THESIS

POST-GLACIAL ALLUVIAL VALLEY DYNAMICS OF THE SOUTH FORK CACHE LA POUDRE RIVER VALLEY AT THE COLORADO STATE UNIVERSITY MOUNTAIN CAMPUS

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ABSTRACT

POST-GLACIAL ALLUVIAL VALLEY DYNAMICS OF THE SOUTH FORK CACHE LA POUDRE RIVER VALLEY AT THE COLORADO STATE UNIVERSITY MOUNTAIN CAMPUS

Wide valley bottoms are physically important sediment storage sites where alluvial records of past landscape dynamics may be preserved. Following deglaciation after the Last Glacial Maximum (LGM), unconfined valleys in the Colorado Front Range experienced periods of fluvial aggradation and incision, creating distinctive valley bottom morphologies and the substrates which influence present-day hydrological and ecological characteristics. The objectives of this study are to investigate the processes and chronology of post-glacial geomorphic evolution of an unconfined portion of the South Fork Cache la Poudre River (South Fork) Valley, Colorado Front Range, to identify the dominant processes and temporal patterns of valley alluviation and incision following LGM retreat at the Colorado State University Mountain Campus (Mountain Campus). Methods used include geologic mapping, ground-penetrating radar (GPR) surveys, coring of valley bottom sediments, radiocarbon geochronology, and analysis of historical aerial images. Mapping of the Quaternary sediments indicates a variety of glacial and fluvial deposits occur in the South Fork Valley, including moraines, two distinct outwash terraces (approximately 8 m and 6 m above the present-day channel, respectively), fluvial terraces 1–2 m high, and an extensive floodplain. Well logs indicate over 10 m of glaciofluvial outwash sediment was deposited upstream of the LGM terminal moraine, and GPR reflections suggest that lateral bar migration, channel filling, and vertical accretion of sediments were important processes of outwash aggradation in the valley. The South Fork River has since incised into the outwash. A fluvial terrace and the modern floodplain are inset within the outwash sediments and are composed of overbank-deposited silt-to-sand sized sediments. Radiocarbon samples of valley sediments indicate that outwash was deposited at least 16.8 ka, with 8–10 m incision occurring after 16.8 ka and prior to 7.8 ka. Fine-grained sedimentation occurred on the fluvial terrace and floodplain from at least 2.1 ka to 1.3 ka. The modern floodplain has been vertically accreting for at least the last 500 years. Historical aerial images show that the South Fork channel was relatively stable from 1938 to the present; the channel planform area changed by no more than 2.5% per year during this period. Additionally, in the last ~80 years, the channel has largely occupied the center of the unconfined valley, reducing connectivity between the channel, terraces, and the valley sides. My results highlight the complex patterns of sediment storage and removal in unconfined valleys, with at least two phases of aggradation and one phase of incision following deglaciation. In addition, the South Fork Valley is relatively geomorphically stable: large volumes of Quaternary sediments have been stored for over 16.8 ka years, and the modern fluvial system has not responded drastically to local disturbances because of low connectivity between hillslopes and the valley bottom. The South Fork Valley is an effective site of fluvial sediment storage following deglaciation despite a long-term trend of sediment removal from the valley in the Holocene. Broader implications of assessing valley bottom stability and long-term sediment storage in mountains include managing unconfined valleys where development pressures, proposed water diversions, and climatically forced changes to the hydrology are occurring. Findings presented herein may provide insights for maintaining riparian biodiversity and surface-subsurface water exchange in formerly glaciated environments

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1. INTRODUCTION

River valleys in mountainous environments integrate landscape processes occurring across hillslopes and channels (Whiting and Brantley, 1993), and provide key sites for sediment and groundwater storage (Glas et al., 2018). Valley bottoms are the locus of sedimentation and erosion in valleys, are defined as the area occupied by channels and adjacent low relief landforms, and are classified as confined or unconfined depending on the ratio of channel width to valley bottom width (Nagel et al., 2014; Fryirs et al., 2016). The unconfined valley bottom morphology of formerly glaciated valleys regulates the influence of geomorphic processes and disturbances at these sites. Unconfined valley bottoms may also contain more complete stratigraphic records and more complex valley bottom morphologies than other valleys in mountains (Livers & Wohl, 2015), yet relatively few data exist on the processes, magnitude, and timing of fluvial sedimentation and erosion following glacier retreat in the Colorado Rocky Mountains (Madole, 2012). In this thesis, I use a multifaceted approach to study how a river in a formerly glaciated valley has deposited and removed sediment following the last major episode of alpine glaciation. To assess the processes and timing of fluvial erosion and sedimentation following deglaciation, I evaluated the relative importance of various fluvial processes which shape the valley, and how the sediment regime of the South Fork Valley changes over time. To expand the scope of my work beyond my study site, I compare my findings to those of two other similar studies performed in the Colorado Front Range. Results may also be compared to studies of sedimentation in formerly glaciated valleys outside of Colorado, which may experience different hydro-climatic, geologic, or anthropogenic conditions than the Colorado Front Range. This work improves our understanding of the post-glacial geologic history of the headwaters of the South Fork Cache la Poudre River and may provide land managers with insights regarding the physical and biological processes that maintain valley bottom characteristics over time.

1.1 Review of Post-Glacial Valley Bottom Evolution

Glacial valleys commonly form the headwaters of mountain rivers. The lack of data on post-glacial valley sediment dynamics limits our understanding of how these landscapes change over time, and how fluvial processes alter valley bottoms that were previously outside the fluvial process domain. Despite the relative dearth of information on the subject, a few studies of post-glacial valley bottom evolution have been completed in southern Rocky Mountains, USA. These studies of valley bottom sediment and landscape dynamics within, or adjacent to the extent of late Pleistocene glaciations, may be categorized into two groups based on the scope of research, as follows: 1) studies in which the author(s) document periods of aggradation and incision, and the development of fluvial landforms at the (sub)basin scale over late-Quaternary timescales; and 2) studies that focus on the importance of geomorphic processes and/or events occurring in the Holocene which cause significant valley bottom morphologic change in a specific valley segment. Examples of the larger spatial and temporal scale studies include Schildgen et al. (2002), Madole (2012), and Layzell et al. (2012), which utilize some combination of surficial geologic mapping, analysis of streamwise longitudinal profiles, stratigraphic description of valley bottom deposits, and Quaternary geochronology. Process-focused studies have documented the potential of flooding (Rathburn et al., 2017), beaver activity (Ives, 1942; Kramer et al., 2012; Polvi and Wohl, 2012), wildfire (Moody and Martin, 2001), and debris flows (Rubin et al., 2012; Grimsley et al., 2016) to shape valley bottoms in the southern Rockies. In addition to these studies of Quaternary valley bottom change, several other studies (e.g., Clow et al., 2003; Leopold at al., 2009) and technical reports (e.g., Braddock and Cole, 1990) provide insights regarding the timing of sedimentation and/or thickness of sediments in southern Rocky Mountain valleys. These additional sedimentation data were collected as parts of paleoclimate, hydrogeologic, and geophysical studies.

Notwithstanding the different methods of examining post-Last Glacial Maximum (LGM) valley bottom evolution, findings of these works can be aggregated to develop a more robust theoretical framework of late-Pleistocene to present geologic history and range of variability of landscape processes affecting Rocky Mountain valleys.

1.1.1 Long-term Valley Bottom Alluviation in the Front Range

Three selected studies, in decreasing order of timescale analyzed, have described the long-term alluvial sediment dynamics of valley bottoms in the Colorado Rocky Mountains. In each, the authors describe how periods of fluvial sedimentation and incision shape the morphology of valley bottoms studied.

Schildgen et al. (2002) identified the characteristics of numerous fluvial terraces along Middle Boulder Creek, northern CO, and utilized ^{14}C and cosmogenic exposure dating to constrain the age of these landforms. While this study was conducted below the LGM glacial extent, findings suggest that the formation of most terraces coincided with, or closely postdated, deglaciation in the headwaters. The formation of smaller terrace features, with risers up to 4 m above the modern channel, is constrained between 2 and 4 ka, and records a late-Holocene episode of aggradation, albeit smaller in magnitude than post-LGM aggradation.

Layzell et al. (2012) utilized surficial geologic mapping, ^{14}C and relative geochronological methods, and described the morphologic relationships and sedimentary characteristics of valley bottom landforms to constrain the post-glacial alluvial history of the Rio Conejos Valley, southern CO. The authors documented episodic periods of fluvial deposition, lateral erosion, and incision following glacial retreat in the valley, with significant aggradation occurring three times, at 8.9–7.6 ka, 5.5 ka, and 3.5–1.1 ka. A record of this deposition was preserved in a series of fluvial terraces. The authors infer that deposition corresponded to periods of increased sediment supply (Layzell et al., 2012). Although the studies of Schildgen et al. (2002) and Layzell et al. (2012) were separated by several hundred kilometers, both documented significant late-Holocene valley bottom alluviation and subsequent incision. Additionally, Layzell et al. (2012) leveraged mapping and other field observations to consider the influences of preexisting (glacial) valley bottom topography on post-glacial valley sedimentation and incision. One key finding from this mapping regarding relict glacial topographic influence is that at tributary glacial confluences the bedrock profile of the main valley is often overdeepened (Layzell et al., 2012). This phenomenon is captured in the numerical experiments of MacGregor et al. (2000), which show that higher ice discharge downstream of tributary junctions promotes abrasion and allows the glacier to vertically incise into basal substrates. At these former ice-confluence sites, the Conejos Valley is filled with ~30 m of outwash or glacial till overlying bedrock. Outwash is fluvially deposited silt to cobble sized sediment originating from a glacier, and usually associated with high discharge and sediment supply conditions. Fluvial processes have incised into the outwash or till, rather than bedrock, and fill-cut terrace sequences exist rather than strath terraces at these sites (Layzell et al., 2012).

Madole (2012) examined post-glacial alluvial dynamics in the northern Front Range, CO via surficial mapping, detailed stratigraphic description, and a thorough (n=50) ^{14}C geochronological assessment. In agreement with the findings of Schildgen et al. (2002) and Layzell et al. (2012), Madole (2012) documented several periods of post-glacial alluvial deposition temporally clustered shortly after deglaciation, and in the mid- and late-Holocene. A significant period of valley-bottom alluviation and incision was documented in the late Holocene, in concurrence with both Schildgen et al. (2002) and Layzell et al. (2012). Also, like that described by Layzell et al. (2012), Madole (2012) describes how glacial valley bottom characteristics and features influence the alluvial history of certain reaches, yet emphasizes that differences in alluvial dynamics resulting from changes in valley geometry do not reflect a nonalluvial condition of these streams.

1.1.2 Review of Processes and Events Causing Valley Bottom Morphologic Change

While the previously described studies document the temporal and spatial variability of alluvial dynamics in valleys within (Layzell et al., 2012; Madole, 2012) and below (Schildgen et al., 2002) the glacial limit, and show similarities across diverse sites in the southern Rocky Mountains, they lack detail on the surficial processes and/or events that drive fluctuations in the sediment regime which correspond to the distinct periods of valley bottom change identified therein. To capture the suite of surficial processes driving alluvial valley bottom change in nearby Rocky Mountain National Park (RMNP), two key studies utilized ground-penetrating radar (GPR) surveys, and analysis of sediment cores and exposed stratigraphy to identify unique sediment packages comprising valley bottom fills (Kramer et al., 2012; Rubin et al., 2012). Classification of the sediments found in RMNP valley bottoms by their grain size distributions, radar properties, and spatial characteristics allowed these authors to infer the conditions responsible for the deposition of specific units. The proportion of sediments delivered to these valley bottoms by each geomorphic process was approximated by the cross-sectional area of each sediment category identified in the GPR surveys.

Rubin et al. (2012) combined GPR surveys with sediment coring and trenching to identify the specific processes contributing to valley bottom sedimentation in the Lulu City Wetland of the upper Colorado River Valley. Rubin et al. (2012) constrained rates of aggradation with ^{14}C ages of valley bottom sediments. The authors documented multiple processes (peat accumulation, and debris flow deposition and reworking) that led to significant aggradation; these processes occurred under both modern conditions and throughout the middle and late Holocene. Rates of valley bottom aggradation increased severalfold after European settlement, yet pre-settlement aggradation rates approached that of modern conditions during periods associated with increased intensity and/or frequency of debris flows (Rubin et al., 2012). While this study uses similar methods to examine processes of sedimentation in a formerly glaciated valley, the Lulu City Wetland has several markedly different characteristics than the South Fork Valley at the CSU Mountain Campus. The upper Colorado River Valley is underlain by highly mineralized volcanic rock, with unstable hillslopes prone to mass wasting (Rathburn et al., 2013). Additionally, the construction and operation of Grand Ditch, located on the valley side above Lulu City, points to greater anthropogenic influences at Lulu City than in the South Fork Valley.

In a similar study, Kramer et al. (2012) used GPR, active seismic refraction, and sediment coring to evaluate the effects of beaver dams on valley bottom sedimentation. Findings suggested that beaver-ponded deposits comprise up to half of all fluvial sediments at Beaver Meadows, that the magnitude of beaver-related sedimentation is similar in and outside of the late Quaternary glacial extent, and that, on average, beaver-related fluvial deposition results in ~1.3 m of aggradation, which is approximate height of a beaver dam (Kramer et al., 2012). The underlying geology of Beaver Meadows is similar to that of the South Fork Valley. The valley at Beaver Meadows was not glaciated at the LGM, though it contains glacial material and is bordered by a LGM-age lateral moraine from an adjacent valleys.

1.1.3 Other Observations of Valley Bottom Sediment Thicknesses or Chronology

Geologic mapping efforts in the northern Colorado Rocky Mountains also document the characteristics of valley bottom sediments. The preexisting geologic map of the South Fork headwaters (Nesse and Braddock, 1989) suggests that damming of a tributary by glacial debris emanating from the main South Fork glacier caused 15–20 m of glacial outwash to fill the Beaver Creek Valley, about 1 km northwest of my study site. Nesse and Braddock (1989) observed that other valley bottoms in the South Fork headwaters which are not filled with outwash material are composed of a thin covering of alluvium or solifluction deposits. In nearby RMNP, Braddock and Cole (1990) described thick alluvial sediments in the bottom of river valleys, especially in valley reaches just upstream of glacial end moraines. Valley bottom sediment thicknesses are approximated at two sites along the upper Colorado River: 15–122 m in the Kawuneeche Valley and 53 m in Big Meadows (Braddock and Cole, 1990).

To showcase the potential of geophysical techniques to describe the shallow subsurface of alpine landscapes without disturbing these sensitive sites, Leopold et al. (2009) used GPR and shallow seismic refraction to measure the thickness and physical properties of Quaternary substrates at Niwot Ridge, Colorado Front Range (Leopold at al., 2009). At two geophysical survey sites crossing a small creek, Leopold et al. (2009) documented between 2 m and 5 m of unconsolidated soil and sediment, overlying glacial or periglacial deposits at one site, and bedrock at another. As previously discussed, Kramer et al. (2012) and Rubin et al. (2012) utilized geophysical techniques to explore the valley alluviation and the volumetric contributions of surficial processes to these valley fills. Additionally, seismic refraction techniques were used to determine valley bottom sediment thicknesses to estimate groundwater storage potential in the Loch Vale basin of RMNP (Clow et al., 2003). Clow et al. (2003) observed glacial till up to 18.6

m thick and wetland sediments up to 2.7 m thick. Finally, GPR surveys along Little Beaver Creek, a tributary to the South Fork, indicate shallow alluvial cover of up to 2 m (Ader et al., 2021).

