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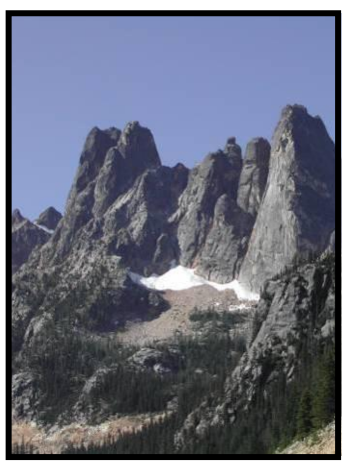
Geomorphology of the Thunder Creek Watershed

Landform Mapping at North Cascades National Park Service Complex, Washington

Natural Resource Technical Report NPS/NCCN/NRTR—2012/567



ON THE COVER

Clockwise from upper right: Thunder Creek main channel; Debris cones in Fisher Creek; Fisher Peak; Headwaters of Skagit Queen Creek; Upper Fisher Basin from just below Easy Pass.

Photographs by, and used with courtesy of, Crystal Briggs, Natural Resource Conservation Service

Geomorphology of the Thunder Creek Watershed

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Natural Resource Technical Report NPS/NCCN/NRTR—2012/567

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Abstract

The report describes the background information, methods and results of a surficial geology inventory within the North Cascades National Park Service Complex (NOCA). The study area for this report is the Thunder Creek Watershed, which flows north from Thunder Basin and is the most heavily glaciated watershed within the park. Tributaries of Thunder Creek include Skagit Queen, West Fork, Fisher, McAllister, Neve, and Colonial Creeks. The headwaters of many of these tributaries are on the Skagit or Pacific Crest, two significant divides that strongly affect the hydrology and climate in the North Cascades (Riedel 2007). This report focuses on how factors such as bedrock geology, glacial history, climate, hydrology, and vegetation have affected landform development in the Thunder Creek Watershed, particularly mass movements.

The Thunder Creek Watershed lies between two major fault systems: the Straight Creek Fault to the west and the Ross Lake Fault Zone to the northeast, which places the watershed is within the crystalline core of the North Cascades. The Thunder Creek Watershed also contains the Thunder Lake Fault. This fault runs mainly north-south, following the trend of the Straight Creek Fault, through the western portion of the Thunder Creek Watershed. Other structural features found in the watershed are northeast/southwest trending compressional faults. The majority of the watershed is variety of orthogneiss and gneiss. The topography of the Thunder Creek Watershed reflects multiple glaciations during the past 2 Ma, which have carved deep U-shaped valleys, steep valley walls and jagged horns and arêtes. The North Cascades were inundated by the south flowing Cordilleran Ice Sheet during the Fraser Glaciation (Armstrong et al. 1965). The most extensive advances of alpine glaciers since the last ice age occurred in the Little Ice Age between 1350 and 1900 AD, depositing Neoglacial moraines.

The climate of the Thunder Creek Watershed is classified as maritime, although drier conditions prevail in the Fisher Creek valley. Climatic conditions vary widely in the Thunder Creek Watershed with large gradients in temperature and precipitation from west to east and with elevation. Snow pack generally reaches its maximum depth at high elevation sites in April to May. Yearly temperature average highs tend to occur in July and August with winter average low temperatures occur in January. The rainy season typically lasts from November through January. Snow, bare rock and ice cover approximately 40 km^2 of the Thunder Creek Watershed. The remainder of the watershed is dominated by conifer species of trees although deciduous species dominate along major river corridors and in avalanche chutes.

A suite of 29 different landforms is currently being mapped at NOCA at the 1:24,000 scale. Landform mapping is specifically being utilized as an input in the creation of a soils distribution map for NOCA. Landforms can either be depositional in nature, such as moraines and alluvial fans, or they can be erosional such as bedrock benches and horns. Many depositional features such as moraines and terraces were formed during the last ice age. Other depositional features such as debris cones and landslides are forming today. Approximate ages are assigned to depositional landforms based on available radiocarbon dates, associated process of formation, volcanic tephra, soil development and vegetation type and age.

Within the watershed, 53% is valley wall and 20% is high elevation cirque; with only 2.6% as riparian (floodplain, valley bottom and alluvial fan). High elevation landforms (cirques,

Neoglacial moraines, ridges, arêtes, other mountains, horns and passes) account for 72.5 km^2, which is 24% of the total watershed area. Aspect has particularly strong control on the development of cirque basins and valley walls, with north and east facing cirques are deeper and broader than those on southerly aspects and also containing lower elevation Neoglacial moraines. Steep cliffs on valley walls with north aspects are contrasted by gentler rises on those with south aspects. Landforms in the watershed, such as broad passes, extensive bedrock bench systems, Pleistocene moraines, Neoglacial moraines, and rounded ridges capture the history of ice sheet advances/retreats and subsequent drainage reversals.

The main stem of Thunder Creek is a broad U-shaped glacial valley with a flat valley bottom, straight profile and low gradient, created by both the southward excursions of the Cordilleran Ice Sheet and the multiple glaciations by alpine glaciers flowing down the major tributaries. Tributary systems were left as hanging valleys with bedrock canyons or narrow, stepped waterfalls at their mouths. Where they join with the main stem of Thunder Creek, these streams deposited alluvial fans. At the mouths of some tributaries, fan terraces were deposited at the end of the last ice age when slopes left bare by retreating glaciers fed massive quantities of sediment to streams. There are several large Pleistocene moraines along Thunder Creek deposited by the ice sheet across the mouths of tributaries (Riedel 1987). These landforms are remnants of moraine-embankments the ice sheet built across the mouths of these valleys as it flowed up the Thunder Creek valley.

A total of one hundred and fourteen landslides have been mapped within the watershed (4.8% of the total watershed area) with twenty-four being large debris avalanches. Debris avalanches encompass 3.4% of the overall watershed area. A total of nineteen of the debris avalanches mapped in the watershed delivered sediment to a stream, and ten of those blocked entirely at one time. They have displaced an estimated volume of 0.675 km^3 of debris. In the Thunder Creek Watershed it appears that the largest debris avalanches are possibly influences by north-south or northwest-southeast trending faults. Three of the largest ones are located in the watershed are located in Fisher Creek in faulted and hydrothermally altered rock. Debris slump/creep deposits are uncommon in the watershed and tend to occur in the valley bottoms, fault zones, or in sections of glacial till and colluvium in the debris apron. Debris torrents are fairly common, indicating the active nature of many of the smaller tributaries, particularly those that follow faults. South-facing river canyons tend to produce flashy floods in the spring, and thus produce debris torrents. One SAIL (snow avalanche impact landform) is located in the watershed at the base of a steep south-facing valley wall in unconsolidated sediment. Most of the mass movements overall tend to be on north (20%) or north-east to east facing (15% for each) slopes.

1- Introduction

The primary purpose of this report is to describe the background information, methods and results of a surficial geology inventory within the North Cascades National Park Service Complex (NOCA). A secondary goal is to provide an overview of bedrock geology, climate and hydrology as they affect landform processes. The study area for this report is the Thunder Creek Watershed, which is defined as Thunder Creek and its tributaries. Thunder Creek flows north into Diablo Lake, a hydroelectric project located within NOCA.

Background information presented in this report focuses on key factors that influence the development of landforms in the Thunder Creek Watershed and the Skagit valley overall. These factors include geology, glacial history, climate, hydrologic setting and vegetation. A brief discussion on landform age follows the background information, to give geomorphic processes a temporal context. A detailed description of methods is then provided before discussing the results and interpretations of the landform inventory.

The results and discussion section of this report gives detailed analysis for the individual sub-watersheds mapped in this study. Discussion of each sub-watershed includes the unique characteristics of the individual valleys and specific examples of landform genesis. Detailed information is gathered for each mass movement in order to reveal both historic and on-going mass wasting occurring in each sub-watershed.

1.1 Applications of Landform Mapping Data

Understanding surficial processes and materials is critical for resource managers in mountainous terrain. Surficial processes such as landslides, floods and glaciation directly impact the human use and management of rugged landscapes. The materials produced by these processes influence soil and vegetation patterns and provide information on geologic hazards, prehistoric landscape use, habitat and ecological disturbance. Knowledge of the function of surficial processes and distribution of materials assists the National Park Service (NPS) in selection of ecological reference sites, identification of rare or threatened habitat, management of risk and cultural resources (Riedel and Probala 2005).

Landform mapping is specifically being utilized as an input in the creation of a soils distribution map for NOCA. Traditional methodologies, relative inaccessibility and estimated high costs have not allowed for extensive soil surveys in the rugged wilderness. Parent material, time (stability/age) and relief are three of five soil-forming factors, so digital landform maps are a critical component in developing new approaches to mapping soils in remote, rugged landscapes. Landforms provide a preliminary landscape delineation that can simplify the soil sampling strategy. Linking soils to landforms is a cooperative effort among NOCA, the Natural Resources Conservation Service (NRCS) state mapping program, the United States Forest Service (USFS), Washington State University and the NPS Soils Program.

Currently the Remote Area Soil Proxy (RASP) model uses Geographic Information Systems (GIS), remote sensing technology and a focused effect to describe soils in the field to model and map the distribution of soils (Rodgers 2000, Briggs 2004, Frazier et al. 2009). Digital GIS data layers such as digital elevation models, current vegetation, wetness index and landforms serve as proxies for the soil-forming factors that control pedogenic processes. A digital soils model using landform data from Thunder Creek watershed shows a strong correlation between landform type and soil order (Briggs 2004). Encouraged by these results, landform maps are being used to develop soil models for the remainder of NOCA. This approach will continue to be developed to obtain soil resource inventories for all NPS units in Washington State.

The Thunder Creek Watershed provides several management challenges for the NPS. One of the few car accessible campgrounds in the park, Colonial Creek Campground (North and South units) is located on a small alluvial fan at the mouth of Colonial Creek, and debris cone at the mouth of Rhode Creek. Washouts and channel avulsion have made this site highly vulnerable during floods. Throughout the watershed, highly bisected and faulted rock of multiple types has lead to the development of massive debris avalanches. Landform maps that document these huge slope failures can aid in the relocation of trails and campground to ensure visitor safety. Since the Thunder Creek Watershed contains the highest concentration of glaciers of any other watershed in NOCA, mapping glacial landforms in the drainage has been essential to understanding the glacial history of NOCA and the region. Landforms played a role in the location and distribution of historical sites in the Thunder Creek valley. The density of pre-historic sites has also been linked to landform type (age).

1.2 Project History

In 1988, staff at NOCA began using an eight landform mapping scheme to assess distribution of archeology sites. This program continued to develop in the early 1990's when a suite of fifteen landforms were mapped to support a general management plan for Lake Chelan National Recreation Area. In 1995, the program expanded to meet the needs of NOCA as a prototype Park for long-term ecological monitoring (LTEM) programs. This included the development of a twenty-three landform scheme to support classification and assessment of aquatic habitat. There are now thirty-seven distinct units in a regional landform scheme, of which twenty-nine are found in NOCA. Landform units are created by discrete geologic processes, many of which are still active and relatively easy to identify. The landform scheme has now been applied to several watersheds within five of the seven NPS units in the North Coast and Cascade Network (NCCN), including NOCA, Mount Rainer National Park (MORA) and Olympic National Park (OLYM), Ebey's Landing National Historical Reserve and San Juan Island National Historical Park.

The development of this program was assisted by the Natural Resource Challenge to obtain twelve basic inventories for all NPS areas, including surficial geology and soils. In 2001, NOCA landform mapping was linked with the United States Forest Service (USFS) multi-scaled "National Hierarchical Framework for Ecological Units" (Cleland et al. 1997) for public lands in the North Cascades. The approach uses a nested system in which each scale (eight total) fit inside one another. Together the USFS and NPS have mapped at three of these scales; 1-Subsection, 2-Landtype Association (LTA) and 3-Landform.

This report gives detailed results for the Thunder Creek Watershed, which includes a discussion of the unique geomorphology and history of the Thunder Creek valley and its tributaries, as well as a summary of landslide inventory data. The valley characteristics of each tributary are presented, with a fine resolution of landform description, landslide activity and any other pertinent information.

2 - Study Area

2.1 Geographic Setting

The Thunder Creek Watershed covers ~ 300 km^2 of the 2,770 km^2 national park, making it the largest individual watershed in NOCA (Fig. 1). The majority of the watershed is located within the park, with the lower valley located in the Ross Lake National Recreation Area (Fig. 1). The watershed is the most heavily glaciated in the park and lower 48 states with an estimated 37 km^2 glaciated. Thunder Creek flows north from Park Creek Pass for 24 km, where it enters the backwater behind Diablo Dam (Fig. 2). The Thunder Arm is part of Diablo Lake, which was created in 1929 by Seattle City Light with the construction of the Diablo Dam in Skagit Gorge. The Skagit River continues west to the Puget Sound and is the largest drainage that flows into the Puget Sound. At 8,000 km^2 in drainage basin size, it supplies more than 30% of the Sound's total freshwater input.

The major tributaries of Thunder Creek are Skagit Queen, West Fork, Fisher, McAllister, Colonial and Neve Creeks (Fig. 2). The watershed boundaries on the west and south are the Skagit and Pacific Crests, respectfully. The Skagit Crest is a chain of mountains stretching from Mt. Spickard on the Canadian Border to Boston Peak (Riedel 2007). This physiographic feature has a significant impact on the weather patterns of the region and is breached at Skagit Gorge (Riedel 2007) (Fig. 2). The Pacific Crest was established as a significant topographic barrier by 17 Ma when Columbia River basalts filled the mouths of several east-draining North Cascades valleys (Waters 1939, Mathews 1964). This important physiographic feature, stretching down the entire west coast of the United States, extends into Mexico and Canada as well. This divide strongly influences the weather, climate and ecology of North America.

Major summits in the watershed include Colonial Peak, Eldorado Peak, Forbidden Peak, Buckner Mountain, Klawatti Peak, Mount Logan, Mount Arriva and the peaks of Ragged Ridge. The downstream boundary of the watershed is where Thunder Creek meets Diablo Lake (370 m), giving the basin a vertical relief of ~ 2400 m. As a result of strong climate gradients, Thunder Creek Watershed exhibits a wide range of climate, vegetation types, soil types, valley morphologies and landforms.

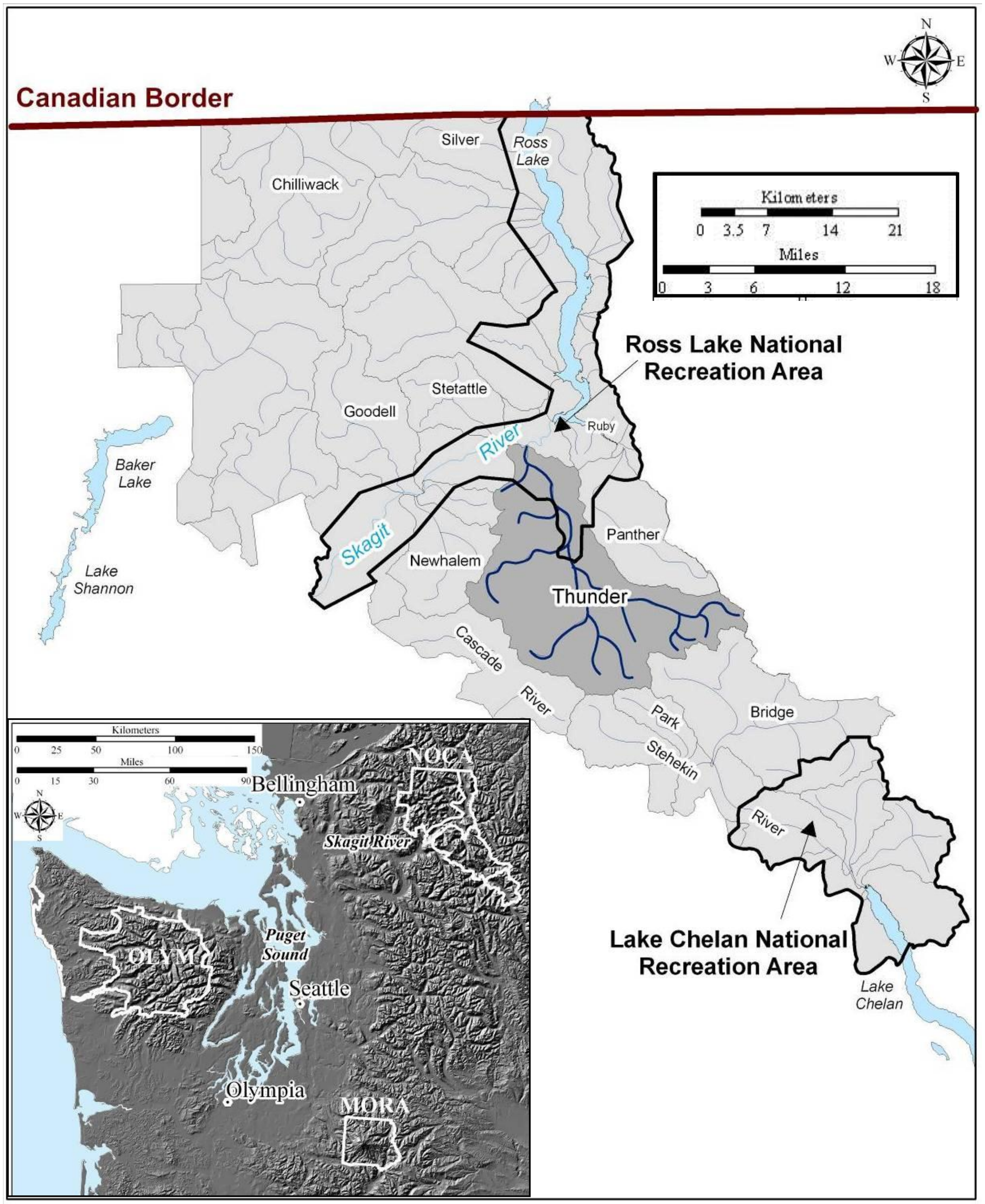

Figure 1. Map showing the location of the Thunder Creek and adjacent watersheds within North Cascades National Park Service Complex (NOCA) with the boundary of Ross Lake and Lake Chelan National Recreation Areas shown. Insert map shows the location of NOCA within Washington State, as well as Mount Rainer (MORA) and Olympic (OLYM) National Parks.

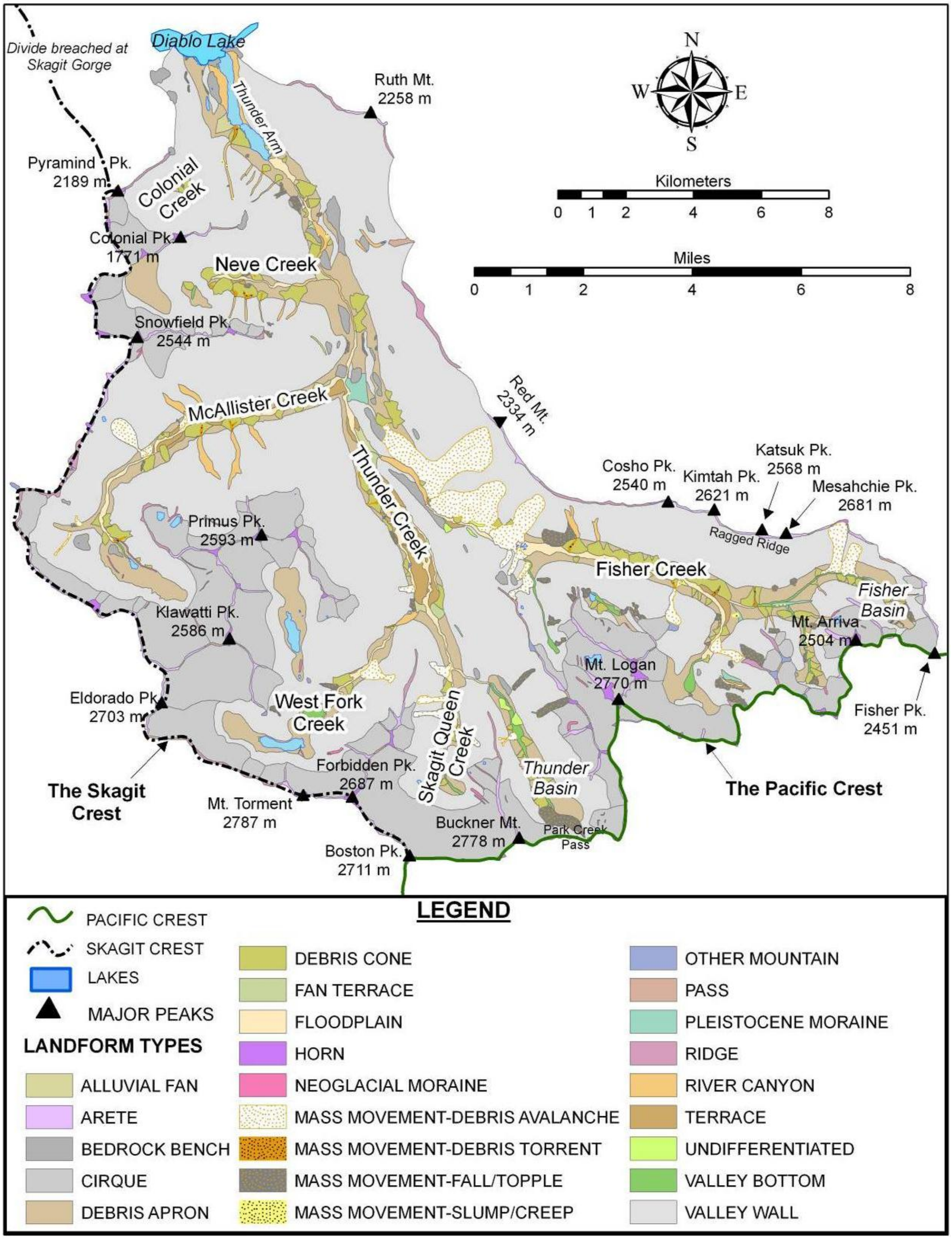

Figure 2. Landform map of the Thunder Creek Watershed with the locations of the main tributary streams and other sites referred to in the text

2.2 Geologic Setting

The bedrock geology of the North Cascades has been mapped at 1:1,250,000 scale by Staatz et al. (1972) and 1:100,000 scale by Tabor et al. (2003). A geologic map for the core of the North Cascades at the 1:200,000 scale has been recently completed (Tabor and Haugerud *in review*). Only the western portion of the Thunder Creek Watershed is covered in the 1:100,000 scale map by Tabor et al. Descriptions in the following paragraphs all reference the work done by Tabor et al. (2003) and Tabor and Haugerud (1999 and *in review*).

