REMAPPING A PORTION OF THE PINGREE PARK QUADRANGLE, COLORADO, TO INVESTIGATE UNCONFINED VALLEY DEVELOPMENT

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ABSTRACT

I remapped the bedrock and surficial geology of a portion of the Pingree Park Quadrangle in the northern Colorado Front Range to focus on bedrock and landscape features that influence the development of wide, unconfined valleys. The goals of the bedrock mapping were to refine the location of geologic contacts, improve unit descriptions, document the degree and style of hydrothermal alteration of bedrock, and increase the number of foliation measurements throughout the field area. Surficial mapping was concentrated in the valley bottoms of the field area and recorded a variety of glacial and fluvial deposits, many of which are not documented in the published geologic quadrangle. Radiocarbon geochronology of alluvial sediments collected in the map area provided age control for the late-Quaternary landscape history. Significant hydrothermal alteration of bedrock exists in the study area, and field observations and analysis of petrographic thin sections note that hydrothermal alteration has replaced most former minerals and/or fabrics in some locations. Furthermore, a record of at least two glaciations can be differentiated in the South Fork Cache la Poudre Valley (South Fork), and glacial deposits suggest a broader glacial extent than previously identified. The most recent glacial advance to reach the mapped portion of the South Fork must have retreated before 13.9 ka. Following Pinedale deglaciation, over 10 m of glacial outwash was deposited within the South Fork Valley upstream of the terminal moraine. Several meters of outwash deposits are found along the South Fork River within and downstream of the glacial extent. Subsequent fluvial incision into the glacial and outwash sediments formed two distinct terraces. Late Holocene overbank deposits surround the modern channel, form the floodplain and low terraces, and are 1-2 m deep.

1. INTRODUCTION

River valleys in mountainous environments integrate Earth surface processes of bedrock erosion, hillslope-to-channel sediment transfer, and transport and/or storage of water and sediments over time (Whiting and Brantley, 1993). Valley confinement -- the degree to which a river can laterally affect the valley bottom through which it flows (via regularly flooding, channel migration, and associated processes) -- is often restricted by valley bounding topographic features in mountainous environments (Nagel et al., 2014). Unconfined valley segments have a high ratio of valley width to bankfull channel width, and often contain deeper deposits of alluvial sediments than confined valley segments (Livers and Wohl, 2015). Confinement often varies longitudinally along mountain streams, and factors including bedrock characteristics, and the thickness and lateral extent of valley bottom substrates determine the degree of confinement in these settings (Fryirs et al., 2016). Both bedrock valley geometry and Quaternary deposits in valley bottoms can confine the active channel; reach-scale channel and floodplain dynamics often reflect the degree of confinement of the river or stream. To gain insight into the development of unconfined valleys in mountainous regions, I remapped a portion of the Pingree Park Quadrangle, CO at 1:12,000 scale. The goals of the mapping were to 1) refine the location of lithologic contacts, improve unit descriptions, document the degree of bedrock hydrothermal alteration, and increase the number of foliation measurements throughout the field area to address lithologic controls on erodibility; and 2) enhance Quaternary map details to document the late-Pleistocene to present landscape history of the South Fork Cache la Poudre River Valley. Unconfined valley segments are important sites of surface, groundwater, and sediment storage, provide key habitat and food for biota, harbor higher levels of biomass and biodiversity than other mountain environments, and are found in mountainous areas worldwide. Despite the importance of unconfined valleys, the lithologic and structural controls on rock erodibility, and formation of wide valley bottoms are poorly understood.

1.1 Study Area

The map area consists of an ~45 km^2 area (Figure 1) centered on the headwaters of the South Fork Cache la Poudre River. The study area includes confined and unconfined valley segments shaped by late-Pleistocene glaciation (Madole et al., 1998), and confined and unconfined segments downstream of the late-Pleistocene glacial extent. Previous mapping in the area indicates that the South Fork Valley is underlain by a diverse suite of Precambrian-age crystalline rocks, both igneous and metamorphic, and several areas of structurally altered rocks, mylonitic and brecciated in texture (Nesse and Braddock, 1989). The presence of a variety of bedrock lithologies, and the transition between glaciated and unglaciated landscapes make the South Fork headwaters an ideal site to examine factors that influence the development of unconfined valleys in mountains. Additionally, the study area is located immediately north of Rocky Mountain National Park and contains the Colorado State University Mountain Campus (Mountain Campus), making findings of this research relevant to land management and educational outcomes.

The geologic history of the area is complex with lithologic heterogeneity over small spatial scales and geologic structures associated with multiple episodes of deformation (Nesse and Braddock, 1989). The oldest rocks in the area are 1.7–1.8 Ga (Peterman et al., 1968; DePaolo, 1981; Cavoise et al., 2002) amphibolite, quartzofeldspathic gneisses and schists, and knotted mica schists. Intrusive igneous rocks that formed 1.4-1.6 Ga include small bodies of weakly foliated Proterozoic Boulder Creek Granodiorite, Silver Plume and Hague's Peak Granite, and bodies of very coarse-grained pegmatite that are related to granitoid emplacement (Nesse and Braddock, 1989). Precambrian rocks with a mylonitic texture are documented in the South Fork Valley at the Skin Gulch and Buckhorn Shear Zones, and in several smaller localities; these structurally altered rocks record localized zones of high strain deformation under ductile conditions (Nesse and Braddock, 1989). Elsewhere in the Colorado Front Range, shear zones containing mylonitic rocks have been identified and may be key sites of hydrothermal alteration associated with the development of the Laramide-age Colorado Mineral Belt (Tweto and Sims, 1963; Caine et al., 2010). Additionally, at other sites in the mainstem Cache la Poudre drainage basin (Figure 1 - inset map), Proterozoic shear zones differ in joint density and weathering characteristics compared to the surrounding crystalline bedrock (Ehlen and Wohl, 2002), and may explain the spatial distribution of strath terraces and unconfined valley segments across the landscape (Wohl, 2008).

