question "is there a distinct periglacial landscape?". Through specific geomorphometric analysis, this chapter draws the conclusion that there is indeed a distinct periglacial landscape that can be identify by objective methods. Cryoplanation terraces are larger landforms than other periglacial features and occupy a substantial portion of the upland Beringian landscape.

The simplicity of identifying CTs on a DEM provides a methodology for recognizing and interpreting the periglacial landscape quickly and relatively easily. Although the methodology is not completely automated and requires advanced knowledge about environmental factors affecting the terrain, geomorphic features in the study area besides CTs, and knowledge about the morphology of CTs, the methodology can be adapted for use across the periglacial realm. The ability to recognize where CTs are located furthers the capability of geomorphometric analysis and facilitates geomorphological mapping.

Chapter 4

General Periglacial Geomorphometry

4.1 Introduction

Following Evans (1972, 1987), the subject of geomorphometry can be subdivided naturally into two subdisciplines, *specific* (treating discrete landscape units) and *general* geomorphometry (treating landscapes as continuous surfaces). This chapter focuses on general geomorphometry in the Yukon-Tanana Upland (YTU), a largely unglaciated region in eastern Beringia that has been affected by periglacial processes throughout most of the Quaternary (Mertie 1937; Wahrhaftig 1965; Péwé, Burbank, and Mayo 1967). The YTU is bounded by the Yukon River in the north and the Tanana River in the south (Figure 4.1).

General geomorphometric analysis in this study uses the methods developed by Strahler (1952) and Pike and Wilson (1971), discussed briefly in Chapter 3. The work presented in this chapter is of a purely exploratory nature and seeks evidence about whether a hypsometric "signature" is apparent in this region and, if so, at what geographic scale(s) it may be apparent. This work will examine Nelson's (1979b) proposition that, owing to the extensive flat-topped ridges and hills in the YTU, the hypsometric integral should be relatively large, i.e., of a magnitude similar to that of a young landscape, as proposed by Strahler (1952). To provide context for this analysis and in response to French's (2016) suggestion that cryoplanation terraces may be inherited features formed under warm desert conditions, a similar analysis has also been conducted on an area in the Basin and Range physiographic province of southwestern USA.

4.1.1 Hypsometry: A potentially useful intersection between geomorphometry and periglacial geomorphology is the hypsometric analysis developed by Strahler (1952) as a method for classifying the landscape based on a function that relates area to altitude. This analytical technique, called *hypsometry*, has two chief components: the hypsometric curve and the hypsometric integral (HI). The hypsometric curve is a graph relating area to altitude, while the hypsometric integral is the area under the curve. Strahler (1952) used the hypsometric curve to classify landscapes based on their developmental stage. Hypsometry was developed while Davis' (1909) cycle of normal erosion was the dominant geomorphic evolution paradigm. The hypsometric curve, as originally conceived by Strahler (1952), relates form to the Davisian concepts of *stage* (youth, maturity, and old-age). Although the Davisian model is now outdated, the concept of hypsometry remains a useful tool for understanding the character of the landscape. In a modern context, the hypsometric integral can be useful for comparing multiple landscape types based on their geometric characteristics.

4.1.2 Application of hypsometry in general periglacial geomorphometry: In an upland periglacial landscape, Nelson (1979b) suggested that hypsometric curves should be convex-upward, with an associated integral greater than 0.5. Strahler (1952) interpreted convex-upward hypsometric curves as representative of younger landscapes. While this may apply (under Davisian assumptions) to the humid, mid-latitude fluvial environments Strahler was studying, the interpretation changes significantly when discussing the periglacial landscape. It is likely that landscapes with numerous cryoplanation terraces would exhibit hypsometric curves with convex-upward shapes. High values of the hypsometric integral and convexity in the hypsometric curve may be expected in the YTU because, under the nivation model of cryoplanation, the landscape erodes by parallel retreat of slopes over a large elevational range, leaving more of the reference solid intact than in a typical mature fluvial environment. Under this interpretation, the convex shape of the hypsometric curve would not necessarily be indicative of age, but rather of the relatively large proportion of land area remaining at higher elevation, even after long intervals of erosion.

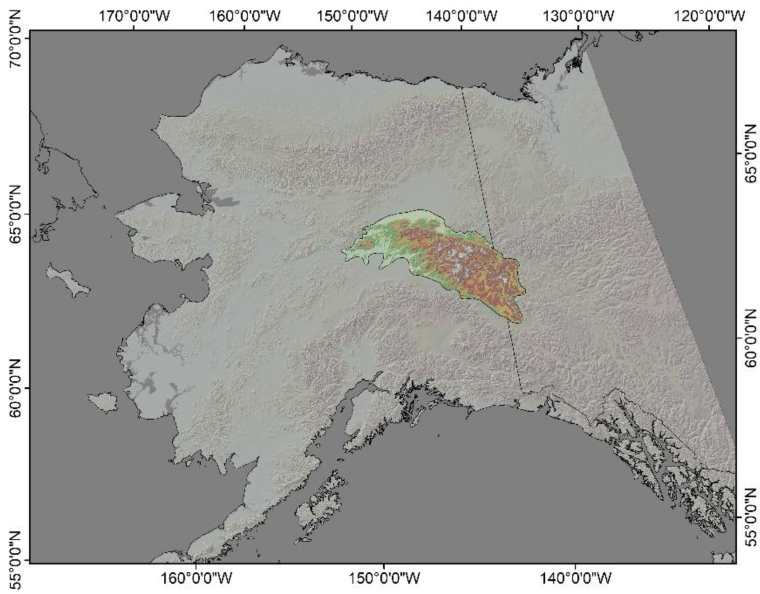

Figure 4.1. The Yukon-Tanana Upland: *Shown in the center of the map, the YTU is indicated in relation to the rest of Alaska.*

Application of geomorphometric techniques to periglacial landscapes allows for quantitative characterization of those landscapes and provides a means for comparison with landscapes formed under different environmental conditions. French (2016) asserted that cryoplanation terraces and cryopediments in northern Yukon Territory may be inherited features, formed under warm and dry conditions, and therefore would be similar to features found in contemporary arid regions. This interpretation follows André (2003) in holding that distinctively periglacial landscapes do not exist. The penultimate section of this chapter (Section 4.3.2) applies the methods used for the Yukon-Tanana Upland to an arid environment in the

Basin and Range region of the southwestern U.S. to evaluate French's assertion. By further identifying differences between the periglacial landscape and those in other parts of the world, this chapter uses quantitative evidence and semi-quantitative analysis to assess whether the concept of a distinctly periglacial upland landscape is warranted.

4.2 General Periglacial Geomorphometry: Methods

The concept of a periglacial landscape involves a diverse assemblage of features that creates a distinct landscape (Chapter 2). Based on ideas from Nelson (1979b), the methods outlined here will investigate whether periglacial areas yield specific ranges of hypsometric integral values and characteristic geometries in their hypsometric curves. Nelson's (1979b) initial work on the hypsometric integral at Indian Mountain near Hughes, Alaska provided a starting point upon which this study was built. Because the hypsometric integral was developed to investigate watersheds, this analysis will focus on watersheds as the basic unit to stratify the Yukon-Tanana Upland region.

Geographic scale is an important consideration in exploratory analysis. Because there can be no *a priori* way of knowing that environmental influences and geomorphic processes operate independent of scale (Phillips 2004), it is critical in exploratory work to operate over a range of spatial scale (e.g., Nelson et al. 1999) in order to determine the most appropriate scale(s) upon which to focus. This point is reflected in the recommendations of a study by Hurtrez, Sol, and Lucazeau (1999), which found results from hypsometric analysis are highly dependent on drainage area. In this study, hypsometric analysis was applied to a series of nested watersheds of progressively larger extent and hydrological characteristics.

4.2.1 Hypsometric integral for the Yukon-Tanana Upland: A DEM for the Yukon-Tanana Upland (YTU) was mosaiced together in ArcGIS from a series of ASTER Global DEM (GDEM) tiles (ASTER GDEM 2018). Using the r.watershed tool in GRASS GIS (GRASS Development Team 2018), a series of nested watersheds were delimited. The GRASS command *r.watershed* delineates watersheds based on a single flow accumulation (D8) algorithm. At the head of the basin, pixels are assigned a value of zero, and at the mouth of the basin the flow accumulation will equal the threshold value set by the user (Hofierka, Mitášová, and Neteler 2009). The watershed thresholds used here increase by factors of 10, from 100 to 1,000,000. Watershed sizes are summarized by descriptive statistics in Table 4.1. The smallest basins are on the size of individual ridges, while the largest basins involve second- or third-order streams. The sites in unglaciated parts of the Yukon-Tanana Upland are a subset of those identified by Reger (1975) (Table 4.2), one of which were mapped and analyzed in Chapters 2 and 3. Originally, the site at Mount Fairplay was included in this analysis. A choice was made to replace the Mount Fairplay site with Sixtymile Butte based on work by Willgoose and Hancock (1997) that showed that catchment geometry strongly influenced the hypsometric curves. Because watersheds at the Mount Fairplay site are more elongated than the other sites, the resultant curves were more concave and had lower integrals. The rest of the sites were chosen to provide coverage across the YTU. Glaciated sites (Table 4.2) were chosen from the map of glaciations in the YTU (Péwé, Burbank, and Mayo 1967). Sites were identified to correspond with areas mapped as glaciated during Late Pleistocene ("Wisconsin") and older ("Illinoian") glaciations. Glaciated watersheds were chosen by virtue of being in close proximity to points identified from the map by Péwé, Burbank, and Mayo (1967).

Table 4.1 Descriptive statistics of watershed size: *Watershed sizes are expressed in square kilometers*

Basin Size	Area (km^2)			
	Min	Mean	Median	Max
100	0.00051	0.09262	0.07524	18.79299
1,000	0.00033	0.70437	0.50005	22.59464
10,000	0.00052	4.79647	1.57025	57.51812
100,000	0.00052	26.21953	0.30715	431.2464

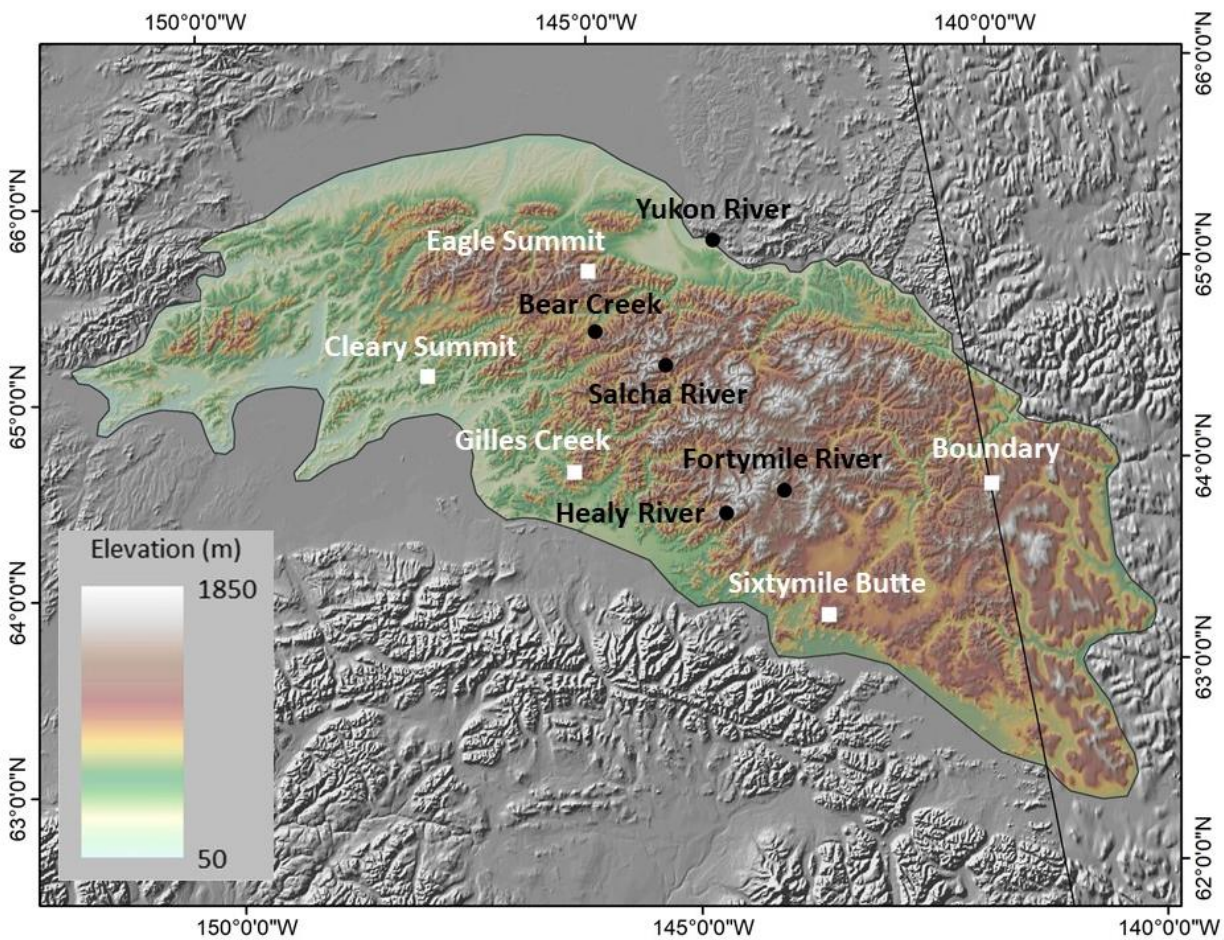

Figure 4.2. Map of study locations for general geomorphometry: Map of the study sites in Table 4.1. Glaciated sites are represented by black circles, unglaciated sites are white hexagons.

Computation of the hypsometric curve was done by extracting elevations from the DEM as a table with the number of pixels at each elevation. The area of each pixel was calculated from the cell resolution (22.78 m) and multiplied by the number of cells with the same elevation to get an area for each elevation value. To produce the hypsometric curve, elevations were normalized based on the ratio of the elevation above each threshold to the total elevation. Area was normalized by taking the area at each elevation and dividing it by the total area. Hypsometric curves were plotted as elevation vs. area with axes ranging from zero to one. This method was applied to each watershed computed for each site.

Table 4.2. Sites for general geomorphometric analysis: Sites are all located within the Yukon-Tanana Upland. Unglaciated sites were identified by Reger (1975), glaciated sites were chosen based on the map by Péwé, Burbank, and Mayo (1967).