1.2 Research Overview

My research examines sediments in a glacial valley in northern Colorado to infer processes of sediment storage and removal following the retreat of the LGM-age glacier circa 13–14.6 ka (Madole, 1980). I focus on the South Fork Cache la Poudre Valley at the CSU Mountain Campus, a relatively broad (>300m wide) and low gradient (<2%) segment of the South Fork River at an elevation above 2750 m because this portion of the upper South Platte drainage basin has thick and laterally extensive alluvial deposits. Low gradient valley segments below 2750 m may also store alluvium, but they are located below the LGM maximum extent, are likely to have bedrock strath terraces (Wohl, 2008), may be incised in response to Neogene exhumation (Anderson et al., 2006), and are more likely to be heavily altered by land use changes and development. I posit that glacio-fluvial and fluvial deposition following glacial retreat is responsible for significant sediment deposition, that the morphostratigraphy of these post-glacial deposits records evidence of past landscape change, and that these landforms influence modern processes of valley bottom alluviation. The questions that I address are as follows:

1. What are the characteristics of post-glacial sediments found in the South Fork Valley?
2. What processes are important to the formation of the valley bottom fill along the South Fork Valley?
3. What is the timing and/or rates of sediment deposition following glaciation and how do these rates/timing vary over time?

My hypotheses and the corresponding rationales are outlined below, with Figure 1 illustrating a relationship between potential geomorphic processes and corresponding trajectories of valley bottom evolution. A simplified view of valley bottom alluvial dynamics is based on increases and decreases in water and sediment discharge, which in turn influence transport capacity of the river, and drive the trajectory of valley bottom evolution.

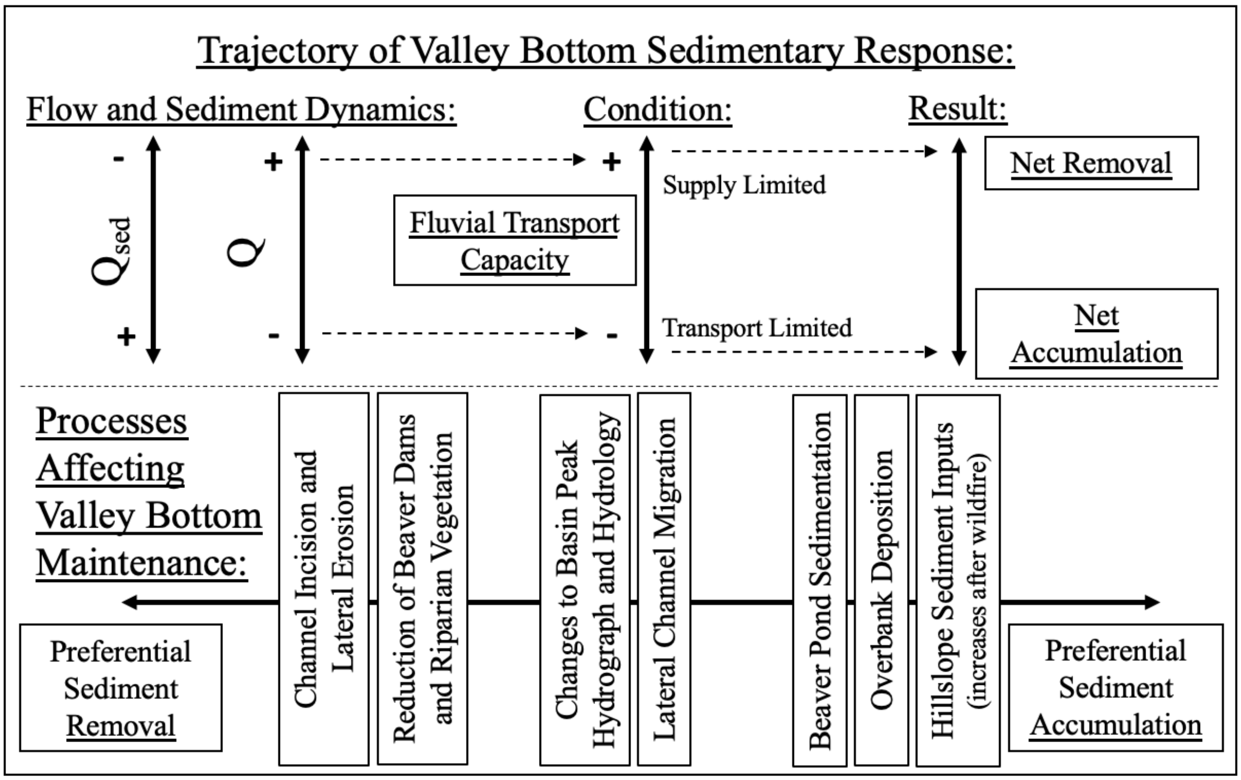


Figure 1: Conceptual model for processes/disturbance conditions promoting accumulation & removal of valley bottom sediments. The top portion outlines the relationship between fluxes of water (Q) and sediment (Q_{sed}) and the trajectory of valley bottom change. The bottom portion highlights key processes of valley bottom maintenance which may contribute to accumulation and removal of sediments. The relative importance of these processes is determined by climate and anthropogenic drivers (e.g., changes to biota, wildfire regime, or glacial/snow melt patterns), and site-specific geomorphic conditions.

1.2.1 Research Hypotheses and Rationale

H1: Vertical accretion of fluvial sediments is the dominant mechanism of post-glacial sedimentation within the South Fork Valley.

The rationale behind this hypothesis is that the channel is not sufficiently sinuous or mobile to create substantial lateral accretion deposits. Work in similar settings suggests vertical accretion is the dominant process of sediment accumulation in other Rocky Mountain valley bottoms (e.g., Kramer et al., 2012; Rubin et al., 2012). The South Fork Valley segment may be too wide for direct hillslope sediment inputs to the valley bottom, but beaver ponding and overbank deposition are likely drivers of sedimentation.

H2: The rate of sediment accumulation and removal in the South Fork Valley over moderate time scales is uniform, and relatively low in magnitude.

The rationale behind this hypothesis is that major episodes of increased sediment supply resulting from wildfires and unusually large snowmelt floods are rare during the Holocene and thus less likely to produce persistent signals in the alluvial record. Perhaps more importantly, the relatively low gradient and broad valley width of the South Fork Valley provide sufficient buffering so that episodic, short duration increases in sediment supply do not commonly occur, and/or do not cause substantial change in sediment storage. Building from H1, overbank sedimentation and beaver ponding are likely to favor gradual, rather than episodic, accumulation of sediments, linking the two hypotheses.

1.2.2 Management Significance

This work is important as a more comprehensive understanding of sediment delivery, storage, and erosion in formerly glaciated valley bottoms may help with their conservation. By facilitating more informed management decisions in formerly glaciated valleys, important landscape and ecosystem services are ensured. Ecosystem services include sediment connectivity, sediment storage, and water storage. Alpine and subalpine valleys are also critical ecosystem integrators, providing key habitat and food for biota (Brighenti et al., 2019), and harboring higher levels of biomass and biodiversity than other mountain environments (Livers and Wohl, 2016). Furthermore, contemporary channels and floodplains are especially sensitive to perturbations to the fluvial system (flow, sediment, vegetation), including climate change (East and Sankey, 2020), and may be key indicators for landscape-wide geomorphic change in mountainous environments. Improved understanding of the processes that create and maintain alluvial fills in glacial troughs can help natural resource managers evaluate the implication of altering the natural range of variability in the supply of water and sediment to these valley bottoms. Finally, this research centers on the CSU Mountain Campus and results of this work may be incorporated into course materials for the approximately 275 undergraduate students who attend natural resource courses there every summer.

1.2.3 Additional Research Objective

Besides examining the late Quaternary geomorphic history of the South Fork Valley at the CSU Mountain Campus, additional data were collected to update the bedrock and glacial geology of the South Fork basin. These spatial data improve the resolution and accuracy of map products in the area and allow for a more comprehensive understanding of the long-term evolution of unconfined valley segments in the South Fork headwaters, and how underlying substrates may influence modern landscape processes.

2. STUDY AREA

2.1 Study Location

The study area for this research is in the headwaters of the South Fork Cache la Poudre River, within the upper South Platte River drainage basin of the southern Rocky Mountains, CO, USA (Figure 2). Much of the South Fork basin is located immediately north of RMNP, though the uppermost portion of the South Fork River and one major tributary to the study area are within the RMNP boundary. The South Fork headwaters drain the northern Mummy Range and flow to the northeast to join the main stem approximately 20 km downstream. Elevation of the study area ranges from ~4080 m to ~2500 m and includes alpine, subalpine, and montane environments. The central focus of this study is the unconfined segment of the South Fork Valley at the CSU Mountain Campus (Figure 2) located upstream of the Last Glacial Maximum terminal moraine, an elevation of approximately 2750 m. Mean annual precipitation at the site is ~60 cm, with most precipitation delivered as snowmelt (Meiman and Leavesley, 1974). Peak discharge along the South Fork occurs in late May to early June, with bankfull flow measured in June 2021 at approximately 5 m^3/s.

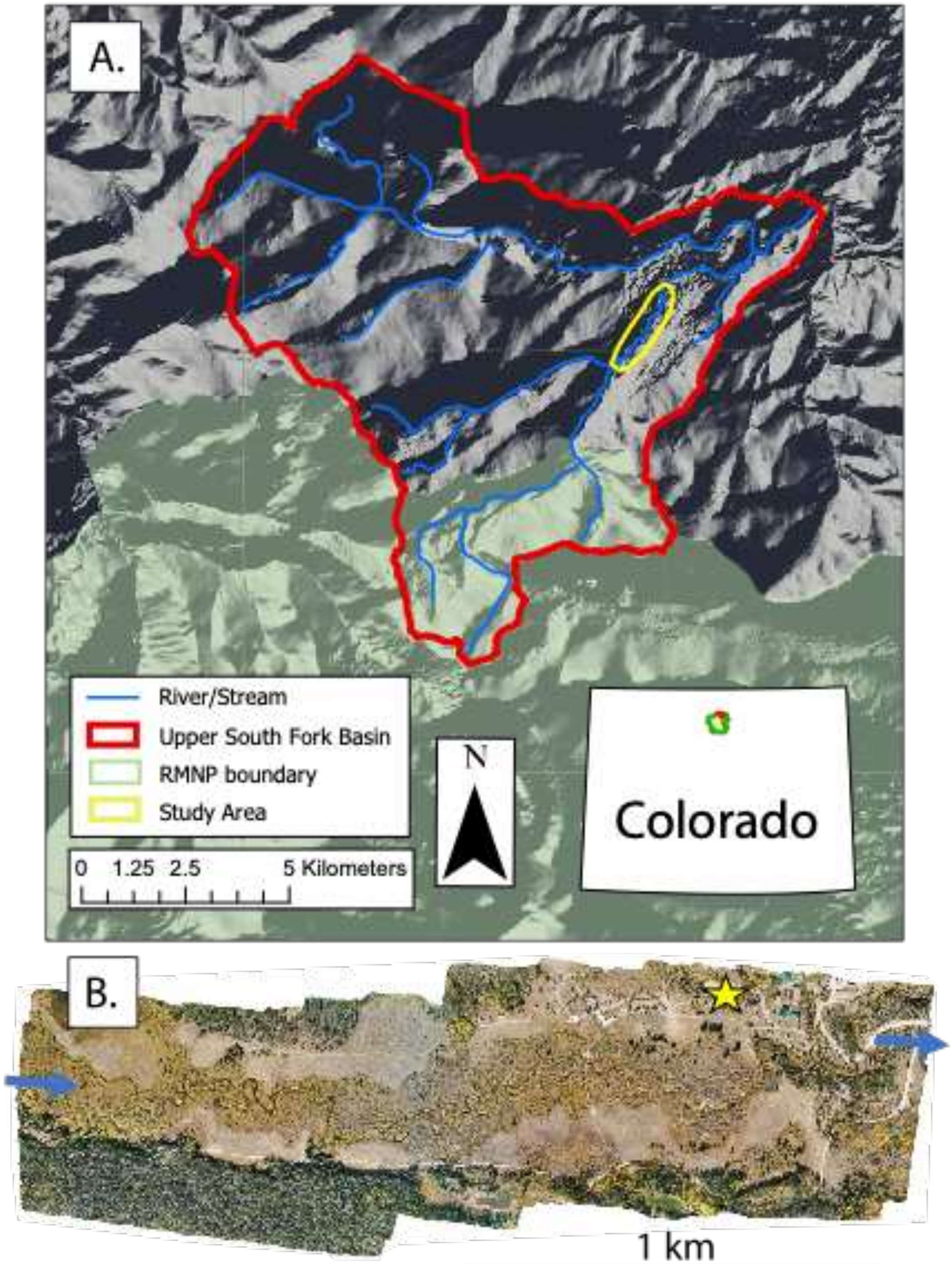


Figure 2: A. Location map of the formerly glaciated headwaters of the South Fork Cache la Poudre River, CO, USA. The yellow polygon represents the study area of this work, centered on the Colorado State University Mountain Campus. Hillshade base map produced from 10 m USGS 3DEP DEM. B. Aerial image of the Mountain Campus property produced from a drone (UAV) survey, September 2019. Flow direction of the South Fork is indicated by blue arrows. The yellow star shows the center of buildings at the Mountain Campus.

2.1.1 South Fork Valley and Channel Morphology

Formerly glaciated valley longitudinal profiles are steeper than fluvially-formed profiles in reaches proximal to the drainage divide, above the long-term equilibrium line altitude, and shallower than fluvially-formed profiles in the ablation zone (Anderson et al., 2006). Further, glacial valleys display ‘u-shaped’ cross sectional morphologies, as opposed to ‘v-shaped’ valleys formed by fluvial incision. Differences in glacial and fluvial transverse profile form introduce significant variability to valley width and channel confinement (e.g., Livers and Wohl, 2015), where glacial valleys near their termini are wider and shallower. At the CSU Mountain Campus, the South Fork Valley has a gradient of ~1%. The South Fork channel ranges between 5–10 m wide and 1–1.25 m deep, primarily single thread with a meandering planform. Reduced slope and stream power (Church, 2002), and limited confinement (e.g., Montgomery, 1999) combine to promote the accumulation of alluvium in glacial troughs. Existing geologic mapping suggests that Quaternary glacial sediments occupy a large portion of the valley bottom (Nesse and Braddock, 1989), with these glacial sediments and landforms situated between the modern channel and the valley walls. The geologic map also shows the valley bottom alluvium unit pinching out just downstream of the Mountain Campus property (Figure 2), with the South Fork River flowing over glacial material and no documented alluvium until the South Fork reaches the edge of the mapped glacial extent. Furthermore, the study site is at an elevation (~2750 m) which is above the proposed ~2300 m threshold for flash floods associated with convective storms in the southern Rocky Mountains (Jarrett, 1993). Only one major tributary, Fall Creek, joins the South Fork River within the study area. Overall, the density of tributaries in the South Fork headwaters is low (Figure 2).