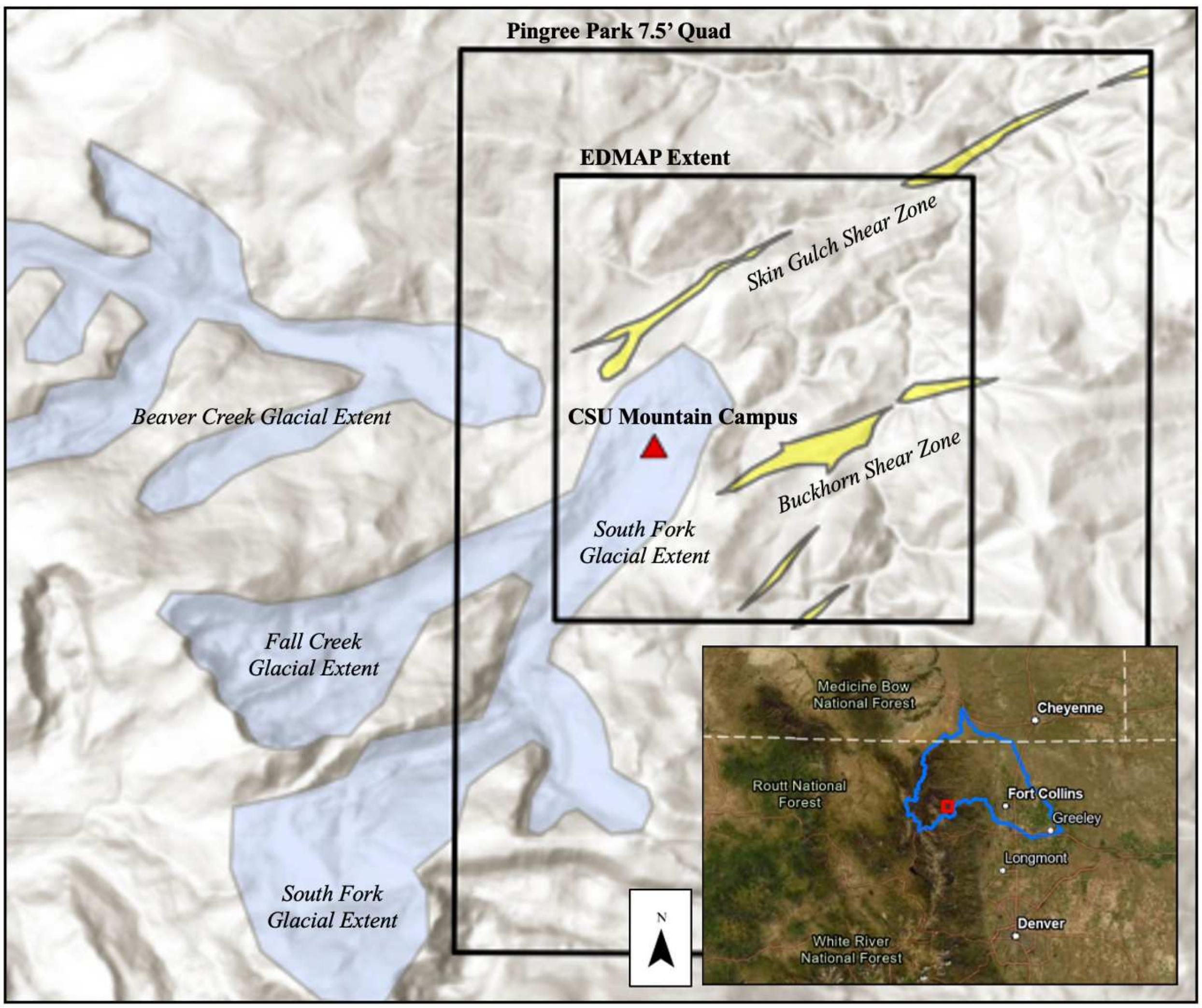

Figure 1. Location map of the study area. The large black rectangle represents the boundary of the existing geologic map of the area (Nesse and Braddock, 1989), and the inset black rectangle represents the EDMAP study area. Glacial extents (blue polygons) are digitized from Madole et al. (1998); shear zones (yellow polygons) are digitized from Nesse and Braddock (1989). The Cache la Poudre drainge basin is outlined in blue on the inset, the field area is the red rectangle.

The Colorado Front Range landscape can be divided into three distinct settings based on the processes responsible for late-Cenozoic erosion of the deep-crustal rocks which core the range. These landscape settings include: i) the dissected, low relief subsummit surface, ii) glacial valleys, and iii) valleys formed by fluvial incision (Anderson et al., 2006b). Inter-valley surfaces erode at a slow and continuous pace, while glacial valleys erode based on ice discharge (Anderson et al., 2006a, 2006b), and fluvial channels respond to changes in the regional base level and variations in flow and sediment dynamics (Schildgen et al., 2002). Multiple episodes of late Pleistocene glaciation occupied the headwater valleys of the South Fork River (Figure 1), potentially including Pre-Bull Lake, Bull Lake, and Pinedale (last glacial maximum) advances (Madole et al., 1998). The most recent major advance, the Pinedale stage, is thought to have begun to retreat in the Front Range ~15 – 12 ka (Madole, 1986), and deglaciation was complete by 11 – 10 ka (Madole, 1980). Previous research has not constrained the age of glacial material or geomorphic relationships between deposits from prior glaciations in the South Fork Valley. The existing geologic map notes that glacial till from the South Fork Valley appeared to dam the Beaver Creek Valley (Figure 1), resulting in 15-20 m of outwash deposition between the moraines of the South Fork and Beaver Creek glaciers (Nesse and Braddock, 1989). Multiple climatic fluctuations following Pinedale glaciation (Doerner, 2007; Benedict et al., 2008) are associated with small scale glacial advance and retreat (e.g., Menounos and Reasoner, 1997), and the changes in river flow and sediment transport responsible for the development of post-glacial alluvial landforms and stratigraphy (e.g., Madole, 2012) in the northern Colorado Front Range.

1.2 Research Overview

Within a given hydroclimatic regime, the factors that affect the processes of vertical and lateral erosion of bedrock that form wide valleys in mountainous regions are not well understood. Lithologic and structural controls, including joint density and spacing in crystalline rocks, have been linked to the formation of strath terraces and unconfined valleys in the Colorado Front Range (Elhen and Wohl, 2002; Wohl, 2008). Grimsley et al. (2018) also noted that hydrothermal alteration may explain differences in erodibility between altered and unaltered rocks near my map area as indicated by increased debris flow frequency in altered volcanic rocks. To address the lack of data on lithological and structural controls on South Fork valley evolution, I added detail to my map to refine the spatial arrangement of contacts and expanded unit descriptions to include the intensity and style of structural and hydrothermal alteration. Additional foliation measurements provide additional data to assess the interaction of foliation orientation and hillslope aspect on regolith production and erosion of the bedrock surface (e.g., Leone et al., 2020).

Whereas bedrock characteristics may set the initial conditions for valley evolution, the Quaternary glacial and post-glacial history of the South Fork Valley impart a final imprint on the modern topography. As such, I mapped glacial landforms to supplement existing knowledge of the glacial geology of the South Fork drainage and to better assess the effects of the glacial-fluvial valley transition on modern stream dynamics and confinement. In addition, I enhanced the detail of Quaternary map units to document landforms produced by episodes of aggradation and degradation in the South Fork Valley, which record the post-glacial landscape history of the study area.

2. METHODS

Several changes to my mapping project occurred during the summer 2020 field season due to unforeseen complications from the COVID-19 pandemic and the Cameron Peak Fire. The pandemic delayed the start to the field season due to a ban on non-essential travel, limited ability for collaborators to participate in field work, and added difficulty coordinating access to privately held lands in the study area. In addition, the field season ended over a month early because of the largest wildfire in Colorado history. The Cameron Peak Fire burned a large portion of the map area and required the evacuation of the authors, per order of local emergency service personnel. Because of these unforeseen events, the decision was made to reduce the map area to the South Fork Valley and neighboring ridges (Figure 2), and to decrease the degree of bedrock and structural data collected to focus on characteristics that influence bedrock erodibility and the evolution of the valley.