Site Name	Glaciated or Unglaciated	Latitude	Longitude
Eagle Summit	Unglaciated	65.47	145.34
Sixtymile Butte	Unglaciated	63.56	143.11
Gilles Creek	Unglaciated	64.46	145.81
Cleary Summit	Unglaciated	65.03	147.43
Boundary	Unglaciated	64.07	140.98
Yukon River	Glaciated	65.54	143.77
Fortymile River	Glaciated	64.22	143.39
Healy River	Glaciated	64.15	144.10
Salcha River	Glaciated	64.94	144.56
Bear Creek	Glaciated	65.16	145.35

4.3 Results from General Periglacial Geomorphometry

4.3.1 Hypsometric analysis of the Yukon-Tanana Upland: Hypsometric analysis of the Yukon-Tanana Upland facilitated classification of the landscape based on a quantifiable parameter allowing for comparison with other sites. Because the Yukon-Tanana Upland is known to have remained largely ice free during the last glacial interval (Péwé, Burbank, and Mayo 1967) and to contain numerous cryoplanation terraces, this analysis provides a means by which to identify a possible geomorphic "signature" for an upland periglacial landscape.

Results from this analysis show trends both in size of watershed and between glaciated and unglaciated terrain. In general, as watershed area increases, the ERR decreases (Appendix; Table 4.3). Not surprisingly, the highest values of the ERR, above 0.5, for unglaciated sites were found at the smallest watershed size (Figure 4.3, Appendix).

The lowest ERR value (0.10) was calculated from the entire Yukon-Tanana Upland. This low value is indicative of the relatively high proportion of the terrain occupied by river valleys around the YTU. The analysis of the entire Yukon-Tanana Upland might also be skewed by the arbitrary boundaries placed on the DEM and the inclusion of a portion of the Yukon Flats. Perhaps a better measure of the low values would be to include the largest watershed size calculated (1,000,000), which yielded an average ERR of 0.23 (Appendix). This value is again lower due to the high proportions of river valleys included in this watershed.

Table 4.3 Comparison of HI for YTU sites: *Eagle Summit, Mount Fairplay, Gilles Creek, Cleary Summit, and Boundary (Reger, 1975) were never glaciated during Pleistocene cold intervals. Sites A-E were chosen from areas that were glaciated during the Pleistocene (*Péwé, Burbank, and Mayo 1967*).*

	Average Hypsometric Integral by Watershed Size				
Site Name	**100**	**1,000**	**10,000**	**100,000**	**1,000,000**
Eagle Summit	0.61	0.56	0.52	0.40	
Sixtymile Butte	0.61	0.50	0.49	0.50	
Gilles Creek	0.44	0.46	0.41	0.37	0.27
Cleary Summit	0.51	0.57	0.54	0.35	0.50
Boundary	0.62	0.57	0.54	0.43	0.48
Yukon River	0.50	0.50	0.36	0.23	0.29
Fortymile River	0.49	0.23	0.36	0.37	0.37
Healy River	0.43	0.43	0.52	0.50	0.37
Salcha River	0.35	0.31	0.36	0.40	0.40
Bear Creek	0.40	0.37	0.39	0.39	0.36

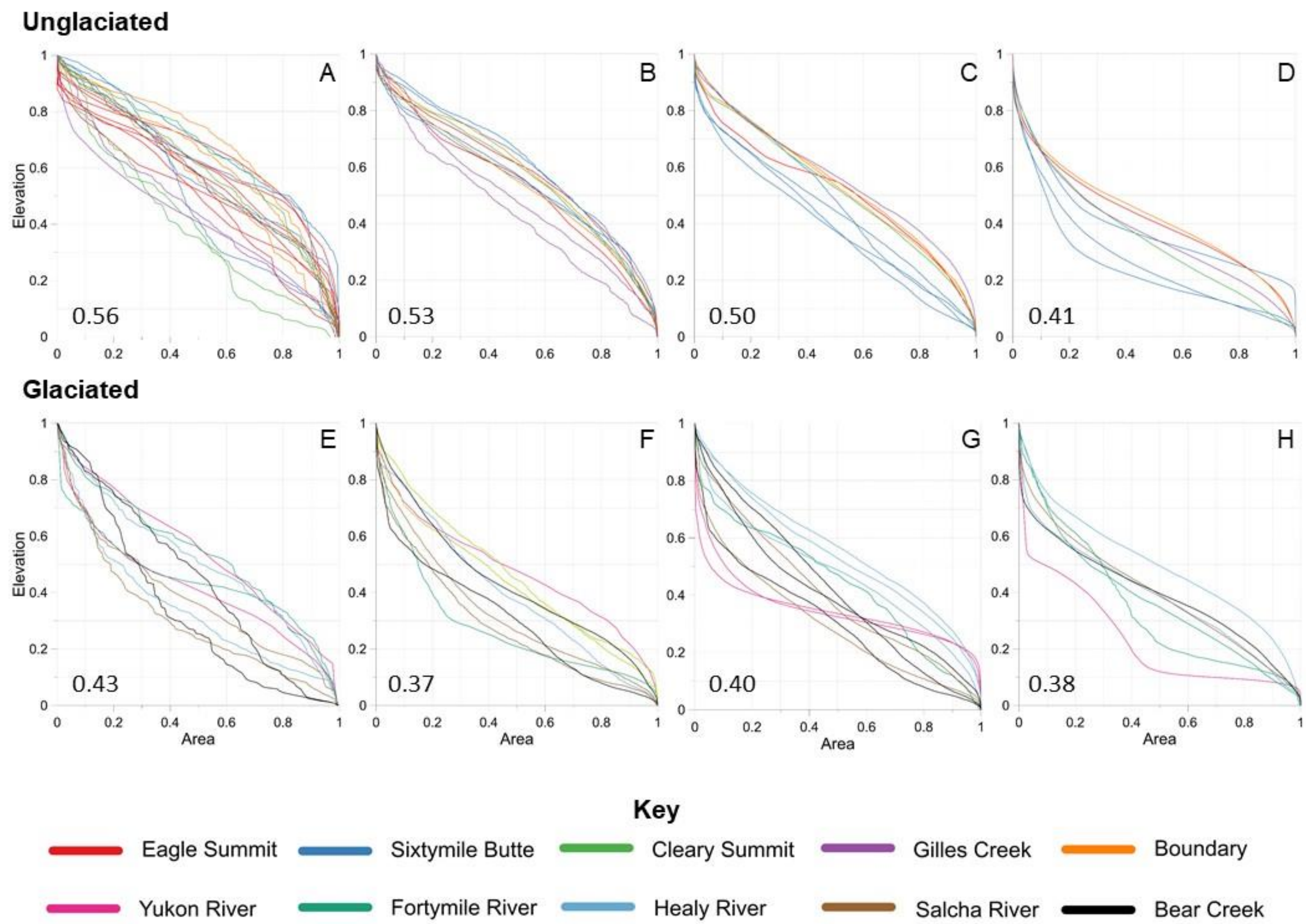

Figure 4.3. Hypsometric curves for Yukon-Tanana Upland study sites: *The top panel shows the unglaciated sites, while the bottom panels shows hypsometric curves for the glaciated sites within the YTU. Individual basin morphology and hypsometric curves are shown in Appendix. Mean elevation relief ratio is indicated in the lower left of each graph.*

The form of hypsometric curves is highly scale dependent and change as a result of the size of the watershed under consideration. Upward convexity is reflective of hillslope mass wasting processes, while upward concavity indicates dominance by fluvial processes (Willgoose and Hancock 1998 p. 621). At the local scale (smallest watersheds), the curves are slightly convex, with flat segments ("benching") in the middle (Figure 4.3 and individual graphs in Appendix). These flat areas are likely to be indications of the presence of flat benches, possibly cryoplanation terraces, although these phenomena also occur in other environments (e.g., El Hamdouni et al. 2008) and are worthy of further analysis to determine the nature of this artifact.

As basin size increases, curves for some of the watersheds in unglaciated terrain become increasingly concave-upward and smooth out, while most retain convexity. At the 1,000 watershed size (Figure 4.3B), the curves are tightly clustered and show pronounced upward convexity. This is in distinct contrast to the curves representing the watersheds developed in glaciated terrain, which again are tightly clustered but show pronounced upward concavity. HI values reflect this disparity between glaciated and unglaciated terrain at this scale (Table 4.3). These characteristics indicate that this scale may be most appropriate for further investigation, although these contrasts are retained at the 10,000 watershed size. At the scale of the entire Yukon-Tanana Upland, the curve is highly concave upward, resembling what Strahler (1952) would have called an old age landscape (Appendix, Figure B4).

4.3.2 Hypsometric analysis of the Basin and Range: To address the concerns of French (2016), the methods used in the YTU were applied to terrain in a warm desert environment of the Basin and Range region of Nevada, USA (Figure 4.4). The Basin and Range study area is bounded by the 117th meridian in the east, as identified by Dohrenwend (1984). The rest of the study area contains multiple sites where Dohrenwend (1984) identified numerous small nivation hollows. Size of the study area was chosen to incorporate the range of elevations from valley bottom to mountain top. Decreasing watershed areas were calculated in GRASS using the r. watershed tool, with threshold values of 10^6, 10^5, 10^4, and 10^3. Five randomly selected sites were used as study sites, with the ERR and hypsometric curve calculated for each watershed size. For the smallest watershed (threshold of 1,000) two additional study sites were selected.

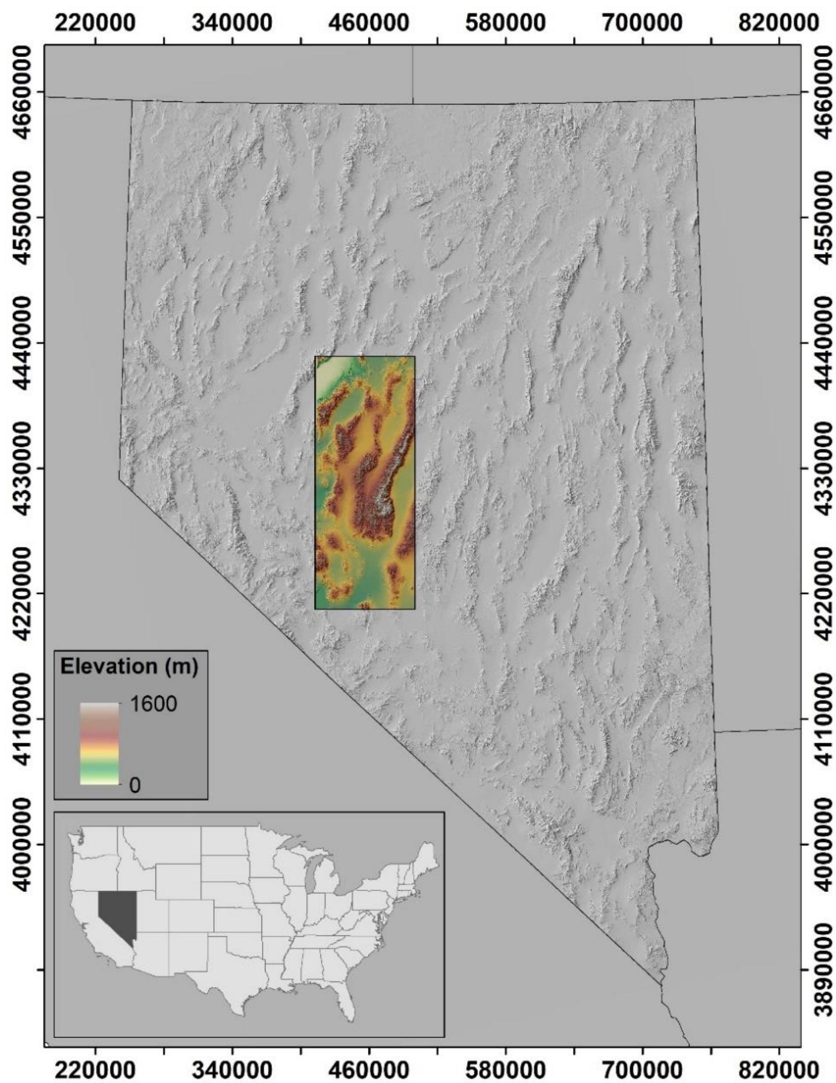

Figure 4.4. Map of Basin and Range study area, NV: *Coordinates are given in NAD 1983 UTM Zone 11N.*

The Basin and Range region (Thornbury 1965, Chapter 24) is climatically very different from the study sites in Alaska. Although the higher peaks in the region were once glaciated, in general the region has remained unglaciated and is largely a warm desert environment (Dohrenwend 1984). This environment provides an ideal contrast to the Yukon-Tanana Upland.

Across watershed scales, the hypsometric integral again decreased with increasing basin size (Figure 4.5, Appendix Figures A14-A17). In the Basin and Range, however, the decrease was not as drastic as it was in the Yukon-Tanana Upland. The smallest watershed has an average ERR of 0.46, less than that of the Yukon-Tanana Upland. The ERR for the largest basin was 0.29, similar to that of the periglacial region, and again reflecting the dominance of fluvial processes. Local hypsometric curves for the Basin and Range area showed a different character from those of the Yukon-Tanana Upland (Figure 4.5). With one exception, the hypsometric curves for the Basin and Range were concave upward.

4.4 Conclusion

The use of hypsometric analysis for quantitative analysis of the periglacial landscape is a powerful tool. Results from this analysis allow for the comparison of watersheds between unglaciated and glaciated areas. This analysis also allows for comparison with different landscape types to identify similarities or differences.