2.2 Geologic History of the South Fork Valley

2.2.1 Bedrock Geology

The headwaters of the South Fork River are underlain by Precambrian-age crystalline rocks, of both igneous and metamorphic origin. 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 1.4–1.6 Ga in age include small bodies of weakly foliated Proterozoic Boulder Creek Granodiorite, and Silver Plume and Hague's Peak Granite. Dikes and sills of the same age are composed of very coarse-grained pegmatite and are related to emplacement of the granitoids (Nesse and Braddock, 1989). The Precambrian rocks of the region have experienced multiple episodes of deformation and localized zones of high strain; mylonitic rocks are identified in the upper South Fork drainage basin (Nesse and Braddock, 1989). Mylonitic rocks recording ductile shear have been identified throughout the Colorado Front Range (e.g., Caine et al., 2010), have been shown to differ in joint density and weathering characteristics compared the surrounding crystalline bedrock (Ehlen and Wohl, 2002), and may explain the spatial distribution of strath terraces and unconfined valley segments at other sites in the Cache la Poudre drainage basin (Wohl, 2008).

2.2.2 Late Quaternary Regional Paleoclimate

Climate reconstructions in the Colorado Front Range have constrained climate dynamics in subalpine ecotones in the late-Quaternary, including the end of the Pleistocene, and throughout the Holocene (11.7 ka to present). LGM glacial recession corresponded with a regional warming trend (Elias, 1996), which was truncated circa 11 ka, and is recorded by downward shifts in tree line, small scale advances of alpine glaciers, and via other proxies (Menounos and Reasoner, 1997; Doerner, 2007). From 9 to 4.5 ka, the regional climate began to warm, and summer monsoonal precipitation increased in magnitude (Vierling, 1998). This shift from a winter to summer dominated precipitation regime led to an increased significance of fluvial processes on the landscape, as recorded by a change in valley bottom sediments from peat to alluvial gravels near La Poudre Pass (Doerner, 2007). The warmest temperatures from the late-Pleistocene to the present were recorded > 6 ka (Doerner, 2007; Shuman, 2012). From circa 6 ka to 4 ka summer monsoonal precipitation is thought to have decreased, and wildfire frequency and/or severity to have increased (Vierling, 1998). By ~4.5 ka the regional climate began to cool again, lowering the alpine tree line and expanding snow and ice patches (Benedict et al., 2008). This colder period lasted until about 3 ka (Maher, 1972; Elias, 1983; 1985). A brief warming may have occurred after this cold period (Doerner, 2007), but generally cooler and drier climate conditions like those at present were established circa 1.8 ka (Vierling, 1998). Though relatively consistent, the climate of the past ~2,000 years has varied somewhat, with a medieval warm period 1200–850 yr. BP (Trouet et al., 2013), and cooler temperatures ~700–100 yr. BP (Doerner, 2007).

2.2.3 Front Range Glacial History

During the late Pleistocene, alpine glaciers occupied pre-existing valleys in the Colorado Front Range on multiple occasions, producing the steeply incised headwalls and low-sloped glacial troughs that remain today (Anderson et al., 2006). A significant record of the maximum extents of these glacial periods are till deposits preserved as terminal moraines in valley bottoms and lateral moraines on valley sides. In the northern Front Range, late Pleistocene glacial till is primarily composed of granitic and gneissic clasts in a finer grained matrix (Madole et al., 1998). At the CSU Mountain Campus, significant deposits of glacial till are mapped on the valley walls, and till composes the South Fork Valley’s floor downstream from the northeastern side of the campus (Nesse and Braddock, 1989). Downstream of the Mountain Campus, glacial material emanating from the South Fork Valley spread out over a broad, largely un-dissected surface, and may have dammed meltwater streams and trapped outwash sediments in one or more locations (Nesse and Braddock, 1989). The glacial sediments mapped downstream and around the CSU Mountain Campus are likely of Pinedale (LGM) age (R. Madole, personal communication, July 2020); recession of Pinedale-age glaciers occurred between 15–12 ka elsewhere in the Front Range (Madole, 1986) and deglaciation was complete by 11–10 ka (Madole, 1980). Prior to the Pinedale, other glaciations documented on the eastern slope of the Colorado Front Range include the Bull Lake (middle-late Pleistocene) and Pre-Bull Lake glaciations, an amalgam of earlier Pleistocene glaciations (Richmond, 1960; Madole et al., 1998). Post-dating Pinedale glaciation, several small glacial advances have been documented in the Front Range, including minor (~1 km) glacial advance at the Younger Dryas, circa 11–10,000 ^{14}C years BP (Menounos and Reasoner, 1997), and a downward migration of the alpine tree line and growth of ice patches in the headwaters of the South Fork River circa 4.2 ka (Benedict et al., 2008). Additional glacial fluctuations occurred throughout the mid-late Holocene in the Front Range, with advances estimated from 4.5–2.7 ka, 1.9–1 ka, and 400–100 years BP, though these Holocene glacial advances were much smaller than late Pleistocene glaciations (Benedict, 1968).

2.3 Late Holocene Landscape History

2.3.1 Modern Climate, Hydrology, and Ecology

In the Colorado Front Range, elevation is positively correlated with mean annual precipitation. The CSU Mountain Campus, located at ~2,750 m, is at the subalpine-montane transition. The headwaters of the South Fork River drain the alpine ecologic zone (Meiman, 1971). Meteorologic and hydrologic data have been collected at the Mountain Campus sporadically over its history, with key periods of observation from 1961–71 CE and again from 2019–present.

From 1966–70 CE, mean monthly temperature was highest in July and August at ~10 °C and lowest in February around –10 °C; mean annual temperature was 2 °C (Meiman and Leavesley, 1974). Modern meteorologic and hydrologic data from instrumentation can be viewed and/or downloaded at the following link: https://datavis.warnercnr.colostate.edu/instrumentation/.
Mean annual precipitation at the CSU Mountain Campus from 1963–71 CE was approximately 53 cm, with most of the precipitation delivered in the winter as snow (Meiman and Leavesley, 1974). Precipitation in the summer usually occurs as rain from convective storms, though measurements of summer precipitation in the South Fork Poudre basin suggest that these convective storms are usually high intensity but short in duration and small in areal coverage, and do not producing significant flooding (Meiman and Leavesley, 1974). Examinations of the hydrology of the upper South Fork Poudre basin revealed two key findings. First, the average annual runoff throughout the basin is about 25 cm, about half of the precipitation delivered to the basin, though runoff is likely greater in alpine and subalpine ecotones (Meiman and Leavesley, 1974). Second, the South Fork hydrograph is snowmelt dominated, with peak flows and approximately 45% of annual discharge occurring in June (Meiman and Leavesley, 1974). This observation aligns with the observations of Jarrett (1993); convective precipitation in the alpine and subalpine is less important to the annual hydrograph as it is at lower elevations. Historical observations of water quality from the upper South Fork basin indicate that the water is "of high quality," with road and/or structure construction and wildfire identified as the two biggest impacts on surface water quality in the upper basin (Meiman and Leavesley, 1974).
Primary vegetation communities in the area are representative of subalpine forests, characterized by lodgepole pine (*Pinus contorta*), Engelmann spruce (*Picea engelmannii*), ponderosa pine (*Pinus ponderosa*), and aspen (*Populus tremuloides*). Riparian vegetation observed in the basin

include river birch (*Betula fontinalis*), alder (*Alnus incana*), and willow (*Salix spp.*) (Meiman, 1971). Many Rocky Mountain animal species are known to inhabit the area, with beaver (*Castor canadensis*) especially important to flow and sediment dynamics of streams. Currently, no active beaver colonies occupy the valley, but evidence of former beaver ponds is present.

2.3.2 Holocene Landscape Disturbance

Modern disturbance regimes impacting Front Range valleys include wildfire, floods, and mass movements. In late summer 2020, the Cameron Peak Fire burned significant portions of the South Fork basin, including at the CSU Mountain Campus, and portions of the montane, subalpine, and alpine areas of the basin. While subalpine and alpine environments are thought to experience wildfires at a lower frequency and/or intensity than montane ecologic zones (e.g., Sibold et al., 2006), the upper South Fork Valley was burned only 26 years prior, in 1994, when the Hourglass fire burned ~6 km^2 surrounding the CSU Mountain Campus. Several reconstructions of the fire history of the region have been completed via analyses of tree rings (e.g., Sibold et al., 2006; Battaglia et al., 2018). A chronology of wildfires in the greater South Fork basin was created from the data of Battaglia et al. (2018) and is based on the years when >=75% of trees cored in the montane ecologic zone of the basin showed evidence of fire scarring (P. Brown, personal communication, February 2021) (Table 1).

Table 1: Late Holocene Wildfire in the South Fork Basin Montane Zone (Battaglia et al., 2018)

Years where 75+% of tree cores show fire scarring, or recorded fire in basin		
1399	1685	1931
1550	1717	1946
1555	1781	1974
1579	1845	1994
1598	1861	2012
1682	1880	2020
	1920	

Effects of wildfire on drainage basins include increased hillslope sediment delivery, changes to runoff patterns, and increased likelihood of landsliding and/or debris flows. The signal of these effects is often recorded by alluviation and/or reworking of hillslope sediments by fluvial action in the valley bottom. While high intensity flooding is uncommon at sites like the upper South Fork, an anomalous long-duration storm in September 2013 caused flooding in the South Fork Valley (Figure 3). Though the magnitude of the September 2013 flood was much greater elsewhere in the Colorado Front Range (~100-year flood), flows in the South Fork were competent enough to mobilize sediment that dammed the entrance of a small water diversion and transported a wooden foot bridge several meters (M. Ryan, personal communication, June 2020).

Figure 3: Photograph of the upper South Fork River during the September 2013 flood. At peak stage of the flood, the river overtopped the pictured bridge, as shown by the debris on the bridge deck. Flow in the image is from left to right, and flow in the foreground is outside of the normal banks (photo courtesy of Jerry Eckert, Mummy Range Subdivision Records).

2.3.3 Anthropogenic Landscape Alteration

At present, the South Fork is the least regulated tributary in the Cache la Poudre River basin and provides an important municipal water supply to the cities of Fort Collins and Greeley. At the CSU Mountain Campus, the only known diversion of surface water from the South Fork River is a small canal that delivers water from the South Fork to a series of ponds constructed by cabin owners. The impact of this diversion is thought to be small as flow returns from these ponds via another diversion structure and/or through subsurface flow. Additionally, wells for the vacation cabins and for the Mountain Campus draw water from the shallow subsurface of the South Fork Valley. Upstream of the campus and neighboring cabins, the watershed is undeveloped US Forest Service and National Park Service land. Anthropogenic land use actions with the potential for landscape disturbances in the valley include the trapping of beaver (beginning ~1830), settlement and exploration for gold (~1850), extensive timber harvest (1868–1870), and the use of splash dams to transport timber downstream (Meiman, 1971; Wohl, 2001; M. Ryan, personal communication, July 2020; Mummy Range Subdivision Historical Record).

3. METHODS

I used several field and remotely sensed methods to investigate processes of sedimentation and erosion, the magnitude of these processes, and the timing of the formation of the South Fork Cache la Poudre Valley's sedimentary fill at the CSU Mountain Campus (Table 2). Field methods included surficial geologic mapping, ground-penetrating radar (GPR) surveys, coring and analysis of valley bottom sediment, and radiocarbon (^{14}C) dating of valley bottom substrates. In addition, I analyzed historical aerial imagery to provide an ~80-year record of channel and landscape change currently occurring in the valley.

Table 2: Summary of Methods, Data Products

Methods	Data Product(s) & Purpose
Surficial geologic mapping	• Spatial distribution & area of valley bottom landforms/sediments • Relative chronology of landforms based on position
Sediment coring	• Stratigraphic columns & descriptions of valley bottom sediment • Depth to key layers & correlation of radar facies • Recover material for ^{14}C geochronology
GPR (common offset)	• Create radar facies model • Image cross sections of the valley sediments • Thickness of valley bottom sediments
GPR (common midpoint)	• Constrain radar velocities
^{14}C geochronology	• Landform absolute age control • Timing of alluviation and erosion in the valley bottom • Approximate rates of alluviation
Analysis of Historical Aerial Images	• Rate of lateral erosion/floodplain creation

3.1 Surficial Geologic Mapping

I completed surficial geologic mapping of the South Fork Valley as part of a larger bedrock and surficial mapping project focused across ~ 40 km^2 of the upper South Fork drainage basin. For the overall project, I mapped at 1:12,000 scale, with bedrock unit designations building on preexisting geological units defined by Nesse and Braddock (1989) from the area. To support bedrock unit description, I collected hand samples to create 16 petrographic thin sections. Thin sections were prepared in July 2020 by Paula Leek Petrographics. To supplement lithologic descriptions, and to describe structural and hydrothermal alteration of bedrock, I imaged each thin section in plane- and cross-polarized light to create photomicrographs at 2.5 times magnification, and higher magnification when necessary (Appendix A). I collected observations of Quaternary landforms and sediment characteristics throughout the map area at the same 1:12,000 scale. Along the South Fork River and its tributaries, I made a higher density of observations and more robust descriptions of the sediments found along these streams. My observations allowed me to map Quaternary valley bottom features at a much finer scale, and improve the description of units, with special emphasis placed on glacial and fluvial landforms and deposits located in the valley bottoms of the South Fork River and its tributaries. These spatial data are leveraged herein to identify the Quaternary landforms in the South Fork Valley, to document the sedimentary and morphologic characteristics of these landforms and deposits, to quantify the spatial extent of certain geomorphic units, and to identify relative age relationships between these Quaternary units.

3.1.1 Field Mapping Methods

In locations of Quaternary sediments, I mapped Quaternary landforms or sediments, correlated between deposits displaying similar morphologic and sedimentological characteristics, and identified relative age relationships between adjacent deposits. At stations used for Quaternary mapping, I noted the type of landform (e.g., fan, terrace, moraine) and/or type of Quaternary sediment (e.g., glacial till, outwash). Surficial geologic map units were distinguished by landform type, position (e.g., proximal to river, near the valley wall, elevation, height above stream), morphologic characteristics (e.g., planar, hummocky, high/low local relief), and by sedimentological and/or stratigraphic relationships. The position of each landform relative to other features was noted. At several sites, I recorded a GPS track around a landform on an iPad to delineate polygons in the field. Otherwise, I noted the length, width and thickness of Quaternary units, and digitized map polygons in ArcGIS. While mapping, I identified points for stratigraphic analysis, sediment coring, ^{14}C sample collection, and locations for GPR surveys.

3.1.2 UAV Survey and Structure from Motion Processing

To aid surficial mapping of the South Fork Valley, the CSU Drone Center completed a UAV (drone) survey of the Mountain Campus property in September 2019. The survey was performed using a DJI Matrice 600 UAV mounted with a Hasselblad L1D-20c camera. Approximately 1320 nadir-oriented images were collected over five flights, each approximately 30 minutes in duration. In conjunction with image collection, 33 ground control targets were placed along the valley floor, and the center point of each target was recorded using an Emlid Reach RS2 GPS receiver. Another Emlid Reach RS2 receiver was configured as a base station. GPS points were processed using the RTKlib program to perform a post-processed kinematic correction. I performed image alignment and structure from motion (SfM) processing in Agisoft Metashape. I selected 23 targets, distributed at different elevations across the model, as ground control points to georeferenced the model and improve its accuracy. I used the remaining 10 surveyed points to verify the accuracy of the model. Model check points indicate a root mean squared error of ~0.30

m or ~1.7 pixels between surveyed locations and the corresponding points in the model. Error primarily occurs in the vertical direction, with an average vertical error of ~0.26 m at the ten check points. A digital elevation model (DEM) and orthomosaic were produced with spatial resolutions of 6.21 and 5.0 cm/pixel, respectively.