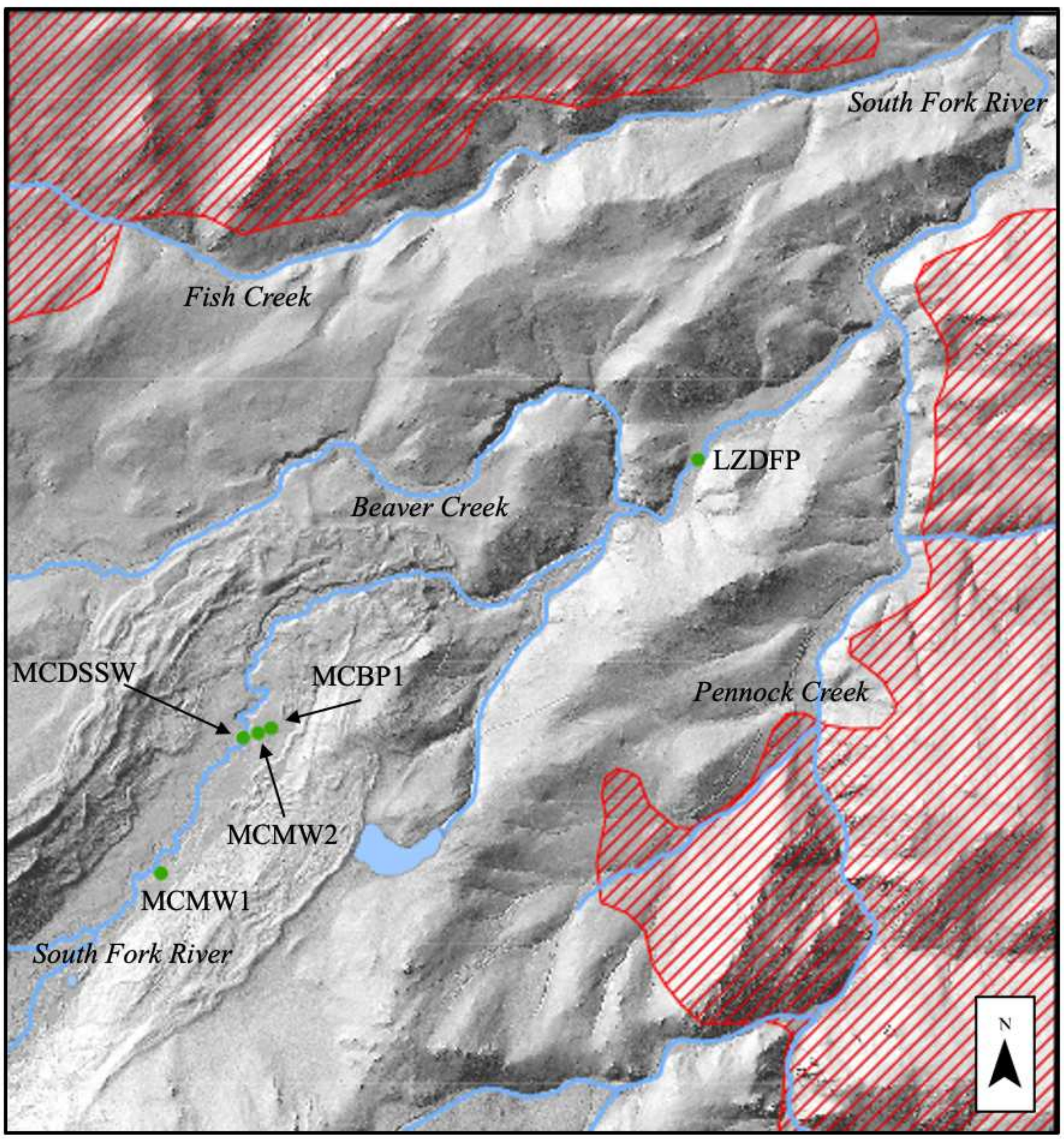

Figure 2. Areas in hatched red fill were not mapped due to a shortened field season; labeled green dots correspond to radiocarbon sample sites.

2.1 Geologic Mapping and Data Collection

I remapped bedrock lithology and Quaternary deposits in my field area at 1:12,000 scale. At over 600 stations, I made observations of bedrock lithology and/or Quaternary morphology and stratigraphy. The location of each station was recorded and plotted on an iPad with GPS capabilities (location accuracy of ~3 m). Station locations were informed by preexisting geologic map data, high resolution shaded relief (hillshade) and aerial imagery (~1 m spatial resolution), and observations made in the field.

I based map unit designations on those of Nesse and Braddock (1989) in their published geologic quadrangle of the Pingree Park area. I enhanced descriptions of existing units and included new units to enhance lithologic and Quaternary detail. At stations with bedrock outcrops, I noted the following: lithology and location of lithologic contacts; presence/absence of a structural fabric(s) or other structural alteration and fabric orientation(s); presence/absence of hydrothermal mineralization, style of mineralization, and quantitative assessment of severity of alteration. Hand samples were collected at some bedrock stations and sent to Paula Leek Petrographics in Denver, CO to produce 16 thin sections. One thin section sample was collected from each lithologic unit identified on the map (besides the pegmatite) to supplement unit descriptions. Additionally, seven samples were collected from outcrops containing rocks that had been hydrothermally or structurally altered.

In locations of Quaternary sediments, I mapped Quaternary landforms or sediments, correlations between deposits displaying similar morphologic and sedimentological characteristics, and identified relative age relationships between adjacent deposits. At stations used for Quaternary mapping, the type of landform (e.g., fan, terrace, moraine) and/or type of Quaternary sediment (e.g., glacial till, outwash) was noted. So too was the spatial extent of each Quaternary unit. Additional sedimentological information was recorded at sites where the stratigraphy was exposed. Some coring of sediments was utilized to provide additional stratigraphic control and to recover sediment samples for radiocarbon analysis.

2.2 Radiocarbon Geochronology

I collected nine samples of fine sediment, believed to be organic rich, for bulk assay using conventional radiocarbon analysis. The nine samples were collected from five unique sediment cores (Figure 2) to provide age control on glacio-fluvial landforms within the South Fork Valley. Two ~10 m deep sediment cores were collected from split spoon samples recovered during drilling of two groundwater-monitoring wells (MCMW1 & MCMW2). Two ~1.5 m deep hand augured cores were also collected at the CSU Mountain Campus (MCBP1 & MCDSSW). Additionally, one hand augured core was collected from a low terrace abutting the South Fork River downstream from the mapped glacial extent (LZDFP). Radiocarbon analyses were performed by the DirectAMS laboratory in Washington State. All radiocarbon samples are aggregate sediment samples, and thus report the average age of accumulated material rather than the specific age of a depositional event. To minimize uncertainty associated with chronological findings all ages are reported in uncalibrated radiocarbon years, as opposed to calendar years before present.