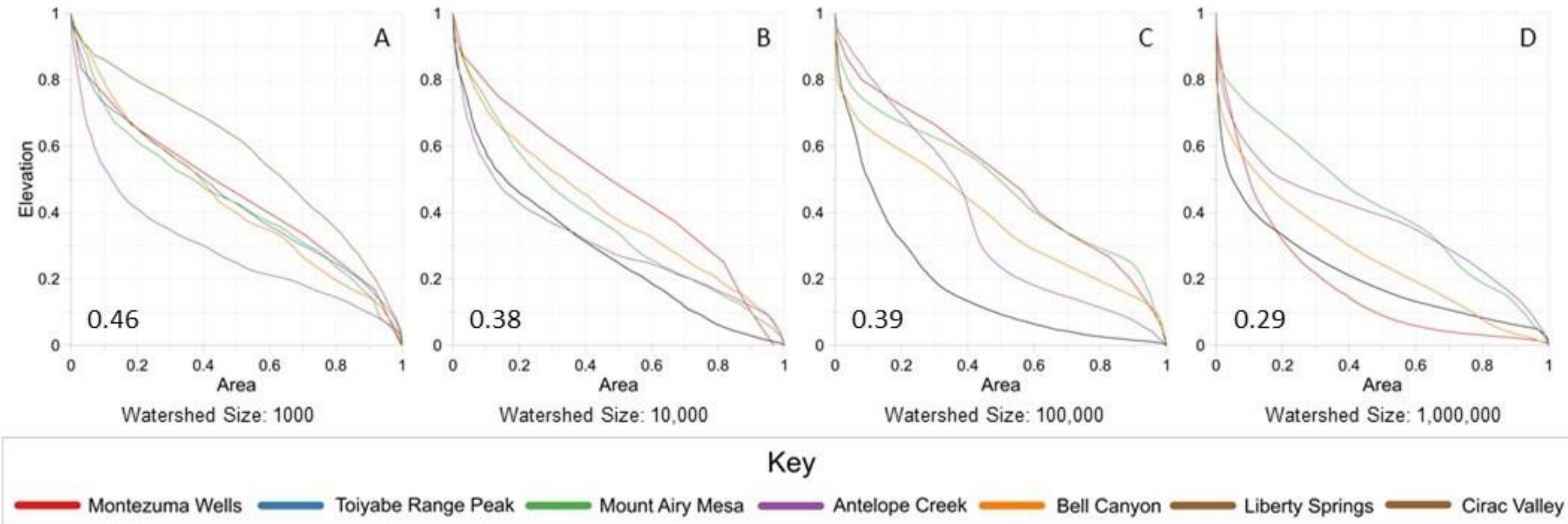

Figure 4.5. Hypsometric curves for Basin and Range study sites: *Comparison of hypsometric curves for the Basin and Range Region at varying basin sizes. Mean elevation relief ratio is indicated in the lower left of each graph.*

Comparison of the hypsometric curves between the glaciated and unglaciated watersheds of the Yukon-Tanana Upland showed differences, especially at intermediate scales. At the scale of the smallest watersheds there appears to be enough variation in the data at both the glaciated sites and the unglaciated sites that no significant trends can be identified. At the broadest scale, owing to the large river valleys throughout the YTU, the geomorphometric signature is that of a mature fluvial landscape. However, in the moderately sized watersheds, the character of the hypsometric curves is both qualitatively and quantitatively different for glaciated and unglaciated terrain. This result indicates an appropriate scale for further analysis.

Results from the analysis of the Yukon-Tanana Upland show that subareas of the YTU are experiencing what early quantitative geomorphologists would have called a youthful stage of development. These authors might have ascribed this “youthful stage” to recent uplift events. The interpretation offered here, however, is that observed ERR values in the medium-sized YTU watersheds are instead artifacts of the prolonged operation of periglacial processes.

While landscapes take long periods of time to form and few regions have undergone periglacial conditions long enough to achieve a landscape approximating Peltier’s (1950 p. 225-227) “old-age stage of the periglacial cycle.” The Yukon-Tanana Upland is, however, one of the oldest and best-developed in the periglacial realm. Despite its nearly unique character in this regard, it is clear that the YTU has not reached anything resembling the end result of the “periglacial cycle” envisioned by Peltier (1950). Indeed, because YTU has been subject to periglacial conditions primarily during Quaternary time (Birot 1968), its distinctiveness lies largely its ubiquitous unconsumed upland remnants. These upland remnants are occupied by cryoplanation terraces, which impart both the region's visual distinctiveness and its geomorphometric signature.

The contrast found between the glaciated and unglaciated areas of the YTU shows that there is a difference in character between periglacial regions and those affected by glaciation. This difference provides another indication that the periglacial landscape is distinct. It also represents an initial step in our understanding of how periglacial landscapes can be characterized quantitatively and the imprint of periglacial processes identified.

In response to French's (2016) suggestion about inherited landscapes, the hypsometry of the Basin and Range stands in distinct contrast with the Yukon-Tanana Upland. Curves generated for the Basin and Range are almost all concave, with no significant benching artifacts and lower values of the elevation-relief ratio. Dohrenwend (1984) identified a number of small nivation hollows in the upper reaches of the Basin and Range landscape. These hollows are much smaller than the cryoplanation terraces found in Alaska, explaining the lack of noticeable benching in the hypsometric curves for the Basin and Range study. The ERR for the entire Basin and Range study area is slightly lower than that of the composite Yukon-Tanana Upland.

Taken as a whole, this chapter provides another indication that there is a distinct upland periglacial landscape, with cryoplanation terraces as its foundation. However, this chapter treats only one area of general geomorphometry. The results of this analysis indicate rich potential for application of other types of general geomorphometric analysis (e.g. Evans and Cox 1974; Florinsky 2017) in periglacial terrain, especially Beringia. As an initial, exploratory step, this study can be regarded as having met with success, although much more work remains. Extensions to the work will necessarily involve improved sampling frames and consideration of other Beringian provinces.

Chapter 5

Conclusions

5.1 Summary of Research

The periglacial landscape is formed through cold climate, non-glacial processes. First coined by Lozinski (1909), the term *periglacial* was originally intended to describe those areas adjacent to Pleistocene glaciers. Since that first definition, the term has been modified to refer to all processes and areas that are part of the cold regions of the world outside of the glacial realm (French 2017). A natural consequence of this terminological expansion and the increased investigations of the cold regions of the earth have led many to deduce that there is indeed a "characteristic periglacial landscape." However, in recent years, several studies (e.g., André 2003; French and Thorn 2006; French 2016) have questioned whether there are distinct landscapes formed by periglacial processes. This skepticism has potential to undermine the discipline of periglacial geomorphology and to distract attention away from process-based studies. This thesis provides an objective assessment of this critique.

5.1.1 Large-scale geomorphological mapping: André's (2003) questioning of the existence of a distinctively periglacial landscape is based primarily on the idea that periglacial processes are not sufficiently powerful to effect landscape-scale modification. Many of the studies conducted in periglacial geomorphology are concerned primarily with the numerous small, surface periglacial landforms. André (2003) is correct that these features alone are operating on a much more local scale and are not sufficient to form a landscape, especially an erosional landscape. However, this criticism fails to take into account two important considerations: (1) that cryoplanation landforms involve entire slope sequences; and (2) that cold, nonglacial landscapes are composed of *assemblages*—small forms that, collectively, impart a striking and decidedly periglacial character to the terrain.

Chapter 2 of this thesis used large-scale geomorphological mapping to identify the components of this periglacial assemblage and to examine how cryoplanation terraces fit into that assemblage. Mapping for this project was conducted at three sites (Mount Fairplay, Eagle Summit, and Iron Creek) that together form a transect across Alaska, which comprises most of eastern Beringia. Beringia was largely unglaciated during the Pleistocene and provides one of the best opportunities to examine the concept of a periglacial landscape, owing to the relatively long period of time in which periglacial processes have operated (Birot 1968). At each site, a series of traditional surveying and terrain analysis methods were performed in order to create maps of the periglacial features present. In addition to the sites in Alaska, a high-elevation site in British Columbia was investigated in order to document features in an environment in which periglacial processes are currently active.

Geomorphological mapping revealed a repeating pattern of landforms at and between sites. Similar features (sorted stripes, sorted polygons, solifluction lobes, tundra vegetation, cryoplanation terraces, etc.) were found at all of the sites. Not only were similar features found at all sites, but the spatial arrangement of these features followed a pattern in relation to cryoplanation terraces. This arrangement is well described as an assemblage of periglacial features that interact to form a geomorphically integrated landscape. It is through this interaction that large features such as cryoplanation terraces are able to form, showing that the form communities span a range of geographic scale. This repeating pattern indicates that these features are interacting and that together they can affect landscape-scale geomorphic change.

5.1.2 *Specific periglacial geomorphometry:* Geomorphometric analysis has been conducted in one way or another for hundreds of years. As a formal subdiscipline of geomorphology, however, it is relatively young and has experienced accelerated growth since the digital revolution (Pike, Evans, and Hengl 2009). The use of geomorphometry in landscape and landform analysis has been integral to the understanding of a variety of different geomorphic subfields. Many studies have used geomorphometry in fluvial, glacial, and mountain landscapes, but very few studies have applied geomorphometric methods to periglacial problems. The need for a subfield of *periglacial geomorphometry is* necessary to strengthen theoretical and methodological ties between periglacial geomorphology and the parent discipline.

Specific geomorphometry is concerned with discrete landforms and is often used to identify landforms (Evans 1987). Chapter 3 uses specific geomorphometric methods to provide an objective, semi-automated means by which to identify cryoplanation terraces. Parametrization of cryoplanation terraces and the use of these parameters to identify the location of CTs complements the methods used in Chapter 2 to examine the concept of a distinctive periglacial landscape. Cryoplanation terraces form the “foundation” or base of the periglacial assemblage. Specific geomorphometric analysis for this thesis used the two-meter resolution Arctic DEM to identify terrain parameters that can be used to identify the locations of cryoplanation terraces. The final semi-automated algorithm for identifying CTs on the landscape used contrasting slope facets as the primary identification parameter. The accuracy of the algorithm was assessed by comparing its output with an extensive dataset produced by more traditional map and air photo interpretation (Reger 1975). The accuracy assessment showed a high degree of agreement between the two methods of CT identification.

Findings from this analysis confirm that cryoplanation terraces are ubiquitous in largely unglaciated upland periglacial regions. The findings show that at every study site, they ascend ridgetops and that nearly all of the hill- and ridgetops are summit-type CTs. In concert with the data from large-scale mapping, this sequence demonstrates that the "foundation" of the periglacial assemblage extends across eastern Beringia.

5.1.3 General periglacial geomorphometry: General geomorphometry is concerned with the continuous land surface and is useful for identifying geomorphic "signatures." Given the question of whether there is a distinctively periglacial landscape, a general geomorphometric investigation is a necessary component of the analysis. In Chapter 4, hypsometric analysis was used to compare periglacial, glacial, and warm desert landscapes and to discern morphological differences between them.

Hypsometric analysis was pioneered by Strahler (1952) and has since seen numerous applications in geomorphology. This analysis proceeded from a deduction that, owing to the extensive flat-crested ridges and hills in Beringian, characteristic hypsometric curves and values of the hypsometric integral will result. Because a relatively large proportion of the terrain exists at higher elevations, the hypsometric curve should be convex upward, and the associated integral should be relatively high (above 0.5). In contrast, glaciated landscapes should have more area at lower elevations, with concave hypsometric curves and relatively low values of the hypsometric integral.

Hypsometric analysis was conducted primarily in the Yukon-Tanana Upland, an extensive area in eastern Beringia, in which cryoplanation terraces abound. This analysis used several of Reger's (1975) local map areas in which to perform hypsometric analysis. Two of the sites, Eagle Summit and Mount Fairplay, were also used for large-scale mapping (Chapter 2). Contrasting glaciated areas within the Yukon-Tanana Upland were identified from Péwé, Burbank, and Mayo (1967).

Watersheds of varying sizes were calculated from a DEM. Threshold values, corresponding to upstream contributing area, were chosen that increase in size by powers of 10 from 100 to 1,000,000. For each watershed centered on the study sites and at each watershed scale the elevation and area were extracted. From these data, the elevation-relief ratio (ERR) of Pike and Wilson (1971) was calculated and the hypsometric curves plotted. This same process was used for both unglaciated and glaciated sites allowing for the comparison of hypsometric curves. Based on French's (2016) assertion that cryoplanation landforms may be residual warm desert landforms, the hypsometric analysis was conducted for an area in the Basin and Range Province of southwestern USA.

Results from the general geomorphometric analysis provide the necessary quantitative characterization of the periglacial landscape. As the scale of the watersheds became more localized, the hypsometric curves became increasingly convex and the associated integrals increased. Information in the hypsometric integral increased with localization. Significant benching could be seen in the curves, which is interpreted to be the result of terraces on the landscape. When the comparison with the glaciated landscapes was done, the associated integrals showed significant differences. This difference is best shown at the 1,000 basin sizes

(~1 km^2). At this scale, the glacial landscapes had lower integrals than those of the unglaciated landscapes, and their hypsometric curves were more concave-upward. The comparison with watersheds in the Basin and Range region showed that there are substantial differences between the two landscapes. The trend of decreasing integrals and curves was seen in this region as well, although the decrease was not as sharp as those observed in the Alaskan periglacial landscapes. This comparison is, however, only an initial exploratory step, and further analysis is necessary to unambiguously identify differences between the two landscape types.

5.2 Is There a Distinctly Periglacial Landscape?

André (2003) was among the first to express skepticism about the existence of a distinctively periglacial landscape by questioning the geomorphic effectiveness of small surficial periglacial forms. André (2003) provided a well-thought-out argument that disputed the existence of periglacial landscapes. However, the work fell into a pitfall typical of contemporary periglacial geomorphology: it focused narrowly on specific small landforms. Many of the studies conducted in periglacial geomorphology in North America are focused on specific landforms. Interconnections between units of the landscape are rarely discussed. The periglacial form community concept was popular in the German language literature into the 1980s but, ironically, diminished just as the rise of geographic information science (e.g., Goodchild 1992) could have led to great progress in the field. This work has largely been ignored in English-language literature. A broader focus that identifies interconnections between periglacial features would allow for a more thoroughly integrated geomorphology. The idea of an integrated periglacial geomorphology would address André's (2003) concerns by identifying how the smaller forms often observed can coalesce to form a distinct landscape.

The concerns of French (2016) are primarily related to his objections to standard narratives depicting cryoplanation terraces and cryopediments as having been formed through periglacial processes. This thesis identifies cryoplanation terraces as the foundation for the periglacial landscape assemblage, a finding that contradicts French's assertions.

Since Cairnes (1912) first postulated a link between CT-like features and nivation, a great deal of evidence (e.g., Demek 1969; Reger 1975; Nelson 1989, 1998) has indicated a link between CTs and climate. After several decades of often speculative critique (see Thorn and Hall 2002) that has increased skepticism about the notion that nivation plays a significant role in CT genesis, fresh evidence supporting the validity of the nivation hypothesis of cryoplanation terrace formation is accumulating (e.g., Nelson and Nyland 2017). Such evidence could lead to cryoplanation terraces soon being viewed as unambiguously periglacial by most geomorphologists. This thesis provides additional evidence in support of the nivation hypothesis, in the form of large-scale maps that link the active nivation process and the cryoplanation terraces found throughout unglaciated eastern Beringia. The processes documented at Frost Ridge are forming incipient terraces that resemble the larger and presumably more mature terraces in central Alaska. Together, this growing collection of evidence indicates a climatic origin for CTs.