3.1.3 Map Development and Analyses

To create the map from field observations, I plotted all observational stations over 2019 National Agriculture Imagery Program (NAIP) aerial imagery, a shaded relief image created from 2015 USGS 3DEP lidar (https://portal.opentopography.org/usgsDataset?dsid=USGS_LPC_CO_SoPlatte_Lot3_2013_LAS_2015) of the field area, and an orthomosaic with 5 cm pixel resolution produced from the 2019 UAV survey of the Mountain Campus. Lidar data were gridded to a 1 m DEM, the same spatial resolution as the NAIP imagery. Using field notes, polygons digitized in the field, and observations from imagery, I digitized polygons of the landforms and/or sediments found in the South Fork Valley. Field-digitized map units were adjusted to remove minor void space between units.

Once the map was completed, I delineated the South Fork Valley bottom at the CSU Mountain Campus. I selected the studied valley bottom as the low relief area between steep lateral moraines, bounded upstream by bedrock outcrops in the valley bottom and bounded downstream where the South Fork River flows over extensive deposits of till comprising the LGM terminal moraine. The selected area contains many alluvial deposits and is fully contained within the Pleistocene glacial extent. Additionally, the South Fork River maintains a uniform planform and consistent gradient through this valley segment. I calculated the area of each Quaternary unit mapped, and the percent of the valley bottom occupied by each unit in ArcGIS Pro.

3.2 Analysis of Sediment Cores and Well Material

To describe the characteristics of sediments preserved in the South Fork Valley, I analyzed sediments recovered from drilling two, ~10m deep monitoring wells, and from nine shallow cores that I collected with a hand auger. The deep wells were planned and sited by Dr. Mike Ronayne (CSU Associate Professor of Hydrogeology) and drilled with a hollow stem auger by Drilling Engineers, Inc. from June 26–28, 2019. Split spoon sediment samples were collected and logged by CSU Geoscience students every ~0.6 m (2 ft) during drilling. The split spoon samples were provided to me by Dr. Mike Ronayne, and allowed me to make observations of sedimentary characteristics, and the depth to sedimentary contacts. The location of cores in the South Fork Valley are shown in Figure 4.

For each core, I recorded the sedimentary texture (grain size, angularity, sorting, etc.) and color. Changes to these characteristics along the core were used to identify boundaries between the different sediment packages in each core. I recorded the depth of these boundaries between distinct sediment types. For sediment cores collected along GPR transects, observations of the depth of changes within the core that could affect the dielectric properties of the substrate are particularly important. I noted changes in sediment moisture content and significant textural changes to support GPR interpretation. Finally, if a core contained organic material or organic-rich sediment that was either near a key contact between sedimentary packages or contained within an important morphostratigraphic unit of the valley bottom, I collected the material and considered it for radiocarbon analysis.

I combined observations of morphological characteristics of landforms with sedimentary characteristics to constrain the geomorphic process responsible for the deposition of that deposit and/or landform. These observations, informed by observations from other similar settings, and preexisting geologic knowledge of the study area, allowed me to categorize sediment packages representing unique depositional regimes.

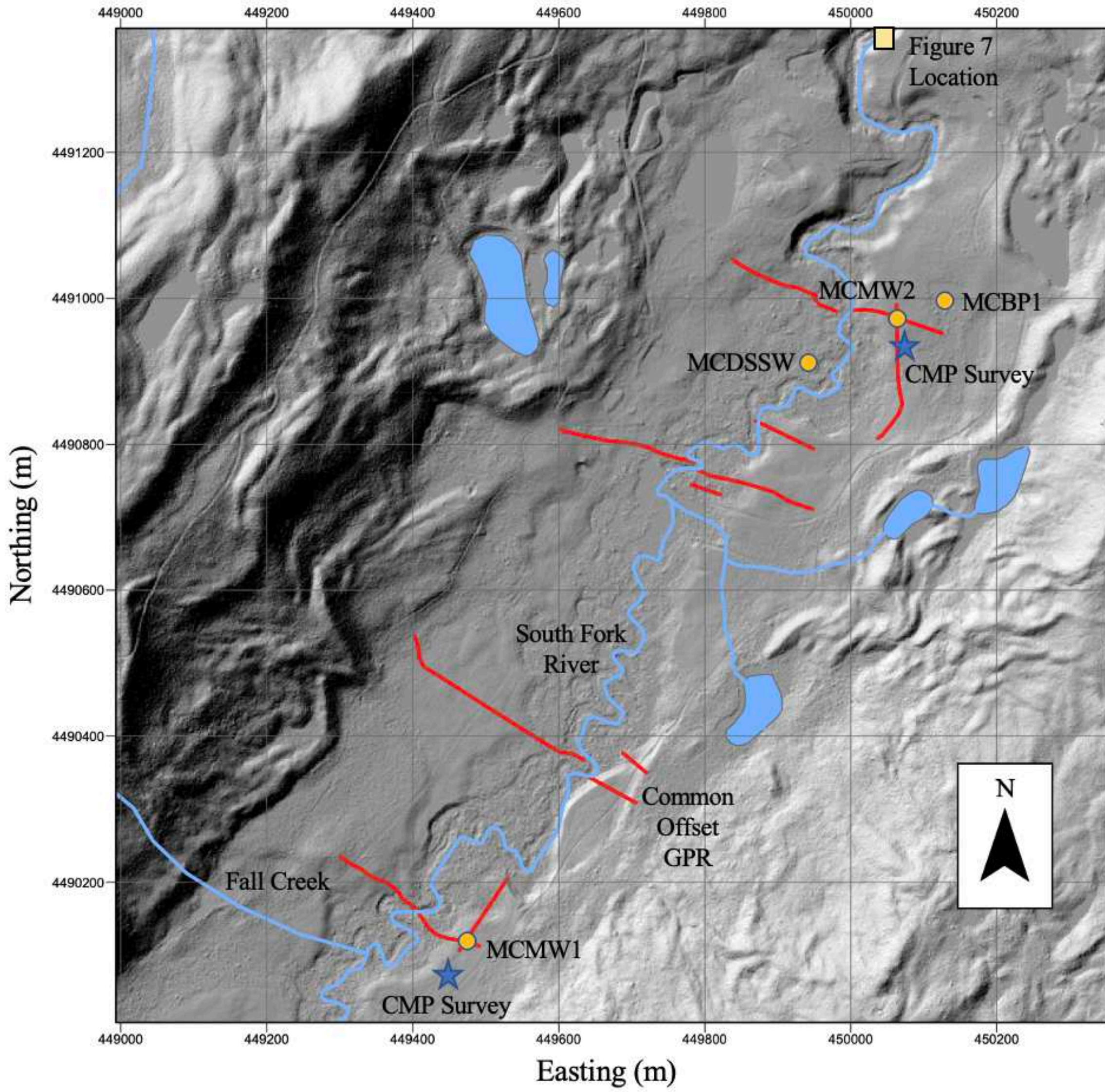


Figure 4: Map of common offset radar surveys (red lines), common midpoint surveys (blue stars), and radiocarbon sample locations (orange circles) at the Colorado State Mountain Campus within the South Fork Cache la Poudre River Valley. MCMW1, MCMW2, and MCDSSW, are ground water wells. Streams and water bodies are from the USGS NHDPlus dataset for the Cache la Poudre Basin, and the hillshade produced from USGS 3DEP lidar data collected in 2015. Flow direction is bottom left to upper right. The map is projected in WGS84 UTM Zone 13N.

3.3 Ground-Penetrating Radar

Ground-penetrating radar has been shown to be an effective geophysical technique for imaging the shallow subsurface in a variety of geomorphic settings (Schrott and Sass, 2008; Van Dam, 2012). Common offset GPR surveys allow researchers to image the subsurface at a resolution which can document not only the vertical changes in subsurface characteristics, as could be captured via coring, but also the horizontal stratigraphy contained within the substrate. These powerful imaging abilities, and the relatively non-invasive nature of the collection of GPR data make it a particularly useful observational tool in sensitive landscapes (e.g., Leopold et al., 2009). I used common offset GPR surveys of cross valley transects to create quasi two-dimensional images of the subsurface at transects crossing the South Fork Poudre Valley. From the surveys, I identified the position of radar reflectors indicative of contacts between physically distinct sedimentary units in the subsurface and created a radar facies model of reflection patterns associated with key sedimentary deposits found in the South Fork Valley. Additionally, I performed two common midpoint (CMP) surveys to estimate radar velocities in valley bottom sediments and decrease the uncertainty associated with the depth axis of cross sectional radargrams.

3.3.1 Ground-Penetrating Radar Surveys

I conducted GPR surveys using a Sensors and Software PulseEkko GPR system (Figure 5). For common offset surveys, I utilized 100 MHz frequency antennas, spaced 1 m apart, and arranged perpendicular to the direction of travel. I collected common offset traces along transects with a trace spacing of 0.25 m, as measured from a tape placed along the transect path. A single Emlid Reach RS2 GPS receiver with an accuracy of ~2.5 m recorded the position of each trace from its position mounted to the GPR frame. For initial surveys, the GPS was mounted to the frame via a metal pole, but this produced significant ringing in the data. A plastic mount (e.g., Figure 5) was utilized for surveys after this issue was identified. Over 1.5 km of common offset GPR data were collected on the transects shown in Figure 4. CMP surveys were collected at two sites (Figure 4) and used a 10 cm move out of each antenna between each trace. Sixty traces were collected in each common midpoint survey.

Figure 5: Sensors and Software PulseEkko GPR system configured to collect a common offset transect (photo courtesy of M. Ronayne)

3.3.2 Ground-Penetrating Radar Data Processing

Common offset GPR data were processed using the ReflexW software package. I imported the data into the software, dewowed (subtracted mean) to remove low-frequency signal recorded by the system and applied a uniform time zero correction to align the surface of the radargram with the ground surface. GPS coordinates were recorded for each trace to correct surveys for topography, and display radargram reflections relative to an absolute datum. As uncertainty of the GPS vertical coordinate produced an artifact in images that made the ground surface appear to be overly bumpy/rough, I sampled the 2015 USGS lidar DEM to obtain a revised elevation value for each trace. To accomplish this, I used the horizontal coordinates of traces to create points, used the points to sample the lidar DEM for elevation values, then applied the updated elevation field to each trace header. To convert the measured two-way travel time to depth, and correlate radargrams with well data, I used the CMP surveys to create a velocity model of South Fork Valley substrates (Appendix B). Using a semblance analysis approach, I calculated a mean velocity of ~0.11 m/ns from the two CMP surveys and applied this value to common offset radargrams. Finally, as mentioned previously, strong interference associated with the metal GPS mount produced "ringing" instrument noise in over half of the common offset surveys. I attempted to remove this noise using bandpass filtering but was unsuccessful at removing the instrument noise without removing a significant amount of real signal observed close to the surface.

3.3.3 Creating a Radar Facies Model

After processing in ReflexW, I categorized radargrams using a radar facies approach (Beres Jr and Haeni, 1991) where clusters of similar reflection patterns were grouped together. I used characteristics such as lateral continuity, shape, amplitude, and thickness of reflectors to develop my radar facies model. Often, I used strong, continuous reflectors which divided less prominent reflectors with different patterns as the boundary between radar facies; these features were crucial to identify the boundaries between different units in the radargrams. I frequently adjusted radar facies groupings while reviewing radargrams, with some groups exhibiting more distinctive patterns than other groups.

3.4 Radiocarbon Geochronology

I selected nine of the potential sediment samples that I had identified while analyzing cores and well samples for conventional radiocarbon analysis. The nine samples were from five unique sediment cores. The five cores that were used to collect radiocarbon samples are as follows: material recovered from the two deep groundwater-monitoring wells (drilled on high terraces in the valley), two hand augured cores collected from a beaver pond and the floodplain, and a hand augured core along the South Fork River ~1 km downstream of the Mountain Campus. The location of ^{14}C sample sites is indicated in Figure 4. I selected sampling locations across a suite of landforms and/or sediment deposit types to constrain the age of key periods of aggradation in the valley. 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.

After selecting samples, I dried the sediments, then packaged a 50–100 g split to be sent for analysis. The DirectAMS laboratory in Washington State performed all radiocarbon analyses. Laboratory results delivered sediment ages as uncalibrated radiocarbon age before present, or no data, if the samples contained insufficient carbon to yield an age. I calibrated by radiocarbon ages with version 8.2 of the CALIB online radiocarbon calibration program (Stuiver et al., 2021), using the IntCal20 Northern Hemisphere radiocarbon age calibration curve (Reimer et al., 2020) to present ages in calendar years.

3.5 Repeat Aerial Image Analysis

To detect channel migration and floodplain formation in the South Fork Valley, I obtained aerial imagery from 1938–2019, orthorectified the images, and manually delineated the areal extent of the South Fork channel in the imagery. The interval between images analyzed (1938, 1946, 1958, 1975, 1981, 2005, 2013, 2019) depended on the availability of imagery of the study area. When imagery was available more frequently than a ~10-year interval, I chose to analyze images from years (e.g., 2005, 2013, 2019) which had the best image clarity for the study site. Images collected from 1938 through 1981 needed to be georeferenced and orthorectified. I used 2019 NAIP imagery as the reference image, and orthorectified the images in ArcGIS Pro. To correct the images, I used 15 matching points in the unreferenced and reference images, distributed across the extent of the pair of images. After referencing the imagery, I clipped images to an extent that included the upper South Fork Valley.

I identified the boundary of the bankfull channel in the study area in the images using a methodology similar to Miller and Friedman (2009). I grouped areas of water in the South Fork River and areas of exposed sediment immediately proximal to the river to approximate the bankfull channel. I determined the extent of floodplain creation between images by selecting any area that had been identified as active channel in the previous image but was no longer part of the channel. Channel polygons were digitized at 1:2,000 scale, which was adequate to differentiate key features in most areas of most images. The 1981 image had inadequate spatial resolution to identify channel features in the South Fork Valley, so no data were collected from this image.

4. RESULTS

4.1 Surficial Geologic Mapping

4.1.1 Valley Bottom Surficial Units

Surficial mapping throughout the study area identified several Quaternary units not included on the preexisting geologic map of the South Fork Cache la Poudre Valley (Nesse and Braddock, 1989). In addition, I subdivided Quaternary units into more specific categories (Table 3) and refined the location of existing contacts of Quaternary units. Specific changes include differentiating two distinct glacial till units of different ages (Qg1 and 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. Terraces and large braid bars composed of well-rounded cobbles, gravel, and sand were reclassified from the previous designation of till and remapped as glaciofluvial outwash sediments. Similarly, fluvial landforms originally mapped as Quaternary alluvium were differentiated into floodplain, terrace, and fan deposits. I differentiated two unique till deposits, two outwash terrace units, a fluvial terrace, and the modern floodplain at the CSU Mountain Campus (Figure 6). The complete geologic map of the South Fork Valley is included in Appendix C.

Table 3: Surficial Units of the South Fork Valley

Unit:	Unit and Inferred Genesis:	Description:
Qg1	Glacial Till (early- or pre-Pinedale): moraine deposition likely occurring prior to the LGM	Smooth, rolling topography, preserved down valley and more distally on valley sides than the high relief glacial deposits (Qg2). No clear ridges, or kettles. Boulders appear more embedded in deposits that younger glacial deposits.