3. RESULTS

3.1 Bedrock Mapping and Analysis

My bedrock map of the South Fork valley is based on the bedrock map of Nesse and Braddock (1989), with some important differences. I refined geologic contacts, added detail to existing units and added new units to capture appropriate lithologic characteristics, improved description of structurally altered rocks, and mapped zones of intense hydrothermal alteration (Table 1). I adjusted the location of several bedrock contacts, and adjusted, modified, and/or created other contacts due to the finer map scale (1:12,000). Map units such as the amphibolite (Xam) and pegmatite (YXp), which commonly outcrop within other units, were mapped in locations where they outcrop prominently instead of continuously across the map in. Where Nesse and Braddock (1989) mapped 'fracture zones' around named shear zones, I instead mapped the location of rocks with mylonitic texture (Figure 3A), which significantly reduced the width of mapped shear zones, especially the Buckhorn Shear Zone (Supplementary Figure 1). To account for the highly altered rocks (Figure 3B) commonly found in the 'fracture zones' of Nesse and Braddock (1989) I identified zones of significant hydrothermal alteration where the rocks were often broken up and did not outcrop well. Common hydrothermal alteration styles in the map area included iron-oxide and iron-sulfide alteration, chlorite and epidote mineralization, and massive silicic replacement (Figure 3B). I mapped the fault that crosses the Skin Gulch Shear Zone (SGSZ) near Fish Creek for a much shorter extent. The only recognizable offset unit that I found was a silicic-mineralized ridge on the northern margin of the SGSZ. Cross cutting relationships were improved by noting that a mafic dike cuts across the Buckhorn Shear Zone east of the Mountain Campus (Supplementary Figure 1). The complete geologic map is included with this report as supplementary material.

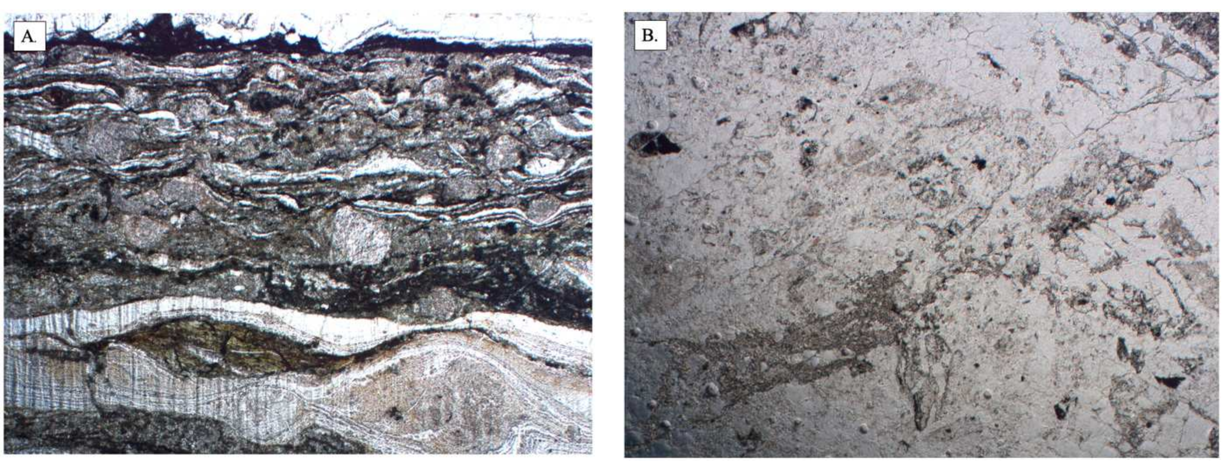

Figure 3. Plane polarized light photomicrographs (2.5x) of thin section samples collected within shear zones. 3A) Mylonite or ultramylonite with prominent brittle-plastic strain; quartz exhibits bulging and sub-grain rotation; pervasive bulging in feldspar; local cataclasis with epidote veins appearing to be involved in brittle deformation. Sample collected from the Buckhorn Shear Zone. 3B) Highly silicified; very fine- to coarse-grained anhedral quartz, randomly oriented with no apparent fabric; very fine-grained chlorite/brown alteration mineral dispersed throughout; any preexisting fabric has been obliterated by silicification. Sample collected within outcrop immediately along the Skin Gulch Shear Zone.

Table 1. Lithologic units mapped in the field area. Many units follow Nesse and Braddock (1989) and utilize names, symbology, and ages proposed therein. Unit descriptions are modified from Nesse and Braddock (1989) based on field and thin section observations made as part of this project.

Unit Name	Symbol	Age	Description
		Igneous Intrusive Rocks	
Silver Plume Granite	Ysp	Middle Proterozoic	Tan to gray. Fine- to medium-grained. Microcline, plagioclase, quartz, biotite, and muscovite (Nesse and Braddock, 1989). Weakly foliated in places with thin biotite-rich intervals. Some mylonitic shear bands present near the South Fork – Pennock Creek confluence, parallel or subparallel to the weak foliation.
Granite of Hague's Peak	Ygh	Middle Proterozoic	Buff to tan. Medium- to very coarse-grained. Quartz, microcline, plagioclase, biotite, and minor muscovite. Some euhedral to subhedral feldspar crystals are 2-8 cm long (Nesse and Braddock, 1989) and aligned due to magmatic flow. Locally pegmatitic.
Mafic Dikes	Yd	Middle Proterozoic	Black, gray, weathers to medium brown. Fine-grained to locally medium-grained. Basaltic to andesitic composition. Primarily composed of plagioclase (mostly euhedral), clinopyroxene, and iron-titanium oxides. At multiple locations, significant iron oxide alteration observed near contact in surrounding unit.
Pegmatite	YXp	Early-Middle Proterozoic	White to Tan. Very coarse-grained. Quartz, plagioclase, K-feldspar, muscovite, biotite, occasionally tourmaline. (Nesse and Braddock, 1989). Found as medium-large map-scale bodies of irregular shape, or as ~1 m thick dikes within outcrops of other units.
Quartzofeldspathic Granitoid	Xqgr	Early Proterozoic	Light gray. Typically coarse-grained, occasionally pegmatitic. Quartz, feldspar, and minor biotite. Some thin, rare intervals of amphibolite. Non-foliated to weakly foliated, but a thin mylonite shear band (~2 cm) is present near the Skin Gulch shear zone.