Bedrock of the North Cascades was formed by a complex series of igneous, metamorphic and tectonic events beginning in the Cretaceous period, 145 – 65 millions of years ago (Ma). Numerous faulting events and intrusions in the North Cascades have created a diverse mosaic of bedrock types. Since the geology is so complicated in this corner of the United States, geologists have summarized it into five broad events:

1. Accumulation of massive bodies of rock (terranes) to the west coast of North America between 200 (Early Jurassic) and 50 Ma (Late Cretaceous);
2. Uplift and erosion of these rocks to create a pre-North Cascades mountain range between 130 (Early Cretaceous) and 50 Ma (Eocene);
3. Intensive movement and faulting 50-40 Ma that fragmented the preexisting mountains;
4. Another phase of mountain uplift that created the modern North Cascades began 40 Ma and continues today; and
5. From about 2 Ma and continuing intermittently the great ice age glaciers created not only the jagged arêtes and horns, but also the broadened passes, rounded ridges and deepened valleys.

2.2.1 Tectonics and Structure

The Thunder Creek Watershed lies between two major fault systems: the Straight Creek Fault to the west and the Ross Lake Fault Zone to the northeast, which places the watershed is within the crystalline core of the North Cascades (Tabor and Haugerud 1999) (Fig. 3). The Straight Creek Fault is thought to be a 400 km long strike-slip extensional fault. It begins in central Washington and extends 210 km into Canada, where it is named the Fraser River Fault Zone (USGS 2003). The fault, located east of Marblemount, extends up through Bacon Creek. Traces of it have been obliterated further north due to the intrusion of Eocene plutons. The fault separates low-grade metamorphic rocks to the west from highly metamorphosed rocks of the North Cascades core to the east. The Ross Lake Fault Zone passes through the watershed and continues beneath Ross Lake. It is part of a 500 km long zone of high angle faults that trends northwest-southeast. This fault separates the metamorphic core of the Cascades from the essentially unmetamorphosed sedimentary and volcanic deposits of the Methow Domain (Methow and Hozomeen terranes) to the east. Traces of the fault are found in Thunder Creek by Mount Logan, Park Creek Pass, Fisher Creek and Colonial Creek.

The Thunder Creek Watershed also contains the Thunder Lake Fault. This fault runs mainly north-south, following the trend of the Straight Creek Fault, through the western portion of the Thunder Creek Watershed. The fault controls the development of Sourdough Creek to the north, Rhode Creek and other drainages within NOCA. In the watershed the fault is mapped through Rhode Creek to McAllister Creek. Traces of the fault are picked up on the southern valley wall of McAllister Creek and they continue through Klawatti Lake to the West Fork.

Other structural features found in the watershed are northeast/southwest trending compressional faults on Red Mountain associated with the Cascade magmatic arc (Tabor et al. 2003). The regional uplift and exhumation that begun in the Eocene (45-36 Ma) continues today as part of the Cascade Magmatic Arc (Reiners et al. 2002). It is estimated that average exhumation rates on the western flank of the Cascades range from 0.14 to 0.33 km/million years (Mitchell and Montgomery 2006) or ~2-5 vertical kilometers of rock in the last 15 million years (Reiners et al 2002 and 2003). There appears to be no appreciable Holocene tectonic activity along any of the faults systems that pass through the Thunder Creek Watershed (USGSa 2009).

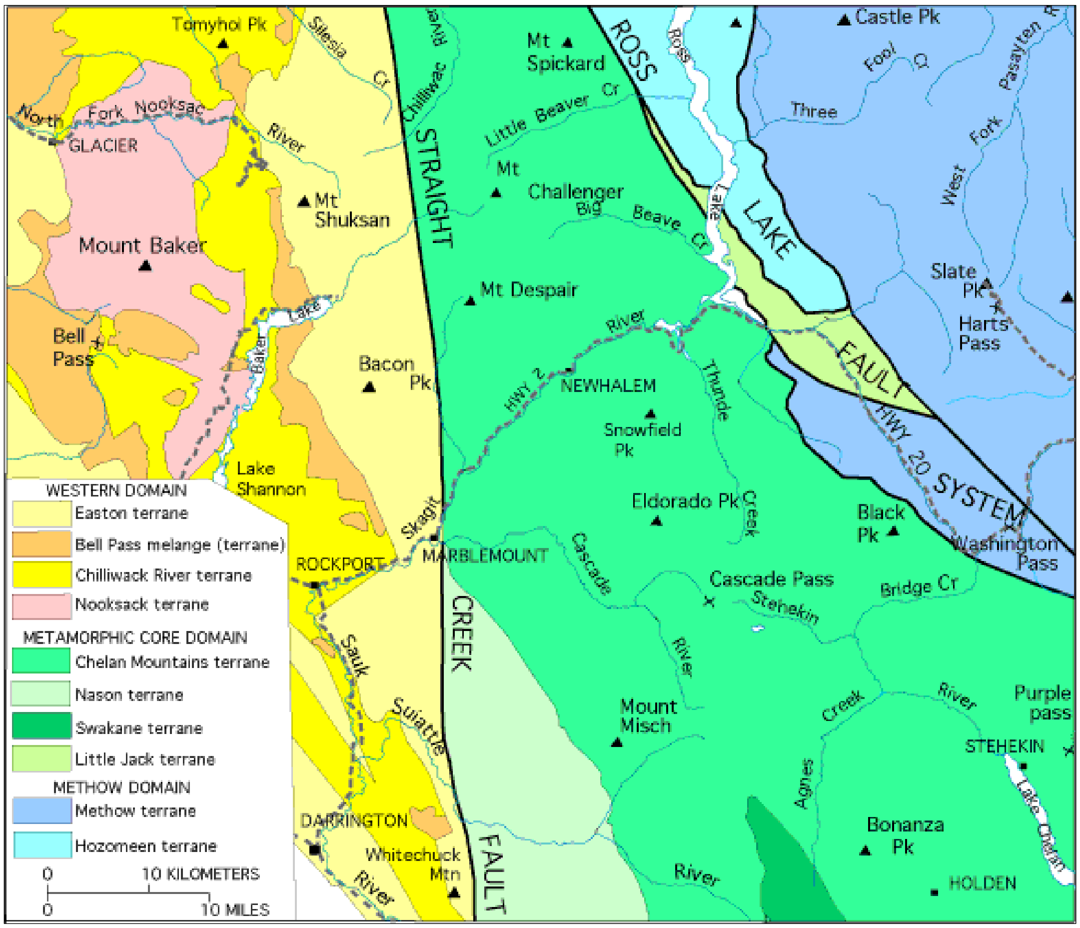

Figure 3. Major fault systems and terranes in the North Cascades (from Tabor and Haugerud 1999).

2.2.2 Geologic Units

A generalized geologic map provides a regional perspective on the geology in the Upper Skagit Watershed and neighboring watersheds (Tabor and Haugerud 1999) (Fig. 4). A detailed description of the geology is found in the Tabor et al. publication (2003) as well as the Tabor and Haugerud publication (*in review*). The summary of the geology in the paragraphs below draws from these two sources.

Several different types of bedrock are found within the Thunder Creek Watershed. Orogenic rocks include Skagit Gneiss Complex, Eldorado and Mount Triumph Orthogneiss and minor pegmatite, all Late Cretaceous to middle Eocene in age. Within the watershed, these bedrock units are found up the West Fork and upper McAlester Creek, with all the major peaks of the Skagit Crest composed of gneiss. The orthogneiss also extends east through the main Thunder Creek valley into lower Fisher Creek where it composes the peaks of Mount Logan and Ruby Mountain.

Just east of Mount Logan the bedrock type changes to fault bounded tonalitic orthogneiss and granodiorite gneiss. Intrusive tonalitic plutons of Cretaceous age from the Black Peak Batholith compose the headwaters of Fisher Creek, notably Mount Arriva, Fisher Peak and Mesachie Peak. This unit is dissected by east to west and northwest to southeast faults. A rare outcrop in the watershed of schist is mapped at the summit of Ruby Mountain. Otherwise the entire watershed is mostly varieties of orthogneiss. Valley bottoms are typically mapped as alpine glacial deposits (boulder till and gravel or sand outwash), alluvium and colluviums of landslide debris and moderately to well-sorted deposits of cobble gravel and sand of valley bottom alluvium.

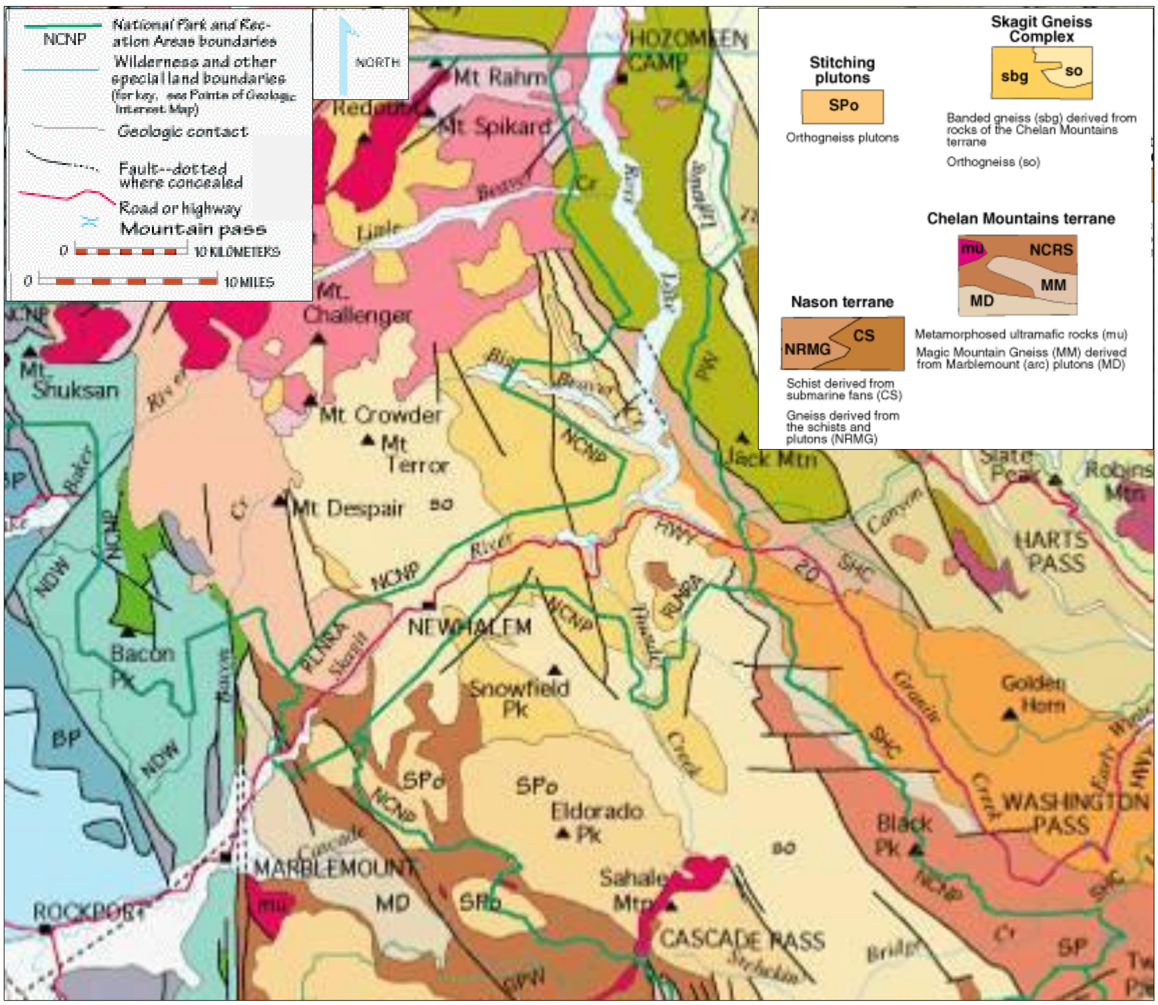

Figure 4. Bedrock map showing the Thunder Creek Watershed (note location of Ross Lake and Thunder Creek) and other watersheds (see Tabor and Haugerud 1999 for more complete key).

2.3 Glacial History

The topography of the Thunder Creek Watershed reflects multiple glaciations 2 Ma, which have carved deep U-shaped valleys, steep valley walls and jagged horns and arêtes. The geomorphologies of the North Cascades during this period have been shaped by both alpine and continental glaciations. Glaciation has altered the fluvial morphology of both local and regional drainage patterns (Riedel et al. 2007). The North Cascades were inundated by the south flowing Cordilleran Ice Sheet during the Fraser Glaciation 35 to 11.5 thousand years ago (Ka) (Armstrong et al. 1965) (Fig. 5).

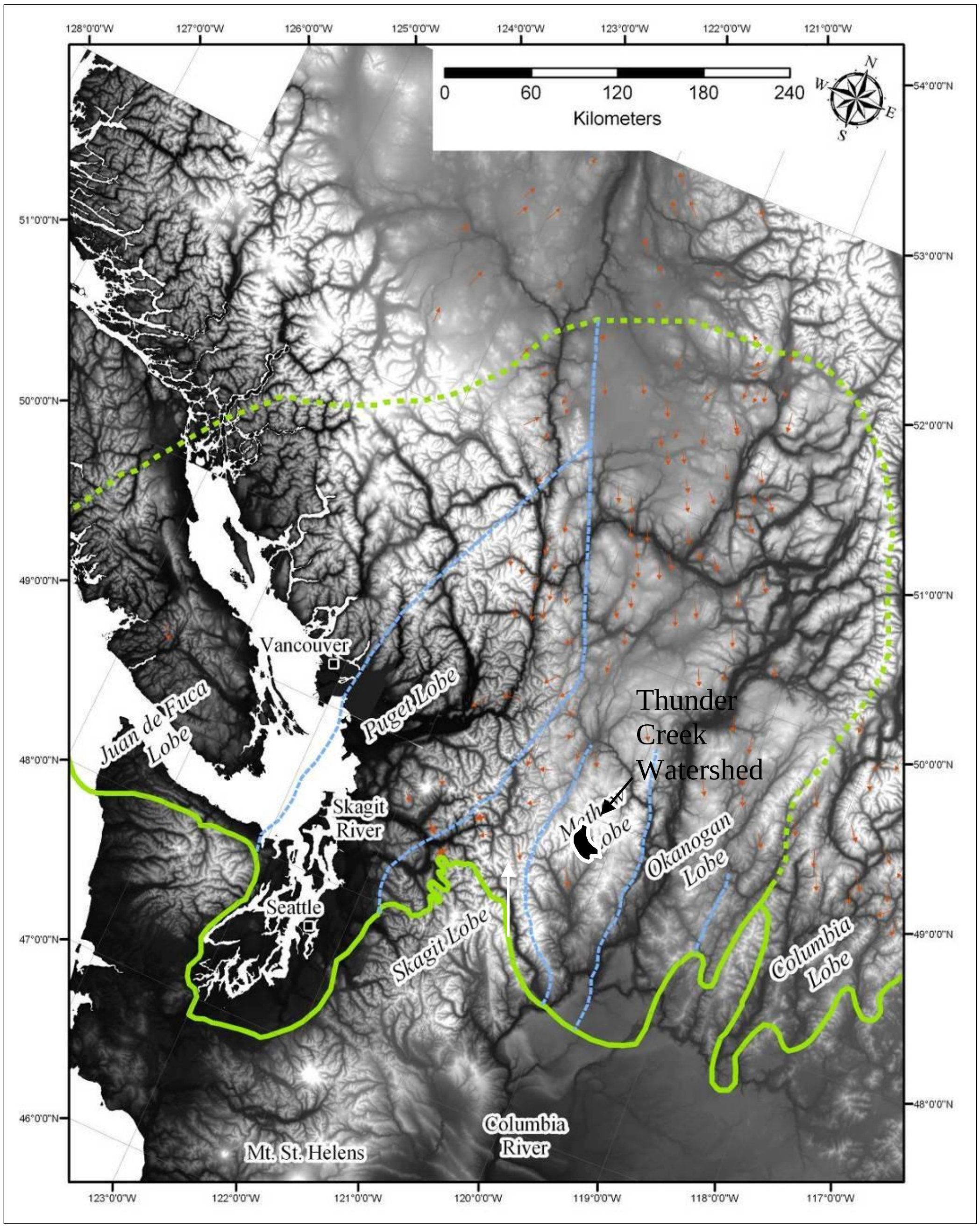

Figure 5. Map of the known extent of the Cordilleran Ice Sheet during the Fraser Glaciation. Note the various lobes of the ice sheet mapped, extending down into the United States.

Drainage of large lakes trapped in valleys in front of the ice sheet across mountain passes caused divide lowering and migration northwards, as well as modification of dendritic, trellis and other drainage patterns (Riedel et al. 2007). At the beginning of the great ice ages 2 Ma, a divide near present day Skagit Gorge separated flow to Puget Sound from flow to the Fraser River. At that time, the Skagit River flowed north into British Columbia, with the headwaters draining Thunder Creek. Erosion of this divide created the Skagit River Gorge, just below Ross Dam, and led to the capture of the upper Skagit drainage system. The divide now separating the Fraser from the Skagit is Klesilkwa Pass in British Columbia, which is flooded by a series of swamps.

Little research has been done on ice sheet glaciation in the North Cascades (Waitt 1977, Riedel 2009). There were at least three major advances of alpine glaciers during the last ice age that are recorded in deposits with the Skagit valley. The Evans Creek advance marks the beginning of the Fraser Glaciation and has been dated in the Skagit valley at ~ 30 Ka calendar years before present (cal. years B.P.) (Riedel 2007). Alpine glaciers advanced to fill valley floors of the Thunder Creek valley. Evans Creek moraines and ice-marginal landforms were subsequently eroded away during glaciations by ice sheet. The Sumas advance has been dated in the Skagit valley from 14.1 to 10.8 Ka cal. years B.P. (Riedel 2007). During this advance alpine glaciers extended for 5-10 km below cirques, leaving prominent moraines in many locations.

2.3.1 Neoglacial

Glaciers in the Thunder Creek Watershed probably reached their minimum extent since the last ice age about 8 Ka. In the next several thousand years, small alpine glaciers advanced and retreated several times during the Neoglacial Period (Porter and Denton 1967) as evidenced by Neoglacial moraines mapped within the watershed and the North Cascades regionally. The most extensive of these advances occurred between 1350 and 1900 AD, in what is called the Little Ice Age.

Glacial advance during the Little Ice Age created hundreds of small moraines and left vast fields of unconsolidated glacial till. Small cirque glaciers and permanent snow fields of today are up to 50% less extensive than at the end of the Little Ice Age, 100 years ago. Presently, cirque alpine glaciers remain at high elevations and most have a north or east aspect and are sheltered from the sun by steep cirque walls and arêtes. The valley glaciers of the Pleistocene and alpine glaciers of the Little Ice Age left behind large amounts of glacial drift, including till and outwash, which has been reworked by subsequent surficial processes, or abandoned as terraces. This sediment likely fills most of the lower parts of Thunder and McAllister valleys to depths of several hundred meters.

There are three hundred and twelve glaciers present within NOCA today. NPS staff members at NOCA are currently monitoring four glaciers including; Noisy and North Klawatti glaciers are on the west side of NOCA, Sandalee Glacier on the east side and Silver Glacier near the Canadian border. A summary of results on the North Klawatti Glacier located in the Thunder Creek Watershed follow in the Hydrology section of this report.

2.4 Climate

The climate of the Thunder Creek Watershed is classified as maritime, although drier conditions prevail in the Fisher Creek valley. Climate is the primary driver of surficial processes that have shaped the watershed, including glaciers, rivers and mass wasting. Climatic conditions vary widely in the Thunder Creek Watershed with large gradients in temperature and precipitation from west to east and with elevation. Climate and weather monitoring within the watershed consists of two Natural Resource Conservation Service (NRCS) snow course sites, a NRCS snowpack telemetry (SNOTEL) site and a Cooperative Network (COOP) station at Diablo Dam (Fig. 6).

Snow course data reveals that the snow pack generally reaches its maximum depth at the higher elevation site (Thunder) by late April while the lower elevation site (Meadow Cabins) generally reaches maximum in March. Maximum snow depth and snow water equivalent (SWE) for the two snow courses are listed in Table 1.

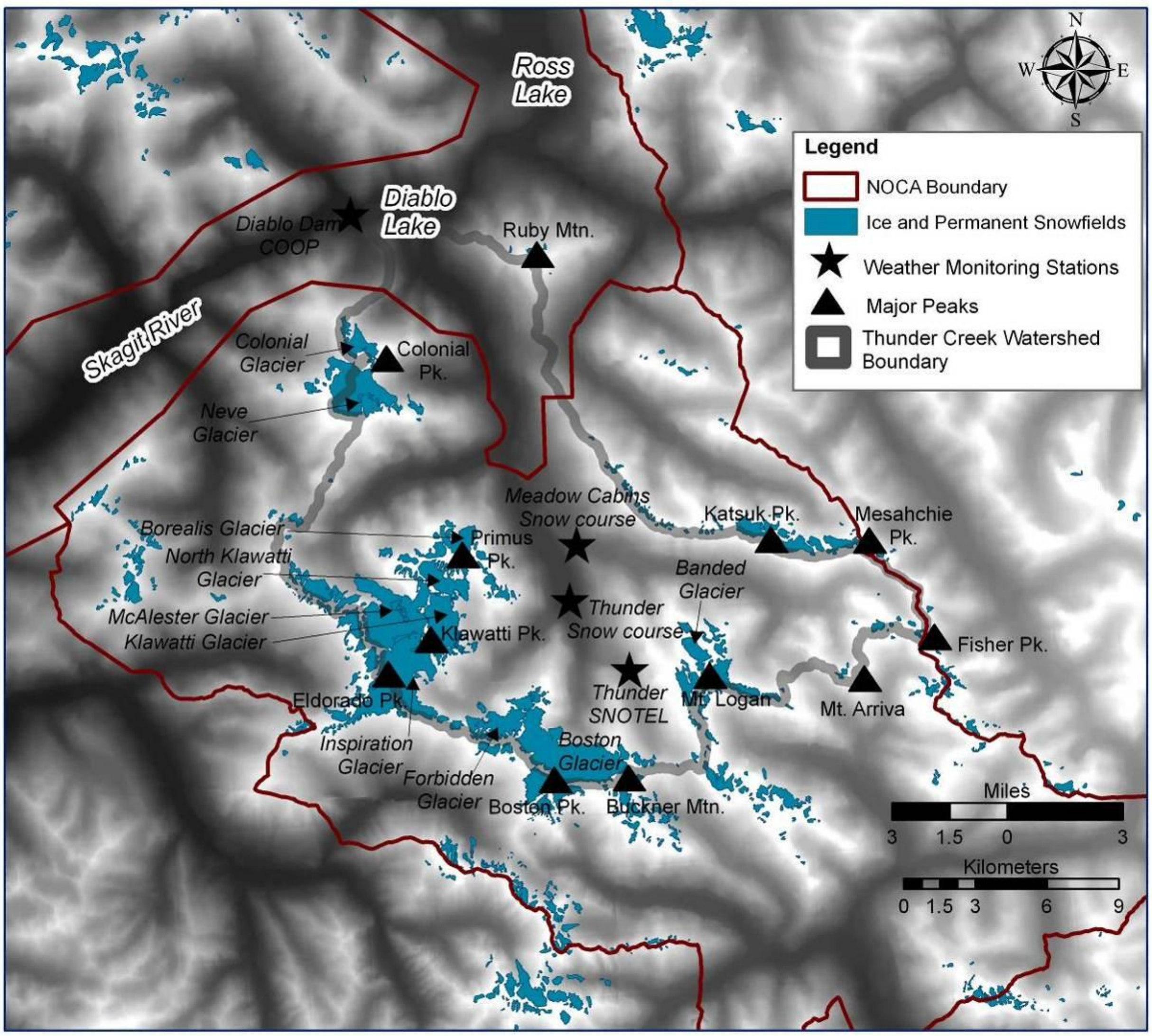

Figure 6. A 90 meter digital elevation model (DEM) showing permanent snowfields and glaciers in and around the Thunder Creek Watershed, as well as the weather monitoring stations.