		Composed of igneous and metamorphic clasts and boulders 0.25–2 m in diameter in a fine, silt and sand sized matrix. Weathering rinds are common on surface clasts.
Qg2	Glacial Till (Pinedale): moraine deposition associated with LGM glaciation	Hummocky topography, with distinct ridges running sub-parallel to the long-valley axis on valley sides. Distinct kettle features common at low slope sites on valley sides and valley bottom downstream of Mountain Campus. Local relief up to ~10 m. Toe slopes of lateral moraines are planar in places. Composed of igneous and metamorphic clasts and boulders 0.25–2 m in diameter in a fine, silt and sand sized matrix. Clasts are not significantly weathered.
Qow1	High Outwash Terrace: glaciofluvial sediments deposited in braided river system and/or delta	Planar surface located at the Mountain Campus, just upstream of the Qg2 end moraine. ~5–8 m above the modern South Fork channel. Appears to grade onto the end moraine, suggesting onlap. Surface of deposit composed of thin organic-rich layer, underlain by sandy silt with some subangular gravel, ~1–2 cm in diameter. Terrace risers consist of fine silt and sand, with sporadic boulders seen along riser scarp. Distinct lack of woody vegetation on terrace except proximal to small seeps or streams.
Qow2	Low Outwash Terrace: glaciofluvial sediments deposited in braided river system	Planar surface located continuously along the South Fork Valley, ~3–6 m above the modern channel. Higher segments are planar, lower terrace segments may slope slightly towards the central valley axis. Surface sediment are primarily brown silt and sand, with some cobbles observed at the surface and in the riser. Similar to Qt1, no vegetation besides

		grasses and small sage grows on this terrace.
Qt	<u>Fluvial Terrace:</u> overbank deposition of fine-grained fluvial sediments	Planar surface, slightly sloping towards the valley center, ~1.5–2 m above the modern channel. Usually grades to modern floodplain without a prominent riser, but higher than the adjacent floodplain and located between floodplain and higher terraces. Surface sediments are fine grained (silt–medium sand), and organic rich; significant grass and large willows grow on these low surfaces.
Qfp	<u>Active Floodplain:</u> overbank deposition of fine-grained fluvial sediments, associated with fluvial lateral erosion of the valley bottom	Planar surface adjacent to, and in almost all locations, bracketing the modern channel. While generally planar, ~0.5–1 m of local relief was observed on the floodplain. The floodplain surface is almost entirely fine grained (silt - medium sand), dark brown, and likely organic rich. At the inside of several meander bends there are points bars, below the overall floodplain surface, composed of sand and gravel, but extend no further than ~10 m from the channel. Observations of channel banks suggests that at most locations along the channel 0.5–1.5 m of fine-grained sediment overlies sand, gravel, or cobbles.

4.1.2 Spatial Extent of Valley Bottom Units

Surficial units at the CSU Mountain Campus are mapped in Figure 6. Moraines surround the valley bottom at the Mountain Campus and cover the valley downstream of the study site. Some planar sections of glacial till are found at the toe of lateral moraines and are considered part of the valley bottom. More proximal to the valley center, two outwash terrace units commonly outcrop along the sides of the South Fork Valley. These outwash terraces are never inset within one another, and the highest terrace is only present at the downstream side of the Mountain

Campus. A fluvial terrace is preserved in some portions of the valley bottom and usually grades to the modern floodplain. The modern floodplain is inset between the terraces and is laterally extensive, particularly in the studied valley segment shown in Figure 6.

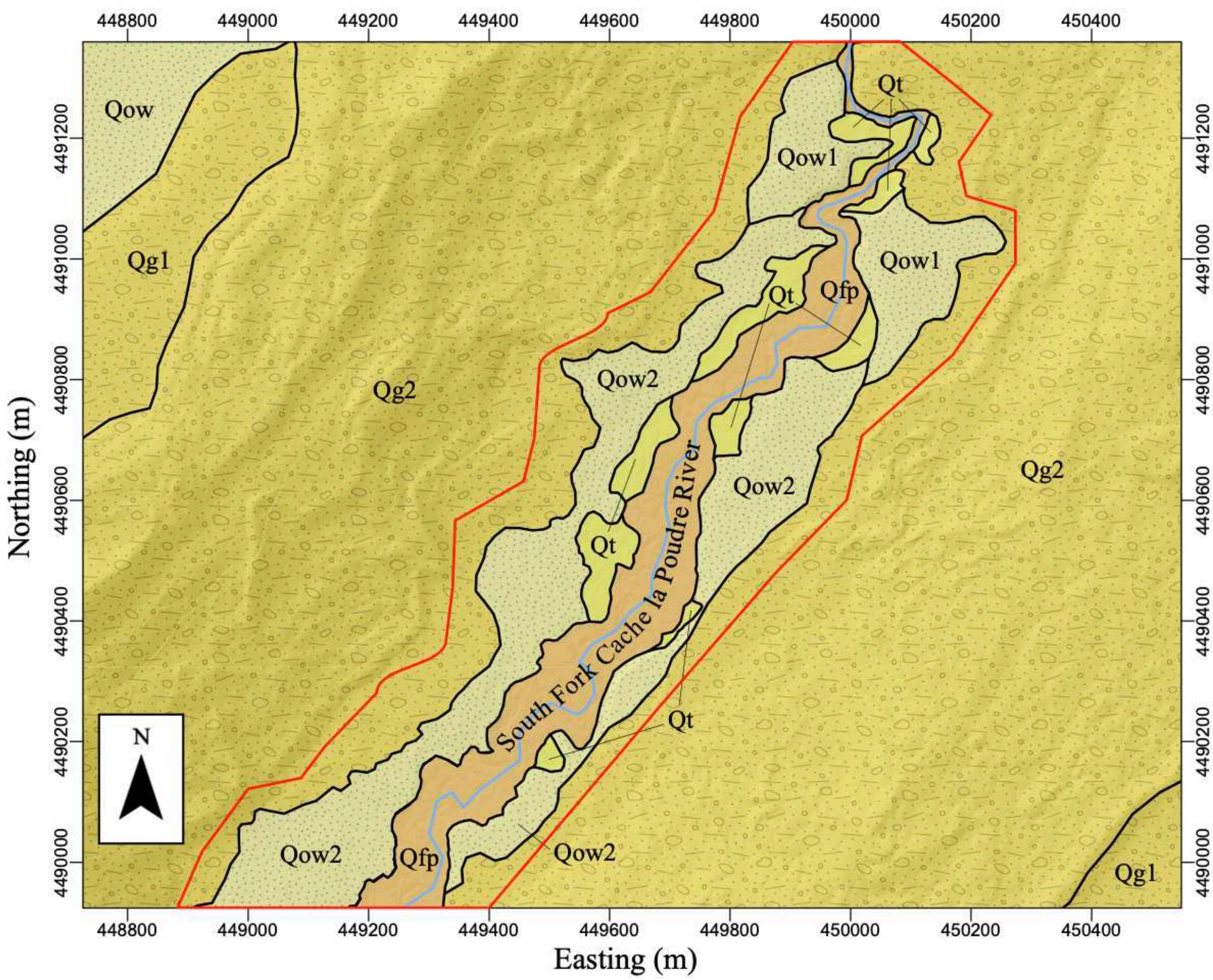


Figure 6: Geologic map of the South Fork Valley at the Mountain Campus. Units include glacial till (Qg1, Qg2), outwash terraces (Qow, Qow1, Qow2), fluvial terraces (Qt), and the active floodplain (Qfp). The valley bottom extent used to calculate percent area occupied by units is delineated in red. Location tick marks are in WGS84 UTM zone 13N. Flow direction of the South Fork is lower left to upper right.

Table 4 reports the extent of each map unit in the South Fork Valley at the Mountain Campus. Glacial deposits (Qg) were the largest unit (346,682 m^2, 37.0%), with outwash terraces (Qow1, Qow2) and the floodplain (Qfp) only slightly smaller. The fluvial terrace (Qt) was the least extensive morphostratigraphic unit in the valley bottom (55,161 m^2, 6.0%).

Table 4: Area of Units in the South Fork Valley

Unit	Area (m^2)	Percent of Valley Bottom
Qfp	192,020	20.8
Qt	55,161	6.0
Qow1/Qow2	334,534	36.2
Qg	346,682	37.0

4.1.3 Other Mapping Observations

In addition to documenting the surficial units of the South Fork Valley bottom, several field observations made during mapping indicate the relative chronology and geomorphic history of the South Fork Valley. Relative age relationships in the South Fork Valley indicate that all till predates inset features, and that terraces decrease in age from Qow1–Qt, but it is unlikely that these units are uniformly distributed temporally following glaciation. The floodplain is the most modern morphostratigraphic unit in the valley. Furthermore, at least two major episodes of aggradation occurred to produce the units observed, and more are possible depending on whether the material composing Qow1 & 2 and Qt & Qfp was deposited during the same periods. Several episodes of post glacial incision and lateral erosion occurred to sculpt the topography observed in the South Fork Valley.

Though never large enough to be map scale, two additional Quaternary deposits were identified within the South Fork Valley. At three sites, one where the South Fork approaches the upstream side of the terminal moraine, and two sites where the South Fork River has incised a small canyon though the moraine sediments, deposits of light tan, laminated silt and sand were found on the valley sides (Figure 7A). At one site where the South Fork cuts through the moraine, the silt deposit was over 3 meters high, and extended over 10 meters laterally along the valley side.

These fine sediments were only found as shallow deposits preserved on banks and valley sides where the South Fork River has incised into other valley bottom sediments. This suggests that they were deposited after most of the post-glacial fluvial incision had occurred. Downstream of the silt deposits large boulder berms/bars, up to ~2 meters in diameter, were identified (Figure 7B). These curvilinear boulder features were usually ~2–4 meters above the modern channel, and in places the boulders appeared to be imbricated against one another. At and near the observed site of the linear boulder features, significant large wood accumulation was noted, some wood appearing to be composed of trees felled by humans.

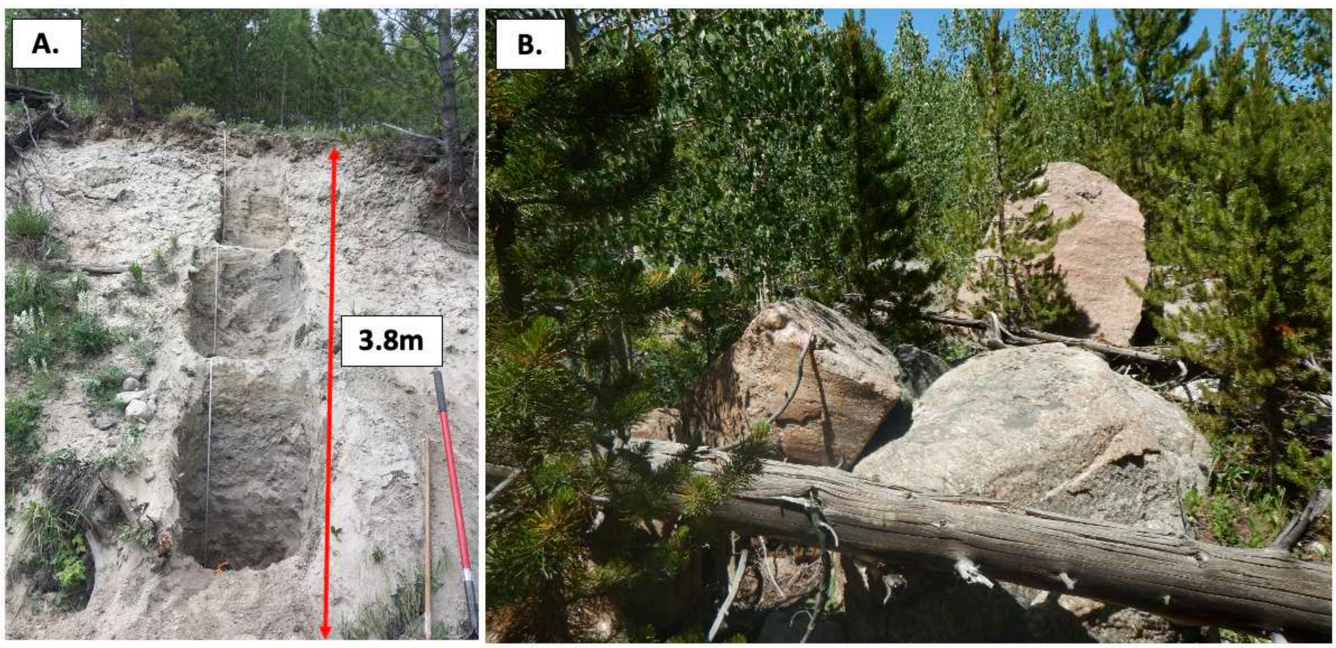


Figure 7: A. Thinly stratified silt and sand deposit located on South Fork Valley wall in the terminal moraine. B. Boulder berm along South Fork River. Location of photos are indicated in Figure 4.

4.2 Coring Results

Sediment samples from two deep wells were analyzed and characterized based on sediment texture. At the upstream deep well (MW1), fine surface sediments overlay ~2 m of coarser sand and gravel, on top of ~7 m of interlayered sand, silt, and clay. In the ~7 m section of the core, a general coarsening is observed with depth. The basal ~1.2 m of the core are composed of coarse sand and gravel. In the downstream deep well core (MW2), finer material, ranging from silt to silty sand dominates the upper ~9.5 m of the core, with three thin interbeds of sand or gravel. The basal ~1.5 m of the core were composed primarily of sand, but some cobbles and/or boulders were encountered during drilling, with a few fragments of these cobbles and/or boulders contained in the bottom of the core, as indicated on well logs and per discussions with individuals present during drilling (M. Ronayne, personal communication, October 2019). These two wells were drilled into outwash terraces, MW1 on terrace unit Qow2 and MW2 on terrace unit Qow1 (Figure 4). Simplified stratigraphic columns of wells MW1 and MW2 are included in Appendix D.

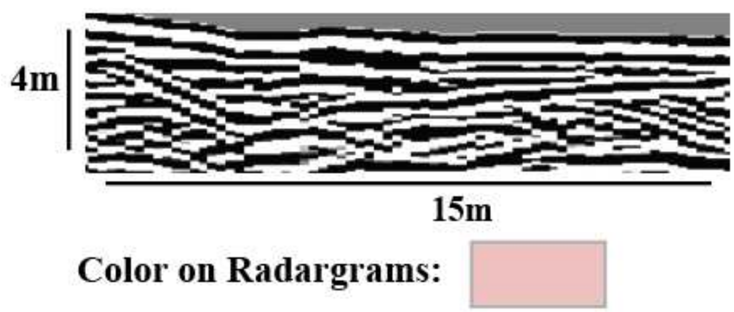
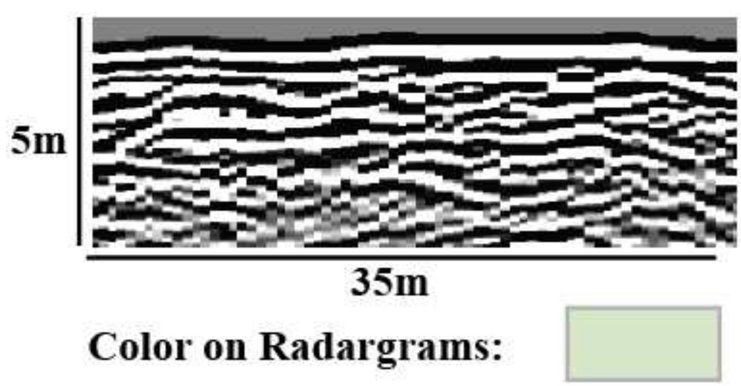
Handheld coring of the modern floodplain and the lowest terrace unit yielded six cores, all ~1–1.5 m deep. In all cores, much of the material was composed of dark brown, organic rich fine sediments, and underlain by sand and gravel of a granitic protolith, like the material found in the modern streambed. Cores collected in a former beaver pond (BP1) situated on top of the high terrace yielded similar results but hit gravel at a slightly shallower depth than observed on the floodplain and/or low terrace. A core collected from a low fluvial terrace downstream of the field site (LZD) also recorded about 1.2 m of fine-grained sediment overlying a coarse basal layer.