Boulder Creek Granodiorite	Xbc	Early Proterozoic	Dark gray. Equigranular, medium- to occasionally coarse-grained. Weakly to moderately foliated by aligned biotite, or weakly developed compositional banding. Plagioclase, quartz, biotite (Nesse and Braddock, 1989). Plagioclase and quartz are tabular. 2-5 cm-spaced foliation planes weather to bladed outcrop pattern.
Metasedimentary and Metavolcanic Rocks			
Quartzofeldspathic Foliated Metamorphic	Xqf	Early Proterozoic	Combined unit of quartzofeldspathic schist (Xqs) and gneiss (Xfg). Light gray to black, with leucocratic zones, buff to tan. Quartz, Feldspar, Biotite. Schist is defined by an abundance of well-foliated intervals of mica schist; quartz and feldspar rich intervals are poorly foliated. Schist has a much higher percent of biotite. Gneiss intervals have mm – cm scale compositional banding, but do not exhibit the outcrop scale leucocratic and melanocratic fluctuations observed in the schist.
Knotted Mica Schist	Xks	Early Proterozoic	Dark gray and brown with pattern of white spots. Medium grained biotite schist with large clots of sillimanite. Migmatitic in several areas with migmatitic rock composed of quartz-feldspar rich layers and biotite rich layers (Nesse and Braddock, 1989). Thin section shows sillimanite clots/mats (larger crystals are boudinaged) quartz, biotite, and tourmaline.
Amphibolite and Hornblende Gneiss	Xam	Early Proterozoic	Dark gray to dark green. Fine- to medium-grained. Massive amphibolite to weakly-foliated hornblende gneiss. Hornblende, plagioclase, and quartz (Nesse and Braddock, 1989). Hornblende is anhedral. Equant anhedral plagioclase grains fill the interstices between hornblende grains. Alignment of minerals and some compositional banding defines the foliation in gneissic intervals. Some hornblende grains have been altered to chlorite and epidote.
Structurally and Hydrothermally Altered Rock Units			
Mylonitic Shear Zone	SZ	Proterozoic	Rocks displaying mylonitic texture (protomylonitic to ultramylonitic) and recording ductile shearing. Finely to very finely foliated with dynamically

			recrystallized matrix. Often dark gray to brown, but variable in color due to alteration and protolith.
Zone of Hydrothermal Alteration	HT	Multiple Ages	Areas of intense hydrothermal alteration, often replaces most to all protolith minerals and/or fabrics present prior to alteration. Common styles include iron-oxide, iron-sulfide, epidote-chlorite, and silicic mineralization. Outcrops within unit are infrequent, and highly weathered where present.

3.2 Quaternary Geologic Mapping:

Surficial mapping throughout the study area identified several Quaternary units not included on the preexisting geologic map (Nesse and Braddock, 1989). In addition, I subdivided Quaternary units into more specific categories (Table 2) and refined the location of existing contacts of Quaternary units. Other specific changes include differentiating two distinct glacial till units of different ages (Qg1 & Qg2) based on the preservation of moraine crests and kettles, embeddedness of boulders and clasts within the finer matrix, and qualitative assessments of clast surfaces. A deposit of till in a small tributary valley was identified (Supplemental Figure 1 – near the center of the southern boundary), expanding the extent of glaciation documented in the South Fork Valley. Terraces and large braid bars composed of well-rounded cobbles, gravel, and sand were reclassified from the previous designation of till and remapped as glacial outwash. Similarly, fluvial landforms originally mapped as Quaternary alluvium, were differentiated into floodplain, terrace, and fan deposits. Surrounding the CSU Mountain Campus, two distinct till deposits, and a variety of glaciofluvial and fluvial landforms were differentiated (Figure 4).

Though never large enough to be map scale, three deposits of light tan, laminated silt and sand (with very isolated gravel clasts) were found along the banks of the South Fork immediately downstream of the CSU Mountain Campus. The largest exposure of these fine sediments (~6 m high by ~13 m long) is on the right bank of the South Fork, ~200 m downstream of where the river enters the terminal moraine. Fine sediments were only found as shallow deposits preserved on banks and valley sides where the South Fork has incised into other valley bottom sediments. This suggests that they were deposited after the majority of post-glacial fluvial incision had occurred.

Table 2. Quaternary units mapped in the field area. Ages are based on proposed age relationships of the geologic history of the South Fork Valley and the greater northern Colorado Front Range (e.g., Madole et al., 1998). Descriptions outline unit characteristics, differentiation within each unit type, and a brief comparison to those provided by Nesse and Braddock (1989).

Unit Type:	Symbol(s):	Age(s):	Description:
Floodplain	Qfp	Modern (0 - 485 yr; this study)	Low relief surface proximal to modern channels. Composed of an upper layer of dark brown, predominantly silt-sized fine sediment (~1 m thick) overlying coarser sand, and rounded gravel and cobble.
Alluvium	Qt, Qal	Holocene (1.5-2 ka; this study)	Planar surfaces 1-2 m above the floodplain (Qt), or undifferentiated alluvium (Qal). Composed of either fine grained sediments (clay – medium sand), or coarser alluvium (sand - cobbles). Multiple fluvial terrace sequences may exist, but all low > ~2m above floodplain terraces are grouped.
Alluvial Fan	Qaf	Pleistocene-Holocene	Coarser (sand - boulder) alluvial sediments deposited in a fan- or cone-shaped deposit at the base of some tributary channels. Material likely deposited by intermittent streams and debris flows.
Glacial Outwash	Qow, Qow1, Qow2	Late Pleistocene (Qow1>13.9 ka; Qow2= 13.9 ka; this study)	Primarily coarse (sand, gravel & boulders), well rounded sediments deposited under glaciofluvial conditions. Subdivided in the mapping into two distinct sets of paired outwash terraces (Qow1, Qow2) and undifferentiated terraces and braid bars (Qow).
Glacial Till	Qg1, Qg2	Pleistocene (Qg2 >13.9 ka; this study. Pinedale glaciation 30-12 ka Madole et al., 1998)	Composed of igneous and metamorphic clasts and boulders in a finer grained matrix. The youngest till deposit (Qg2) has significant (~5-10 m) local relief and forms crisp moraine crests and kettles. High on the valley sides and downstream of the younger till, deposits are more weathered and lower relief (Qg1).