Table 1. Summary of data from two snow course sites located in the Thunder Creek Watershed (NRCS 2009a). All measurements were taken as of May 1st unless stated otherwise. Data is provisional and subject to revision.

	Thunder	Meadow Cabins
Elevation (m)	732	579
Period of Record	1948-Present	1945-Present
Record Snow Year	1954	1954
Max. Depth (cm)	254	61
Max. SWE (cm)	113	26
Lowest Snow Year	2005	1992
Min. Depth (cm)	30	0
Min SWE (cm)	7	0
Max. Depth recorded (date/cm)	April 1999/295	March, 1972/135
Max. SWE (cm)	109	0

A SNOTEL site is located within Thunder Basin at 1280 m and has been operating since 1988. At this site, yearly temperature highs tend to occur in July and August, with maximums reaching 34° C. Winter lows tend to occur in December and February, with minimums reaching -30° C. November is routinely the wettest month, averaging 34.5 cm. Most precipitation occurs during the winter months of November through January, averaging 49% of the total. Inversely, the summer months of July-September tend to be the driest, averaging only 8.5% of total precipitation. A summary of additional weather and climate information is found below in Table 2.

Table 2. Summary of a SNOTEL site (NRCS 2009b) and the NWS COOP site at Diablo Dam (NWS COOP 2009). Data is provisional and subject to revision.

	Thunder	Diablo Dam
Watershed	Thunder	Lower Skagit
Elevation (m)	1280	400
Beginning Year of Data Collection	1987	1914
End Year of Data Collection	In Service	In Service
Mean Annual Temperature (° C)	2.3	9.14
Average Low Temperature (° C)/Month	-9.5/Dec. & Feb.	-2.7/Jan.
Average High Temperature (° C)/Month	21.2/Aug. & July	25.3/Aug. & July
*Mean Annual Precipitation (cm)	180.3	191.3
Average High Precipitation (cm)/Month	42.0/Nov.	32.0/Dec.
Average Low Precipitation (cm)/Month	1.9/Aug.	5.6/July

2.5 Hydrologic Setting

Hydrologic processes have significant effects on landform development, specifically in the formation of river canyons, floodplains, valley bottoms, terraces, debris cones, alluvial fans and deltas. Erosional processes related to seasonal fluxes in rainwater and snowmelt also directly influence development of mass movements. Specific examples of the effect of the hydrology on landform development are addressed in the Discussion section.

In general, the discharge of streams and rivers in the Thunder Creek Watershed often decreases drastically in late summer and winter, when glacial melt water dissipates and rainfall is minimal. These times of low flow can expose sand and gravel bars and dry up side channels. Rivers and creeks can typically reach flood stages in the North Cascades during both the spring and late fall, with fall floods more dominant at lower elevations and further west. Spring floods dominate at higher elevations and further east if their headwaters are east of the Skagit and Pacific Crests. South-facing aspects tend to produce more flashy flows due to a general lack of water holding capacity. First and second order streams on south-facing slopes are prong to flash floods from summer thunderstorms. Those lying in faults that have deep canyons often produce debris flows.

Large rain on snow events typically occur during the late fall and cause large changes to channels and terraces as they transport debris, erode river banks and mobilize large woody debris. During large magnitude events water levels rise, shifting channel and gravel bar positions and reintroducing water to side channels. Typically a large amount of sediment and woody debris can be provided from smaller side channels to Thunder Creek, as well as to the Thunder Arm.

A USGS stream gauging station is located near the mouth of Thunder Creek and has operated since 1920 (USGSb 2009) (Fig. 7). Monthly mean flows tend to be the highest in June and July, averaging 37 m^3/sec, and lowest in March, averaging 6.2 m^3/sec. It would appear from the data that most of the large flood events (over 280 m^3/sec) on record are all in the fall except for one, revealing influence of rain-on-snow events on the hydrology of the watershed. The highest peak annual flow on record occurred on October 20, 2003 at 504 m^3/sec (water year 2004) (Fig. 7). Major flooding due to rain-on-snow events in recent years likely caused significant channel reorganization in this watershed that is not reflected in this report. Landform mapping of Thunder Creek valley was originally completed in 2000. No field checks have been done since this time to evaluate the effects of subsequent floods.

Glacially fed streams dominate the hydrologic regime of the Thunder Creek Watershed and help to produce a continual flow of water throughout the year; with glacial runoff contributes an average of 32% of the summer (May to September) runoff, based on data from 1993 to 2007 (NOCA 2009). Another study found that in the Thunder Creek Watershed, glacier melt contributions varied from 0.6 to 56.6% and the onset of glacier melt ranged from June 13th to July 26th (Chennault 2004). This contribution from glacial ice and snowfields is critically important for sustaining local hydroelectric industries. Also, the cooler run-off provided by glacial melt water is essential to ensuring the survival of endangered salmon and trout species. Permanent snowfields and glaciers that feed the Thunder Creek Watershed are extensive in all sub-watersheds (Fig. 6).

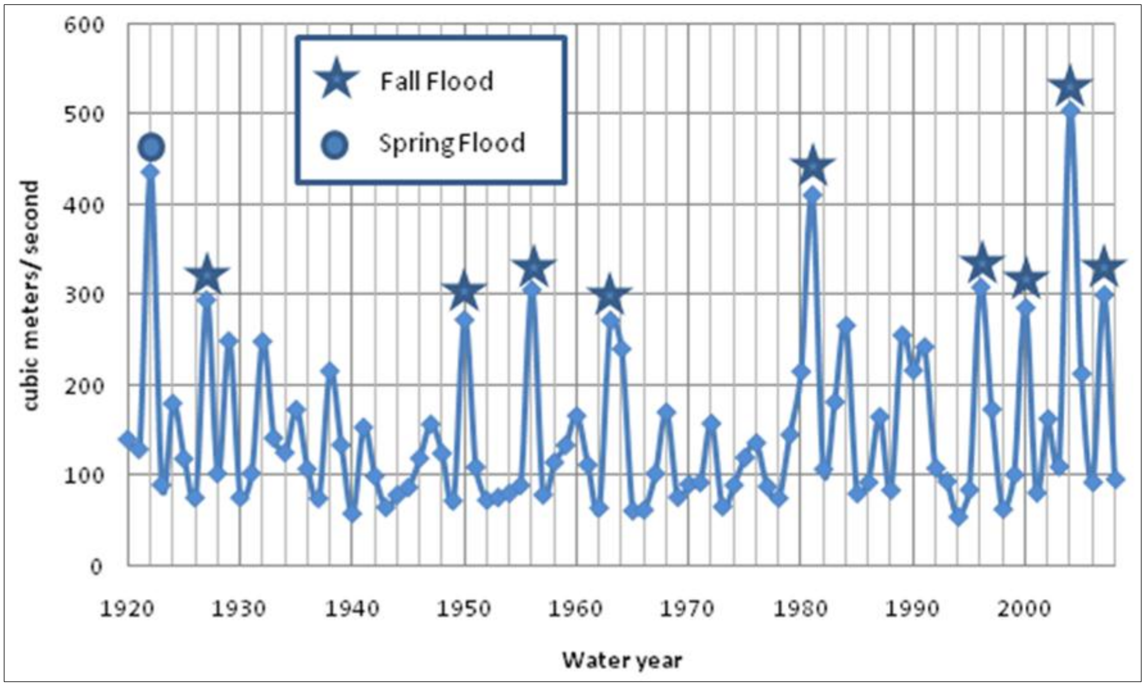

Figure 7. Peak annual flow for Thunder Creek from 1920 to 2008 (USGSb 2009).

As of 1998, there are 51 glaciers that occupy an area of 36.8 km^2 (~ 12 percent of the watershed) in the Thunder Creek Watershed (Granshaw 2001). Boston Glacier, at the head of Skagit Queen Creek, is the largest glacier in the North Cascades at 6 km^2. Glacial inventories based on 1950-1960 air photos (Post et al. 1971) have been compared to a 1998 inventory (Granshaw 2001). The study concluded 8.3 km^2 of ice was lost in NOCA with 35 percent of that total lost in the Thunder Creek Watershed alone (2.9 km^2).

The glacier monitoring program at NOCA provides significant insight into the contribution glaciers are making to the overall watershed total run-off. NOCA has been conducting a mass balance study on North Klawatti Glacier since 1993 (NOCA NPS 2009). North Klawatti Glacier, located on the northeast face of the Austera Towers and the southwest face of Primus Peak, is one of the four glaciers monitored by the NPS (Fig. 6).

Below are a summary of results for North Klawatti Glacier (Fig. 8). The North Klawatti Glacier, at elevation 1775 – 2400 m, while having some net positive years, has been losing mass since the end of the Little Ice Age in 1900. Photographs of the Neve and Colonial Glaciers also reveal the overall decline in glacier mass over the last fifty years (Figs. 9 and 10). Additional historical photographs of the Banded Glacier on Mount Logan, the Borealis Glacier on Primus Peak, the Buckner Glacier on Mount Buckner and more can be viewed online (http://www.nps.gov/noca/naturescience/glacial-mass-balance8.htm). More detail regarding the status of glaciers and the methods of glacier monitoring within NOCA and MORA can be found in several locations (Riedel et al. 2008, NOCA NPS 2009, Riedel et al. *in review*).

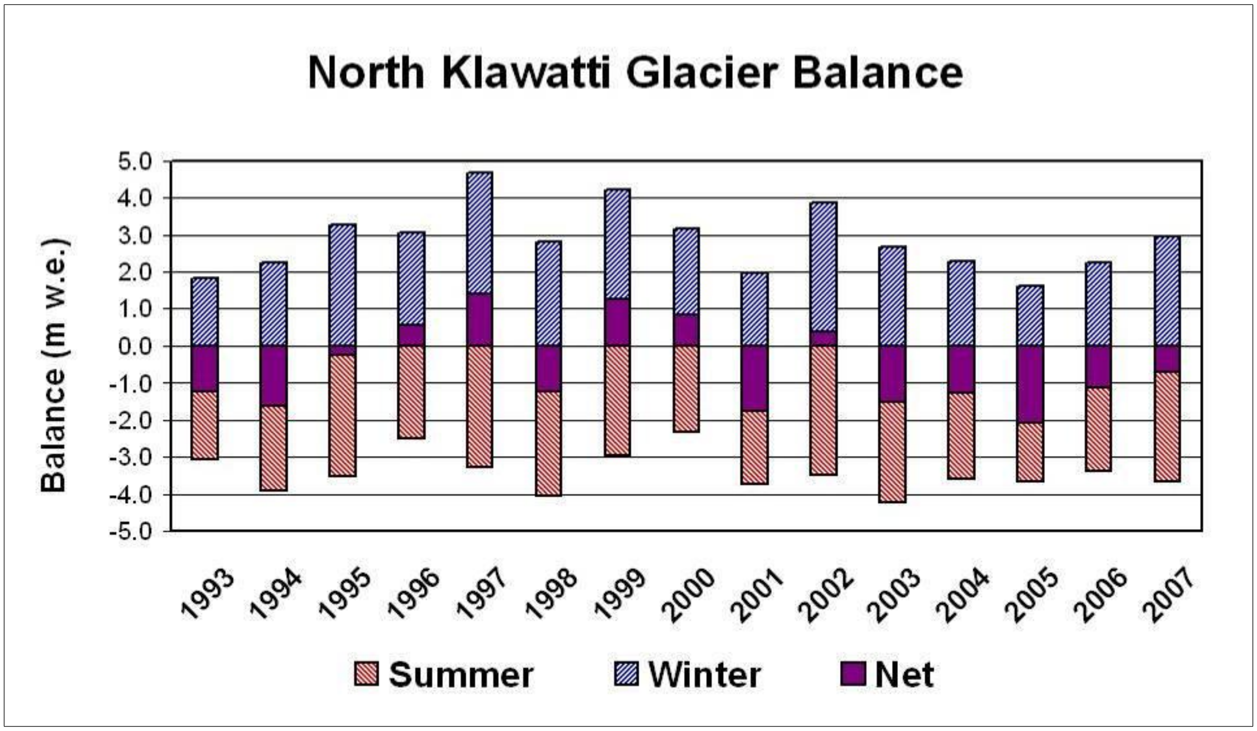

Figure 8. Mass balance chart of North Klawatti Glacier. The vertical axis is the amount of water gained (winter balance), lost (summer balance) and retained (net balance; solid bar) in meters of water equivalent averaged across the glacier.

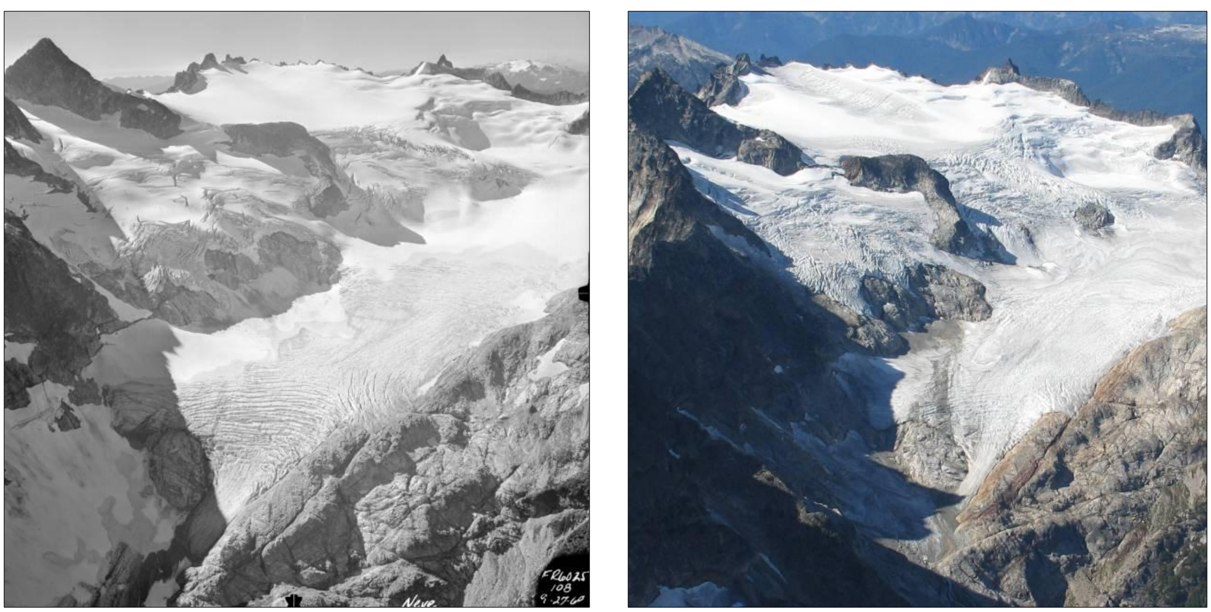

Figure 9. Photograph of Neve Glacier taken on September 27, 1960 on left (Post et al. 1971) and on September 28, 2005 on right (Photo courtesy of John Scurlock).

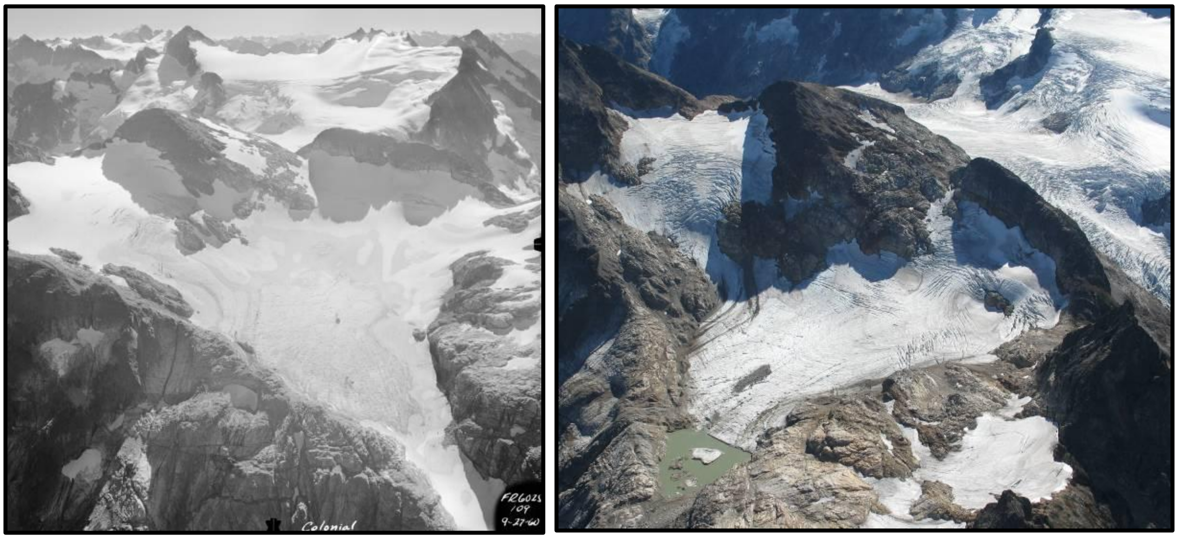

Figure 10. Photograph of Colonial Glacier taken on September 27, 1960 on left (Post et al. 1971) and on September 28, 2005 on right (Photo courtesy of John Scurlock).

2.6 Vegetation

Snow, bare rock and ice cover approximately 40 km^2 of the Thunder Creek Watershed. The remainder of the watershed is dominated by conifer species of trees. Conifers dominate over hardwoods due to the regional high precipitation that occurs in the winter and relatively dry summers (Franklin and Dyrness 1973). Tree line, the upper limit of closed forest, occurs at 1700 m. Above this, scattered trees and subalpine vegetation form subalpine parkland which transition into subalpine meadow. The upper limit of vegetation is the sparsely vegetated alpine zone. The alpine vegetation dominates at elevations above ~ 2000 m. Alpine vegetation is comprised primarily of lichens, mosses and sedges. Heavy snow creates a wide zone between 1750 m and 2000 m of subalpine fir (*Abies lasiocarpa)*/mountain hemlock (*Tsuga mertensiana*) and open meadow communities dominated by heather shrubs (Phyllodoce spp., Vaccinium spp. and Cassiope spp.) or moist meadow communities. Wildflowers such as Indian paintbrush, mountain bistort, mountain harebell, tiger lily and red columbine occur in subalpine meadows. East of the Skagit Crest, alpine larch (*Larix lyallii*) is commonly found in the subalpine and alpine zone.

Below the subalpine forested communities is the montane forest from 1700 to 400 m. Pacific silver fir (*Abies amabilis*) and western hemlock (*Tsuga heterophylla*) dominate this zone. Douglas-fir (*Pseudotsuga menziesii)*, western hemlock (*Tsuga heterophylla)* and western red-cedar (*Thuja plicata)* make up the lowland forest below 400 m along with western yew (*Taxus brevifolia)*. Lodgepole pine tends to dominate on exposed bedrock benches. Avalanche chutes are typically dominated by a dense cover of red alder (*Alnus rubra)* and vine maple (*Acer circinatum*). Red alder and black cottonwood (*Populus balsamifera* spp. *trichocarpa*) forests dominate the riparian zone. In areas of oxbows, isolated river channels and slow water along the river help wetlands develop. Wetlands within the lower Thunder Creek Watershed are dominated by obligate wetlands species such as sedges and rushes.

3 - Landform Mapping at NOCA

3.1 National Hierarchical Framework for Ecological Units

NOCA landform mapping is linked with the USFS multi-scaled "National Hierarchical Framework for Ecological Units" (Cleland et al. 1997) for public lands in western Washington (Table 3). Together the USFS and NPS have mapped at the Subsection (1:250,000), LTA (1:62,500) and Landform (1:24,000) scales. Ecological land units describe the physical and biological processes that occur across the landscape and are used for ecosystem classification and mapping purposes (Davis 2004).

Table 3. Map scale and polygon size in the National Hierarchical Framework for Ecological Units (Cleland et al. 1997).

Ecological unit	Map scale range	General polygon size
Domain	1:30,000,000 or smaller	1,000,000s of square km
Division	1:30,000,000 to 1:7,500,000	100,000 of square km
Province	1:15,000,000 to 1:5,000,000	10,000s of square km
Section	1:7,500,000 to 1:3,500,000	1,000s of square km
Subsection	1:3,500,000 to 1:250,000	10s to low 1,000s of square km
Landtype association	1:250,000 to 1:60,000	1,000s to 10,000s of ha
Landtype	1:60,000 to 1:24,000	100s to 1,000s of ha
Landtype phase (Landform)	1:24,000 or larger	<100 ha

3.1.1 Subsection (1:250,000)

The first product was a seamless coverage in the North Cascade region at the Subsection scale where the focus is on climate, bedrock geology and topography at a regional scale. The LTA scale is mapped by watershed and units are based on topography and process. Landscape mapping units are defined on the basis of climate, bedrock geology and topography at a regional scale. Features of the landscape such as regional hydrologic divides, contacts between major bedrock terranes and glaciated topography are boundaries of Subsection mapping units. In the North Cascades, the draft Subsection map (Fig. 11) identifies 17 mapping units; including: Major Valley Bottoms, Crystalline Glaciated Cascade Mountains, Volcanic Cones and Flows, Sedimentary Cascade Hills, etc. These units were developed by Wenatchee National Forest (Davis 2004) and applied to the west slope of the Cascades by staff from Wenatchee National Forest and NOCA (Riedel and Probala 2005).The Thunder Creek Watershed is part of the Crystalline Cascade Mountains and Wenatchee Highlands subsections.