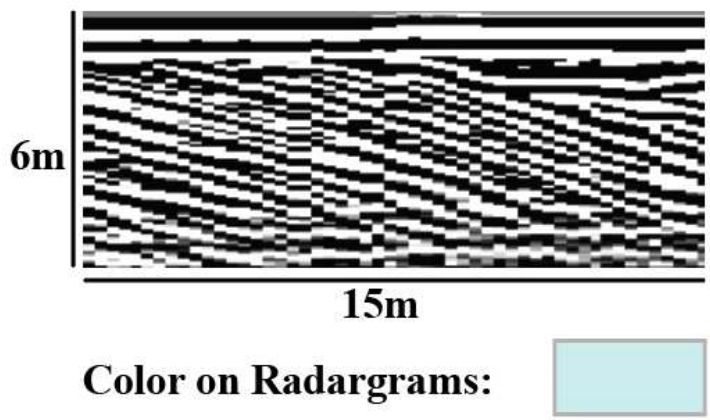
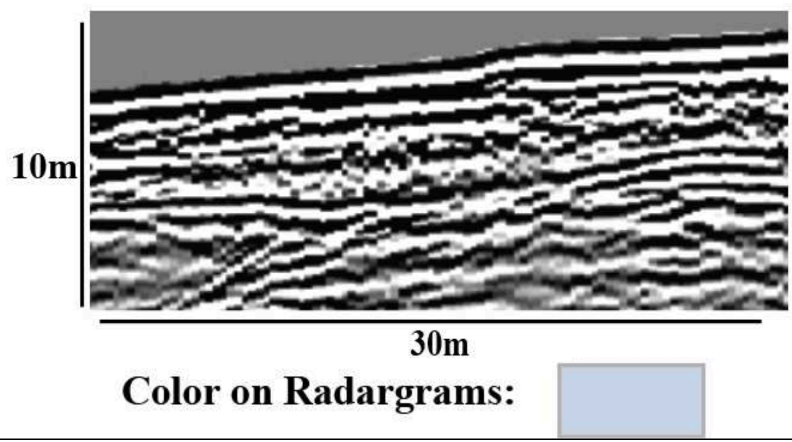
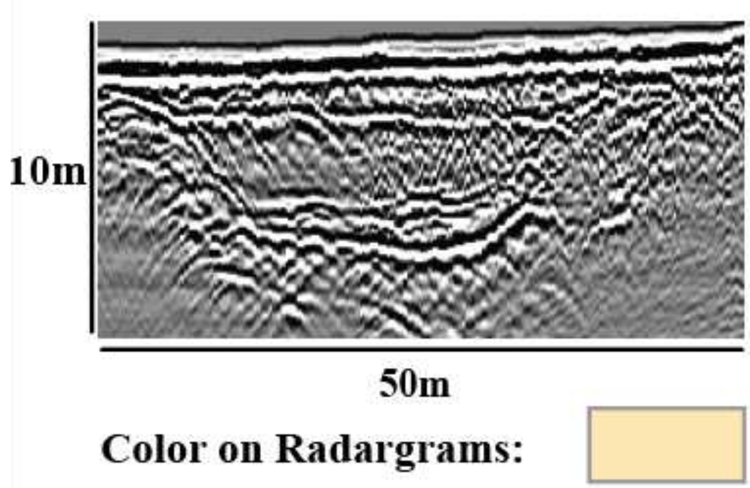
4.3 Ground Penetrating Radar Results

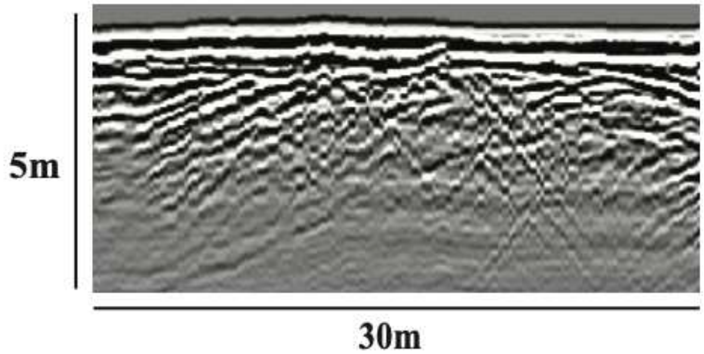
4.3.1 Radar Facies Model

Common offset GPR surveys contained several distinctive groups of reflection patterns which I used to create a radar facies model of the South Fork Valley sediments (Table 5). Initial categorization was based solely on radar reflection patterns, but later iterations of the model leveraged surficial mapping and coring information to better interpret the geophysical signals and to tie the radar facies model to the inferred processes of sedimentation associated with each facies unit. The unique radar facies observed in cross-valley transects are as follows: i) thin (~1 m) package of sediments across terraces, horizontal and continuous reflectors; ii) a thin layer of horizontal-subhorizontal reflectors across floodplain, semi continuous, with a non-horizontal strong reflector at the base; iii) a 5–8 m thick package of dipping reflectors contained within terraces; iv) a 2–5 m thick package of semi-continuous sub-horizontal reflectors in terraces; v) a mix of horizontal reflections and diffractions contained above a strong, u-shaped reflector; vi) a package defined by frequent point diffractions, usually underlaying other radar facies.

Table 5: Radar facies observed in the South Fork Valley

Example from radargram:	**Description & Interpretation of Facies:**
	(i.) A ~0.5–1 m thick layer of continuous horizontal reflectors. Thickness of units increases when reflector at base diverges from ground surface, like at in the left side of the example radargram. **Physical interpretation:** Flat lying surface sediments and/or soil.
	(ii.) A thin (~1–2 m) layer of horizontal-subhorizontal reflectors, laterally semi-continuous, with a strong subhorizontal reflector below. **Physical interpretation:** Fine grained floodplain sediments over fluvial gravels.

	(iii.) A ~5–8 m thick package of regularly dipping reflectors, continuous along dip, either with no clear reflector at bottom, or truncated by strong horizontal reflector. **Physical interpretation:** Bar fronts created by bar migration – reflectors at bottom show channel base during channel migration – lateral accretion sediments in multithread system.
	(iv.) A ~2–5 m thick package of semi-continuous, sub-horizontal reflectors. **Physical interpretation:** Horizontally deposited fluvial sand and gravel.
	(v.) A mix of horizontal reflections and diffractions from point reflectors which are truncated by a strong u-shaped reflector. **Physical interpretation:** Paleo channel filled by coarse and fine channel filling sediment.

 **Color on Radargrams:**	(vi.) Package defined by frequent point reflections, usually underlaying other radar facies. **Physical interpretation:** Glacial till. Prominent point reflectors are boulders in till.

4.3.2 Stratigraphy of the South Fork Valley

GPR surveys were crucial to investigating the stratigraphy of valley bottom sediments in the South Fork Valley. Using the radar facies outlined above, I characterized four cross-valley profiles which included all radar facies identified, and crossed all surficial units documented via surficial mapping (Figure 8). All annotated radargrams are included in Appendix E and the location of each are identified in Figure 8. The depth of penetration by radargrams was about 5–10 m yet varied significantly. This may be due to stronger signal attenuation in certain materials, or deviations from the average velocity calculated from CMP surveys. Spatial patterns observed in the distribution of radargrams include that channel fills are most common in upstream transects (Profile 1, Profile 2), and that dipping reflectors representing bar migration were most clear in the center of the valley (Profile 2, Profile 3), though dipping reflectors may be present, albeit less clear in Profile 1 (Figure 8). Profile 4 is located on the Qow1 outwash terrace and does not appear to have dipping reflectors. Additionally, till is only documented on the northwest side of the valley (Profiles 2, 3, and 4).

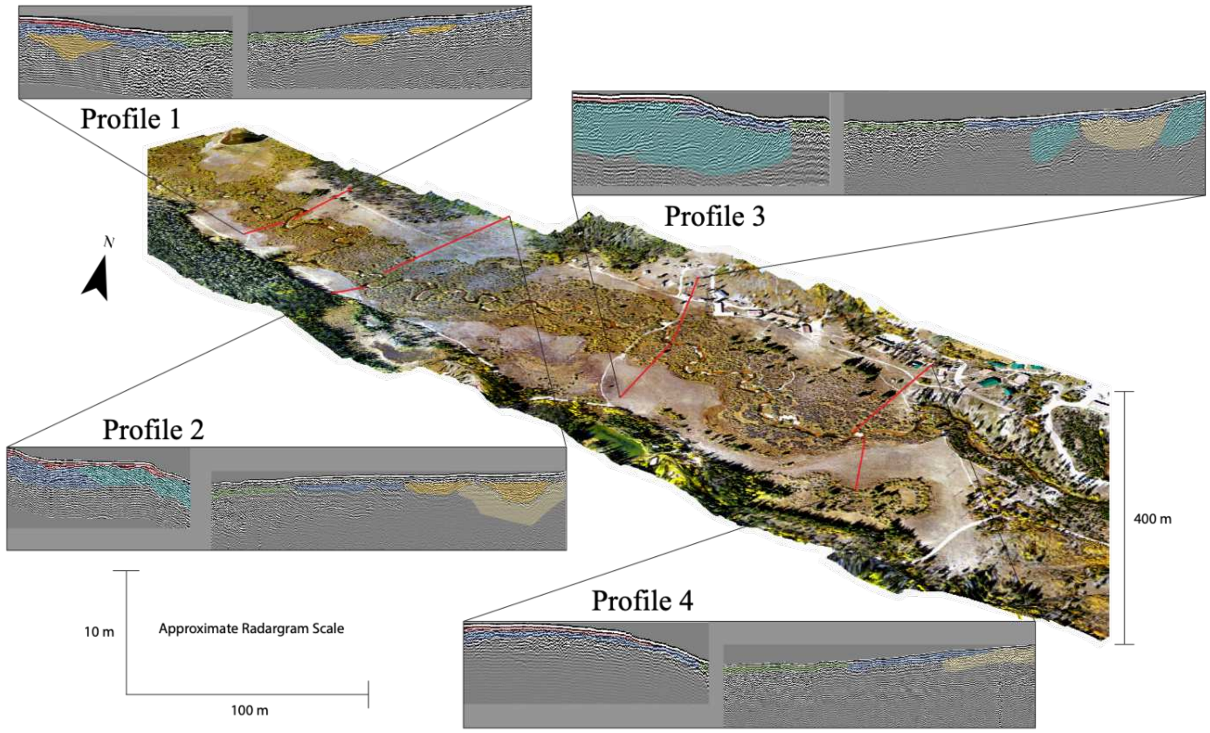


Figure 8: Annotated cross sectional radargrams of the South Fork Valley. Colors correspond to the colors outlined in the radar facies table. Cross-valley profiles increase in number downstream.

Cross sectional radargrams show complex stratigraphic relationships between sediments preserved in the South Fork Valley. Some stratigraphic relationships indicate that floodplain sediments onlap on flat lying gravels, and that channel fills are abruptly truncated at their upper margin with flat lying gravels overlying (Figure 9). Dipping reflectors are apparent in the upper portion of Profile 3 but may also be present near the center of the lower portion of Profile 2 (Figure 10). Flat lying surface sediments are found in transects crossing the treads of outwash terraces on southeast side of the valley and vary in thickness from ~0.5–1.5 m (Figures 9 and 10). Semi-continuous, subhorizontal reflectors interpreted as vertically accreted floodplain sediments are apparent in both Profiles 1 and 2 and are roughly uniform in thickness across both radargrams (Figures 9 and 10). Strong point reflections interpreted as boulders in till are present proximal to the northwest valley margin of Profiles 2, 3, and 4 (Figure 8). Till appears to have been incised by two filled paleochannels on the northwest side of Profile 2 (Figure 10). Strong reflection patterns exist at depth in the valley center underneath reflections associated with floodplain sediments (Figures 8). These strong reflectors often display chaotic reflection patterns (e.g., Figure 9), and occasionally subparallel dipping reflectors (e.g., Figure 10), yet these sub-floodplain substrates were not observed at the surface or in any cores. Therefore, these reflection patterns were not identified in the classification of radargrams. Overall, cross valley radargrams consistently show 1–2 m thick reflection patterns associated with vertical accretion in the center of the South Fork Valley. Closer to the valley sides, reflection patterns are primarily associated with channel fill, bar migration, and flat lying sand and gravel facies. Till is infrequently identified in radargrams and is only seen close to the valley sides.

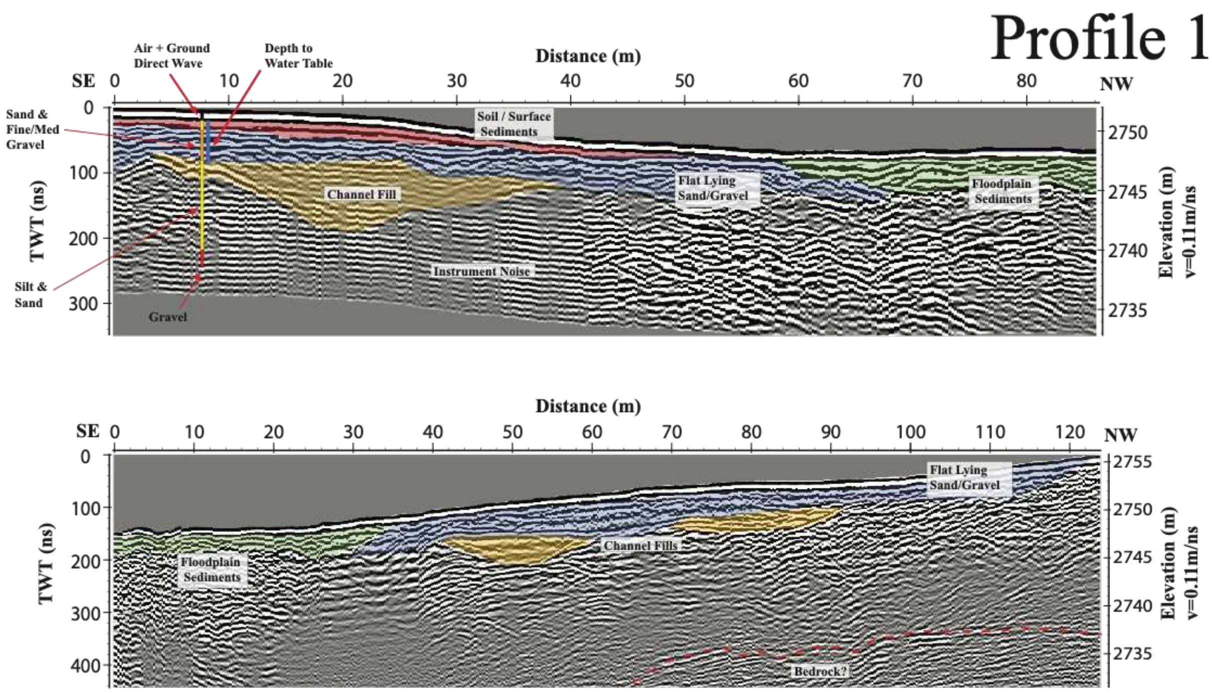


Figure 9: Upstream-most cross valley radargram (Profile 1). Cross sectional view is looking upstream. Radar facies include floodplain sediments, surface sediments, flat lying gravels, and channel fills. Channel fills and gravels are the most extensive radar facies. Facies interpretations are correlated with a simplified stratigraphic column from well MW1 (top left). Till may be present near the surface at the far left, but the reflection pattern is not clear. A deep reflector may represent bedrock, but this is uncertain. All cross valley radargrams are included in Appendix E.