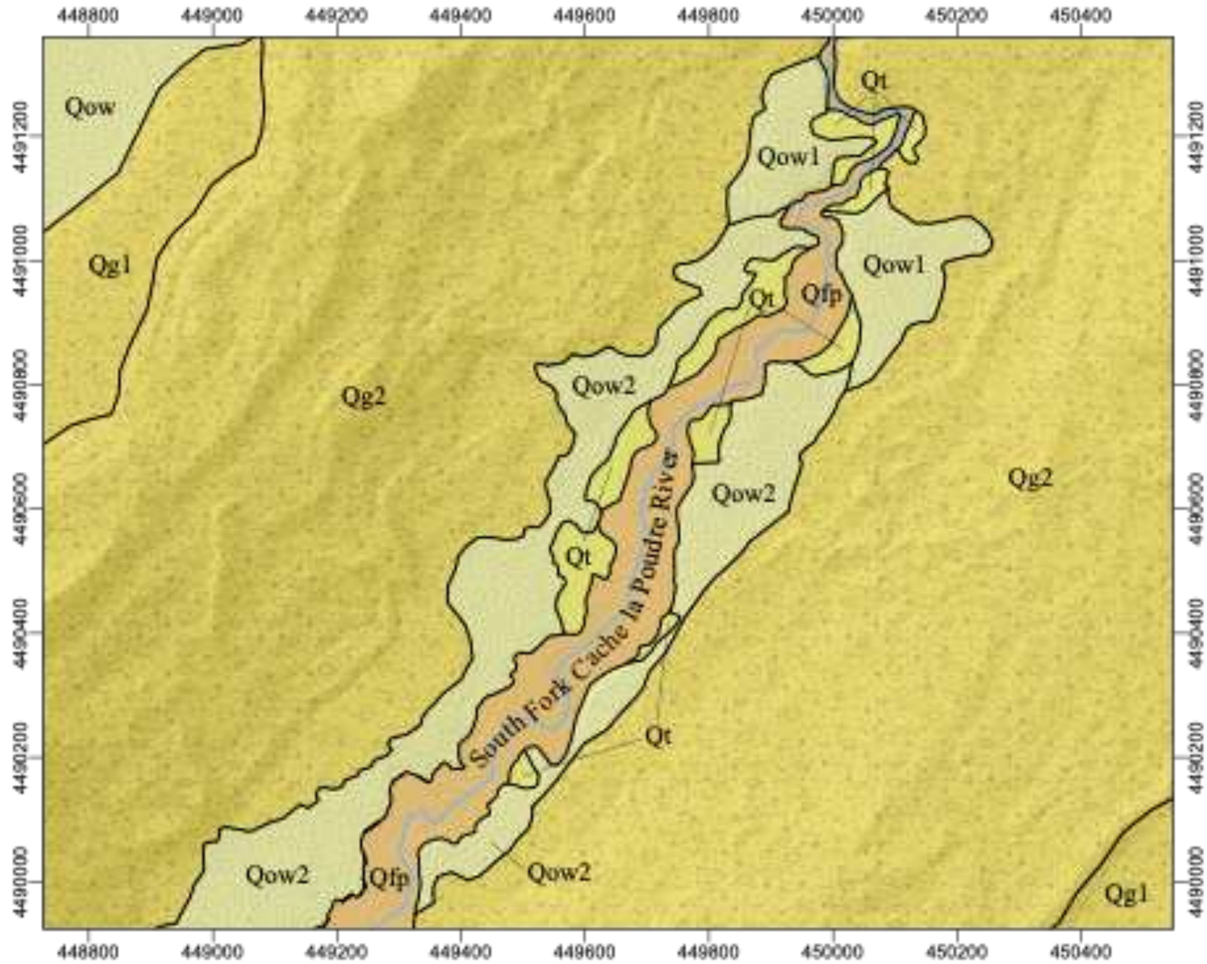

Figure 4. Sample geologic map of the South Fork Valley at the Mountain Campus. Units include glacial till (Qg1, Qg2), outwash terraces (Qow, Qow1, Qow2), fluvial terraces (Qt), and the active floodplain (Qfp). Location tick marks are in WGS UTM zone 13N. The complete geologic map is included with this report as supplementary material.

3.3 Radiocarbon Analysis:

Of the nine bulk sediment samples analyzed for radiocarbon, six samples contained enough carbon to yield an age. Three samples of fine-grained sediment, believed to be organic rich, were collected from the core at MW2 (Figure 2), though none contained sufficient carbon to provide an age. Radiocarbon ages (Table 3) range from 13865 to 485 radiocarbon years before present. The sample that yielded the oldest age was collected from the upstream deep well sediments (MCMW1). Samples of Holocene age (~7 ka to ~1.5 ka) were cored from a wet meadow perched atop a high terrace (MCBP1) and from a low terrace (LZDFP). The youngest age was collected from a core on the South Fork floodplain, within ~10 m of the active channel (MCDSSW). The uncertainty of each age is reported as one standard deviation from the mean of each sample.

Table 3. Summary of radiocarbon sample ages, location, and sample depth. Samples which did not yield a radiocarbon age are signified by a dash in place of a numerical age value.

Location ID:	Sample Depth:	Map Unit:	^{14}C Age BP:	1 σ Error:
MCMW1	3.65-4.25 m	Qgt2	**13,865**	**59**
MCBP1	0.3-0.4 m	On top of Qgt1	**6,982**	**33**
MCBP1	0.8-0.9 m	On top of Qgt1	**1,634**	**25**
MCDSSW	0.95-1.03 m	Qfp	**485**	**20**
LZDFP	0.35 m	Qt	**1,457**	**21**
LZDFP	1.1-1.2 m	Qt	**2,117**	**23**
MCMW2	3.65-4.25 m	Qgt1	**-**	**-**
MCMW2	4.9-5.5 m	Qgt1	**-**	**-**
MCMW2	7.3-7.9 m	Qgt1	**-**	**-**

4. DISCUSSION

4.1 Controls on Bedrock Erodibility

Bedrock mapping results suggest that the presence of mylonitic textured shear zone rocks, where outcropping, are not directly associated with decreased rock strength in the South Fork Valley. These units were generally preserved on ridges between valleys and were much smaller in area than originally mapped by Nesse and Braddock (1989). Mylonites observed in thin section ranged from protomylonitic to ultramylonitic texture, and several thin sections from shear zone rocks recorded significant veining and cataclastic textures. Mylonitic, veining, and cataclastic textures indicate the rocks were deformed under a variety of conditions, with brittle deformation often overprinting ductile fabrics (where present). The transition of deformation from ductile to brittle conditions may explain the lack of outcrops displaying mylonitic texture along strike of the mapped shear zones and suggests that different segments of the shear zones in the field area may record slightly different deformation histories. Cataclastic deformation occurring along shear zones may better explain a decrease in rock strength than ductile deformation of shear zone rocks.

Zones of intense hydrothermal alteration were commonly found along mapped shear zones, as well as other areas of the map. Field observations of hydrothermally altered zones generally noted highly weathered rocks at the surface, lack of good outcrops, and difficulty in identifying the original lithology of bedrock at these stations. In some thin sections, the alteration was significant enough to completely obliterate any prior fabrics contained within rocks, and where some prior fabrics were preserved, hydrothermal mineralization was often associated with brittle fracturing of the rock. In some cases, silicic mineralization appeared to improve rock strength, as evidenced by large outcrops found continuously along the areas of most intense silicic mineralization, yet most other mineralization was associated with a dearth of outcrops, and highly weathered bedrock primarily found as float. These findings suggest that hydrothermal alteration throughout the field area, potentially in conjunction with brittle fracturing localized along shear zones may have the largest influence on rock strength and the erodibility of bedrock in the South Fork Valley.

4.2 Quaternary Landscape History of the South Fork Valley

Results from Quaternary mapping and radiocarbon analysis of valley bottom sediments indicate that the South Fork Valley has experienced significant change since the late Pleistocene, especially within glaciated areas. The area around the CSU Mountain Campus was glaciated at least twice, with the recent-most glaciation retreating at least 13.9 ka. The glacial landforms associated with this glaciation are well defined, with crisp moraine crests and kettles which have yet to fully fill with sediment. Based on radiocarbon ages, and similar morphology to other Pinedale Stade deposits (R. Madole, personal communication), I believe the younger till deposits in the study area (Qg2) are associated with the Pinedale period, considered to last from ~30 ka to ~12 ka (Madole et al., 1998). Till deposits located beyond the extent of Qg2 that display more subdued local relief (Qg1) are potentially associated with the Bull Lake Stade, yet no absolute age control is available to constrain the age of these deposits. Alternately, these deposits could have been formed by an earlier Pinedale glacial advance, and experienced significant topographic degradation during the later Pinedale advance. Due to this uncertainty, I consider the Qg1 unit pre-late-Pinedale. Multiple glacial advances in the South Fork Valley have affected the landscape, and relict glacial topography strongly influences the post-glacial evolution of the South Fork landscape. Nowhere is this seen more than at the Mountain Campus, located on the South Fork River at the transition between the low-gradient glacial trough and the high relief terminal moraine of both glaciations (Figure 5).