The question of what constitutes a landscape is a complicated one. French (2016) and André (2003) conclude that there is not a characteristic periglacial landscape, but their conception of "landscape" is unknown. Neither study provided an explicit definition of the term. It is a given that the formation of a landscape requires long intervals of geological time, which are unusual in the periglacial realm. Many contemporary periglacial regions have only recently been affected by periglacial processes, and insufficient time has elapsed for periglacial processes to have had substantial effects on landscape development. However, if there is an extensive and distinct periglacial landscape, it is almost certainly in Beringia (Birot 1968). Even so, because periglacial processes have been active in Beringia only since the beginning of the Quaternary (~ 1.8 million years), this landscape may be relatively young. Stated in Davisian terms, any postulated cycle of cryoplanation (Peltier 1950; Demek 1969) has not reached completion in many locations. However, there is a distinct character to upland Beringia, and at the mesoscale (1-10 km^2), this region constitutes a periglacial landscape. Evidence for this character has been presented in this thesis in the form of a repeating pattern of interacting features that, together, comprise a morphologically distinctive assemblage. The combination of the assemblage and the signatures found through geomorphometric analysis convincingly demonstrates that there is a distinct character to the landscape. The key to understanding the periglacial landscape lies in the recognition that cryoplanation terraces form the foundation of a multiscale assemblage. The answer to the question of whether this region constitutes a periglacial landscape is a resounding "yes" at the scale of cryoplanation terraces and individual mountains, but at regional scales exploratory hypsometric analysis indicates a less definitive answer is appropriate. Scale dependence is not uncommon in geomorphic work (Phillips 2004; Rasemann et al. 2004; Hurtrez, Sol, and Lucaseau 1999), and at regional and subcontinental scales Beringia is best characterized as polygenetic.

5.3 Recommendations for Future Work

Continuation of this work would be useful for furthering our collective understanding about the place of cryoplanation terraces in mainstream periglacial geomorphology and contradicts those who challenge the concept of a “characteristic periglacial landscape.” Arising from this analysis are several avenues for future work that follow the general themes of this thesis: (1) geomorphological mapping; (2) periglacial geomorphometry; and (3) refined definition of the periglacial landscape.

5.3.1 Geomorphological mapping: Continuation of geomorphological mapping will provide further insight into the nature of the periglacial assemblage. The first step in this mapping effort would be to increase the sample size of periglacial features identified on terrace treads. Metrics on the size, shape, and morphology of the features are highly useful and an increased number would provide the ability to quantify the parameters of the assemblage.

With the increased availability of remotely sensed imagery, particularly that obtained from unmanned aerial vehicles and small satellite technology, much of this mapping could be done inexpensively, at high resolution, and over extensive areas. Ground truthing of remote sensing data using rigorous sampling frameworks would allow for thorough evaluation of this work and would facilitate the creation of a wide range of large-scale maps of periglacial assemblages.

5.3.2 Specific periglacial geomorphometry: Periglacial geomorphometry has great potential to address the research questions of periglacial geomorphologists. While the algorithm explored in this thesis achieved success, further refinement would help to reduce errors and potentially create a fully automated algorithm. This refinement might use additional terrain analysis to further filter out areas where CTs are absent or to identify the precise locations of scarp-tread junctions.

The algorithm proposed in this thesis was necessarily tested at a relatively small number of sites. Given the imminent prospect of full coverage of Beringia by the Arctic DEM, these procedures can soon be applied to much larger areas. The algorithm could be applied to a large region, such as the Yukon-Tanana Upland, as a way to identify the periglacial nature of that area and to identify those locations where CTs are ubiquitous in the landscape. By applying the algorithm over a larger area, the boundaries of the periglacial landscape could be defined.

5.3.3 General periglacial geomorphometry: The hypsometric analysis performed here demonstrates that a morphometric "signature" exists in terrain subject to erosion under periglacial conditions and provides good indication of differences between glacial and periglacial landscapes at certain scales. Additional work to provide a large sample size for statistical analysis would be beneficial for this comparison. Once concrete, quantifiable differences are identified, these can be used, in conjunction with spatial-analytic methods, to predict the locations of areas in which "periglacial erosion" has been substantial.

One particularly interesting avenue for further analysis was postulated by Mertie (1937). In his travels through the Yukon-Tanana Upland, Mertie (1937) suggested that if all the flat-topped ridges were connected they would form a gently sloping elevated plain extending from east to west. Mertie also explicitly linked this surface with nivation and altiplanation (cryoplanation). Nelson and Nyland (2017) noted that the elevation trends of CTs in eastern Beringia follow a similar trend, rising from the Bering Sea to the Alaska-Yukon border. The consistency of these observations indicates that Mertie's surmise may well be correct. This type of analysis would provide an interesting and possibly definitive theoretical study.

5.3.4 Cryoplanation terraces: As the foundation of the periglacial landscape, it is important to understand the genesis of cryoplanation terraces. Further investigations of cryoplanation terraces to understand how they form are necessary. Process-based investigations of nivation processes and their relation to the periglacial assemblage are essential for understanding how CTs relate to the broader periglacial landscape. Further work at sites such as Frost Ridge, where periglacial processes are highly active, would provide a useful juxtaposition with the older dormant terraces in Alaska. Understanding the age of terraces and the length of time they take to form would provide an indication of the amount of time the periglacial landscape has been forming. If an understanding of the time CTs take to form can be achieved, these features could bolster the notion of the "characteristic upland periglacial landscape."

APPENDIX

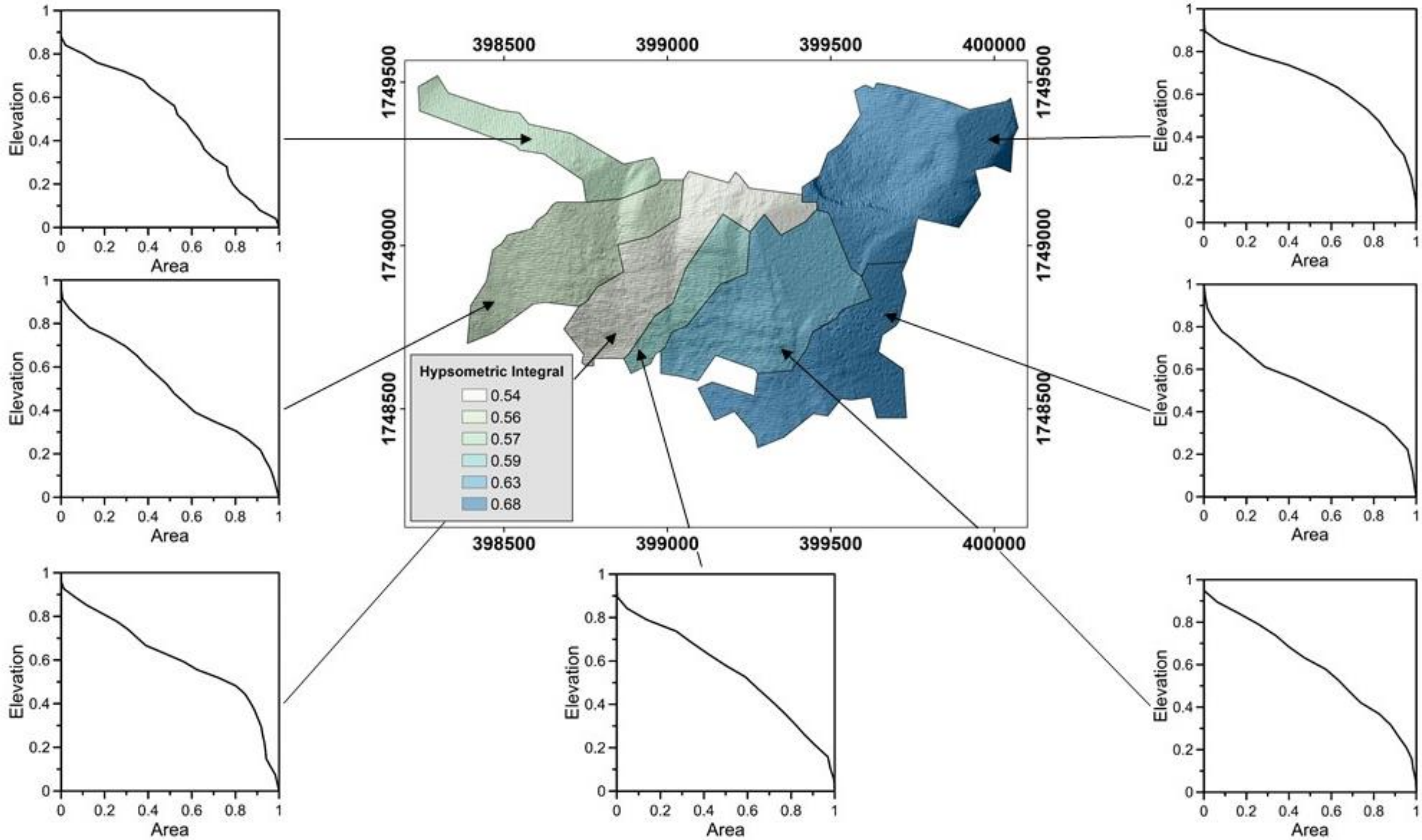

***Figure A1**. **Hypsometric curves and integrals for 100 watershed size at Eagle Summit, AK:** The Hypsometric Integrals are shaded in the map and the resulting hypsometric curves for the watersheds outline the map. Coordinates on the map are from UTM Zone 6N.*

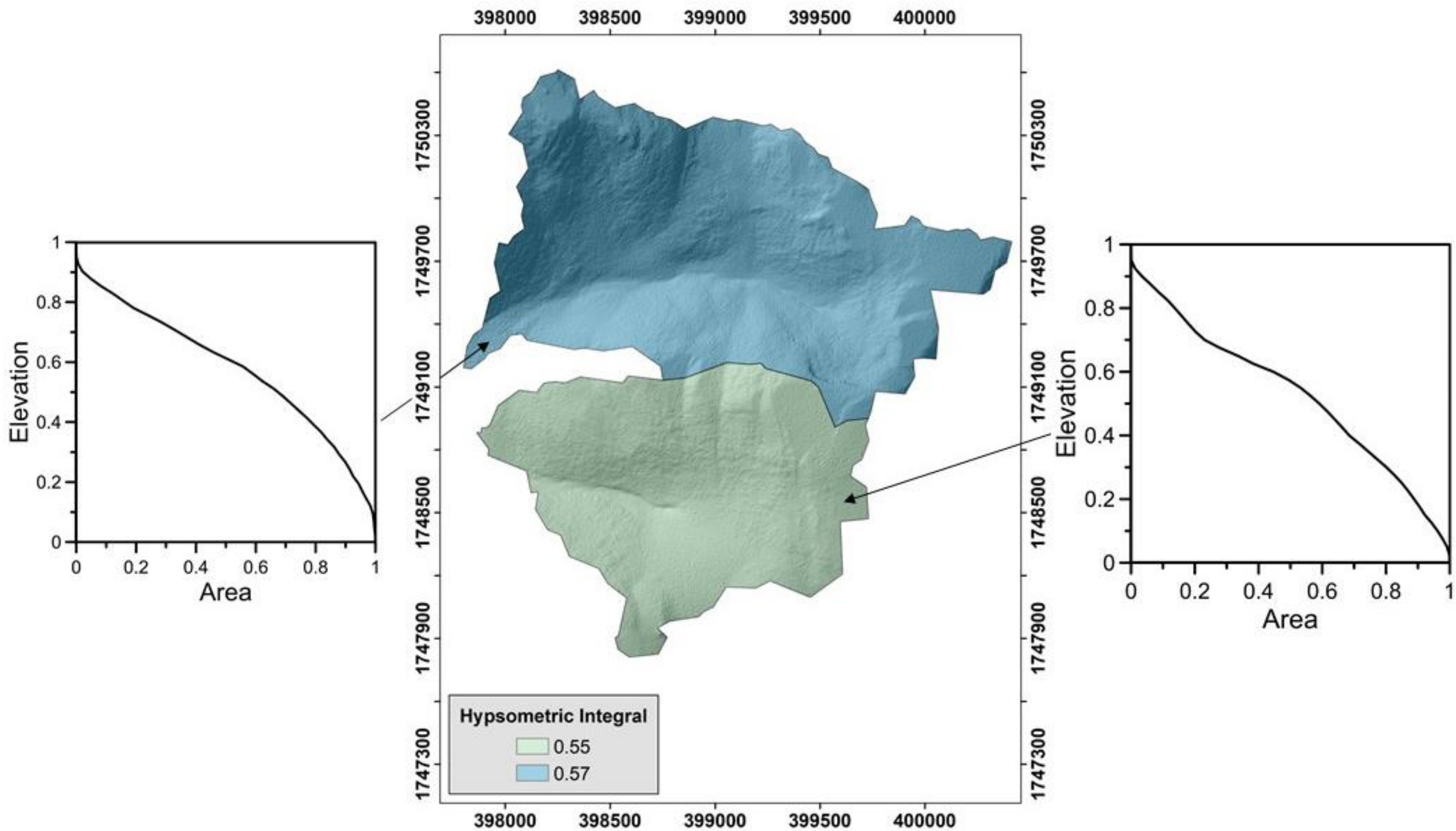

Figure A2**. **Hypsometric curves and integrals for 1,000 watershed size at Eagle Summit, AK: *The Hypsometric Integrals are shaded in the map and the resulting hypsometric curves for the watersheds outline the map. Coordinates on the map are from UTM Zone 6N.*