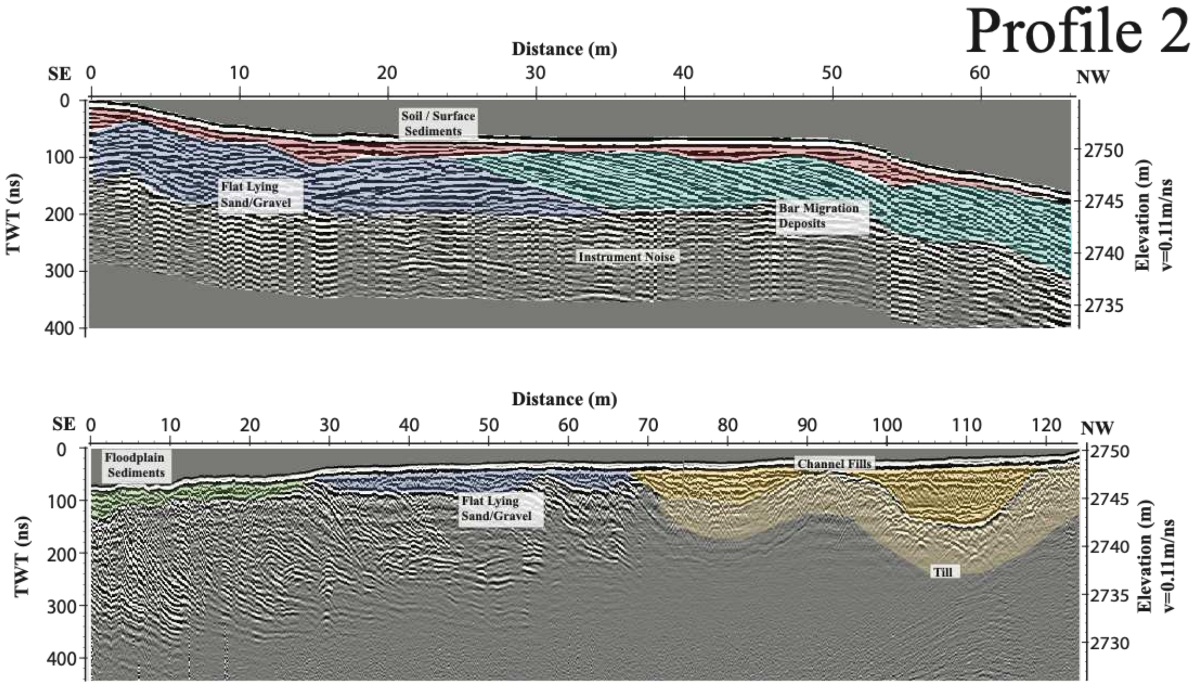


Figure 10: Second from upstream-most cross valley radargram (Profile 2). Cross sectional view is looking upstream. All radar facies are identified in this cross section. Lateral accretion deposits and flat lying gravels are the most common pattern. Channel fills are clearly identified overlying till (bottom right). All cross valley radargrams are included in Appendix E.

4.4 Radiocarbon Ages

Six of the nine bulk samples sent for radiocarbon analysis contained enough carbon to return an age (Table 6). Three samples collected from the MW2 well contained insufficient carbon to provide an age. Calibrated radiocarbon ages range in age from circa 16.8 ka to roughly 500 yr. BP. The oldest sample was collected from the core of the upstream deep well (MCMW1) on the lower (Qow2) outwash terrace (Figure 4). A sample from a former beaver pond (MCBP1) atop the higher outwash terrace (Qow1) produced an age of ~7.8 ka. Two samples collected from a fluvial terrace ~1 km downstream of the Mountain Campus (LZDFP) produced ages of ~2.1 ka at the base of the terrace and ~1.3 ka at 35 cm depth. The floodplain sample was collected from the base of the fine-grained sediment forming the floodplain, ~10 m from the present-day channel, and produced an age of roughly 500 years BP. Sediment ages are presented as ranges, reflecting a 95% confidence interval for the calibrated age of each sample. Full data tables provided by DirectAMS are included in Appendix F.

Table 6: Radiocarbon Sample Ages and Locations

Location ID:	**Sample Depth:**	**Map Unit:**	**^{14}C Age BP:**	**Calibrated Age Range (2 σ):**
MCMW1	3.65–4.25 m	Qow2	13,865	**16,743 – 16,976**
MCBP1	0.3–0.4 m	On top of Qow1	6,982	**7,779 – 7,857**
MCBP1	0.8–0.9 m	On top of Qow1	1,634	**1,514 – 1,543**
MCDSSW	0.95–1.03 m	Qfp	485	**511 – 526**
LZDFP	0.35 m	Qt	1,457	**1,310 – 1,334**
LZDFP	1.1–1.2 m	Qt	2,117	**2,049 – 2,120**
MCMW2	3.65–4.25 m	Qow1	**-**	**-**
MCMW2	4.9–5.5 m	Qow1	**-**	**-**
MCMW2	7.3–7.9 m	Qow1	**-**	**-**

4.5 Analysis of Aerial Imagery

The total area of the South Fork channel in each of the orthorectified images (e.g., Figure 11) ranged from 42,765 to 54,888 m^2 (Table 7). The average channel area in the study area was 50,698 m^2 from 1938–2019. The magnitude of change in channel area never exceeded 20% between successive images. Roughly 10^4 m^2 of new floodplain was created between each successive image (Figure 12). When the extent of floodplain creation is normalized per year, the rates of floodplain creation (m^2/year) are similar, ranging from 957–2,233 m^2/year, with a mean value of 1,638 m^2/year. All images are shown with the bankfull channel outlined through the study area in Appendix G.

Table 7: Areal Change of Channel and Floodplain from Aerial Images (1938–2019)

Image Year	Total Channel Area (m^2)	Period of Change	Percent Channel Area Change	Area of new Floodplain (m^2)	Rate of Floodplain Creation (m^2/year)
2019	42,765	2013 – 2019	-17.8	12,934	2,156
2013	51,999	2005 – 2013	0.2	8,011	1,001
2005	51,874	1975 – 2005	-5.3	28,701	957
1975	54,794	1958 – 1975	5.2	23,930	1,408
1958	52,097	1946 – 1958	-5.1	24,888	2,074
1946	54,888	1938 – 1946	18.1	17,861	2,233
1938	46,471	-	-	-	-

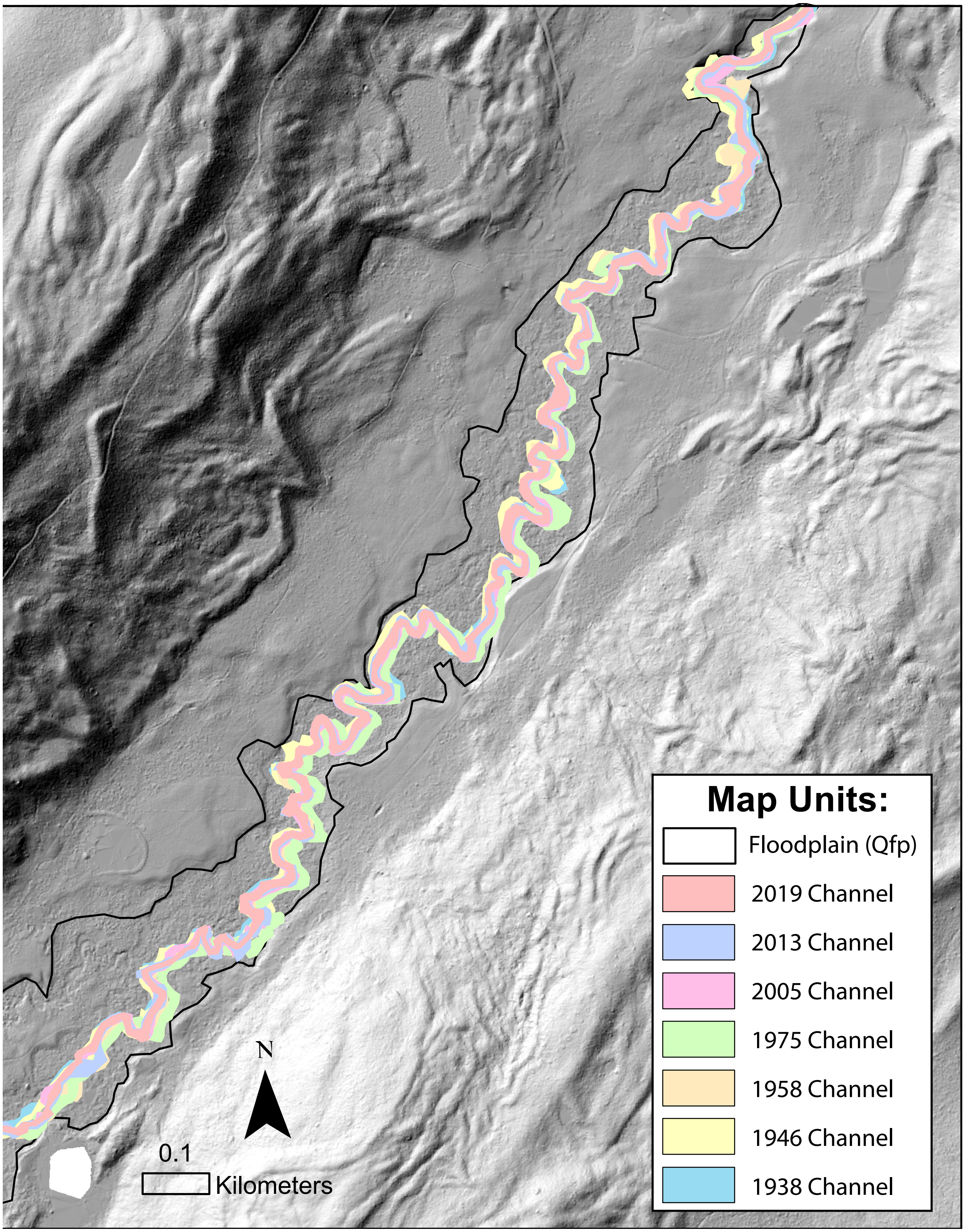


Figure 11: Extent of the South Fork bankfull channel in aerial images. Polygons are overlain with the oldest channel extent furthest in background. A 3DEP lidar-derived hillshade is the base map.

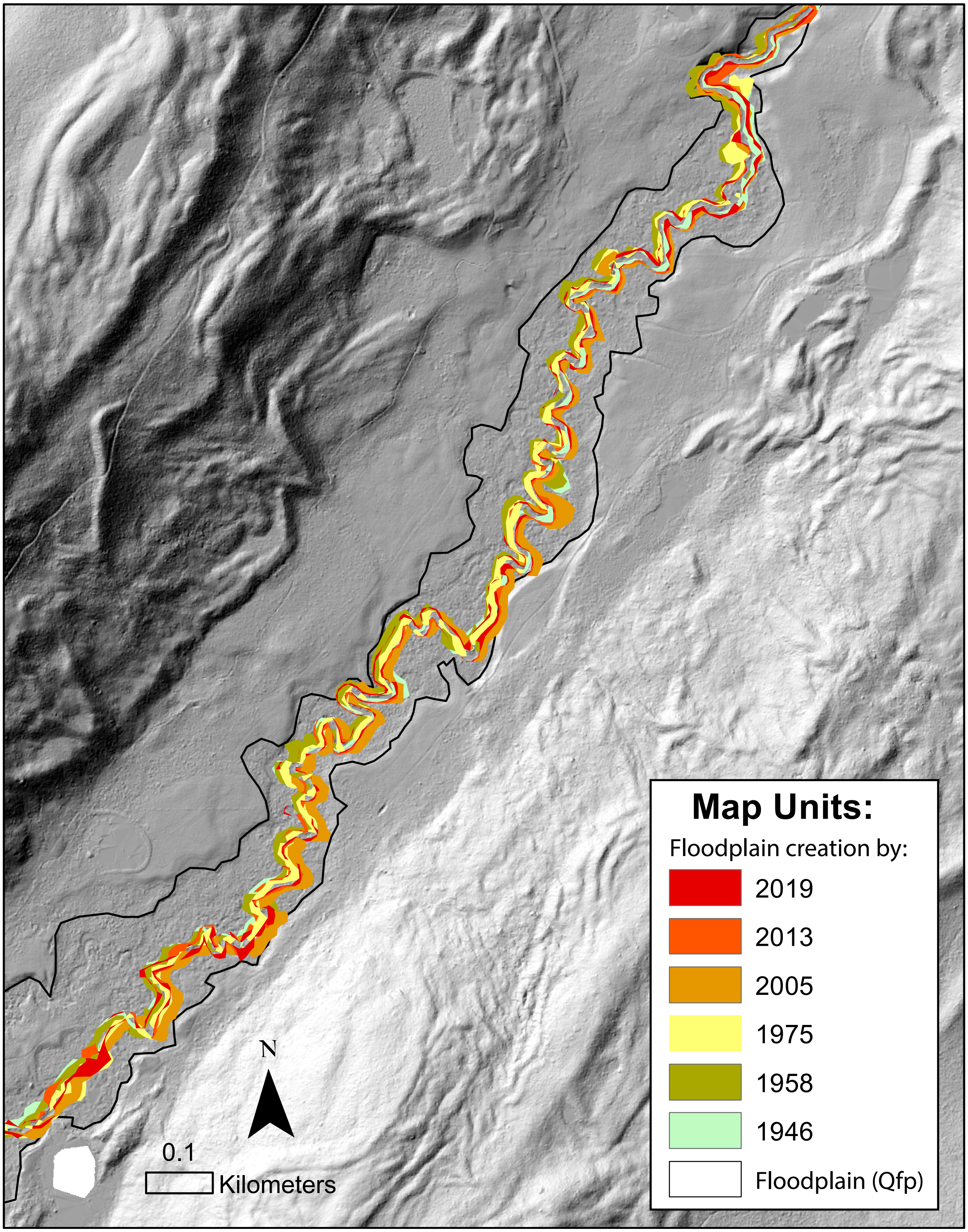


Figure 12: Extent of newly created floodplain between each successive image pair; the most recently formed floodplain area is plotted as the top layer. A 3DEP lidar-derived hillshade is the base map.

5. DISCUSSION

5.1 Late Quaternary Landscape Change of the South Fork Valley

5.1.1 Interpreted Landscape History

Examination of valley sediments indicates that the South Fork Valley has experienced significant change in the late Quaternary. The area around the CSU Mountain Campus was glaciated at least twice, with the most recent glaciation retreating prior to 16.8 ka. The glacial landforms associated with this glaciation are well defined, with sharp moraine crests and kettles which have yet to fully fill with sediment. Based on radiocarbon ages and similar morphology to other Pinedale age deposits (R. Madole, personal communication, July 2020), the younger till deposits in the South Fork Valley (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 glacial period, yet no absolute age control is available to confirm this age. Alternately, these deposits could have been formed by an earlier Pinedale glacial advance and experienced significant topographic degradation during the more recent Pinedale advance. Because of this uncertainty, I consider the Qg1 unit to be pre-late-Pinedale. Multiple glacial advances in the South Fork Valley have modified the landscape, and relict glacial topography strongly influences the post-glacial evolution of the South Fork landscape. The South Fork River gradient steepens where the river has incised into the terminal moraines of both glaciations (Figure 13).