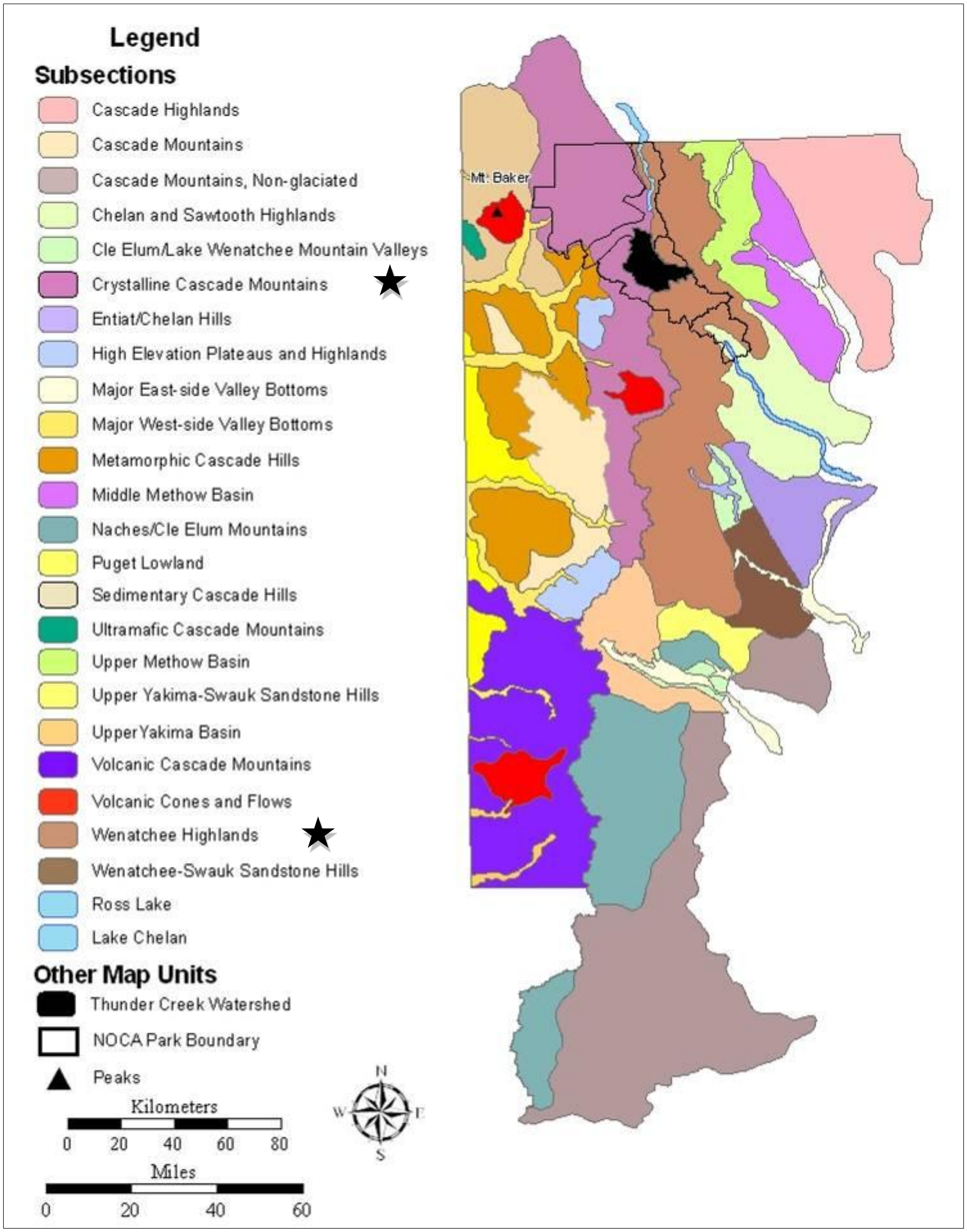

Figure 11. Subsection map (1:250,000) of the North Cascade region showing the location of the Thunder Creek watershed and North Cascades National Park.

3.1.2 Landtype Association (1:62,500)

Landscape scale ecological units or Landtype Associations (LTAs) are the smallest scale within the hierarchical framework that meets most NPS challenges and management needs. At this mapping scale, geomorphic process and topography become more important than climate and bedrock geology. The first step in mapping LTAs is to identify large scale erosional features of mountains and valleys such as valley bottom, cirque basin, glaciated valley and river-cut valley (Davis 2004). Final map units incorporate data on vegetation and bedrock type. For example, in the North Cascades, a valley would be broken into three units that coincide with major elevation-controlled changes in vegetation and topographic breaks. Mapping is conducted by interpretation of 1:62,500 scale stereo aerial photography and topographic maps. At this time no LTA mapping has been completed for the Thunder Creek Watershed.

3.1.3 Landtype Phase (Landform) (1:24,000)

These are the smallest functional units of the landscape that are created by discreet geologic processes, most of which are active in the watershed today. These subdivisions of Landtypes, or landforms, are based on topographic criteria, hydrologic characteristics, associations of soil taxa and plant communities. They are readily identified on topographic maps and aerial photographs, but often require field-verification when they are located beneath closed canopy forest on valley floors. A suite of 29 different landforms is currently being mapped at NOCA and are listed below in Table 4. A detailed description of each landform which includes information on location, associated landforms, process, material, mapping guidelines and potential natural vegetation will be published in separate NPS Technical Report.

Table 4. Landform (1:24,000) legend for North Cascades National Park.

Unit	Description
-High elevation landforms (primarily erosional in genesis)	
H	Horn
A	Arete
C	Cirque
O	Other Mountain
R	Ridge
P	Pass
NM	Neoglacial Moraine
PG	Patterned Ground
- Valley Slope landforms (primarily erosional in genesis)	
VW	Valley Wall
RC	River Canyon
BB	Bedrock Bench
-Transitional landforms between valley slope (erosion) and valley floor (deposition)	
MM-F	Rock Fall and Topple
MM-A	Debris Avalanche
MM-S	Slump and Creep
MM-DT	Debris Torrent
MM-SG	Sackung
MM-SL	Snow Avalanche Impact Landform
DA	Debris Apron

Table 4. Landform (1:24,000) legend for North Cascades National Park (continued).

Unit	Description
DC	Debris Cone
AF	Alluvial Fan
-Valley bottom landforms (primarily depositional in genesis)	
FP	Floodplain
VB	Valley Bottom
T	Terrace
FT	Fan Terrace
SH	Shoreline
D	Delta
-Other landforms	
PM	Pleistocene Moraine
E	Esker
U	Undifferentiated

3.2 Landform Age

Landforms can either be depositional in nature such as moraines and alluvial fans; or they can be erosional such as bedrock benches and horns. Many depositional features such as moraines and terraces were formed during the last ice age while other depositional features such as debris cones and landslides are forming today. Landform age can vary greatly within a watershed depending on the surficial process that created it. Approximate ages can be assigned to depositional landforms based on their available radiocarbon dates, associated process of formation, volcanic tephra, soil development and vegetation type and age. The approximate ages of landforms at NOCA reflect their stability and are listed below in Table 5. Data were obtained from several different radiocarbon dates on a variety of landforms within NOCA by the park geology and archeology programs (Mierendorf et al. 1998, Mierendorf 1999, Riedel 2007).

Table 5. Approximate landform surface ages at North Cascades National Park.

Landform	Age
Debris cone, floodplain, alluvial fan	<500 years
Most neo-glacial moraines	<300 years
Valley walls	100-12,000 years
High outwash terraces and fan terraces	10,000-12,000 years
Pleistocene moraines	12,000 and 18,000 years
Bedrock benches, horns, arêtes	12,000 years
Mass movements (landslides)	0-14,000 years

3.2.1 Landforms and Soils

The North Cascades provide a challenging environment to compile a traditional soil survey. Studies in the North Cascades and the surrounding vicinity link pedogenic processes to soil-landscape relationships and provide insight to the links between landforms and soils (Rodgers 2000, Briggs 2004, Briggs et al. 2006). Soil distribution is closely linked to the geomorphic processes at play over the last 15 Ka. NRCS soil scientists incorporate landform maps into the RASP modeling scheme as an indicator of soil stability and parent material (Rodgers 2000, Briggs 2004, Frazier et al. 2009).

As a result of the Cordilleran Ice Sheet scouring much of the North Cascades, bedrock as a parent material seldom influences soil formation. Upon retreat of the ice sheet, glacial drift was deposited unevenly across the landscape. This glacial drift, along with subsequent tephra deposits, provides the primary parent materials for soil formation. The most significant tephra layer in the North Cascades is that of Mount Mazama, deposited ~7.6 Ka cal. years B.P. (Zdanowicz et al. 1999). In large part it is the preservation, mixing and removal of this tephra that provides one indication of landform stability, age and soil type. It is theorized, for example, that the majority of slope readjustment occurred between 13 to 9 Ka cal years B.P. as evidenced by the significant amount of tephra preserved on the valley walls (Briggs et al. 2006).

Soil classification within NOCA is largely determined by the presence or absence of tephra. The dominant soil orders found within NOCA include Andisols, Inceptisols, Entisols, Spodosols and to a far lesser extent Histosols (Soil Survey Staff 1999). Andisols have a thick (> 36 cm) mantle of material strongly influenced by volcanic tephra. Inceptisols have either a thin mantle (< 36 cm) of volcanic tephra influenced material or highly mixed volcanic tephra and glacial drift throughout the soil profile. Entisols within NOCA are distinguishable by the absence of volcanic tephra within the soil profile. Spodosols on the other hand are more a product of pedogenic processes rather than parent material. Spodosols require a certain amount of landscape stability for pedogenic process to operate over time. As such, Spodosols are typically associated with older, more stable landforms that readily preserve tephra and provide long lived plant communities. Histosols are typically found in areas with persistent water tables that preserve organic matter within the soil profile.

Each landform inherently suggests a certain degree of stability and parent material type. The older and/or more stable landforms such as Pleistocene moraines and bedrock benches typically support the formation of Andisols and Spodosols. Stable landscapes preserve volcanic tephra in distinct mantles and allow pedogenic processes to operate over extended periods of time. The degree of pedogenic development is also determined by other soil-forming factors such as vegetation and climate. Differentiating between Andisols and Spodosols ultimately comes down to the morphological expression (presence or absence of albic and/or spodic horizons) observed within the soil profile (Soil Survey Staff 1999). Other landforms that typically support Andisol formation (valley walls, debris aprons) may lack long term stability. However, through gravitational redistribution, tephra may accumulate and ultimately result in the formation of Andisols. Landforms formed primarily through alluvial erosion tend to lack soil material strongly influenced by volcanic tephra. On landforms such as debris cones, terraces and alluvial fans, Inceptisols dominate. Entisols are found on the youngest landforms most susceptible to recent flooding (floodplains and terraces) or recent deglaciation (cirques and little ice age moraines) that the soil profile lacks the influence of volcanic tephra. Histosols are the most independent of landform as they simply require an accumulation of organic matter (Soil Survey Staff 1999). This accumulation of organic matter can be found in micro-depressions and floodplains throughout the park where water tables are persistent and organic decomposition is slower than accumulation.

4 – Methods

4.1 Preliminary Methods

At the beginning of the mapping process NOCA was divided into watersheds that are mapped separately. This project recognizes a watershed as a major drainage system on a forth order or larger stream. Each watershed is further broken down into smaller units referred to as sub-watersheds. These landform maps represent a compilation of several quadrangles over a number of years of field work. A combination of mapping techniques used to conduct this inventory include the use of color stereo-pair 1998 air photos at the 1:12,000 scale, USFS LTA line work, bedrock geology maps and field investigations. Initially, the pattern of contour lines on United States Geological Survey (USGS) 7.5 minute topographic maps in conjunction with the 1:12,000 air photos are used to outline landforms. Though some landforms (e.g., debris avalanches, bedrock benches and debris cones) are easily identifiable using air photos and contour lines, other landforms (e.g., terraces, floodplain boundaries and small mass movements) require field identification. The minimum size for a mapping unit is approximately 1,000 m^2 with some exceptions for smaller units like Neoglacial moraines and slumps.

4.1.1 Field Methods

Each field trip typically focuses on a sub-watershed unit within a watershed. Before entering the field, a task list of areas to visit is developed. As much ground as possible is surveyed, but efforts are concentrated within the valley bottom. Generally, walking the banks of rivers enables mapping of terraces, slumps and floodplain boundaries. Places where the valley bottom is wide or complex, cross sections are made from one side of the valley to the other. Some landforms need further exploration and are investigated in more detail as needed. While in the field, geologists transfer landform boundaries onto USGS 7.5 minute maps or update boundaries previously mapped in the office. Fieldwork also generates additional information about terrace heights and material type; this information is recorded in field notebooks along with sketches of valley cross-sections. A draft version of the landform description report is used to aid in the identification of landform units while in the field.

4.1.2 Digitizing Methods

After identifying landforms and drawing the boundaries, each area is peer-reviewed for accuracy and mapping consistency. Landform linework is then transferred onto a new 7.5 USGS minute paper quadrangle, which serves as the final map. All boundaries of landforms are then drawn onto Universal Transverse Mercator registered Mylar and a large format scanner transfers lines into digital format. Using GIS software, scans are edited and polygons, which represent landforms, are labeled resulting in a final digitized map (Fig. 2). As each polygon is labeled, the shape and location is checked for accuracy. Using the most up to date National Agriculture Imagery Program (NAIP) imagery from the United States Department of Agriculture (USDA), small scale changes can be made in landform placement. Also, 10 meter digital elevation models (DEMs) are overlaid with the landform layer, enabling more fine-tuned editing of placement. If additional editing is needed, on screen digitizing is completed. Landform surveys are occasionally updated as new landforms are identified and new areas are surveyed. The GIS is then updated to accommodate these changes.

4.2 Areas Surveyed

There are no roads that enter the main Thunder Creek Watershed, but State Highway 20 provides access to the trailhead at Thunder Arm. From here access is limited to this trail system which follows Thunder Creek up valley and splits at the confluence of Thunder and Fisher Creeks. The Thunder Creek trail continues up and over Park Creek Pass (1848 m) and the Fisher Creek trail continues up and over Easy Pass (2000 m). There are also unmaintained climbing and animal trails that were followed throughout the watershed when available.

All field investigations in the Thunder Creek Watershed were completed in 1995 – 1999 by Jon Riedel, Rob Burrows and Jeanna Wegner of the NOCA Resource Management staff. These areas were accessed by trail and also by traveling in the riverbed via wading. Field visits to each major tributary were attempted from the main stem of Thunder Creek. However, due to difficult travel (e.g. canyons, thick vegetation, cliffs and minimal trail availability) some areas were not field checked. The tributaries that were field checked include the main stem of Thunder Creek, Fisher, Lower McAllister and Skagit Queen Creeks. The West Fork, uppermost McAllister and Neve Creeks were mapped via aerial photographs. Future surveys of valley heads may be conducted if opportunities arise. Minimal high elevation ground surveys were performed due to abundant air photo coverage and good visibility due to lack of vegetation on high elevation landforms. High elevation surveys completed include visits to North Klawatti Glacier, Easy Pass and Park Creek Pass. Aerial surveys were made via several helicopter flights while in transit to other NPS research projects.

5 - Results and Discussion

5.1 General Watershed Overview

The results and discussion of the Thunder Creek Watershed landform mapping are divided into the main stem and its sub-watersheds of the West Fork, Skagit Queen, McAllister, Neve, Colonial and Fisher Creeks. Thunder Creek begins on the north-west cirque of Buckner Mountain, which holds the Thunder Glacier (Figs. 2 and 6). Along with Park Creek Pass and Mount Logan, this forms the southeast boundary of the watershed, dividing it from the Stehekin River Watershed along the Pacific Crest. West of Buckner Mountain, the peaks of the Skagit Crest define the watershed along its south and southwestern border from the Cascade River Watershed. Continuing north, the Skagit Crest continues to confine the watershed on its western border, separating it from the Lower Skagit Watershed. The northeastern border of the watershed is defined by Ruby Mountain, Fourth of July Pass and Red Mountain. Fourth of July Pass is a broad divide that separates the watershed from the eastward flowing Panther Creek. Red Mountain transitions east into Ragged Ridge, which confines the northern border of the Fisher Creek drainage. Easy Pass and the peaks of the Pacific Crest define south-east to south boundary of the watershed. Fisher Pass marks the local drainage divide between the west flowing Skagit River system and the south to southeast flowing Columbia system. The outlet of Thunder Creek spills into Diablo Lake, part of the Lower Skagit Watershed

Throughout the watershed, steep cliffs on north aspects are contrasted by gentler rises on south aspects. Climate asymmetry is pronounced in the watershed. McAllister, Neve, Colonial, West Fork and Skagit Queen Creeks flow off the wetter Skagit Crest, and have U-shaped valleys to their junctions with Thunder Creek. Fisher Creek's valley head is on the drier Pacific crest and its U-shaped profile is replaced by a V-shaped river canyon on its lower 10 km.

The overall geomorphology of the Thunder Creek Watershed is mainly valley wall, which accounts for 53% of the total watershed. Formed by the actions of continental and alpine glaciation, valley walls dominate the landform inventory of NOCA overall (Table 6). High elevation cirques account for another 20% of the watershed, which only 2.6% is riparian (floodplain, alluvial fan and valley bottom). High local relief is reflected by the fact that debris aprons, debris cones and mass movements account for 13% of the Thunder Creek Watershed.

Table 6. Summary of area of each landform type within the Thunder Creek Watershed.

Landform Type	Number Observed	Area (km^2)	Percent of the Chilliwack River Watershed
Valley Wall	32	161.33	52.95
Cirque	68	62.32	20.46
Debris Apron	124	27.26	8.95
Mass Movement – Debris Avalanche	24	10.35	3.40
Debris Cone	120	9.57	3.14
Floodplain	11	5.57	1.83
Arete	85	4.38	1.44
River Canyon	29	3.89	1.28
Mass Movement – Fall/Topple	57	3.78	1.24
Bedrock Bench	36	3.40	1.12
Terrace	42	2.94	0.97
Ridge	29	2.36	0.77
Horn	40	2.07	0.68
Valley Bottom	14	1.65	0.54
Pleistocene Moraine	11	0.67	0.22
Alluvial Fan	7	0.60	0.20
Neoglacial Moraine	44	0.53	0.17
Pass	38	0.52	0.17
Mass Movement – Debris Torrent	23	0.42	0.14
Undifferentiated	10	0.39	0.13
Fan Terrace	5	0.33	0.11
Other Mountain	10	0.29	0.10
Mass Movement – Slump/Creep	10	0.04	0.01
Mass Movement-SAIL	1	0.003	0.00
Totals	869	304.663	100

5.1.1 High Elevation Landforms

High elevation landforms (cirque, Neoglacial moraines, ridges, arêtes, other mountain, horns and passes) account for 72.5 km^2, which is 24% of the total area in the watershed (Table 6). The majority of this area is cirque basin covered by modern glaciers. Being the most heavily glaciated watershed in NOCA, there are several particularly well-developed cirques. They are located on the north faces of Colonial Peak, Snowfield Peak, Primus Peak, Klawatti Peak, Forbidden Peak, Mount Torment, Mount Logan, Mount Buckner and Boston Peak as well as the northeast faces of Klawatti Peak, Eldorado Peak, Austera Peak and Mount Logan. Aspect has particularly strong control on the development of cirque basins. North and east facing cirques have had more active glaciers and freeze-thaw processes that create deep cirques. They also tend to extend to lower and contain Neoglacial moraines that terminate at lower elevations then their south and west facing counterparts. These patterns are noted throughout the watershed.

Impacts from the ice sheet are evident throughout the Thunder Creek Watershed and include broadened passes and ridges, enlarged valley cross-sections, beheaded valleys, truncated valley spurs and thick accumulations of till and outwash. Tributary systems were left as hanging valleys with bedrock canyons or narrow stepped waterfalls at their mouths. The Cordilleran Ice Sheet filled valleys to depths of ~ 2000 m, or more than a mile thick. Only the magnificent horns along the Pacific and Skagit Crest were high enough to stand above the ice sheet as nunataks. Lower ridges and mountains were mostly rounded by the ice sheet and contain glacial striae and polished bedrock. Advance rates of the ice sheet are estimated at 130 m/yr in Puget lowland, while ice funneled down the Skagit valley here probably reached speeds 5-6 times this rate (Evans 1990). Valleys like Thunder, Chilliwack, Upper Skagit and Pasayten, which trend north/south, are particularly broad since they were parallel to ice sheet flow (Riedel 2007).

The best examples of Pleistocene glacial deposits are found in this watershed are in Fisher Creek. Recent glacial activity is recorded in Neoglacial moraines. These landforms were deposited by alpine glaciers in the last 700 to 100 years. There are forty-four Neoglacial moraines in the Thunder Creek Watershed. The majority of them are present at the valley heads of McAllister, Skagit Queen and Thunder Creek, recording evidence of a climate more favorable to glacier growth and stability. Comparison of modern glacier cover to the extent reached to deposit these Neoglacial moraines indicate that the watershed has lost 22.5 to 12.8% of its glacial cover since the end of the Little Ice Age (Chennault 2003).

5.2 Valley characteristics

5.2.1 Main Stem of Thunder Creek

The valley head of the main stem of Thunder Creek begins at Park Creek Pass and surrounding cirques basins (Fig. 12). The pass is a narrow notch at elevation 1890 m and its morphology indicates that a small tongue of the ice sheet flowed through the pass (Fig. 13). Two impressive peaks make up the headwall. To the west of Park Creek Pass is the northeast facing cirque of Buckner Mountain. Holding the Thunder Glacier (~0.2 km^2), the cirque extends down to 1550 m and contains one Neoglacial moraine. To the east of Park Creek Pass is a series of cirques, horns and arêtes on the south side of massive Mount Logan. Cirques on this side of the pass extend down to 1780 m and contain several smaller glaciers and snowfields (~1.1 km^2 total). There are a total of three Neoglacial moraines in the northwest facing cirque of Mount Logan, directly northeast of the pass.