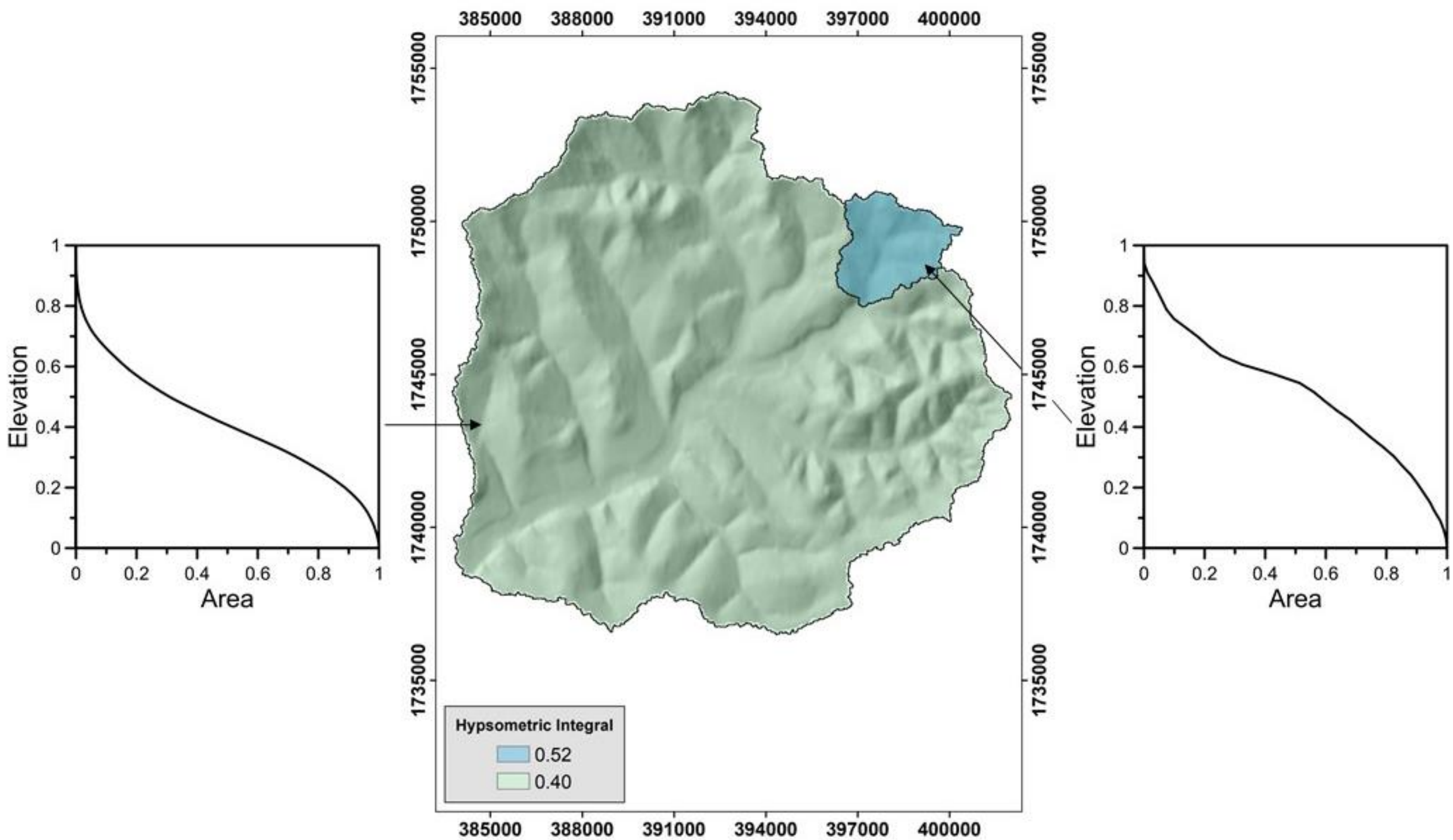

Figure A3*. *Hypsometric curves and integrals for 10,000 and 100,000 watershed sizes at Eagle Summit, AK: *Hypsometric integral for the watershed thresholds of 10,000 (blue) and 100,000 (green) with the resulting hypsometric curves on the outside. This region is centered on Eagle Summit.*

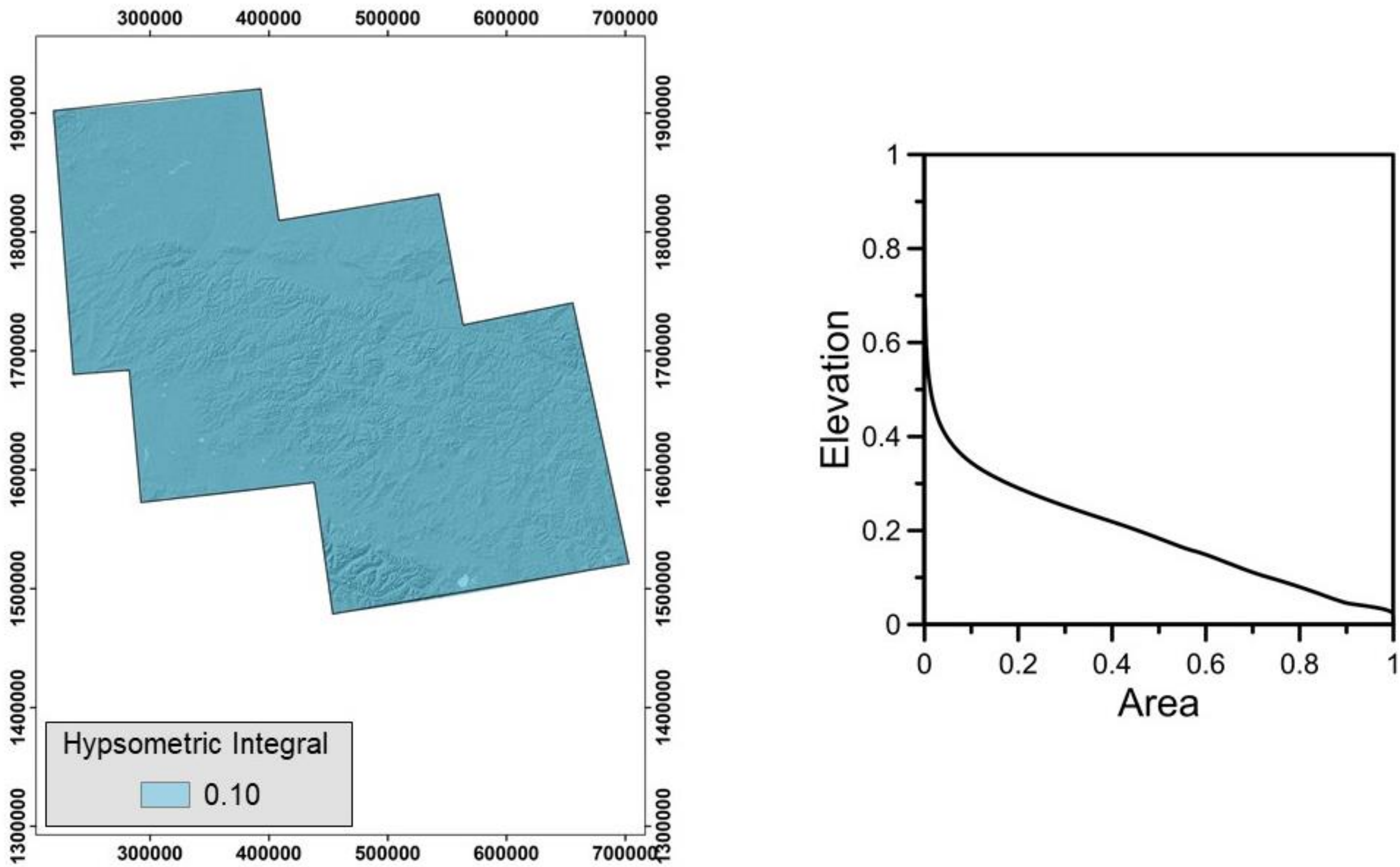

Figure A4*. *Hypsometric curve and integral for entire Yukon-Tanana Upland: *Coordinates on the map are in meters.*

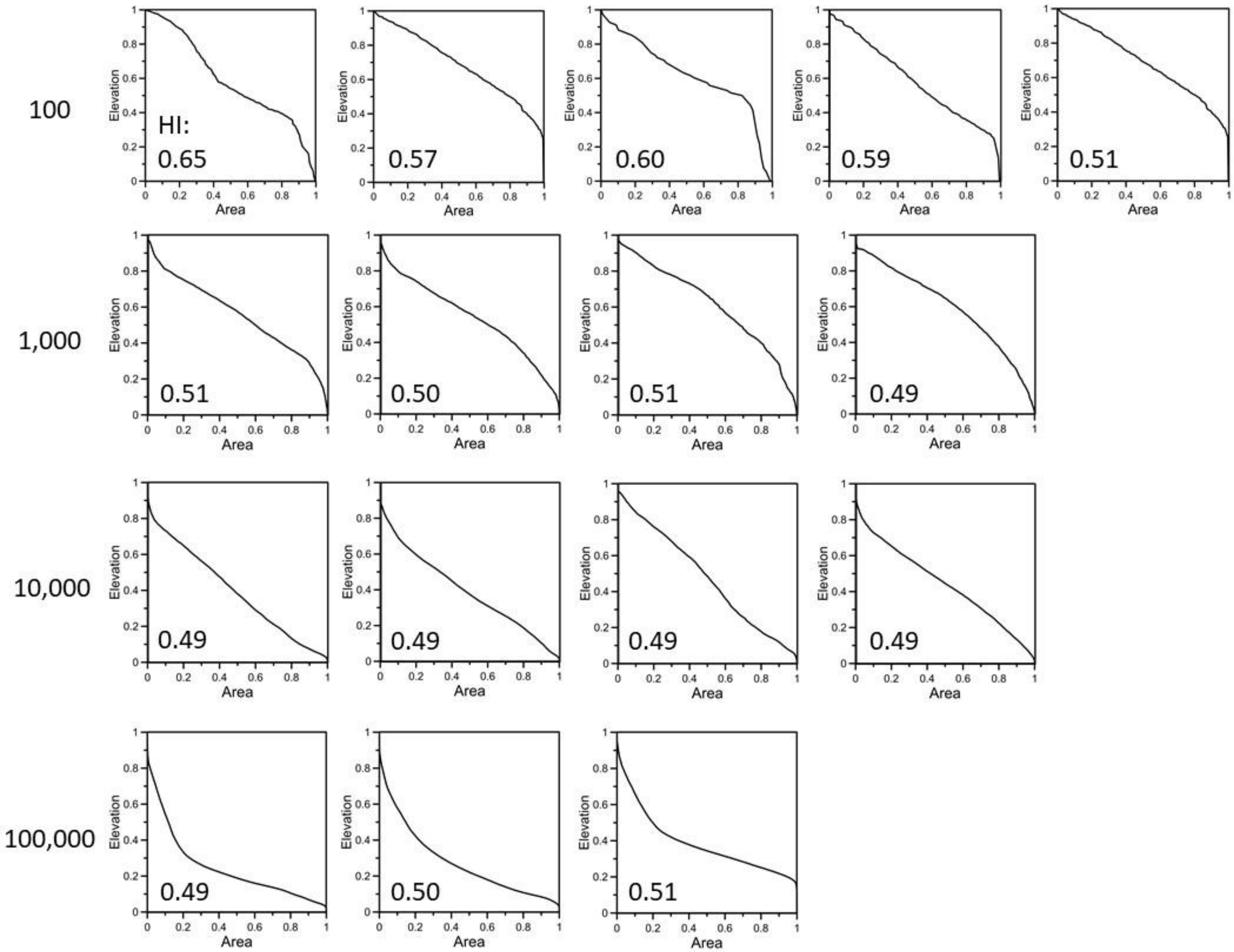

Figure A5. Hypsometric curves and integral for Sixtymile Butte, AK: *The numbers on the left indicate watershed size.*

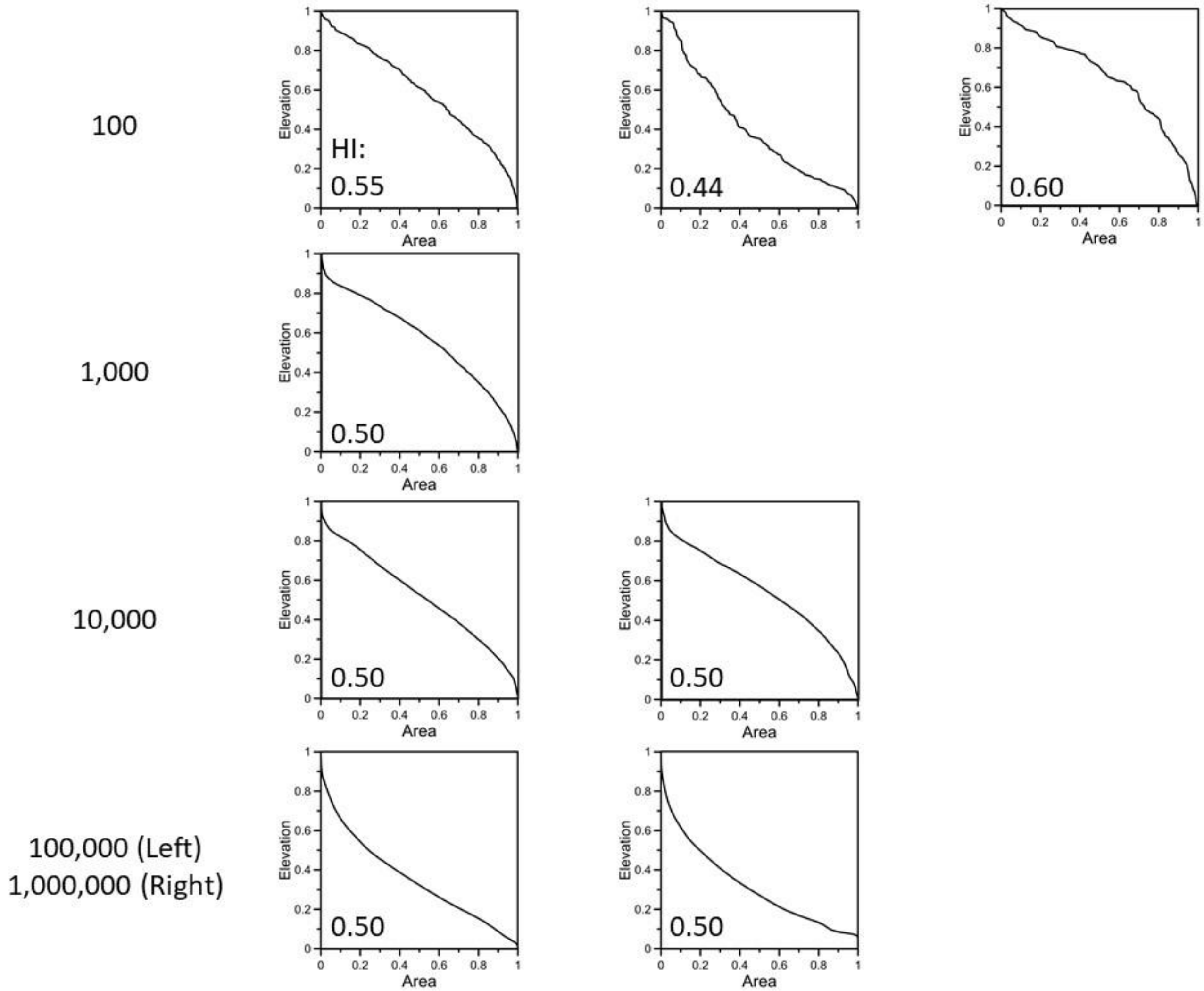

Figure A6. Hypsometric curves and integral for Cleary Summit, AK: *The numbers on the left indicate watershed size.*