Two sets of high terraces are preserved along the South Fork River at the CSU Mountain Campus, the higher of which has a tread 5-8 m above the floodplain (Qow1), the lower 3-6 m above the floodplain (Qow2). The terraces consist of interlayered coarse (sand-cobble) and fine (clay-sand) sediments and are not present at other locations in the study area. Several sediment samples from each terrace were analyzed for radiocarbon geochronology. The sample collected from the lower terrace (Qow2) produced the 13.9 ka age used to constrain the timing of glacial retreat, but none of the three samples from the higher terrace contained enough carbon to produce an age. Due to the greater relief above the adjacent floodplain and continuous slope of the Qow1 surface onto the terminal moraine, I consider Qow1 to have formed prior to Qow2, and to represent the maximum height of aggradation of the valley following Pinedale glaciation. Qow1 likely formed shortly after glacial retreat. Qow2 is composed of similar outwash material and is believed to represent the post-glacial valley bottom surface after 1-2 m of incision. Significant fluvial incision and planation by the South Fork River has occurred since the formation of the Qow2 surface, with a wide modern floodplain (Qfp) and low terraces (Qt) located inside of the two high terrace surfaces. Other outwash deposits (Qow) are present along the South Fork within and downstream of the terminal moraine zone, preserved as large braid bars, or along valley walls where the river has incised through the terminal moraine. These deposits are usually 2-6 m above the modern channel and are coarser (clasts are medium cobbles to boulders) than the outwash units found at the Mountain Campus. River incision through several meters of outwash deposits suggests significant incision has occurred following a period of rapid aggradation at the end of glacial conditions. In some places where the South Fork has incised into till and outwash, deposits of fine, laminated sediments were noted, likely deposited in ponded water. This suggests that the South Fork was dammed somewhere in the terminal moraine during or following post-glacial fluvial incision, though no definite dam sites were found along the South Fork.

Downstream of the confluence of the South Fork and Beaver Creek, outwash sedimentation was either of a much lower magnitude, or the outwash sediments there have been thoroughly eroded or reworked. Instead, the primary valley bottom features are the modern floodplain, intermittent terraces ~1-2 m above the floodplain, and hillslope sediments. Radiocarbon samples from this low terrace surface indicate that this feature was formed between ~2.1 ka and ~1.4 ka. About 1 m of incision has occurred since then, with one floodplain sediment sample collected ~10 m from the modern channel returning an age of 485 years. The observation of abandoned meander features and live riparian vegetation on portions of the Qt surface support the likelihood of a period of late-Holocene incision by the South Fork River.

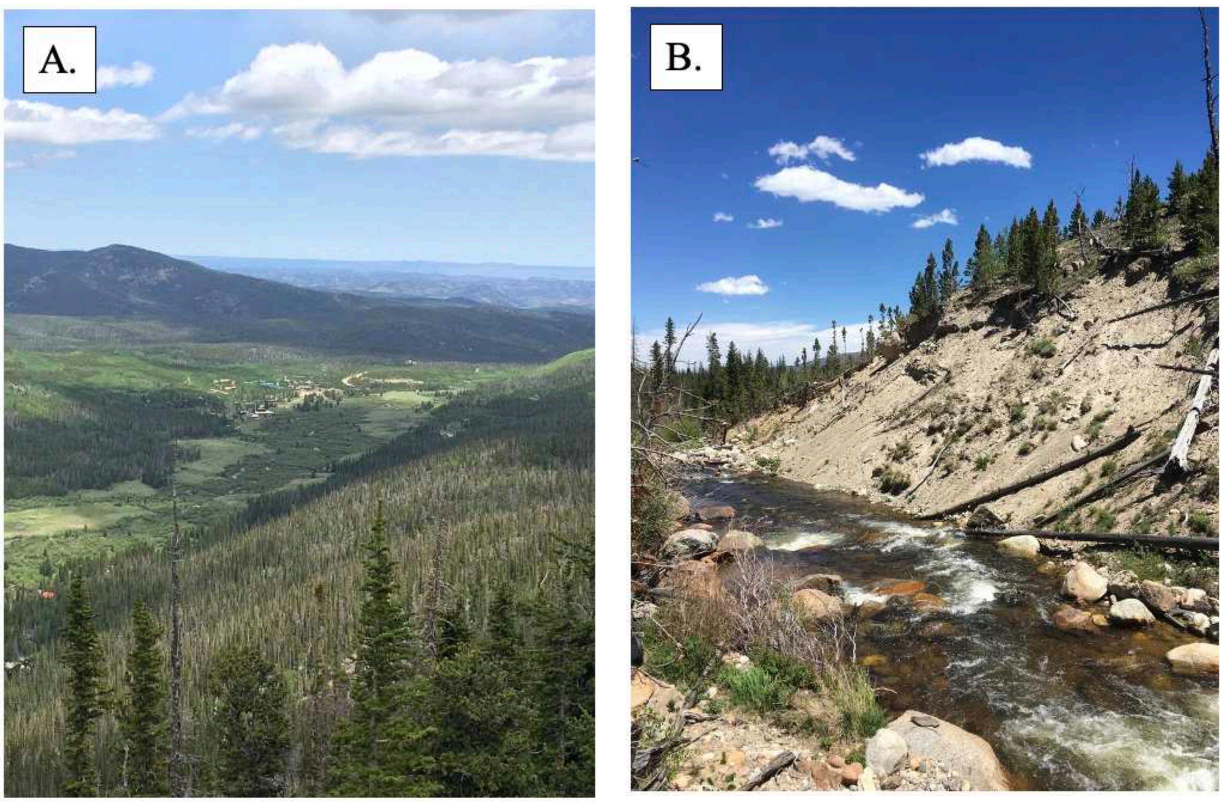

Figure 5. Images of the South Fork River Valley. 5A) South Fork Valley at the CSU Mountain Campus. Floodplain and low terraces are darker green due to extensive willow (*Salix spp.*) cover. Outwash terraces are lighter in color and much less densely vegetated. Flow is from left to right. 5B) South Fork River within the terminal moraine. Bed and bank substrates are much coarser grained than at the Mountain Campus, and the river is much more confined. Flow from right to left.

4.3 Further Work:

Important additional research that could substantiate and/or leverage this mapping effort includes the following:

- Expand the spatial scope of lithologic and surficial mapping to other unconfined valley segments in the South Fork drainage basin.
- Perform a quantitative assessment of bedrock strength for each lithologic unit, of structurally altered rocks, and of zones of intense significant hydrothermal alteration.
- Utilize additional isotopic geochronology and/or develop a quantitative relative chronology of Quaternary features (e.g., soil development, clast weathering) to better constrain the Quaternary landscape history of the South Fork drainage.
- Examine the depth, stratigraphy, and spatial variability of alluvial fills in unconfined valleys to better understand the development of valley fills and their effects on valley confinement.