The Thunder Creek headwaters flow northwest into Thunder Basin, a hanging valley with a flat valley floor. The creek parallels a northwest-southeast fault mapped on the upper valley wall, as well as three mapped near Park Creek Pass. A large rock fall (503,906 m^2) composed of granodioritic orthogneiss of the Skagit Gneiss Complex is also mapped near these faults, which possible influenced its formation. Travelling northwest from Park Creek Pass, valley bottom begins at elevation 1475 m as Thunder Creek meanders by several debris cones on both sides of the valley. On the east-facing valley wall, a debris avalanche composed of orthogneiss delivered ~127,600 m^3 of sediment to the creek. On the west-facing valley wall, two rock falls/topples within orthogneiss are also mapped, as is one Pleistocene moraine that terminates at elevation 1640 m. The west-facing cirques of Mount Logan contain one Neoglacial moraine at elevation 2100 m. Two unidentified units that could be Pleistocene moraines or remnants of debris avalanche deposits are mapped in this stretch of valley bottom.

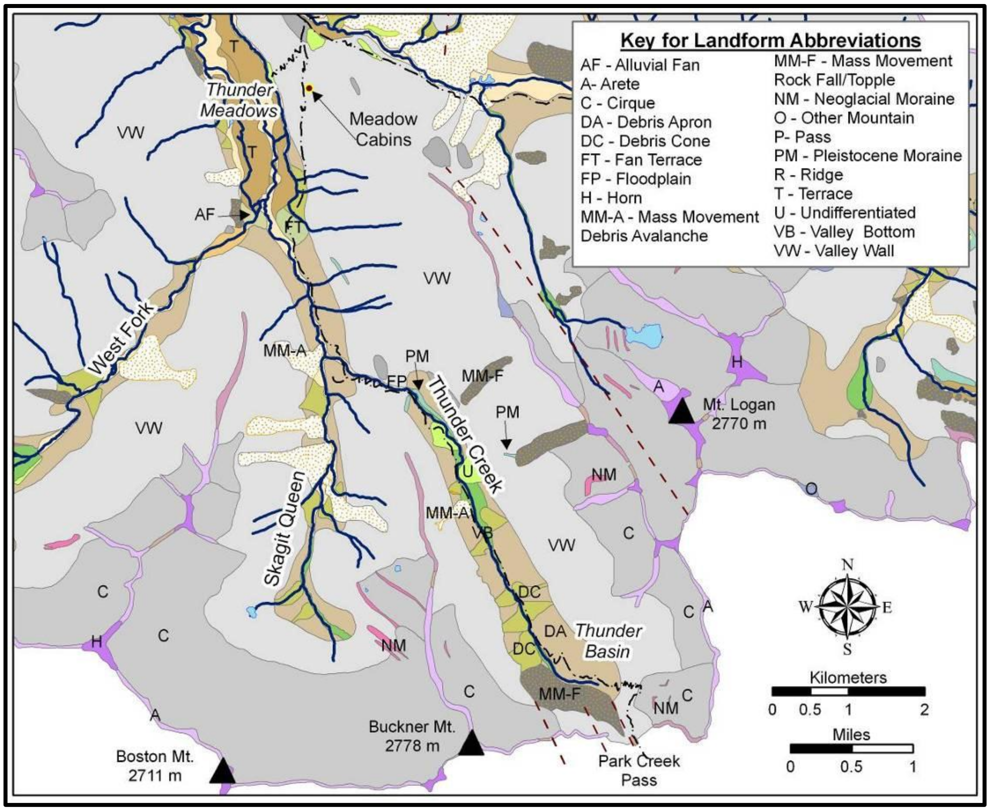

Figure 12. Landform map of Upper Thunder Creek, black dot-dashed lines are trails and red dashed lines are faults.

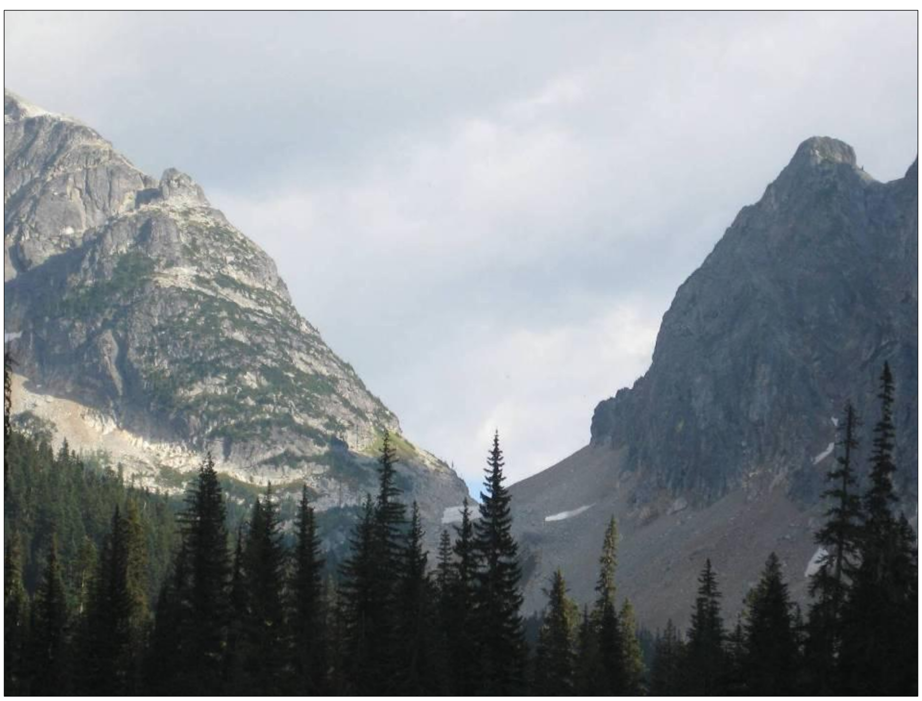

Figure 13. The distinct narrow notch of Park Creek Pass, photograph taken from Thunder Basin. NPS Photo.

The transition from valley bottom to floodplain occurs at elevation 1220 m. Guidelines for determining this transition are based on flood plain width, presence or absence of river terraces, gravel bars, or bedrock and stream gradient (Jarrett 1990). At this transition, there are Pleistocene moraines on either side of the creek. Continuing northwest, Skagit Queen Creek merges with Thunder Creek. No alluvial fans or terraces are mapped here due to the steep stream gradient, but a debris avalanche in orthogneiss is located on the east-facing valley wall. Thunder Creek turns north at this intersection to follow the trend of the Thunder Lake Fault. In this reach it passes a Pleistocene moraine located at elevation 850 m on the west-facing valley wall.

Below its junction with the West Fork, the character of Thunder Creek changes dramatically as it enters Thunder Meadows. The floodplain width changes from an average of 0.06 km above the West Fork outlet to 0.2 km in the meadows. The extensive wetlands, floodplain and terraces in the meadows lie in an over-deepened part of the valley. As recently as about 500 years ago much of the meadow was a lake. Although it appears that the meadow may be moraine-damned, it is more likely that bedrock control at the outlet is responsible. The large alluvial fan of Fisher Creek may also have had some influence.

On the reach between the West Fork and the Fisher Creek outlet, Thunder Creek passes between 18 terraces, reflecting the drop of stream gradient, velocity and sediment load (Figs. 12 and 14). Debris cones are located on both sides of the valley. The historical structure known as Meadow Cabins is located on the valley wall directly above the large wetland known as Thunder Meadows. The cabin was built on an undifferentiated landform that might a Pleistocene moraine or simply a mound of glacial till. The landform provided a building site out of the extensive wetlands below and was likely in order to avoid floods on Thunder Creek. Two rock falls/topples and one debris avalanche, all composed of orthogneiss, are on the east-facing valley wall.

The waters of Fisher Creek enter the creek at elevation 610 m, where an extensive alluvial fan is deposited that constricts the floodplain. At this location the Thunder Creek bed load changes from one dominated by pebbles and gravel to one dominated by boulders and cobbles. Along the eastern valley wall below the mouth of Fisher Creek is an extensive bedrock bench system (Fig. 14). These features formed because ice flowing down Fisher Creek was blocked by a large glacier in the Thunder Creek valley. The smaller Fisher valley glacier was thus forced against the valley wall and cut a prominent bedrock bench as it flowed parallel to the Thunder Creek valley glaciers. Most extensive bedrock benches in the North Cascades form in this manner.

Continuing north to the outlet of McAllister Creek, the creek flows between two small terraces. Just prior to the McAllister Creek junction, the creek flows past a large (384,446 m^2) Pleistocene moraine on the east side of Thunder Creek. Deposits at this side are more than 30 m thick and are composed mainly of glacial till. At the junction with McAllister Creek the main Thunder Creek channel is constricted by two bedrock benches that are the lower end of a valley spur. Additional benches are present on the valley wall of this section, as are rock falls within the debris apron. Thunder Creek then enters into a river canyon for a length of nearly 4 km. While in the river canyon, Neve Creek enters the main stem, depositing an alluvial fan at the confluence. The waters off of Fourth of July pass also enter Thunder Creek from the east. A series of pools carved into a bedrock bench by melt water from the ice sheet, known as the Panther Potholes, are located on the valley wall just below Fourth of July Pass.

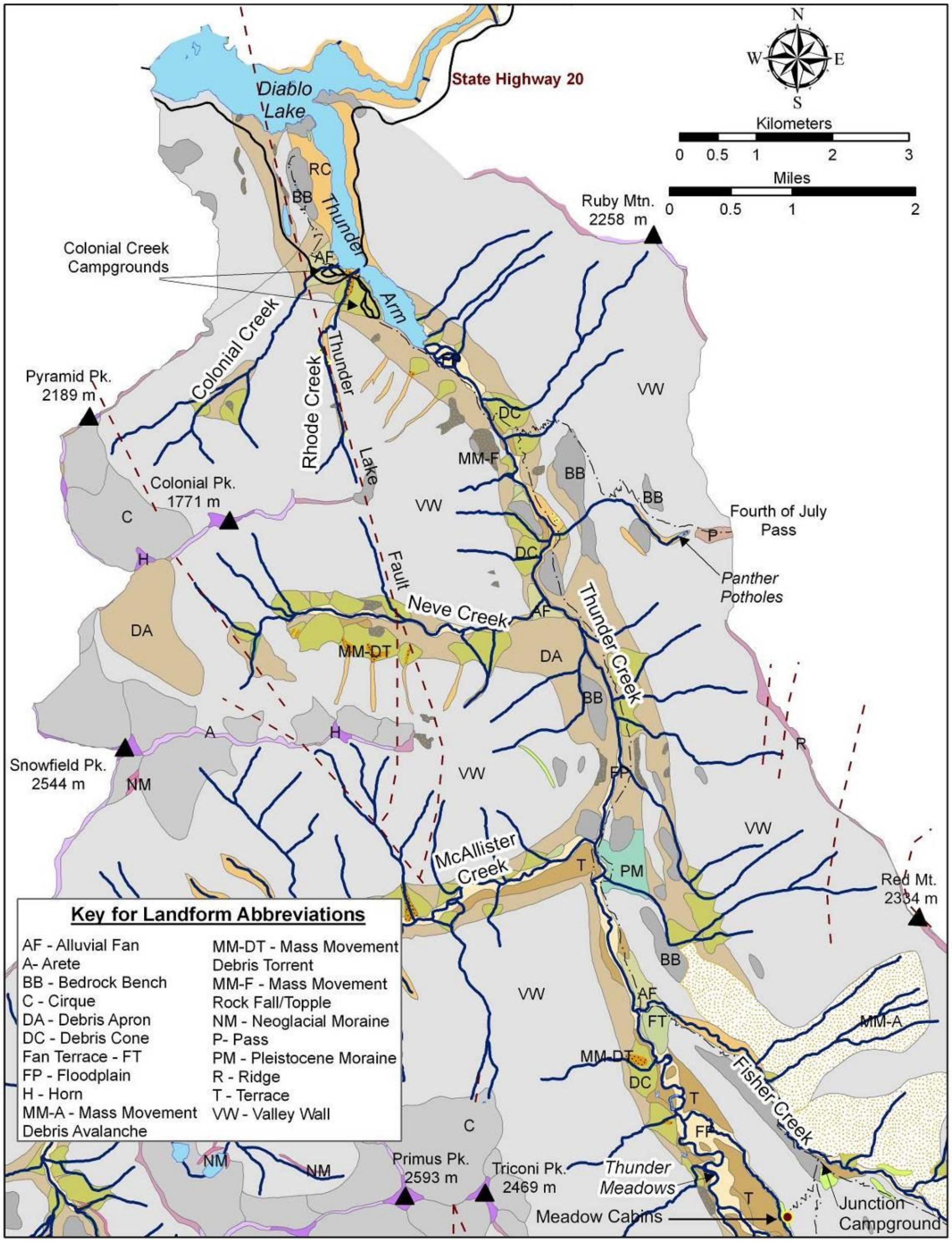

Figure 14. Landform map of Lower Thunder Creek, black dot-dashed lines are trails and red dashed lines are faults.

Upon emerging from the river canyon north of Neve Creek, lower Thunder Creek passes through a 0.36 km wide floodplain flanked by debris cones and alluvial fans of small unnamed creeks. Steeply graded side streams enter via river canyons on the west side of the creek. Thunder Creek enters Thunder Arm at elevation 370 m. The area beneath the lake is mapped as floodplain for one kilometer, and then the valley becomes a deep river canyon at Colonial Creek and enters the Skagit Gorge. Along the shores of Thunder Arm several side streams contribute run-off, including Rhode and Colonial Creeks. Rhode Creek enters Thunder Arm via a debris cone, which contains the south unit of Colonial Creek campground. A debris torrent is mapped on the outlet of Rhode Creek. The Thunder Lake Fault, which controls the trend of the entire main drainage, is mapped directly along Rhode Creek and parallel to the Thunder Arm. Colonial Creek enters Thunder Arm just after it passes underneath State Highway 20, spilling out on an alluvial fan into the north unit of the Colonial Creek campground. A small Pleistocene moraine is located at elevation 400 m at the west side of the mouth of the Thunder Creek valley.

Extensive bedrock benches (Fig. 14) between Diablo and Ross Dams represent the base of the U-shaped trough carved through Skagit Gorge by the Cordilleran Ice Sheet. The ice sheet diverged to flow in three directions from the area near Ross Dam, including down the Skagit Gorge and up Thunder and Ruby Creeks (Riedel et al. 2007).

5.2.2 Skagit Queen Creek

Skagit Queen Creek runs for 3 km in a north-south orientation likely due to the influence of the Thunder Lake Fault. The creek drains from the headwall of the Boston Glacier, the largest glacier in the NOCA at 6.8 km^2 (Fig. 6). The main Boston glacier cirque extends down to 1830 m, and this well-defined cirque is contained between Boston Peak, Buckner Mountain and Forbidden Peak (Fig. 15). Jagged arêtes connect these peaks, which are collectively known as Ripsaw Ridge. Below Boston Glacier this cirque are two Neoglacial moraines, extending down to 1622 m. Two smaller cirques to the northeast of the Boston Glacier, on the northwest ridge of Buckner, each contain a Neoglacial moraine. These two cirques extend down to 1622 m with the lower Neoglacial moraine terminating at 1646 m.

Valley bottom begins at elevation of 1219 m in the Skagit Queen valley. In this reach numerous debris cones are present. The transition to floodplain occurs at 1097 m. The drainage is composed mainly of valley wall and debris apron units for the remaining reach, except for four debris avalanches, with one at the outlet of the creek. Three of the four are east-facing, the largest of which blocked the creek for an unknown time. It is estimated that all these debris avalanches combined delivered 421,000, 000 m^3 of sediment to the valley floor. These major failures in Skagit Queen Creek are mapped as occurring in Eldorado orthogneiss of the Eldorado pluton and Skagit Gneiss Complex orthogneiss. The east-facing valley wall is steeper and more prone to mass wasting then the west-facing valley wall, due to aspect and its strong influence on land-forming processes. Two small mining camps are located in the drainage, dating back to 1905 (Fig. 15).

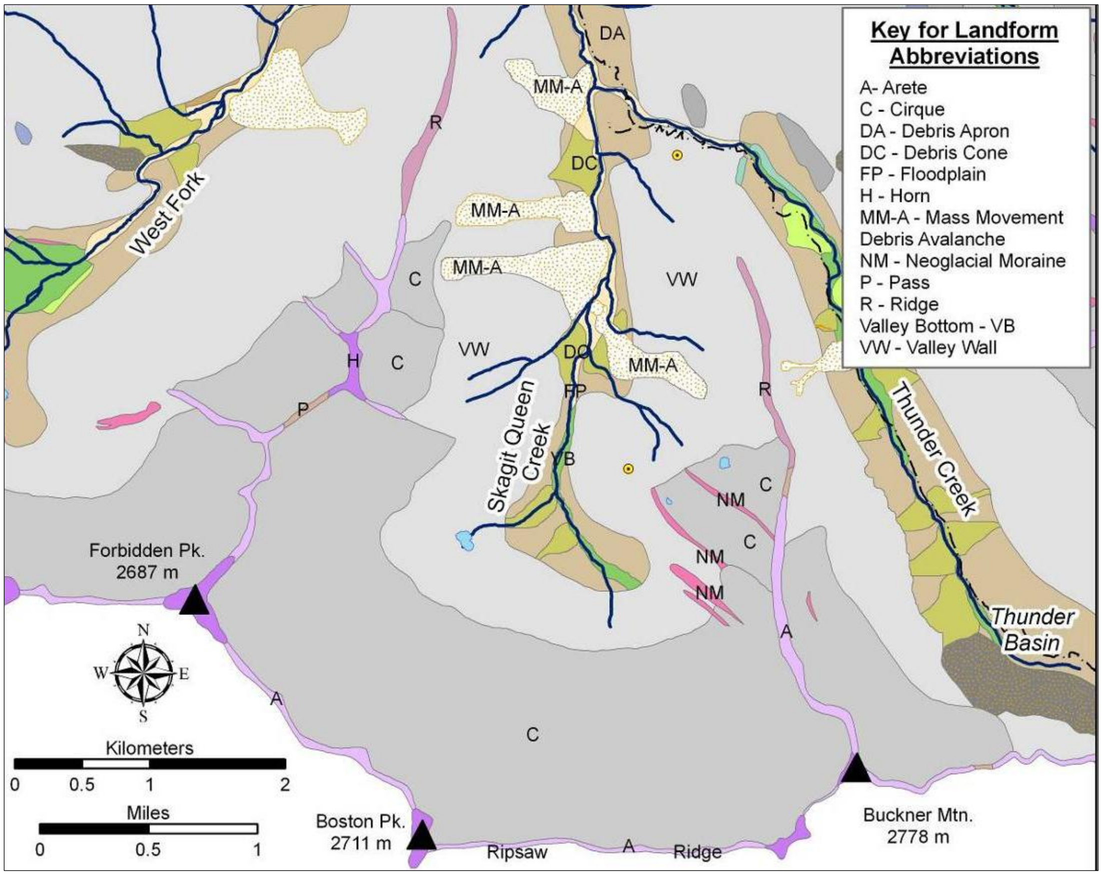

Figure 15. Landform map of Skagit Queen Creek, black dot-dashed lines are trails and red dashed lines are faults. The two yellow circles are the location of mining camps.

5.2.3 West Fork

The source of the West Fork is the Inspiration Glacier (4.6 km^2) on Eldorado and Klawatti Peaks and the Forbidden Glacier (1.8 km^2) of Forbidden Peak (Fig. 6). The glacial cirque on Forbidden Peak extends down to 1707 m (Fig.16). Two cirque basins form the north-western edge of Mount Torment and they extend down to 1707 and 1768 m. The Inspiration Glacier is split into two large cirque basins which extend down to 1829 and 1707 m. The Tepeh Towers form the connecting arête between Eldorado and Klawatti Peaks. The run-off of Inspiration and Forbidden glaciers flow into Moraine Lake, located at an elevation of 1377 m. This lake appears to be in an over-deepened, bedrock floored, trough. On the lake's south-west shore, two Neoglacial moraines are present between elevations 1512 and 1377 m, however it is the bedrock that controls the lake depth. Another Neoglacial moraine is present just to the west, below the Forbidden Glacier. From Moraine Lake the West Fork flows northeast down a stair-stepped valley to the valley bottom at elevation 1268 m. This stair-stepped valley at West Fork is due to resistant rock, presence of faults that run across the valley and north-east aspect.

The valley bottom is wide (0.5 km) in this valley and there is one Neoglacial moraine mapped within it. The transition to floodplain in the West Fork occurs at elevation 1219 m just west of the outlet of Klawatti Creek. This tributary to the West Fork drains two major glaciers; Klawatti Glacier (2.2 km^2) and North Klawatti Glacier (1.8 km^2). Combining the area of these glaciers with Inspiration and others, the West Fork contains more glacial ice than any other tributary of Thunder Creek. The run-off from the Klawatti glaciers gathers into Klawatti Lake, which along with its outlet stream follows the Thunder Lake Fault (Fig. 15). Klawatti Creek enters via a debris cone into the West Fork valley.

The West Fork travels in a narrow floodplain until it reaches a river canyon. In this stretch of floodplain, there is one rock fall/topple and a large debris avalanche on the south side of the creek, both composed of Eldorado Orthogneiss. At the mouth of the West Fork river canyon an alluvial fan is deposited that is abutted by one last rock fall composed of Skagit Gneiss Complex orthogneiss. Here the West Fork enters Thunder Creek, where the floodplain is quite broad, and has deposited an alluvial fan.