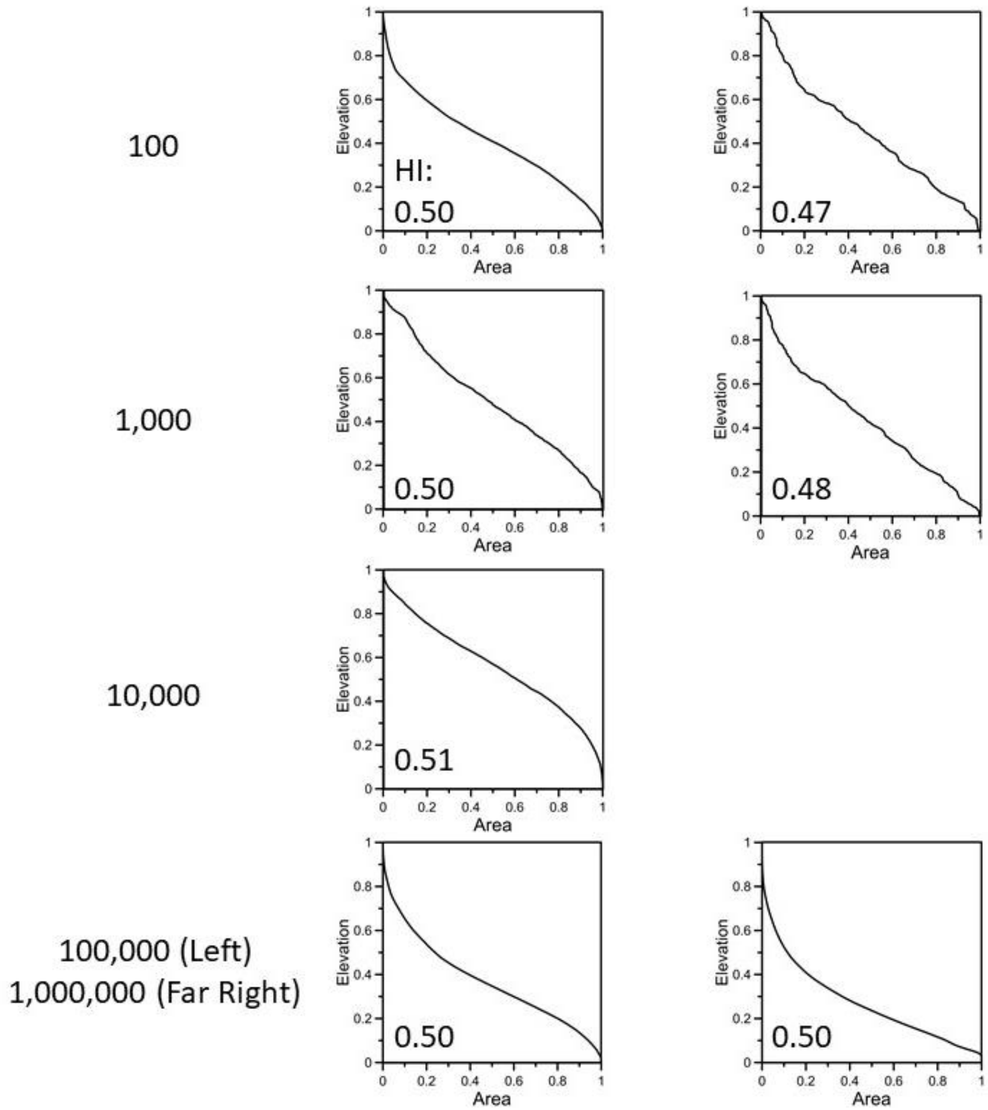

Figure A7. Hypsometric curves and integral for Gilles Creek, AK: *The numbers on the left indicate watershed size.*

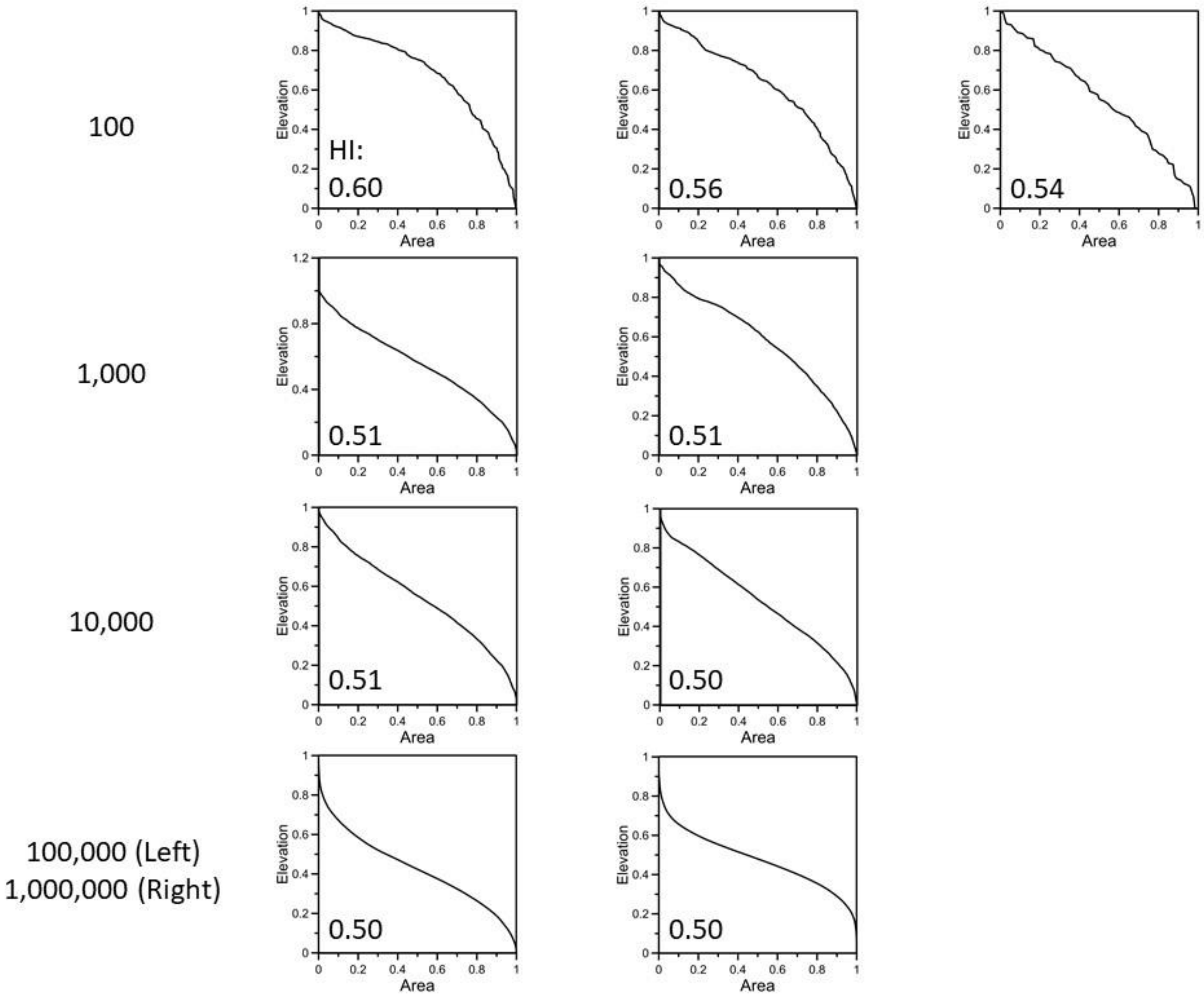

Figure A8. Hypsometric curves and integral for Boundary, AK and Yukon Territory: *The numbers on the left indicate watershed size.*

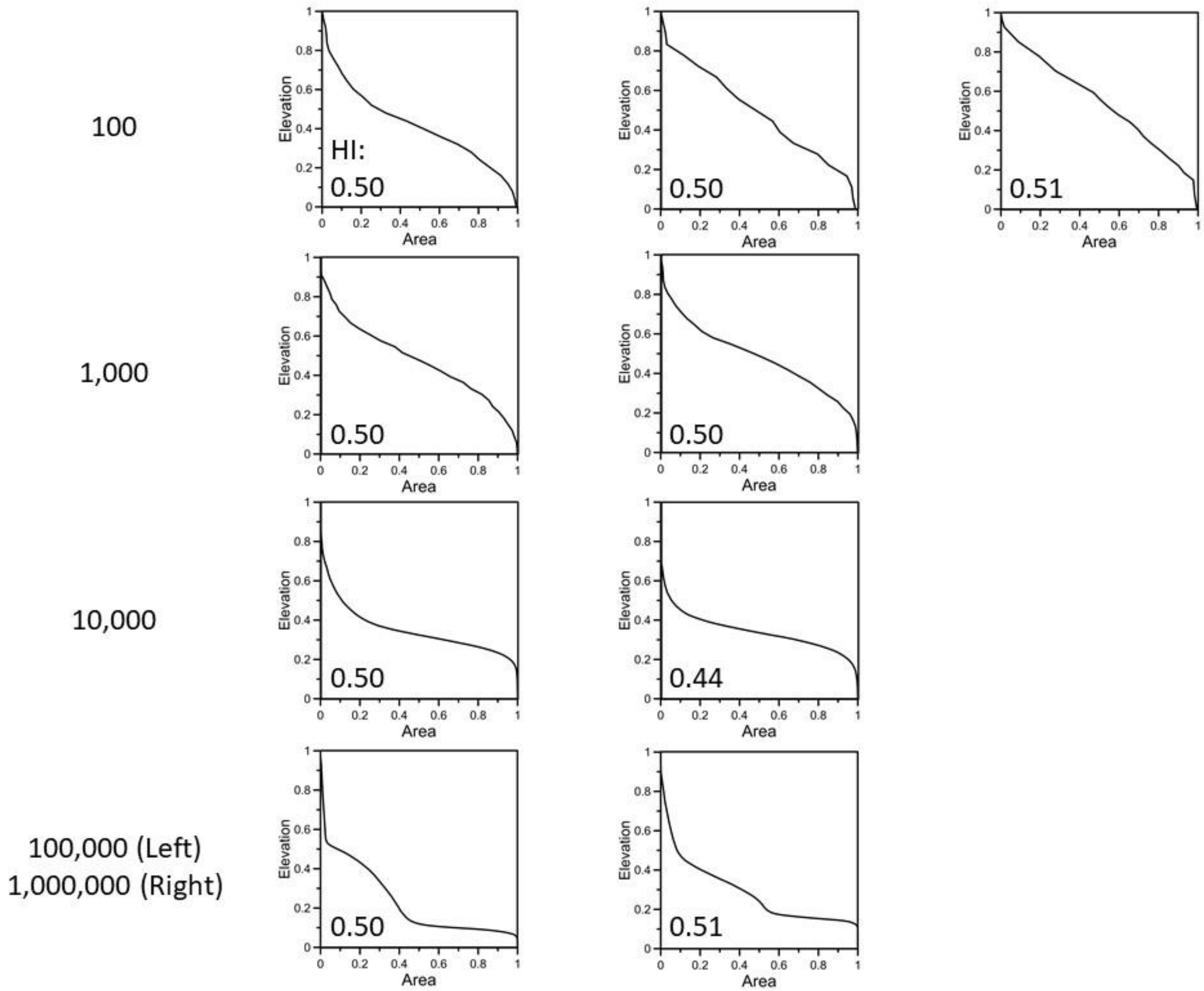

Figure A9. Hypsometric curves and integral for the glaciated site at Yukon River: *The numbers on the left indicate watershed size.*