5. CONCLUSIONS

Remapping a portion of the Pingree Park Quadrangle revealed two unconfined valley segments within the upper South Fork Cache la Poudre Valley, one inside and one downstream of the late Pleistocene glacial extent. Outside of the glacial extent, valley confinement may be related to bedrock characteristics. In these areas, this project refined the bedrock mapping of the area, and described areas of structurally and hydrothermally altered rocks in a more robust manner. These data could be used by others to perform a quantitative assessment of rock strength to assess the lithologic controls of bedrock erodibility and understand how bedrock characteristics relate to the development of unconfined valleys in mountains. At the formerly glaciated unconfined valley segment, glacial incision and deposition of a large terminal moraine by at least two episodes of glaciation is likely responsible for the development of the valley geometry. The last glaciation to affect that valley segment must have retreated prior to 13.9 ka. Following Pinedale deglaciation, over 10 m of glacial outwash was deposited within the South Fork Valley upstream of the terminal moraine. Subsequent fluvial action has reshaped valley bottoms throughout the study area, in and outside of the glacial extent, forming two high terraces composed of glacial outwash, and numerous alluvial terraces 1-2 m above the modern floodplain.

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7. REFERENCES

Anderson, R. S., Molnar, P., & Kessler, M. A. (2006). Features of glacial valley profiles simply explained. *Journal of Geophysical Research: Earth Surface*, *111*(F1).

Anderson, R. S., Riihimaki, C. A., Safran, E. B., & MacGregor, K. R. (2006). Facing reality: Late Cenozoic evolution of smooth peaks, glacially ornamented valleys, and deep river gorges of Colorado's Front Range. *Special Papers-Geological Society of America*, *398*, 397.

Benedict, J. B., Benedict, R. J., Lee, C. M., & Staley, D. M. (2008). Spruce trees from a melting ice patch: Evidence for Holocene climatic change in the Colorado Rocky Mountains, USA. *The Holocene*, *18*(7), 1067-1076.

Caine, J. S., Ridley, J., & Wessel, Z. R. (2010). To reactivate or not to reactivate—Nature and varied behavior of structural inheritance in the Proterozoic basement of the eastern Colorado Mineral Belt over 1.7 billion years of Earth history. *Field Guide-Geological Society of America*, *18*, 119-140.

Cavosie, A. J., Sharp, Z. D., & Selverstone, J. (2002). Co-existing aluminum silicates in quartz veins: A quantitative approach for determining andalusite-sillimanite equilibrium in natural samples using oxygen isotopes. *American Mineralogist*, *87*(4), 417-423.

DePaolo, D. J. (1981). Neodymium isotopes in the Colorado Front Range and crust–mantle evolution in the Proterozoic. *Nature*, *291*(5812), 193-196.

Doerner, J. P. (2007). Late quaternary prehistoric environments of the Colorado front range. *Frontiers in Colorado Paleoindian Archaeology: From the Dent Site to the Rocky Mountains. Boulder, CO: University Press of Colorado*, 11-38.

Ehlen, J., & Wohl, E. (2002). Joints and landform evolution in bedrock canyons. *Transactions, Japanese Geomorphological Union*, *23*(2), 237-255.

Fryirs, K. A., Wheaton, J. M., & Brierley, G. J. (2016). An approach for measuring confinement and assessing the influence of valley setting on river forms and processes. *Earth Surface Processes and Landforms*, *41*(5), 701-710.

Grimsley, K., Rathburn, S., Friedman, J., and Mangano, J., 2018, Debris flow occurrence and sediment persistence, Upper Colorado River Valley, CO, *Environmental Management*, 58:76-92.

Leone, J. D., Holbrook, W. S., Riebe, C. S., Chorover, J., Ferré, T. P., Carr, B. J., & Callahan, R. P. (2020). Strong slope-aspect control of regolith thickness by bedrock foliation. *Earth Surface Processes and Landforms*, *45*(12), 2998-3010.

Livers, B., & Wohl, E. (2015). An evaluation of stream characteristics in glacial versus fluvial process domains in the Colorado Front Range. *Geomorphology*, *231*, 72-82.

Madole, R. F. (1980). Time of Pinedale deglaciation in north-central Colorado: Further considerations. *Geology*, *8*(3), 118-122.

Madole, R. F. (1986). Lake Devlin and Pinedale glacial history, Front Range, Colorado. *Quaternary Research*, *25*(1), 43-54.

Madole, R. F., VanSistine, D. P., & Michael, J. A. (1998). Pleistocene glaciation in the upper Platte River drainage basin, Colorado. *Geologic Investigations Series Map I-2644*. US Geological Survey: Reston, VA.

Madole, R. F. (2012). Holocene alluvial stratigraphy and response to climate change in the Roaring River valley, Front Range, Colorado, USA. *Quaternary research*, *78*(2), 197-208.

Menounos, B., & Reasoner, M. A. (1997). Evidence for cirque glaciation in the Colorado Front Range during the Younger Dryas chronozone. *Quaternary Research*, *48*(1), 38-47.

Nagel, D. E., Buffington, J. M., Parkes, S. L., Wenger, S., & Goode, J. R. (2014). A landscape scale valley confinement algorithm: Delineating unconfined valley bottoms for geomorphic, aquatic, and riparian applications. *Gen. Tech. Rep. RMRS-GTR-321.* Fort Collins, CO: US Department of Agriculture, Forest Service, Rocky Mountain Research Station. 42 p.

Nesse, W. D., & Braddock, W. A. (1989). Geologic Map of the Pingree Park Quadrangle, Larimer County, Colorado, 1: 24,000 scale. *US Geological Survey Map GQ-1622.* US Geological Survey: Reston, VA.

Peterman, Z. E., Hedge, C. E., & Braddock, W. A. (1968). Age of Precambrian events in the northeastern Front Range, Colorado. *Journal of Geophysical Research*, 73(6), 2277-2296.

Schildgen, T., Dethier, D. P., Bierman, P., & Caffee, M. (2002). 26Al and 10Be dating of late Pleistocene and Holocene fill terraces: a record of fluvial deposition and incision, Colorado Front Range. *Earth Surface Processes and Landforms*, *27*(7), 773-787.

Tweto, O., & Sims, P. K. (1963). Precambrian ancestry of the Colorado mineral belt. *Geological Society of America Bulletin*, *74*(8), 991-1014.

Whiting, P. J., & Bradley, J. B. (1993). A process-based classification system for headwater streams. *Earth Surface Processes and Landforms*, *18*(7), 603-612.

Wohl, E. (2008). The effect of bedrock jointing on the formation of straths in the Cache la Poudre River drainage, Colorado Front Range. *Journal of Geophysical Research: Earth Surface*, *113*(F1).