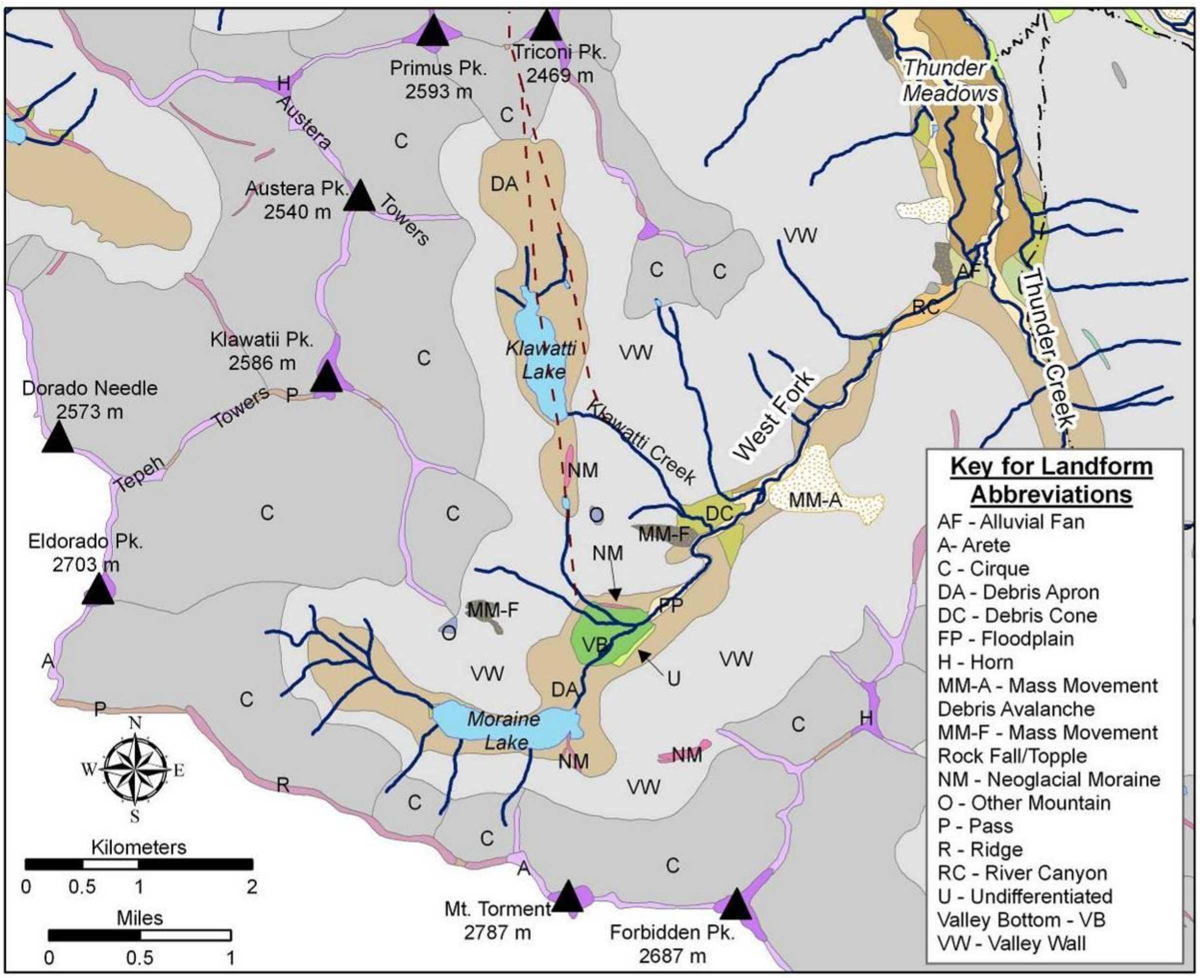

Figure 16. Landform map of the West Fork, black dot-dashed lines are trails and red dashed lines are faults.

5.2.4 Fisher Creek

Fisher Creek, the largest tributary of Thunder Creek, drains the southern slopes of Red Mountain and Ragged Ridge (Cosho, Katsuk, Kimtah and Mesahchie Peaks) and the northern slopes of Fisher Peak, Mount Arriva and Mount Logan along the Pacific Crest (Figs. 17, 18 and 19). The western orientation of the valley places the valley walls in extreme north and south facing aspects. The headwaters of Fisher Creek originate from the northwest flanks of Fisher Peak, in a cirque that extends down to 1841 m. Fisher Creek flows northwest in valley bottom passing two Pleistocene moraines and a river terrace in its uppermost reach (Riedel 2007). The creek then bends to the west and intersects with two large debris avalanches. Deposits from these mass movements come down to the creek and indicate they blocked the creek channel at one time, forcing the creek to the opposite side of the valley. East to west faults run through the debris area and may have influenced these slope failures. At this location there is also a landform known as a SAIL (snow avalanche impact landform). It is located in front of these debris avalanches and is marked in Figure 18. SAILs are depressions and ridge-like deposits created by a snow avalanche impact hitting saturated and unconsolidated sediments. The steep south-facing slopes along with loose material from the avalanches make this an ideal location for SAIL formation.

Fisher Creek then meanders slightly southwest where it flows alongside a massive Pleistocene (75,856 m^2) moraine that comes out of a cirque basin on the north face of Mount Arriva. Once Fisher Creek reaches this moraine, it heads directly west and tumbles ~100 m off of the hanging valley of Fisher Basin. The valley bottom becomes floodplain at elevation 1305 m and then merges with Douglas Creek. This side-drainage contains waters sourced at Fisher Pass and the Douglas Glacier on Mount Logan and may possibly be influenced by neighboring northwest-southeast trending faults. The upper reaches of the Mount Logan cirque basin contain no Neoglacial moraines due to the steep slopes of the cirque floors. The Douglas Glacier cirque extends down to 1768 m in elevation. Fisher Pass is a low elevation (1670 m) broad divide, that carried ice from the Cordilleran Ice Sheet into Stehekin valley, and is a likely a major wildlife migration route.

Figure 17. Fisher Basin from Easy Pass. NPS Photo

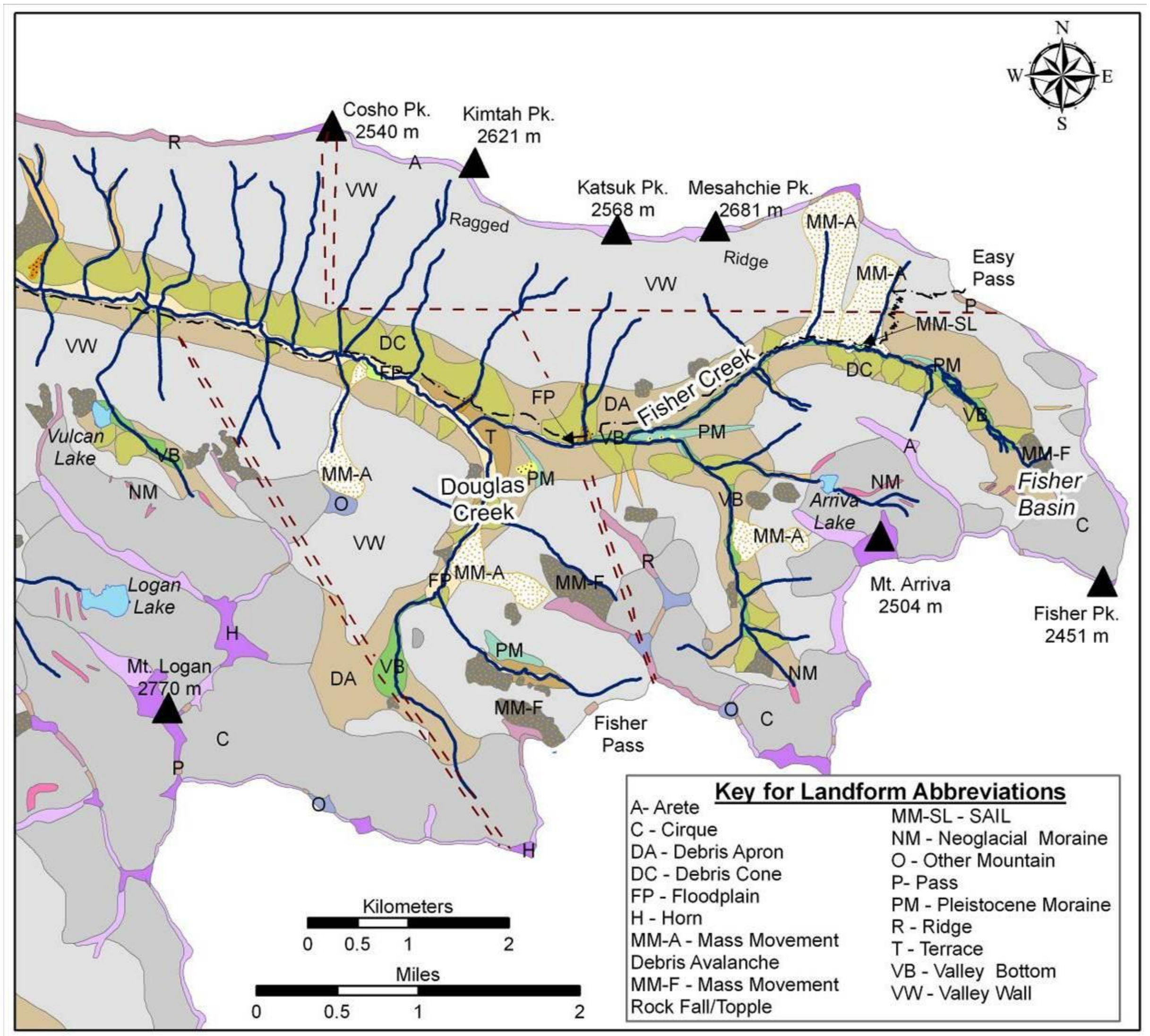

Figure 18. Landform map of Upper Fisher Creek, black dot-dashed lines are trails and red dashed lines are faults.

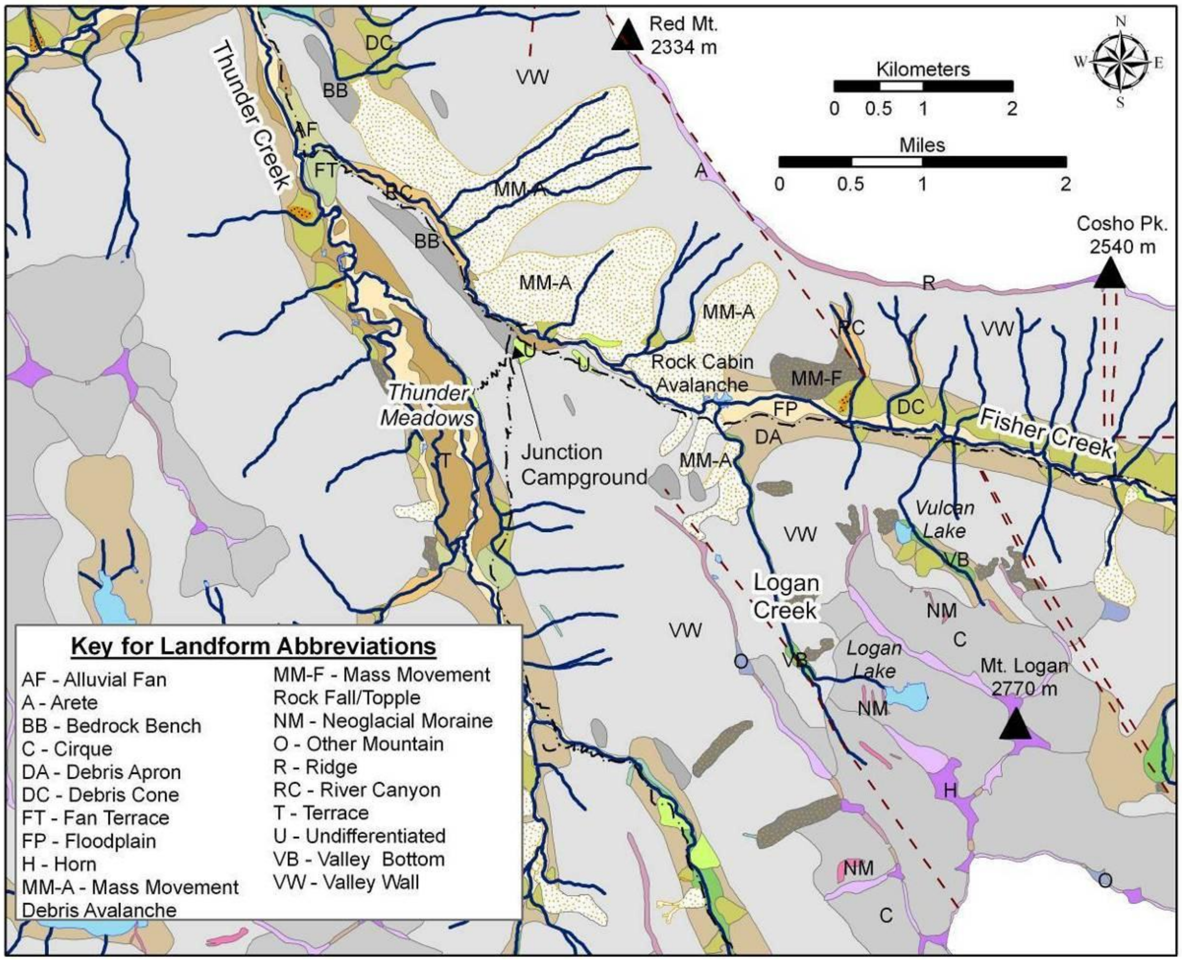

Figure 19. Landform map of Lower Fisher Creek, black dot-dashed lines are trails and red dashed lines are faults.

The lower main stem of Fisher Creek was blocked by the Rock Cabin Avalanche (Fig. 19). Prior to reaching Rock Cabin Avalanche, another unnamed side-drainage contributes waters from the north face of Mount Logan and Vulcan Lake. This cirque basin extends down to elevation 1829 m and contains one Neoglacial moraine. At Rock Cabin Avalanche, waters from Logan Creek, which drains the Banded and Fremont Glaciers, enter into Fisher Creek. The headwall cirque basins of Logan Creek extend down to an elevation of 1829 m, containing a total of five Neoglacial moraines. Logan Creek, like the other unnamed side-drainages discussed above, follows the trend of northwest-southeast trending faults present throughout the Fisher Creek Basin and on its surrounding peaks.

The Fisher Creek valley near the mouth is defined by numerous debris avalanches and rock falls in the area of Rock Cabin. The bedrock geology at this location is labeled as heavily faulted rocks of the Skagit Gneiss Complex. Hydrothermal alteration of the gneiss near Red Mountain also likely played a role in a cluster of landslides. Three debris avalanches, all on the north side of the creek are especially large (over 1,190,000 m^2 in size) and appear to be younger to the east. From Rock Cabin Avalanche, Fisher Creek flows 5 km through the debris avalanches and a river canyon. Several large waterfalls can be observed along the trail as Fisher Creek plunges toward

Thunder Creek. Fisher Creek enters the main stem at Thunder Creek via an alluvial fan, with two abandoned fan terraces on its south bank. Fan terraces, also known as a paraglacial fan, were deposited at the end of the last ice age when slopes left bare by retreating glaciers fed massive quantities of sediment to streams such as Fisher Creek.

5.2.5 McAllister Creek

The headwaters of McAllister Creek begin from two well-defined cirques that contain McAllister Glacier on the east face of the Dorado Needle and the northwest face of Klawatti Peak (Fig. 6). These cirques reach down to 1841 m in elevation and contain a total of four Neoglacial moraines. Five other cirques to the west also contain some smaller glaciers. The valley bottom for McAllister Creek begins at the termination of the McAllister Glacier, at elevation 1207 m, where a small lake is present. At this location, two Neoglacial moraines are along the debris apron-valley wall boundary. Draining northwest from the lake outlet, McAllister Creek transitions quickly into floodplain from valley bottom at 1113 m. The creek turns to the northwest and flows past large debris avalanche (431,125 m^2) that blocked the creek at one time. Isolation and Pegasus Lakes are located on the valley walls above this point of the valley.

Continuing northeast past the debris avalanche, the character of the valley changes significantly. Terraces, ranging from 1.2 to 3 m in height, appear along the side of the floodplain. Debris cone and debris apron landforms dominant the character of the lower valley. Debris torrents are present on some of the debris cones. Above the valley walls in this section, cirques contain a total of six Neoglacial moraines, the lowest of which terminates at elevation 1524 m. A small fan terrace is present near the mouth, but otherwise the creek appears graded to the Thunder Creek floodplain. There is a large Pleistocene moraine (384,446 m^2) mapped at this confluence, on the east bank of Thunder Creek. Landslide activity in McAllister Creek seems to be low overall likely due to stable bedrock.

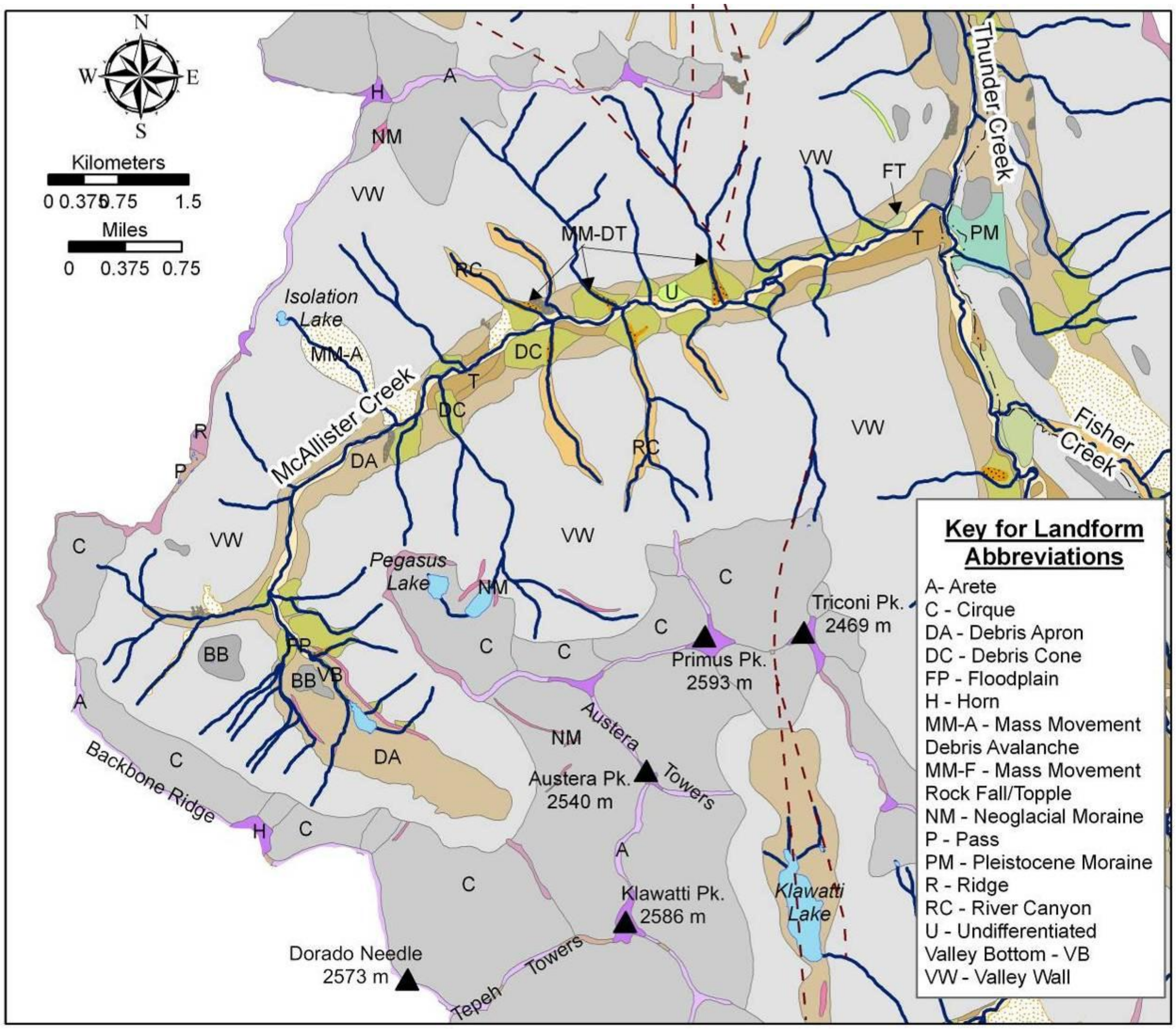

Figure 20. Landform map of McAllister Creek, black dot-dashed lines are trails and red dashed lines are faults.

5.2.6 Neve Creek

Neve Creek drains northeast into Thunder Creek for ~ 4 km (Fig. 21). The headwaters are defined by several small cirques, the largest of which holds the Neve Glacier on Snowfield Peak. These cirques extend down to 1951 m and contain no Neoglacial moraines. The Neve Creek valley bottom begins at elevation 1402 m, quickly transitioning to floodplain at elevation 940 m after cascading over the hanging valley. The Neve Creek valley floor is dominated by debris cone/debris apron landforms, with one small rock fall on each side of the creek in glacial till and gravel deposits. Six of the debris cones have evidence of active debris torrents, with five of them on the south-facing wall. Two terraces are present downstream of the beginning of the floodplain. Neve Creek enters a river canyon after exiting the floodplain, where it travels to the alluvial fan at its mouth. The Thunder Lake Fault does bisect the drainage, likely influencing the geometry of Neve Creek's side tributaries.