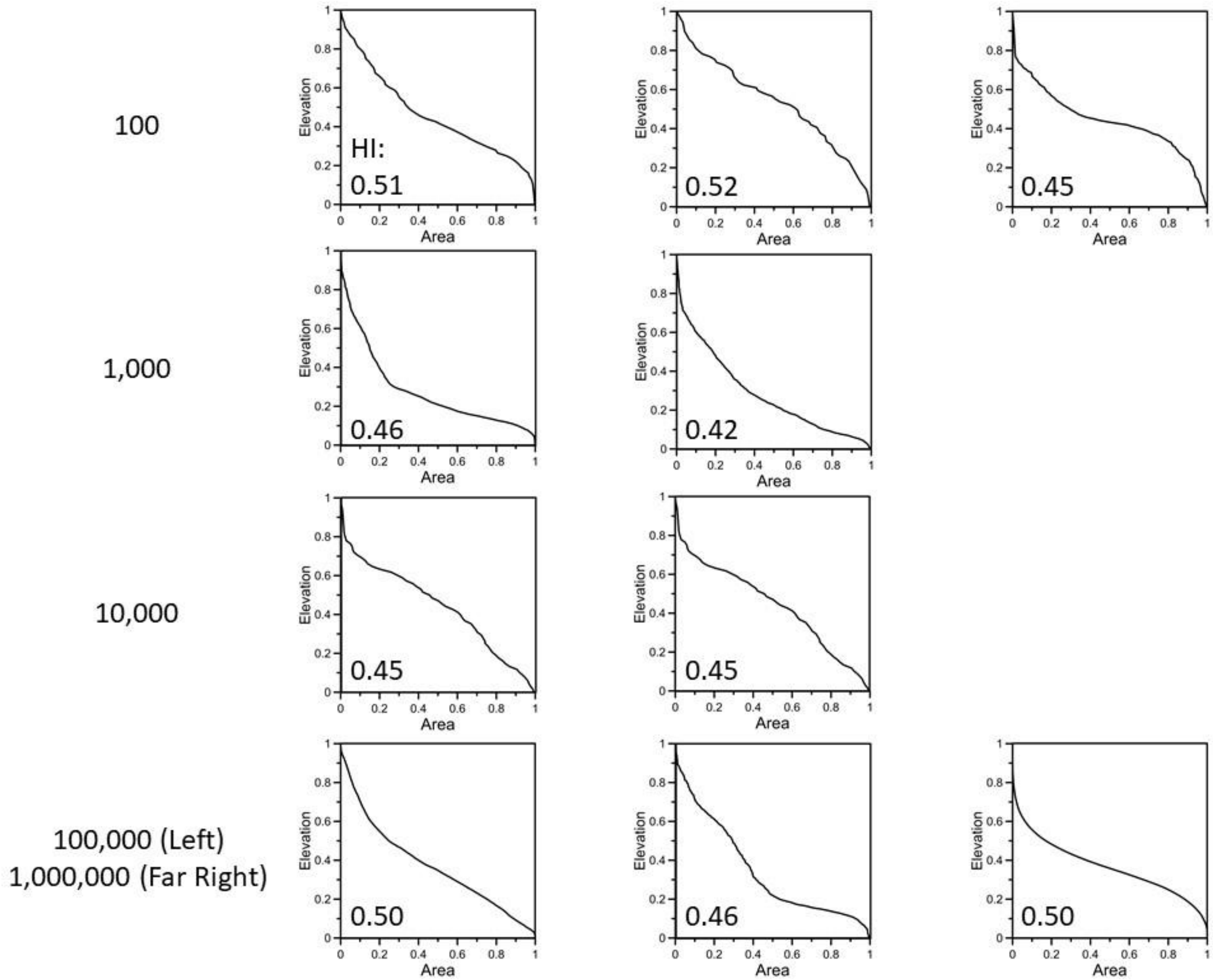

Figure A10. Hypsometric curves and integral for glaciated site at Fortymile River: *The numbers on the left indicate watershed size.*

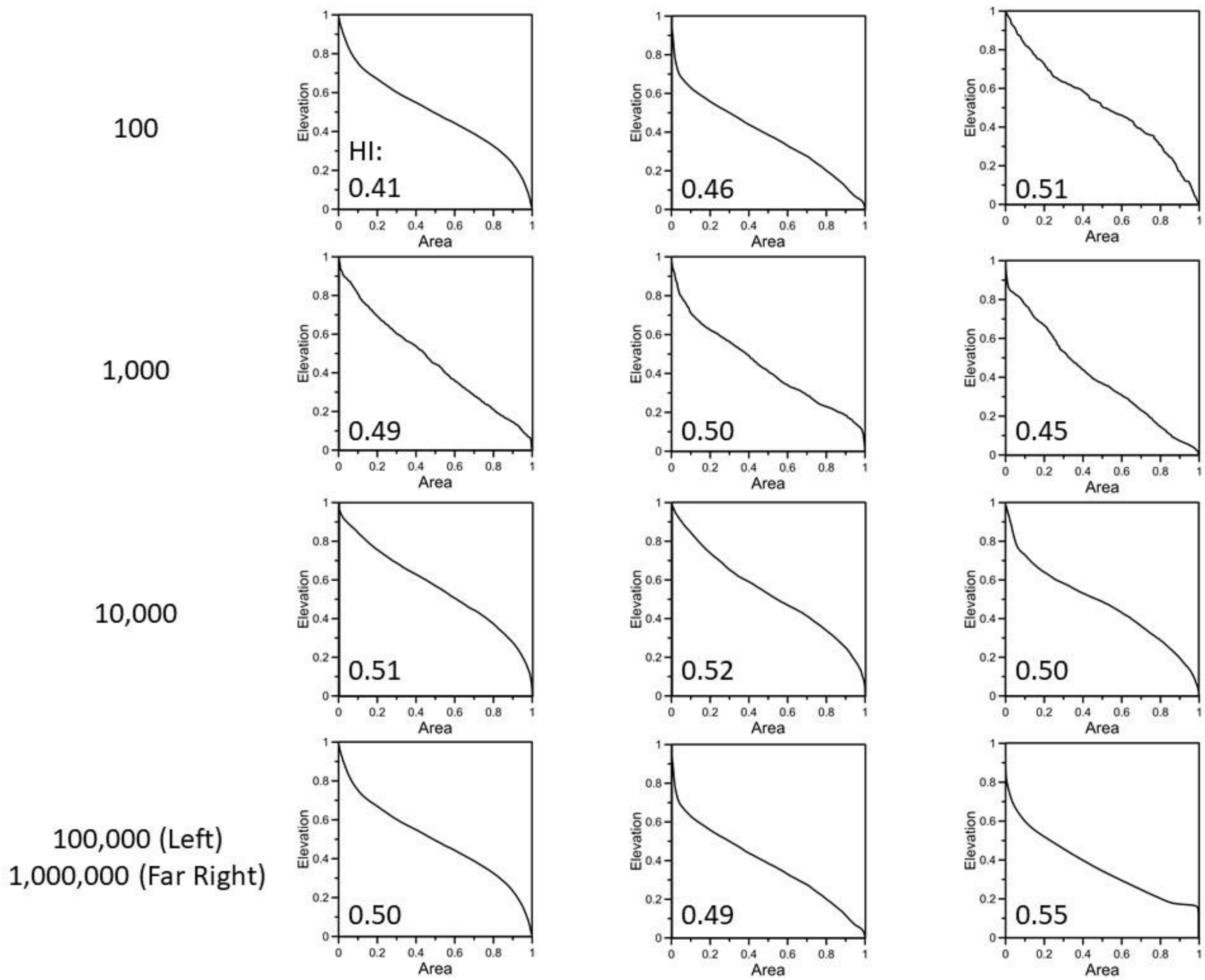

Figure A11. Hypsometric curves and integral for glaciated site at Healy River: *The numbers on the left indicate watershed size.*

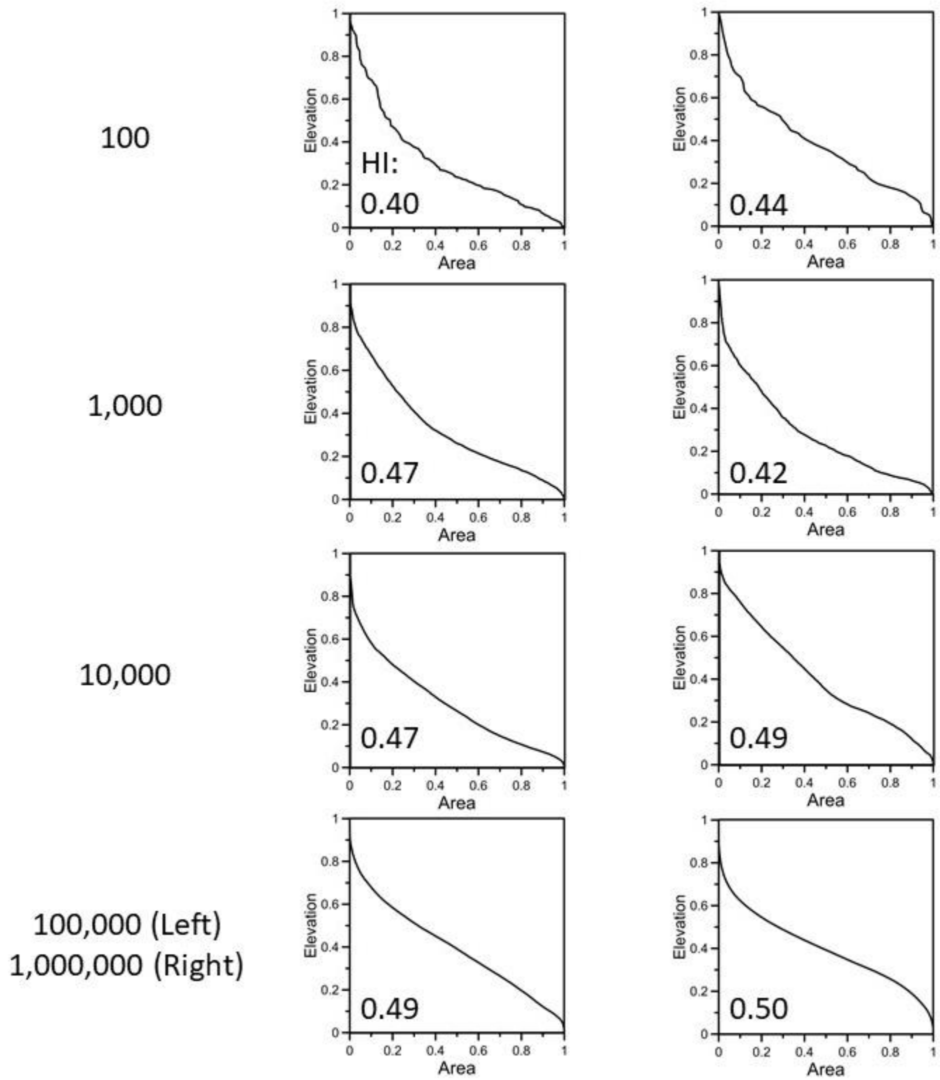

Figure A12. Hypsometric curves and integral for glaciated site at Salcha River: *The numbers on the left indicate watershed size.*

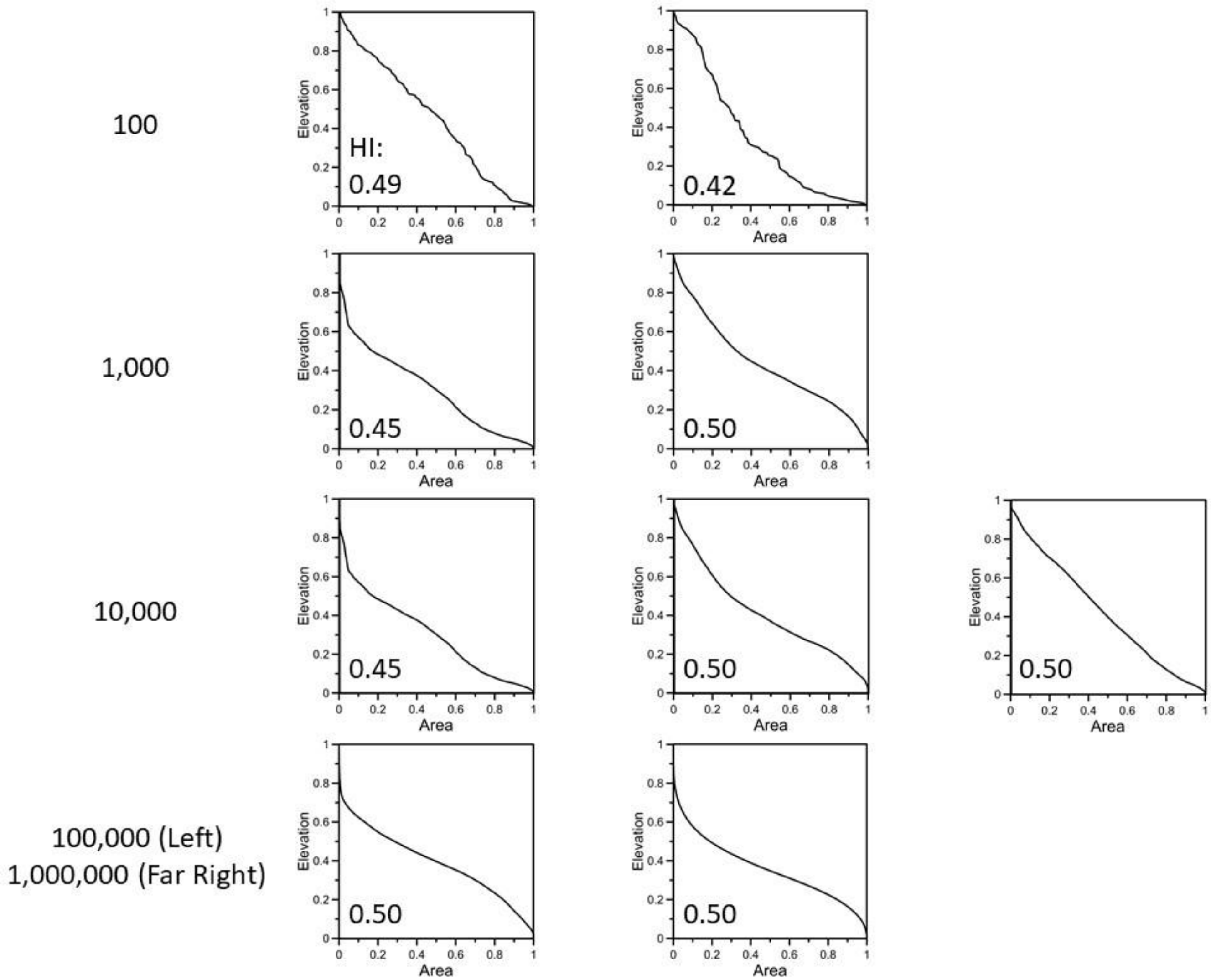

Figure A13. Hypsometric curves and integral for glaciated site at Bear Creek: *The numbers on the left indicate watershed size.*