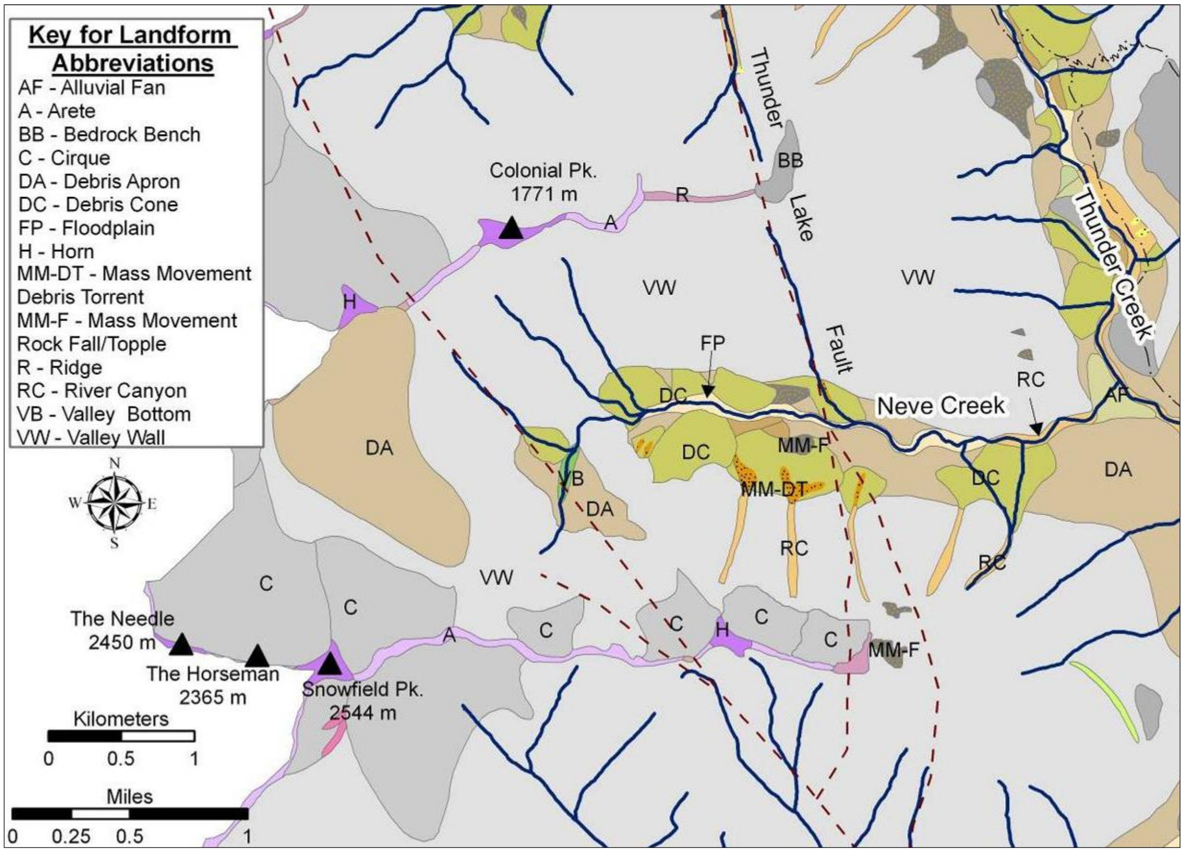

Figure 21. Landform map of Neve Creek, black dot-dashed lines are trails and red dashed lines are faults.

5.2.7 Colonial and Rhode Creeks

Colonial Creek drains the cirques of Pyramid and Pinnacle Peak, as well as the cirque between Paul Bunyan's stump and Colonial Peak (Fig. 22). The Colonial Glacier (1 km^2) is the principal source of meltwater in this sub-watershed. Colonial Creek drains northeast for ~ 4 km from its headwaters to Thunder Creek. Rhode Creek also originates from the upper reaches of Colonial Peak, and steeply drops to the valley below. The trend and debris torrent activity of Rhode Creek valley are controlled by the Thunder Lake Fault (Fig. 22). There are a number of small slumps mapped within the canyon of Rhode Creek.

Colonial Creek enters the main Thunder Creek valley via an alluvial fan while Rhode Creek merges with Thunder Arm via an active debris torrent. Rhode Creek is returning to old channel to the southeast of its current outlet that was blocked by the Forest Service when south unit of Colonial Campground was built in the early 1960s. While Colonial Cree alluvial fan is heavily developed by the north unit of Colonial Creek Campground, there is no record of any channel manipulation.

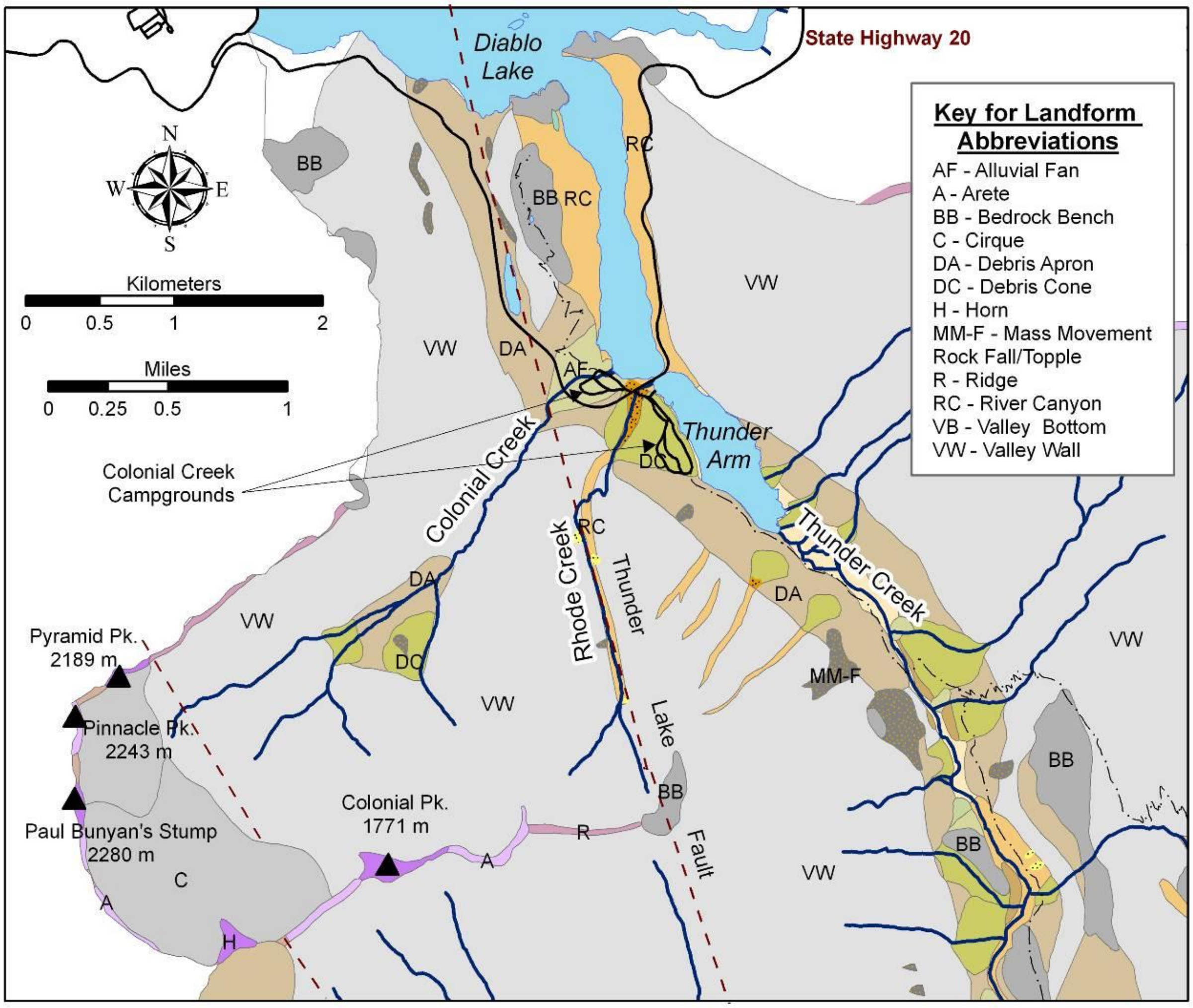

Figure 22. Landform map of lower Thunder Creek, Colonial Creek and Rhode Creek. Black dot-dashed lines are trails and red dashed lines are faults.

5.3 Thunder Creek Watershed Landslide Inventory

Information on unstable and active landslides can guide the selection of long-term ecological monitoring (LTEM) reference sites or building/maintaining public facilities such as trails, campgrounds and bridges. A landslide database was created to accompany landform maps with data collected on 18 characteristics of each landslide, including age, activity, bedrock geology, material type and area. For debris avalanches, depth of the failure and the volume of sediment delivered to river/creek were also recorded. Reviewing this data can tell a great deal about the overall stability of a particular area of the watershed, which can be related to factors such as bedrock type, aspect and proximity to faults.

By reviewing the location, size and composition of these mass movements, some general observations can be made (Table 7). Debris slump/creep deposits are uncommon in the watershed and tend to occur in the valley bottoms, fault zones, or in sections of glacial till and colluvium in the debris apron. Debris torrents are fairly common, indicating the active nature of many of the smaller tributaries, particularly those that follow faults. South-facing river canyons tend to produce flashy floods in the spring, and thus produce debris torrents. Typically steep river canyons are also sites for temporary debris dams that funnel sediment down to debris cones. As mentioned throughout this report, most of the mass movements overall tend to be on north (20%) or north-east to east facing (15% for each) slopes. There is only one SAIL (snow avalanche impact landform) in the watershed at the base of a large debris avalanche. This is an ideal location for SAIL formation, with steep slopes and unconsolidated material. It is likely that there are more SAILS in the watershed, and the North Cascades overall, that have not yet been identified since they are typical small and difficult to pick out on NAIP imagery or aerial photographs.

Table 7. Summary of the Thunder Creek Watershed landslide inventory data.

Mass Movement Type	Number of Each Type	Surface Area (m^2)	% of Total Watershed
Debris Avalanche	24	10,353,632	3.40
Debris Fall/Topple	57	3,779,230	1.24
Debris Torrent	23	418,664	0.14
Debris Slump/Creep	10	39,020	0.01
SAIL	1	2,512	0.00
Totals	114	14,593,060	4.79

A total of one hundred and fourteen landslides have been mapped within the watershed and twenty-four are large debris avalanches (Table 7). These deposits deserve special mention for the sediment they delivered to the main stem of the system and the river channel dynamics they created upon blocking the channel. Debris avalanches encompass ~3.4% of the overall watershed area. They have displaced an estimated volume of 67,500,000 m^3 of debris. A total of 19 of the debris avalanches mapped in the watershed delivered sediment to a stream, and ten of those blocked entirely at one time. Evidence of blockages on the river include massive debris avalanches delivered directly to the river channel and debris avalanches 'pushing' the river across to the far side of its channel, resulting in meanders controlled by debris deposits.

In the Thunder Creek Watershed it appears that the largest debris avalanches are possibly influences by north-south or northwest-southeast trending faults. Geologically, the watershed is fairly homogenous with the majority of the watershed being composed of Skagit Gneiss. Therefore, it is likely that the pattern of faulting and subsequent alteration of rock has a larger effect on mass movement formation then the overall bedrock geology. Three of the largest ones are located in the watershed are located in Fisher Creek. Near the mouth of the creek these debris avalanches, a total of 6,180,000 m^2 in area, are adjacent to a series of northwest-southeast faults and hydrothermally altered rocks on Red Mountain. The avalanches appear to be younger to the east and delivered an estimated 28,400,000 m^3 of sediment to the valley floor. Other notable concentrations of debris avalanches are found in Skagit Queen Creek and Upper Fisher Creek.

6 - Future Work

6.1 Progress Report

The field component of the landform mapping at North Cascades National Service Complex (NOCA) is 100% complete. Light detection ranging (LiDAR) data for Goodell and Newhalem Creeks is to be available by December of 2009. Subsequent editing of the GIS landform layer for these two drainages is planned during the winter of 2009/2010. The field component of the landform mapping at Mount Rainier National Park (MORA) is 100% complete. The landform maps are currently being digitized and entered in the MORA GIS database. LiDAR data was also made available in May of 2009, so editing of the GIS layer is anticipated during the winter of 2009-2010. The field component of the landform mapping at Olympic National Park (OLYM) is 40% complete. Future work will focus on a continuation of the landform mapping project at these three National Parks. The scheduled completion date for NOCA is 2010; 2010 for MORA and 2012 for OLYM.

7 - Literature Cited

Almack, J., Gaines, W., Morrison, P., Eby, J., Naney, R., Wooten G., Fitkin, S. and Garcia, E. 1993. North Cascades grizzly bear ecosystem evaluation; final report. Interagency Grizzly Bear Committee, Denver, Colorado.

Armstrong, J., Crandell, D., Easterbrook, D. and Noble, J. 1965. Late Pleistocene stratigraphy and chronology in southwestern British Columbia and northwestern Washington. Geological Society of America Bulletin 76:321–330.

Briggs, C., Busacca, A. and McDaniel, P. 2006. Pedogenic processes and soil-landscape relationships in North Cascades National Park, Washington. Geoderma 137:192-204.

Briggs, C. 2004. GIS-Based Mapping of Soil Distribution in Thunder Creek Watershed, North Cascades National Park, Washington. Thesis. Washington State University, Pullman, Washington, USA.

Chennault, J. 2004. Modeling the contributions of glacial meltwater to streamflow in Thunder Creek, North Cascades National Park, Washington. Thesis. Western Washington University, Bellingham, Washington, USA.

Chennault, J. 2003. Contributions of glacial meltwater to streamflow in Thunder Creek, North Cascades National Park, Washington: A modeling study. GSA Abstract # 151-6.

Cleland, D., Avers, P., McNab, W., Jensen, M., Bailey, R., King, T. and Russell, W. 1997. National hierarchical framework of ecological units. Pages 181-200 *in* M. Boyce and A. Haney, editors. Ecosystem management applications for sustainable forest and wildlife resources. Yale University Press, New Haven, CT, USA.

Davis, C. 2004. Landtype Associations of North-Central Washington. USDA Forest Service, Wenatchee, Washington, USA.

Evans, I. 1990. Ice streams in the southwest sector of the Cordilleran Ice Sheet. Unpublished manuscript, University of Durham.

Franklin, J. and Dyrness, C. 1973. Natural Vegetation of Oregon and Washington, Oregon State University Press, USA.

Frazier, B., Rodgers, T., Briggs, C. and Rupp, R. 2009. Remote area soil proxy modeling technique. Soil Survey Horizons 50:62-67.

Granshaw, F. 2001. Glacier Change in the North Cascades National Park Complex, Washington State, USA, 1958-1998. Thesis. Portland State University, Portland, USA.

Jarrett, R. 1990. Paleohydrologic techniques used to define the spatial occurrence of floods, Geomorphology 3:181-195.

Mathews, W. 1964. Potassium-argon age determination of Cenozoic volcanic rocks from British Columbia. Geological Society of America Bulletin 75:465-468.

Mierendorf, R. 1999. Precontact Use of Tundra Zones of the Northern Cascades Range of Washington and British Columbia, Archaeology in Washington 7:3-23.

Mierendorf, R., David, H. and Sullivan, G.1998. An Archaeological Site Survey and Evaluation in the Upper Skagit River Valley, Whatcom County, Washington. Technical Report NPS/CCCNOCA/CRTR-98/01. National Park Service. Fort Collins, Colorado.

Mitchell, S. and Montgomery, D. 2006. Influence of a glacial buzzsaw on the height and morphology of the Cascade Range in central Washington State, USA. Quaternary Research 65:96-107.

National Weather Service Cooperative Network Station (NWS COOP). 2009. COOP data from the Diablo Dam site. Online. (http://www.wrcc.dri.edu/cgi-bin/cliMAIN.pl?wa7185). Accessed on 9 May 2009.

Natural Resource Conservation Service (NRCS). 2009a. Snowcourse data for Thunder, Meadow Cabins and Park Creek Ridge snowcourse sites. Online. (http://www.wcc.nrcs.usda.gov/snowcourse/sc-data.html). Accessed on 6 May, 2009.

Natural Resource Conservation Service (NRCS). 2009b. SNOTEL data for Thunder and Park Creek Ridge SNOTEL sites. Online. (http://www.wcc.nrcs.usda.gov/snotel/Washington/washington.html). Accessed on 6 May 2009.

North Cascades National Park Service Complex (NOCA). 2009. Glacier Monitoring program. Online. (http://www.nps.gov/noca/naturescience/glacial-mass-balance1.htm). Accessed on 22 July, 2009.

Porter, S. and Denton, G. 1967. Chronology of Neoglaciation in the North American Cordillera. American Journal of Science 265: 177-210.

Post, A., Richardson, D., Tangborn, W. and Rosselot, F. 1971. Inventory of Glaciers in the North Cascades Washington, US Geological Survey, Professional Paper 705-A.

Reiners, P., Ehlers, T.A., Garner, J.I., Mitchell, S.G., Montgomery, D.R., Vance, J.A. and Nicolescu, S. 2002. Late Miocene erosion and uplift of Washington Cascade Range. Geological Society of America Bulletin 31:767-770.

Reiners, P., Ehlers, T., Mitchell, S. and Montgomery, D. 2003. Coupled spatial variations in precipitation and long-term erosion rates across the Washington Cascades. Nature 426: 645-647.

Riedel, J. 2009. Cordilleran Ice Sheet in Skagit Valley, Washington and British Columbia. Talk presented to the Annual Canadian Quaternary Association Meeting in Vancouver, 2009.

Riedel, J. 2007. Late Pleistocene glacial and environmental history of Skagit valley, Washington and British Columbia. Dissertation. Simon Fraser University, Canada.

Riedel, J. 1987. Chronology of Late Holocene glacier recessions in the Cascade Range and deposition of a recent esker in a cirque basin, North Cascades Range, Washington. Thesis. University of Wisconsin-Madison, USA.

Riedel, J., Burrows, R. and Wenger, J. 2008. Long term monitoring of small glaciers at North Cascades National Park: A prototype park model for the North Coast and Cascades Network, Natural Resource Report NPS/NCCN/NRR—2008/000. National Park Service, Fort Collins, Colorado.

Riedel, J., Haugerud, R. and Clague, J. 2007. Geomorphology of a Cordilleran ice sheet drainage network through breached divides in the North Cascades Mountains of Washington and British Columbia, Geomorphology.

Riedel, J. and Probala, J. 2005. Mapping ecosystems at the landform scale in Washington state, Park Science 23-2: 37-42.

Riedel, J., Wenger, J. and Bowerman, N. *in review.* Long term monitoring of glaciers at Mount Rainier National Park. Natural Resource Technical Report NPS/PWR/NCCN/NRTR – National Park Service, Oakland, CA.

Rodgers, T. 2000. Modeling soils of the Sawtooth and Paysayten wilderness areas with a GIS. Thesis. Washington State University, Pullman, Washington, USA.

Schaetzl, R., Anderson, S. 2005. Soils: Genesis and Geomorphology. Cambridge University Press, New York, USA.

Soil Survey Staff. 1999. Soil Taxonomy, 2nd edition. USDA-Natural Resources Conservation Service, Washington, DC, USA.

Staatz, M., Tabor, R, Weis, P. and Robertson, J. 1972. Geology and mineral resources of the northern part of North Cascades National Park, Washington. U.S. Geological Survey Bulletin 1359.

Tabor, R. and Haugerud, R. 1999. Geology of the North Cascades: A mountain mosaic. The Mountaineers, Seattle, Washington, USA.

Tabor, R., Haugerud, R., Brown, E. and Hildreth, W. 2003. Geologic Map of the Mount Baker 30- by 60-minute quadrangle, Washington. U.S. Geological Survey, Miscellaneous Investigations Map, I-2660.

Tabor, R. and Haugerud, R. *In Review*. Geologic Map of the North Cascades.

United States Geological Survey (USGS). 2003. Fault number 553, Straight Creek Fault, in Quaternary fault and fold database of the United States. Online. (http://earthquakes.usgs.gov/regional/qfaults). Accessed on 28 November 2007.

United States Geological Survey (USGS)a. 2009. Earthquake Database. Online. (http://neic.usgs.gov/neis/epic/epic.html). Accessed on 5 March, 2009.

United States Geological Survey (USGS)b. 2009. Peak annual flow for streams in Washington, by county. Online. (http://nwis.waterdata.usgs.gov/nwis/peak?state_cd=wa&format=station_list&sort_key=station_nm&group_key=county_cd&set_logscale_y=1&date_format=YYYY-MM-DD&rdb_compression=file&hn2_compression=file&list_of_search_criteria=state_cd). Accessed on 8 October 8, 2009.

United States Geological Survey (USGS). 2003. Fault number 553, Straight Creek Fault, in Quaternary fault and fold database of the United States. Online. (http://earthquakes.usgs.gov/regional/qfaults). Accessed on 2 November, 2007.

Waitt, R Jr. 1977. Evolution of glaciated topography of upper Skagit drainage basin, Washington. Arctic and Alpine Research 9:183-192.

Waters, A. 1939. Resurrected erosion surface in central Washington. Geological Society of America Bulletin 50:638-659.

Zdanowicz, C., Zielinski, G., Germani, M. 1999. Mount Mazama eruption: calendrical age verified and atmospheric impact assessed. Geology 27: 621–624.

Appendix A: Landslide Inventory for the Thunder Creek Watershed

List of landslide characteristics documented for each landslide is reviewed in this appendix. There are 18 characteristics for all landslides, with an additional four characteristics collected for debris avalanches.

1. Quadrangle Number: Each USGS 7.5 minute quadrangle in NOCA was assigned a unique value. Quadrangle values are as follows:

USGS Quadrangle	Value	USGS Quadrangle	Value
Mt. Sefirt	1	Crater Mtn.	19
Copper Mtn.	2	Sauk Mtn.	20
Mt. Redoubt	3	Marblemount	21
Mt. Spickard	4	Big Devil Peak	22
Hozomeen Mtn.	5	Eldorado Peak	23
Skagit Peak	6	Forbidden Peak	24
Shuksan Arm	7	Mt. Logan	25
Mt. Shuksan	8	Mt. Arriva	26
Mt. Blum	9	Sonny Boy Lakes	27
Mt. Challenger	10	Cascade Pass	28
Mt. Prophet	11	Goode Mtn.	29
Pumpkin Mtn.	12	McGregor Mtn.	30
Jack Mtn.	13	McAlester Mtn.	31
Bacon Peak	14	Agnes Mtn.	32
Damnation Peak	15	Mt. Lyall	33
Mt. Triumph	16	Stehekin	34
Diablo Dam	17	Sun Mtn.	35
Ross Dam	18	Pinnacle Mtn.	36

2. Mass Movement Number: Each mass movement in the watershed is assigned a unique value.

3. Sub-Watershed: Refers to the river or creek name that dominates the drainage where the mass movement is located.

4. Mass Movement Type Number: Each type of mass movement has a number as follows:

USGS Quadrangle	Value
Rock Fall/Topple	1
Creep/Slump	2
Debris Avalanche	3
Debris Torrent	4
Sackung	5
Snow Avalanche Impact Landform (SAIL)	6

5. Identification Number: Consists of the quadrangle number, mass movement number and mass movement type number (e.g. a rock fall on the Copper Mtn. quadrangle with the assigned number of 11 would be 2-11-1)

6. Material Type: Refers to the type of material contained in the mass movement. The four different material types are rock (R), soil (S), till (T) and debris (D).

7. Age: Relative age if known, occasionally specific dates are recorded if the event was observed. When data is recorded, the type of dating will be noted.

8. Sediment Delivered to Stream: A yes or no or blocked category based on NAIP imagery and aerial photographs

9. Bedrock Type: Used Tabor et al (2003) and Tabor and Haugerud (in review) to identify bedrock type of the landslide. Refer to this map for a key to the symbols used in the database.