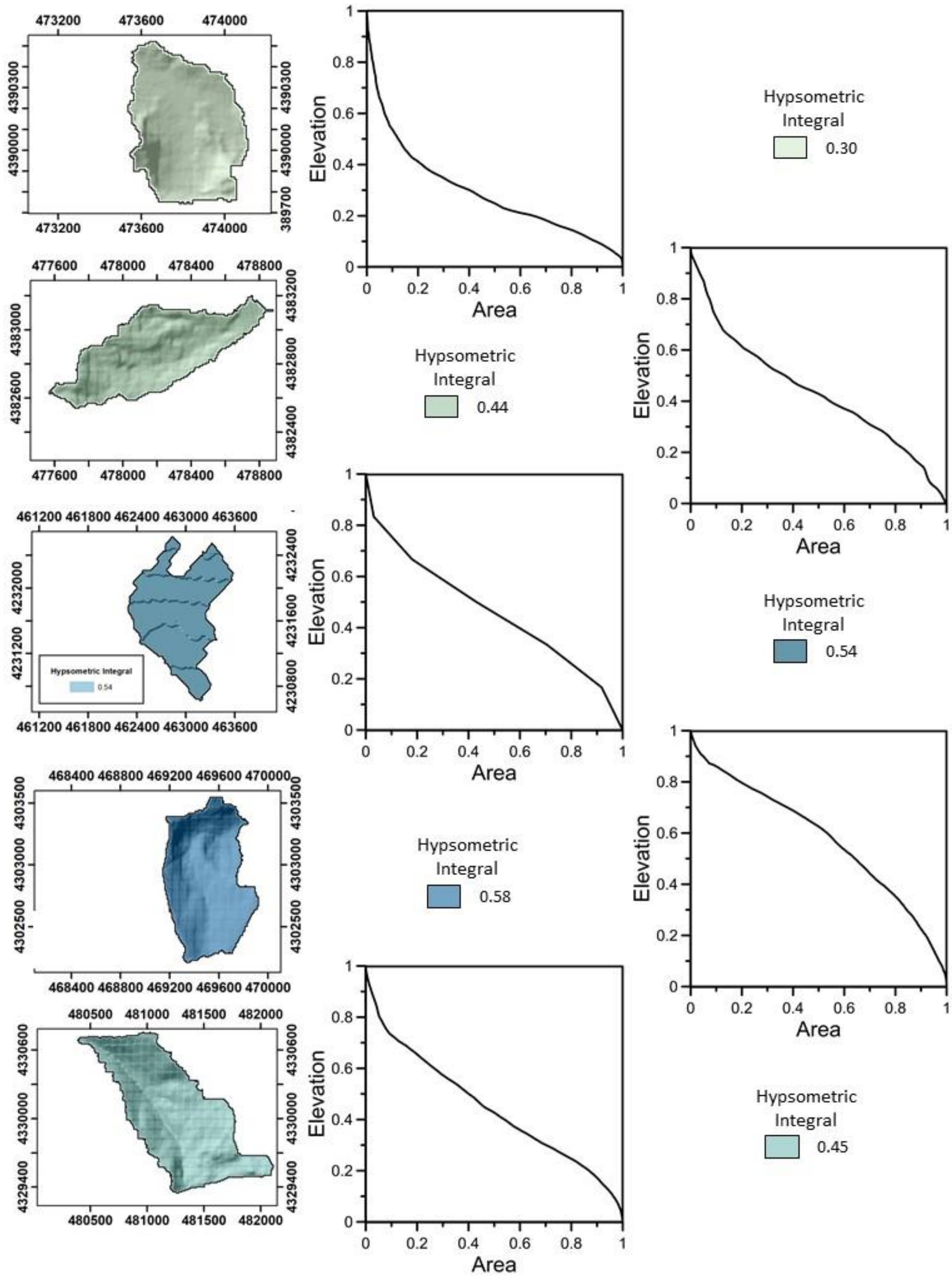

Figure A14. Hypsometric curves for the 1,000 watershed size in the Basin and Range: *Watershed threshold is 1,000 and the watersheds were chosen at random.*

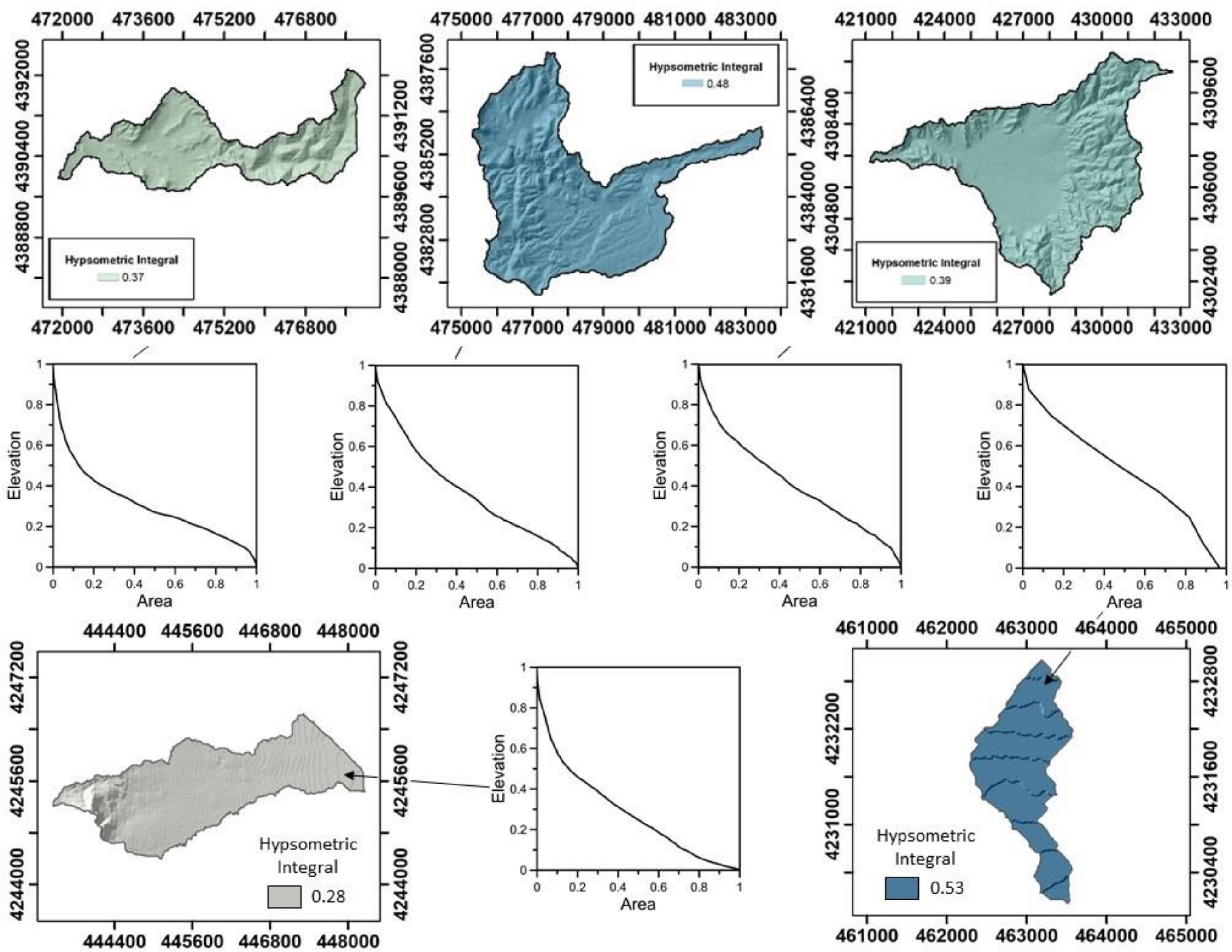

Figure A15. Hypsometric curves for the 10,000 watershed size in the Basin and Range: *Watershed threshold is 10,000 and the watersheds were chosen at random.*

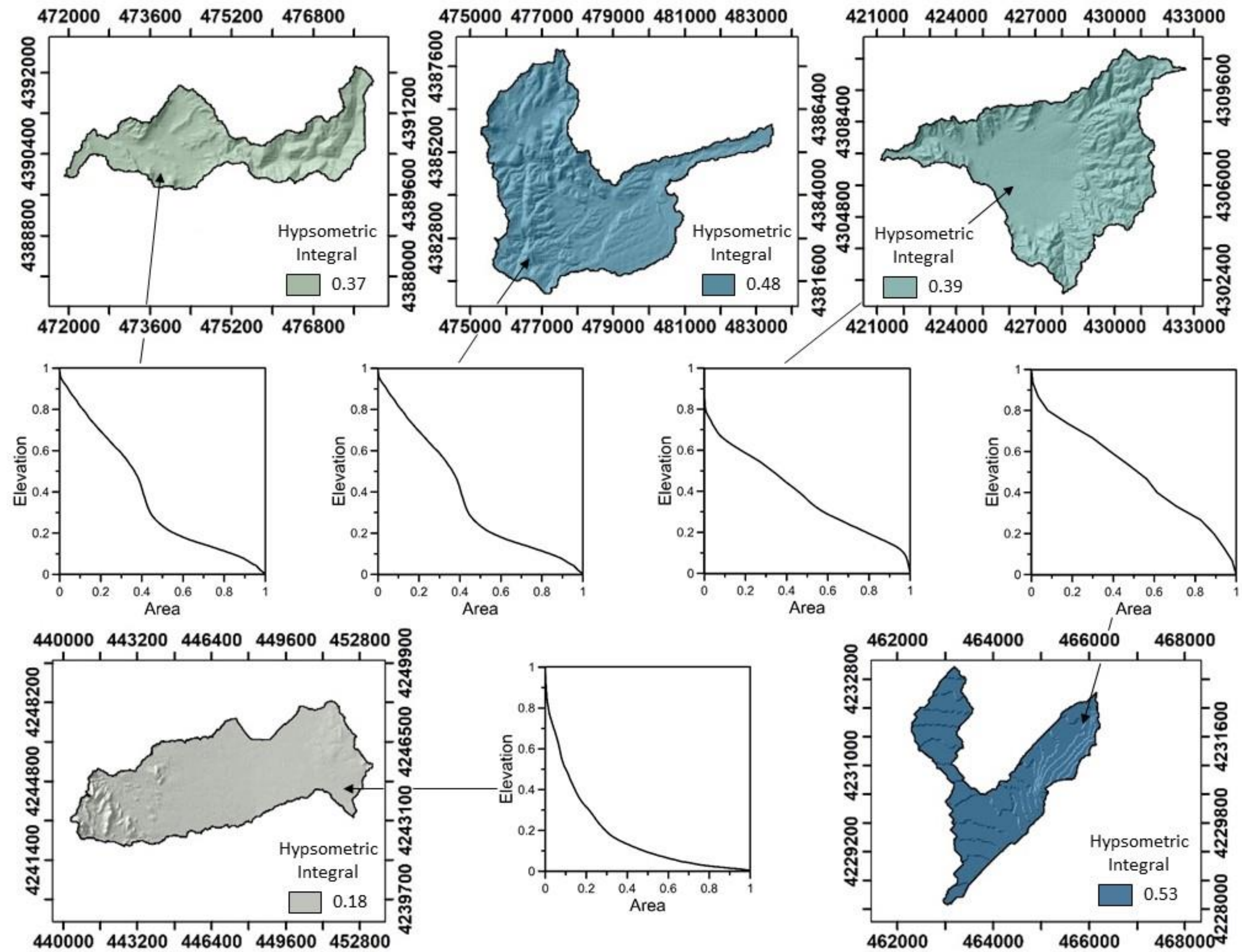

Figure A16. Hypsometric curves for the 100,000 watershed size in the Basin and Range: *Watershed threshold is 100,000 and the watersheds were chosen at random.*

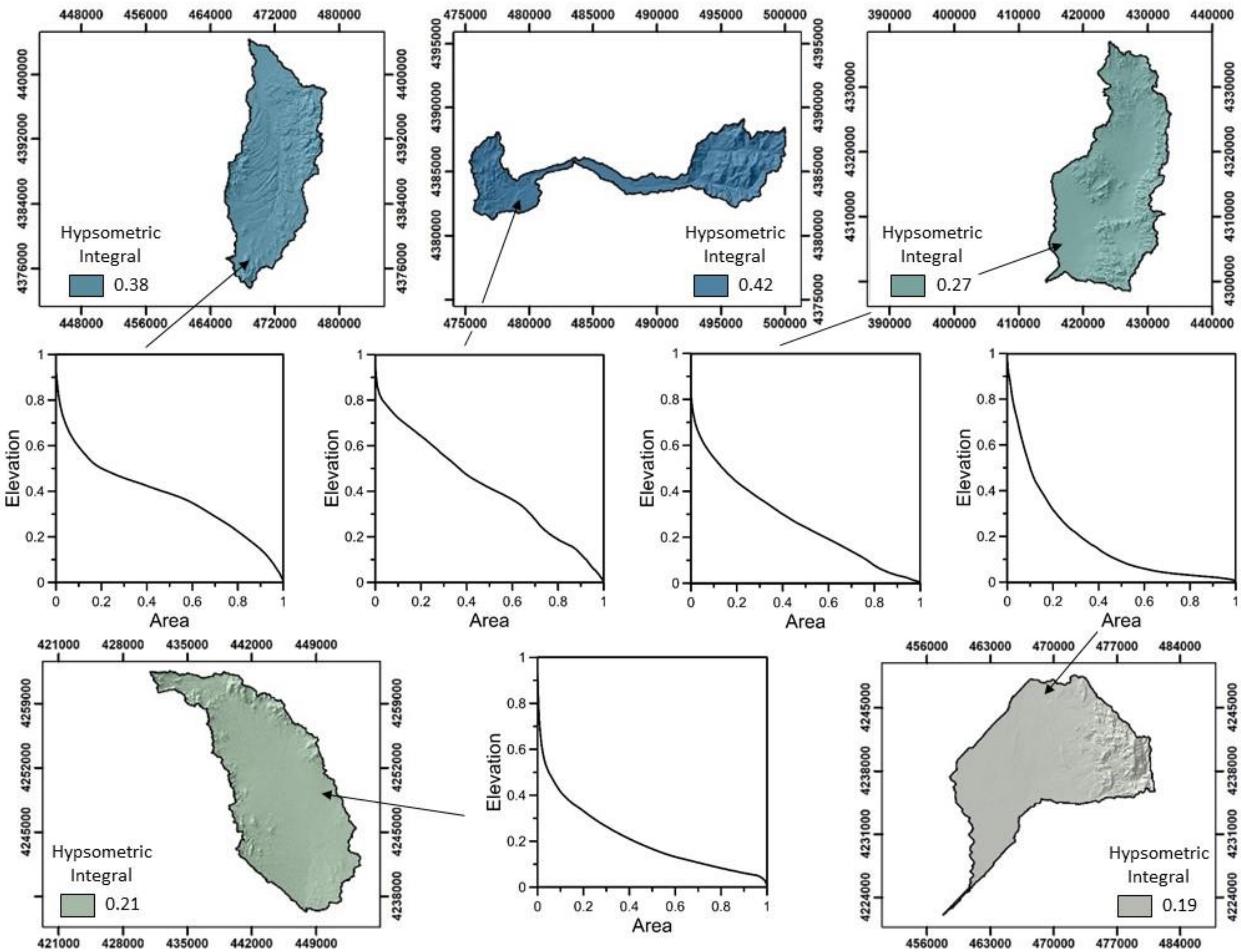

Figure A17. Hypsometric curves for the 1,000,000 watershed size in the Basin and Range: *Watershed threshold is 1,000,000 and the watersheds were chosen at random.*

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