10. Length: Refers to the average length (from top to bottom) of the total mass movement. For debris avalanches both the cavity and the deposit is included in the average length measurements. For debris torrents and rock falls/topples, only the deposit is measured. Due to the small size of slumps, the length is taken in the field if possible by measuring the height exposure including any cracking above the crown. Measurements are in 2-D. The measurement is taken off GIS with the measuring tool and is recorded in meters.

11. Width: Refers to the average width (generally following on contour) of the total mass movement. For debris avalanches both the cavity and the deposit is included in the average width measurements. For debris torrents and rock falls/topples, only the deposit is measured. Due to the small size of slumps, the length is taken in the field if possible by measuring the width of the exposure. The measurement is taken off GIS with the measuring tool and is recorded in meters.

12. Volume of Sediment of Debris Avalanches: Refers to the amount of material deposited by a debris avalanche. Measurements are taken by calculating volume only of the cavity and are recorded in meters. Formula as follows:

$$((1/6)*3.14*\text{Length of Cavity}*\text{Width of Cavity}*\text{Depth of Cavity})$$

13. Length of Cavity: Used to calculate volume of sediment in debris avalanche. Refers to the average length (from top to bottom) of the cavity and measurement is taken off the GIS and is recorded in meters.

14. Width of Cavity: Used to calculate volume of sediment in debris avalanche. Refers to the average width of the cavity and measurement is taken off the GIS and is recorded in meters.

15. Depth of Cavity: Used to calculate volume of sediment in debris avalanches and refers to the thickness of material. Depth is recorded in the field if possible. If not possible, measurement should be taken by the cavity of the debris avalanche. The cavity can be estimated using a topographic map in lieu of field information. Depth is recorded in meters.

16. Surface Area: Refers to the exposed area in 2-D and is recorded in m^2 and km^2. Measurement is taken off the GIS for all mass movements.

17. Slope Aspect: Refers to the slope aspect that the mass movement originated from and not the deposit. It is measured off the quadrangle using a compass and is recorded in degrees from true north.

18. Percent Slope: Recorded for each landslide, value is calculated by rise over run (45 degrees = 100% slope).

19. Position: Refers to four possible locations of where landslides originated; Valley Bottom (VB) defined as anything below the valley wall unit, Divide (D), Valley Wall (VW), or Channelized (CH) if confined to a channel.

20. Form: Refers to the general slope form of the landslides; concave (CC), convex (CV), flat (FL) and complex (COMP).

21. Top Elevation: Refers to the top most extent of the mass movement. Recorded in meters and measurement is taken from a 7.5 Minute Quadrangle.

22. Toe Elevation: Refers to the lowest extent of the mass movement. Recorded in meters and measurement is taken from a 7.5 Minute Quadrangle.

QUAD #	MM #	SUB-drainage	I.D. #	MM TYPE (1-4)	MATERIAL TYPE	AGE (IF KNOWN)	SED. DEL. TO STREAM? (Y/N/BLKD)	BEDROCK TYPE
26	1	Upper Fisher	26-1-1	1	R		Y	Kit
26	2	Upper Fisher	26-2-3	3	D		B	Kepc
26	3	Upper Fisher	26-3-3	3	D		B	Kit
26	4	Upper Fisher	26-4-1	1	R		N	Kit
26	5	Upper Fisher	26-5-1	1	R	1500	N	Kit
26	6	Upper Fisher	26-6-3	3	D	1500	Y	Kit
26	7	Upper Fisher	26-7-1	1	R		Y	Kit/Tkns
25	8	Douglas	25-8-1	1	R	<100	N	Tko
25	9	Douglas	25-9-1	1	R	>1000	N	Tko
25	10	Douglas	25-10-1	1	R	>100	Y	Tko
25	11	Douglas	25-11-1	1	R	>100	Y	Tko
25	12	Douglas	25-12-3	3	D		N	Tko
25	13	Douglas	15-13-1	1	R		N	Tko
25	14	Douglas	25-14-1	1	R		Y	Tko
25	15	Douglas	25-15-2	2	T		N	Tko
25	16	Upper Fisher	25-16-2	2	T		Y	Kit/Q
25	17	Upper Fisher	25-17-2	2	T		Y	Kit/Q
25	18	Upper Fisher	25-18-2	2	T		Y	Kit/Q
25	19	Upper Fisher	25-19-4	4	D		Y	Kit
25	20	Lower Fisher	25-20-4	4	D		Y	Kit/Tko
25	21	Lower Fisher	25-21-1	1	R		N	Tks
25	22	Lower Fisher	25-22-4	4	D		Y	Tko/Q
25	23	Lower Fisher	25-23-1	1	R		N	Tko/Tks
25	24	Logan	25-24-3	3	R		B	Tks
25	25	Logan	25-25-3	3	R		B	Tks
25	26	Lower Fisher	25-26-3	3	R		N	Tks
25	27	Lower Fisher	25-27-3	3	D		B	Tks
25	28	Lower Fisher	25-28-3	3	D		B	Tks
25	29	Skagit Queen	25-29-1	1	R		Y	Tkeo
25	30	Skagit Queen	25-30-1	1	R		N	Tks
25	31	Skagit Queen	25-31-1	1	R		N	Tks
24	32	Lower Fisher	24-32-3	3	D		Y	Tks

QUAD #	MM #	SUB-drainage	I.D. #	MM TYPE (1-4)	MATERIAL TYPE	AGE (IF KNOWN)	SED. DEL. TO STREAM? (Y/N/BLKD)	BEDROCK TYPE
24	33	Skagit Queen	24-33-3	3	D		B	TKso
24	34	Skagit Queen	24-34-3	3	D		B	TKeb
24	35	Skagit Queen	24-35-3	3	D		Y	TKeb
24	36	Skagit Queen	24-36-3	3	D		BLKD	TKso
24	37	West Fork	24-37-1	1	R		Y	TKeb
24	38	Thunder Meadows	24-38-1	1	R		N	TKso
24	39	Thunder Meadows	24-39-3	3	D		Y	TKso
24	40	Thunder Meadows	24-40-1	1	R		N	TKso
24	41	Thunder Meadows	24-41-4	4	D		Y	TKso
24	42	Lower Thunder	24-42-2	2	T		Y	TKso
24	43	Lower McAllister	24-43-3	3	D		N	TKsn
24	44	Lower McAllister	24-44-4	4	D		Y	TKsn
24	45	Lower McAllister	24-45-1	1	R		Y	TKsn
24	46	Lower McAllister	24-46-4	4	D		Y	TKsn
24	47	Lower McAllister	24-47-4	4	D		Y	TKsn
24	48	Lower McAllister	24-48-4	4	D		Y	TKsn
24	49	Lower McAllister	24-49-4	4	D		Y	TKso
23	50	Upper McAllister	23-50-4	4	D		Y	TKeb
23	51	Lower McAllister	23-51-1	1	R		Y	TKsgp
23	52	Lower McAllister	23-52-3	3	D		Y	TKsbg
23	53	Lower McAllister	23-53-4	4	D	>100	Y	TKsbg
18	54	Lower Thunder	18-54-1	1	R		N	TKso
18	55	Lower Thunder	18-55-1	1	R		N	TKso
18	56	Lower Thunder	18-56-1	1	R		N	TKsbg
18	57	Lower Thunder	18-57-1	1	R		N	TKsbg
18	58	Lower Thunder	18-58-2	2	T		N	TKsbg
18	59	Lower Thunder	18-59-2	2	T		N	TKsbg
18	60	Lower Thunder	18-60-1	1	R		N	TKsbg
18	61	Lower Thunder	18-61-1	1	R		Y	TKsbg
18	62	Lower Thunder	18-62-1	1	R		N	TKsbg

QUAD #	MM #	SUB-drainage	I.D. #	MM TYPE (1-4)	MATERIAL TYPE	AGE (IF KNOWN)	SED. DEL. TO STREAM? (Y/N/BLKD)	BEDROCK TYPE
18	63	Lower Thunder	18-63-4	4	D		Y	TKsbg
18	64	Rhode Creek	18-64-2	2	T		Y	TKsbg
18	65	Rhode Creek	18-65-1	1	R		Y	TKsbg
18	66	Rhode Creek	18-66-2	2	T		Y	TKsbg
18	67	Rhode Creek	18-67-2	2	T		Y	TKsbg
18	68	Lower Thunder	18-68-1	1	R		N	TKsbg
18	69	Lower Thunder	18-69-4	4	D		Y	TKsbg
18	70	Colonial Creek	18-70-1	1	R		N	TKsbg
18	71	Neve Creek	18-71-4	4	D		Y	TKsbg
18	72	Neve Creek	18-72-4	4	D		Y	TKsbg
18	73	Neve Creek	18-73-4	4	D		N	TKsbg
18	74	Neve Creek	18-74-1	1	R		Y	Qag
18	75	Neve Creek	18-75-1	1	R		N	Qag
18	76	Neve Creek	18-76-4	4	D		N	TKsbg
18	77	Neve Creek	18-77-4	4	D		N	TKso
18	78	Neve Creek	18-78-4	4	D		Y	TKsbg
18	79	Lower Thunder	18-79-1	1	R		N	TKso
26	80	Upper Fisher	26-80-1	1	R		Y	Tkto
26	81	Upper fisher	26-81-1	1	R		Y	Tkto
25	82	Upper Fisher	25-82-1	1	R		N	Tkto
25	83	Upper Fisher	25-83-1	1	R		N	Tkto
25	84	Upper Fisher	25-84-1	1	R		N	Tkto
25	85	Douglas	25-85-1	1	R		N	Tkto
25	86	Douglas	25-86-1	1	R		N	Tkto
25	87	Douglas	25-87-1	1	R		Y	Qag
25	88	Douglas	25-88-1	1	R		Y	TKto
25	89	Lower Fisher	25-89-3	3	D		Y	TKto
25	90	Lower Fisher	25-90-1	1	R		N	TKto
25	91	Lower Fisher	25-91-1	1	R		N	Tkto

QUAD #	MM #	SUB-drainage	I.D. #	MM TYPE (1-4)	MATERIAL TYPE	AGE (IF KNOWN)	SED. DEL. TO STREAM? (Y/N/BLKD)	BEDROCK TYPE
25	92	Lower Fisher	25-92-1	1	R		N	Tkso
25	93	Logan Creek	25-93-1	1	R		N	TKsg
25	94	Logan Creek	25-94-1	1	R		N	Tkso
25	95	Logan Creek	25-95-1	1	R		N	Tkso
25	96	Logan Creek	25-96-1	1	R		N	Tkso
25	97	Thunder Creek	25-97-3	3	D		Y	Tkso
25	98	Thunder Creek	25-98-4	4	D		Y	Tkso
25	99	Thunder Creek	25-99-1	1	R		N	Tkso
24	100	Thunder Creek	24-100-4	4	D		N	Qag
24	101	West Fork	24-101-4	4	D		Y	TKsg
24	102	West Fork	24-102-3	3	D		Y	Tkgo
26	103	Fisher	26-103-1	1	R		Y	TKto
23	104	McAllister	23-104-3	3	D		Y	Tkef
23	105	McAllister	23-105-1	1	R		Y	Qag
23	106	McAllister	23-106-3	3	R		N	Qag/Tkeb
24	107	West Fork	24-107-1	1	R		N	TKcb
24	108	McAllister	24-108-1	1	R		N	Qf
18	109	Thunder Creek	18-109-1	1	R		N	TKso
25	110	Logan Creek	25-110-3	3	D		Y	Tkso/TKsbg
25	111	Fisher	25-111-4	4	D		Y	TKto
18	112	Neve Creek	18-112-1	1	R		N	Tkso
25	114	Upper Fisher	18-113-6	6	D		Y	Kepc

MM#	For all Types				Values for Volume Calculations: For MM-As Only			
	Length m.	Width m.	Surface Area m^2	Surface Area km^2	Length m.	Width m.	Depth m.	Volume m^3
1	456	1286	578006	0.578006				
2	942	355	368772	0.368772	216	368	15.24	633964.4928
3	1438	427	59672	0.059672	480	578	109.728	15931803.34
4	195	241	40282	0.040282				
5	196	155	33822	0.033822				
6	751	172	160866	0.160866	208	231	21.336	536496.2803
7	326	302	98497	0.098497				
8	34	45	2054	0.002054				
9	63	130	10219	0.010219				
10	174	483	99712	0.099712				
11	82	68	6043	0.006043				
12	664	156	132716	0.132716	151	268	24.384	516410.5293
13	252	693	213143	0.213143				
14	707	52	55317	0.055317				
15	106	160	18181	0.018181				
16	32	46	1546	0.001546				
17	23	40	1146	0.001146				
18	22	41	1160	0.00116				
19	601	42	1439	0.001439				
20	362	51	23079	0.023079				
21	234	231	55722	0.055722				
22	431	66	26986	0.026986				
23	398	825	385809	0.385809				
24	626	120	84563	0.084563	147	106	30.4	247899.232
25	782	195	164486	0.164486	276	147	38	806841.84
26	540	152	84796	0.084796	245	158	61	1235752.233
27	1926	543	1194657	1.194657	373	538	109.728	11523567.99
28	1914	1159	1962357	1.962357	501	569	24.384	3637754.106
29	345	1231	503906	0.503906				
30	216	1039	219518	0.219518				
31	2383	1150	3018672	3.018672	757	1103	30.4	13283831.96
32	315	55	27983	0.027983	262	175	30.4	729442.9333
33	1189	168	168556	0.168556	239	143	30.4	543733.2853
34	858	88	92961	0.092961	372	201	45.7	1788272.076
35	216	1039	219518	0.219518				

MM#	For all Types Length m.	Width m.	Surface Area m^2	Surface Area km^2	Values for Volume Calculations: For MM-As Only Length m.	Width m.	Depth m.	Volume m^3
35	309	213	67419	0.067419	168	143	18.2	228820.592
36	523	116	66994	0.066994				
37	109	370	47569	0.047569				
38	463	160	82055	0.082055	86	145	12.2	79616.79333
39	97	390	41755	0.041755				
40	278	96	29122	0.029122				
41	24	40	1325	0.001325				
42	192	248	55751	0.055751	139	85	30.4	187968.7733
43	266	89	23978	0.023978				
44	240	92	22753	0.022753				
45	329	58	20379	0.020379				
46	406	56	25062	0.025062				
47	295	97	22819	0.022819				
48	500	79	48215	0.048215				
49	391	46	22128	0.022128				
50	316	64	19627	0.019627				
51	1438	275	493500	0.4935	361	509	103.632	9965457.966
52	81	52	4639	0.004639				
53	55	95	8225	0.008225				
54	90	51	8064	0.008064				
55	71	50	4995	0.004995				
56	57	28	2566	0.002566				
57	40	76	3705	0.003705				
58	51	29	2042	0.002042				
59	144	104	15119	0.015119				
60	210	426	108385	0.108385				
61	339	135	65594	0.065594				
62	59	69	4273	0.004273				
63	27	34	1194	0.001194				
64	64	40	3360	0.00336				
65	57	60	4794	0.004794				
66	53	43	3927	0.003927				
67	132	65	9025	0.009025				
68	465	80	40676	0.040676				
69	124	49	8784	0.008784				
70	309	213	67419	0.067419	168	143	18.2	228820.592

MM#	For all Types				Values for Volume Calculations: For MM-As Only			
	Length m.	Width m.	Surface Area m^2	Surface Area km^2	Width m.	MM#	Length m.	Width m.
71	100	23	2389	0.002389				
72	119	31	3209	0.003209				
73	222	81	20669	0.020669				
74	86	213	26908	0.026908				
75	94	192	22570	0.02257				
76	237	94	27230	0.02723				
77	207	33	6564	0.006564				
78	203	32	7323	0.007323				
79	64	664	43958	0.043958				
80	182	260	43201	0.043201				
81	147	322	50170	0.05017				
82	135	318	41451	0.041451				
83	80	147	11279	0.011279				
84	167	169	34341	0.034341				
85	116	193	24229	0.024229				
86	197	739	143706	0.143706				
87	101	84	9651	0.009651				
88	134	171	25336	0.025336				
89	1003	175	228211	0.228211	241	474	73	4364119.58
90	45	91	6879	0.006879				
91	123	476	76172	0.076172				
92	138	131	33248	0.033248				
93	349	139	55756	0.055756				
94	384	120	50823	0.050823				
95	310	167	63950	0.06395				
96	362	92	38937	0.038937				
97	513	113	70557	0.070557	100S/70N	50S/71N	12S/37N	127635.7667
98	115	10	1196	0.001196				
99	141	809	120350	0.12035				
100	326	30	11710	0.01171				
101	317	18	6432	0.006432				
102	860	270	319195	0.319195	150	261	30.5	624899.25
103	92	262	21196.996	0.021197				
104	322	92	34776.637	0.0347766	73	47	12.2	21905.79133
105	91	129	12044.089	0.0120441				

MM#	For all Types				Values for Volume Calculations: For MM-As Only			
	Length m.	Width m.	Surface Area m^2	Surface Area km^2	Width m.	MM#	Length m.	Width m.
106	830	44	43291.27	0.0432913	61	60	12.2	23367.88
107	269	171	43190.848	0.0431908				
108	113	39	4739.0684	0.0047391				
109	84	380	36360.379	0.0363604				
110	793	208	227933.05	0.2279331	145	284	24.4	525841.1467
111	213	38	9226.6016	0.0092266				
112	96	251	25722.7	0.0257227				
113	81	80	10735.187	0.0107352				
114	23	89	2,512.122	0.0025121				

MM#	Form	Aspect (°)	Percent Slope (%)	Position	Top (m)	Toe (m)
1	FL	26	159	VW	2377	1646
2	COMP	202	55	VW	2073	1548
3	COMP	195	57	VW	2316	1524
4	FL	340	108	VW	1951	1743
5	FL	310	82	VW	1768	1585
6	COMP	280	79	VW	2134	1548
7	FL	0	87	VW	2256	1939
8	FL	20	82	VW	1658	1615
9	FL	5	41	VW	1658	1615
10	FL	35	57	VW	1768	1579
11	FL	20	64	VW	1670	1609
12	COMP	290	73	VW	1890	1341
13	FL	25	97	VW	2012	1634
14	FL	110	57	VW	1707	1219
15	CC	300	52	VW	1280	1219
16	CC	180	36	VB	1396	1384
17	CC	180	39	VB	1402	1390
18	CC	202	68	VB	1414	1396
19	CV	181	929	CH	1500	1305
20	CV	210	17	CH	1231	1164
21	FL	80	352	VW	1707	914
22	CV	220	32	CH	1244	1097
23	FL	185	77	VW	1768	1073
24	FL	40	58	VW	1494	1116
25	FL	30	52	VW	1536	1073
26	FL	25	70	VW	1487	1073
27	COMP	220	53	VW	2073	1042
28	COMP	200	46	VW	1774	914
29	FL	5	81	VW	1951	1451
30	FL	340	372	VW	2329	2024
31	FL	320	59	VW	2316	1707
32	COMP	234	38	VW	1804	792
33	FL	310	23	VB	1097	1012
34	COMP	110	69	VW	1829	994
35	FL	85	82	VW	1707	975
36	FL	80	114	VW	1268	853

MM#	Form	Aspect (°)	Percent Slope (%)	Position	Top (m)	Toe (m)
37	FL	100	61	VW	1402	1024
38	FL	90	48	VW	732	646
39	COMP	90	75	VW	975	628
40	FL	45	85	VW	695	610
41	CV	100	20	VB	671	616
42	CC	290	18	VB	628	622
43	COMP	205	31	VB	792	707
44	CV	120	38	VB	817	683
45	FL	130	25	VB	744	683
46	CV	5	47	VB	853	689
47	CV	130	7	VB	732	701
48	CV	350	34	VB	780	671
49	CV	176	73	VB	744	360
50	CV	250	46	VW	1305	1097
51	FL	14	49	VW	988	817
52	COMP	138	62	VW	1646	780
53	CV	151	13	VB	732	719
54	FL	240	73	VB	823	762
55	FL	290	48	VB	792	719
56	FL	90	104	VW	780	671
57	FL	90	102	VW	792	695
58	CC	250	98	VB	549	463
59	CC	240	126	VB	536	463
60	FL	255	132	VW	671	457
61	FL	80	98	VW	732	427
62	FL	35	105	VW	914	451
63	CV	30	70	VB	549	500
64	CC	320	122	VW	1122	1073
65	FL	30	116	VW	1012	914
66	CC	60	75	VW	732	671
67	CC	260	87	VW	792	732
68	FL	40	86	VB	549	427
69	CV	20	13	VB	439	378
70	FL	340	76	VB	963	902
71	CV	40	47	VB	1036	988
72	CV	40	38	VB	1036	988

MM#	Form	Aspect (^{o})	Percent Slope (%)	Position	Top (m)	Toe (m)
73	CV	10	46	VB	975	853
74	FL	105	47	VB	841	780
75	FL	20	34	VB	805	756
76	CV	0	38	VB	975	890
77	CV	10	49	VB	853	744
78	CV	140	31	VB	792	732
79	FL	269	32	VB	223	180
80	FL	230	88	VW	1890	1719
81	FL	230	101	VW	1926	1756
82	FL	20	137	VW	1914	1707
83	FL	190	113	VW	1573	1475
84	FL	150	83	VW	1682	1487
85	FL	215	80	VW	1902	1780
86	FL	30	68	VW	1951	1768
87	FL	350	55	VB	1585	1512
88	FL	85	80	VW	1329	1183
89	COMP	5	80	VW	2012	1244
90	FL	40	188	VW	1920	1792
91	FL	10	16	VW	1768	1719
92	FL	265	58	VW	1792	1634
93	FL	355	68	VW	2048	1743
94	FL	280	47	VW	1451	1268
95	FL	290	64	VW	1999	1731
96	FL	230	97	VW	2097	1737
97	COMP	70	82	VW	1768	1317
98	CV	120	68	VB	1433	1347
99	FL	320	77	VW	2316	1707
100	CV	70	23	VB	707	622
101	CV	80	63	VB	975	792
102	COMP	300	64	VW	1524	951
103	FL	180	60	VB	695	622
104	COMP	180	97	VW	1463	1167
105	FL	175	58	VW	1268	1189
106	COMP	30	43	VW	1670	1305
107	FL	100	68	VW	1878	1609
108	FL	120	55	VW	805	732

MM#	Form	Aspect (°)	Percent Slope (%)	Position	Top (m)	Toe (m)
109	FL	95	58	VB	622	536
110	COMP	40	72	VW	1829	1189
111	CV	350	30	VB	1244	1195
112	FL	340	82	VW	1829	1658
113	FL	130	130	VW	1536	1762
114	CC	88	32	VB	1540	1520

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