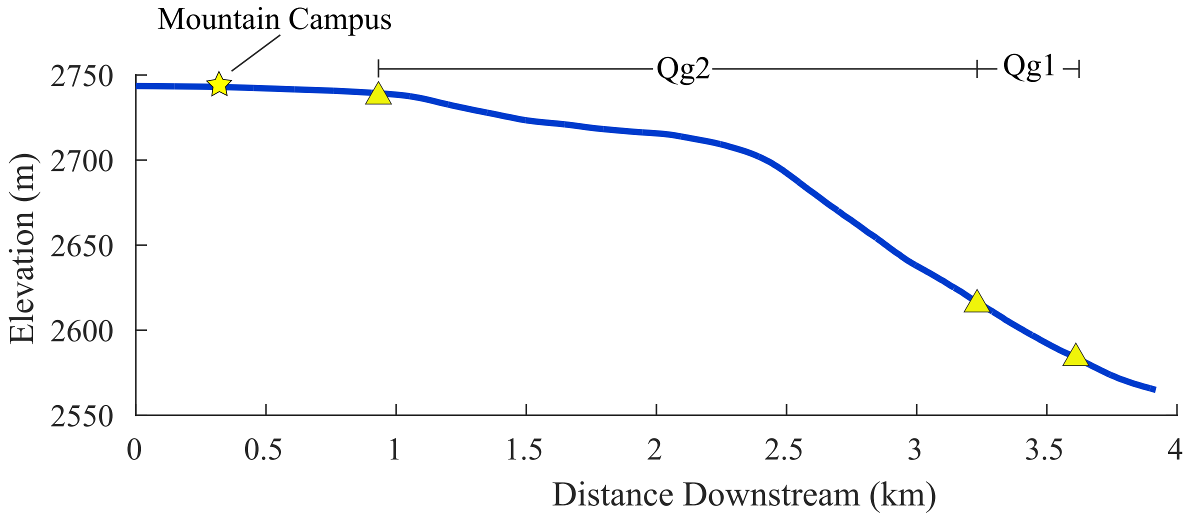


Figure 13: Long-valley profile of the South Fork channel from the CSU Mountain Campus to the late Quaternary glacial extent. Yellow star represents the location of Mountain Campus buildings. Yellow triangles are where the South Fork crosses geologic map contacts. Elevation values are sampled from the 2015 USGS lidar.

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) (Figure 14). The terraces consist of interlayered coarse (sand-cobble) and fine (silt-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 16.8 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 interpret Qow1 to have formed prior to Qow2, and to represent the maximum height of aggradation of the valley following Pinedale (LGM) glaciation. Qow1 likely formed shortly after glacial retreat. Qow2 is composed of similar outwash material and represents the post-glacial valley bottom surface after 1–2 m of incision into the outwash sediments that form Qow1 and Qow2. Significant fluvial incision and lateral erosion 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 (Figure 14). 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 the South Fork Valley. In some places, where the South Fork has incised into till and outwash, areas of fine, laminated sediments were identified, likely deposited in ponded water (Figure 7A). This suggests that the South Fork may have been dammed somewhere in the terminal moraine complex during or following post-glacial fluvial incision, though no definitive dam sites were found along the South Fork.

Between the outwash terraces, the primary valley bottom features are the modern floodplain and intermittent terraces ~1–2 m above the floodplain. These units are composed of 1–2 m of silt and sand sized material. Radiocarbon samples from this low terrace surface indicate that this feature was formed between ~2.1 ka and ~1.3 ka. The bed of the South Fork River is coarser (medium sand – gravel) than terrace and floodplain sediments, therefore overbank deposition is likely the process responsible for the aggradation of this material. The presence of this terrace suggests that about 1 m of incision has occurred in the last ~1 ka, with lateral erosion occurring across the floodplain. 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. The South Fork channel likely stabilized about 500 years ago, with one floodplain sediment sample collected ~10 m from the modern channel dated to ~500 years. This cessation of incision in the last 500 years is not certain; incision by the active channel and the accretion of overbank material could be coeval.

5.1.2 Sediment Regimes & Geomorphic Controls on Sediment Dynamics

Three prominent phases of landscape change are revealed by the sediments preserved in the South Fork Valley. Following glacial retreat from the South Fork Valley, an initial phase of rapid aggradation occurred, depositing over 10 m of material in the South Fork Valley. Initial aggradation sediments are silt to gravel in size, and display flat-lying and dipping reflection patterns. In places, strong, u-shaped reflectors separate differing radar reflector patterns above and below. Dipping reflectors are interpreted as bar migration deposits, and the u-shaped features are interpreted as filled paleochannels. Grain size and stratigraphic characteristics of these sediment suggest a sediment-rich system with one or more highly mobile channel(s). Occurring around 16.8 ka, this period of sedimentation likely had much higher discharge and sediment supply than at present, is associated with significant lateral accretion of sediments, and set the stage for landscape change throughout the late Pleistocene and Holocene. Figure 14 shows the idealized configuration of the sediments associated with this phase of change, and the location of the 16.8 ka radiocarbon sample is plotted.

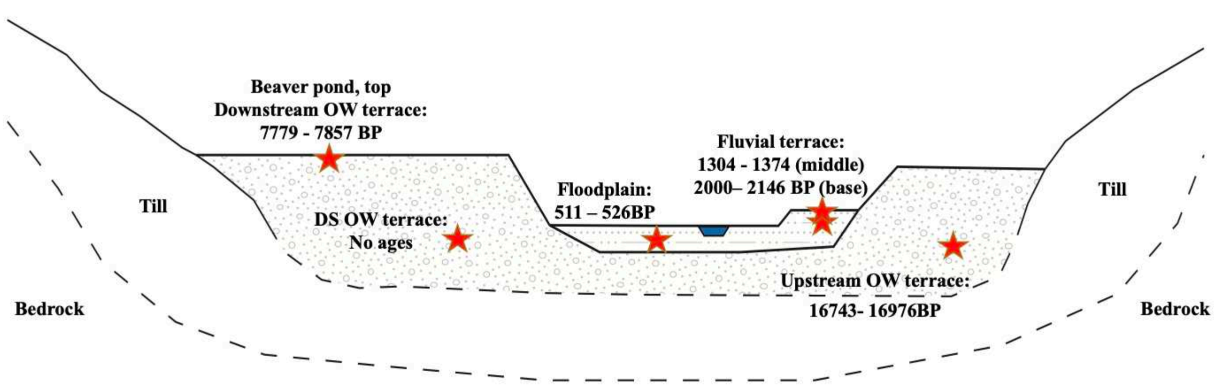


Figure 14: Idealized cross section of the South Fork Valley at the CSU Mountain Campus. The two inner-most sediment packages represent the two distinct phases of fluvial aggradation within the South Fork Valley. Incision has inset the floodplain and low terrace (dashed pattern), in the surrounding outwash material (dotted patterns). Dashed lines indicate where unit contacts were not identified in cross valley radargrams.

Following initial sediment accumulation, fluvial incision and lateral erosion formed the broad, low relief surface of the floodplain and low terrace. This incision lowered the valley bottom 5–8 m along the South Fork Valley, disconnecting the channel from the valley bottom surface associated with the outwash terraces. The open area in the center of Figure 14 suggests the magnitude of sediments removed from the South Fork Valley in the late Quaternary. Abandonment of the outwash valley bottom surfaces must have occurred prior to 7.8 ka, as a well-preserved beaver pond damming a seep is located on this surface and yielded fine-grained sediment of this age. This period of incision is not well constrained, but likely ceased prior to 2.1 ka, the age that a low terrace preserved downstream of the Mountain Campus began to form. This low fluvial terrace, also preserved at the Mountain Campus, signals the third period of valley bottom change. From ~2.1 ka to ~1.3 ka, fine grained, overbank deposition formed a low terrace along the South Fork. Fine grained, overbank deposition formed the floodplain at the Mountain Campus, with basal floodplain sediments dating to 500 years BP. A period of ~1 m of incision is likely to have occurred in the last 1000 years, separating the low terrace from the floodplain.

In addition to the supply of water and sediment to the South Fork Valley, the geomorphology of the valley has a profound influence on the post glacial alluvial response. The wide, low gradient valley geometry created by glacial incision makes the South Fork Valley an effective setting for the long-term storage of sediments. Further, the terminal moraine just downstream of the Mountain Campus is a local base level control, governing incision by the South Fork River into the valley bottom sediments at the Mountain Campus. Incision is the dominant vertical change of the South Fork channel following the initial period of aggradation, but incision is likely slow in the study area, and only in response to channel lowering at the knickpoint located in the terminal moraine (Figure 13).

5.1.3 Sediment Thickness at the CSU Mountain Campus

The penetration of GPR surveys in the South Fork Valley ranged from ~5–10 m, though interpretation of geophysical signals was increasingly uncertain at depth due to signal attenuation and an inability to correlate radar reflection patterns with observations from mapping or coring. Generally, outwash sediments were >5 m thick, with underlying till documented on the NW side of the valley in Profiles 2–4. Otherwise, the base of outwash sediments is not documented. Overbank sediments on the floodplain and fluvial terrace are ~1–2 m thick, with a clear reflector separating overbank sediments from sediments below. Depth of GPR penetration appears to increase under the modern floodplain, with well-defined reflection patterns appearing to ~10 m depth, but this apparent increase in penetration is likely due to a lower propagation velocity caused by saturated sediments and/or different properties of the substrate. Though reflection patterns are well defined under the floodplain, they are not interpreted as part of the facies model due to a lack of surficial or cored observations of these sediments. Coring and deep well logs also provide controls on the thickness of valley bottom sediments. Both deep wells were drilled on outwash terraces on the SE side of the valley and did not conclusively reach till but indicate that outwash terraces are greater than 10 m thick in places. Augered cores support GPR observation of 1–2 m of floodplain sediments but were not able to penetrate deeper than the gravels at the base of the floodplain. Additional subsurface information in the South Fork Valley comes from the water intake well installation report for the Mountain Campus. The well log indicates ~16 m of 'glacier fill' overlain by ~6 m of 'brown clay and boulders' and capped by ~3 m of 'surface material' (Colorado Division of Water Resources, 1985). While the log lacks detailed stratigraphic descriptions, it suggests that sediments in the South Fork Valley are at least 25 m thick, and that outwash sediments on the NW side of the valley at least 3 m thick.

5.1.4 Regional Correlations of Aggradation and Incision

Key periods of aggradation and incision in the South Fork Valley included aggradation around 16.8 ka, incision following post-glacial aggradation, occurring prior to 7.8 ka, and two phases of late Holocene aggradation, 2.1–1.3 ka and 500 years ago to present. The earliest phase of aggradation predates all phases of aggradation documented in the Roaring River and the Conejos River valleys (Layzell et al., 2012; Madole, 2012). The oldest post-LGM sediments dated along the Roaring River are ~12.9 ka (Madole, 2012) and the oldest sediments along the Conejos River were deposited ~12.4 ka (Johnson et al., 2011). Both sites recorded fluvial incision between the oldest phases of aggradation and subsequent aggradation. Aggradation in the Roaring River Valley occurred at ~7.7 ka, from ~5.2–3.8 ka, and over the last ~2 ka (Madole, 2012). Periods of aggradation in the Conejos Valley occurred ~8.9–7.6 ka, ~5.4 ka, and in the last ~1.9 ka (Layzell et al., 2012). The South Fork Valley does not appear to record the early Holocene (~8 ka) or mid Holocene (~5 ka) periods of aggradation, yet all valleys share similar late Holocene aggradational conditions. The lack of ~16 ka sediments in the Roaring River Valley and Conejos Valley may be due to later deglaciation of these sites. Early and mid-Holocene terraces may not have formed in the South Fork Valley, or terrace sediments may have been removed via lateral erosion by the South Fork channel. The late Holocene period of aggradation observed along the Roaring River, Conejos River and the South Fork River points to similar conditions occurring across the southern Rockies. Cooler and drier climate conditions, similar to those at present were established circa 1.8 ka (Vierling, 1998). Though relatively consistent, the climate of the past ~2,000 years has varied, with a medieval warm period occurring 1200–850 yr. BP (Trouet et al., 2013), and cooler temperatures from ~700–100 yr. BP (Doerner, 2007). These small-scale climate oscillations may be important for late Holocene aggradation. Significant landscape alteration associated with European settlement and land use in the Rockies (e.g., Wohl, 2001) is likely a key influence on modern channel conditions in these valleys.

5.2 Evaluation of Hypotheses

H1: Vertical accretion of fluvial sediments is the dominant mechanism of post-glacial sedimentation within the South Fork Valley.

My first hypothesis is not supported. Lateral accretion and channel filling deposited the fluvial sands and gravels contained within outwash terraces Qow1 and Qow2, the most common sediment deposits in the South Fork Valley. Outwash sediments commonly displayed dipping reflectors in the GPR surveys, which I interpret to represent bar fronts formed via lateral bar migration. Channel fills are also common in outwash terrace stratigraphy. Some vertical accretion of material may have occurred in this primary phase of aggradation within the South Fork Valley, but this was not detected in GPR radargrams or surface observations. Vertical accretion of fluvial sediments is an important mechanism of sedimentation during the period of late Holocene (~2.1 ka – present) sedimentation that formed the modern floodplain and the low fluvial terrace of the South Fork Valley. Processes contributing to late Holocene vertical accretion include overbank deposition and beaver ponding of sediments. This suggests that vertical accretion of sediments is the dominant process of sedimentation in the South Fork Valley at present, yet it was not historically.

H2: The rate of sediment accumulation and removal in the South Fork Valley is uniform over moderate time scales, and relatively low.

My second hypothesis is largely not supported over the post-glacial period. Instead of uniform accumulation of sediments, the South Fork's late Quaternary history includes distinct periods of accumulation and removal of valley bottom sediments. An overall trend of valley bottom lowering through the Holocene, following the initial period of aggradation in the valley is observed. This long-term trend of incision in the Holocene was punctuated by periods of aggradation, occurring from ~2.1 ka to ~1.3 ka, and in the last 500 years, further refuting this hypothesis. Lateral erosion by the South Fork River also removed sediments from the valley, forming the wide, low relief valley bottom which contains the floodplain and the low fluvial terrace. This hypothesis may be accurate in that aggradation rates in the valley are relatively low outside of the period of outwash sedimentation. Approximate aggradation rates on the floodplain and terrace are ~0.002 m/yr and ~0.001 m/yr, respectively, with 1 m of aggradation occurring between 500 yr. BP and the present and ~0.8 m aggradation from 2.1–1.3 ka. Low aggradation rates may be due to the slow rate of accumulation via overbank deposition, lack of direct hillslope connectivity to the channel at the Mountain Campus, and/or the valley's wide morphology moderating the effects of local disturbance events.

5.3 Comparison to Other Front Range Valleys

Previous studies of the sediment dynamics and valley bottom stratigraphy of formerly glaciated valleys in northern Colorado include the work of Rubin et al. (2012) at the Lulu City Wetland, and the work of Polvi and Wohl (2011) and Kramer et al. (2012) at Beaver Meadows (Figure 15). Comparing my findings to these analogous sites provides a broader context, and highlights characteristics of the South Fork which influence its geomorphic evolution and sedimentary regime. Specifically, I focus on the dominant processes of sediment accumulation, observed sediment depths, and valley bottom stratigraphy of these valleys, chosen because they were studied using similar techniques.

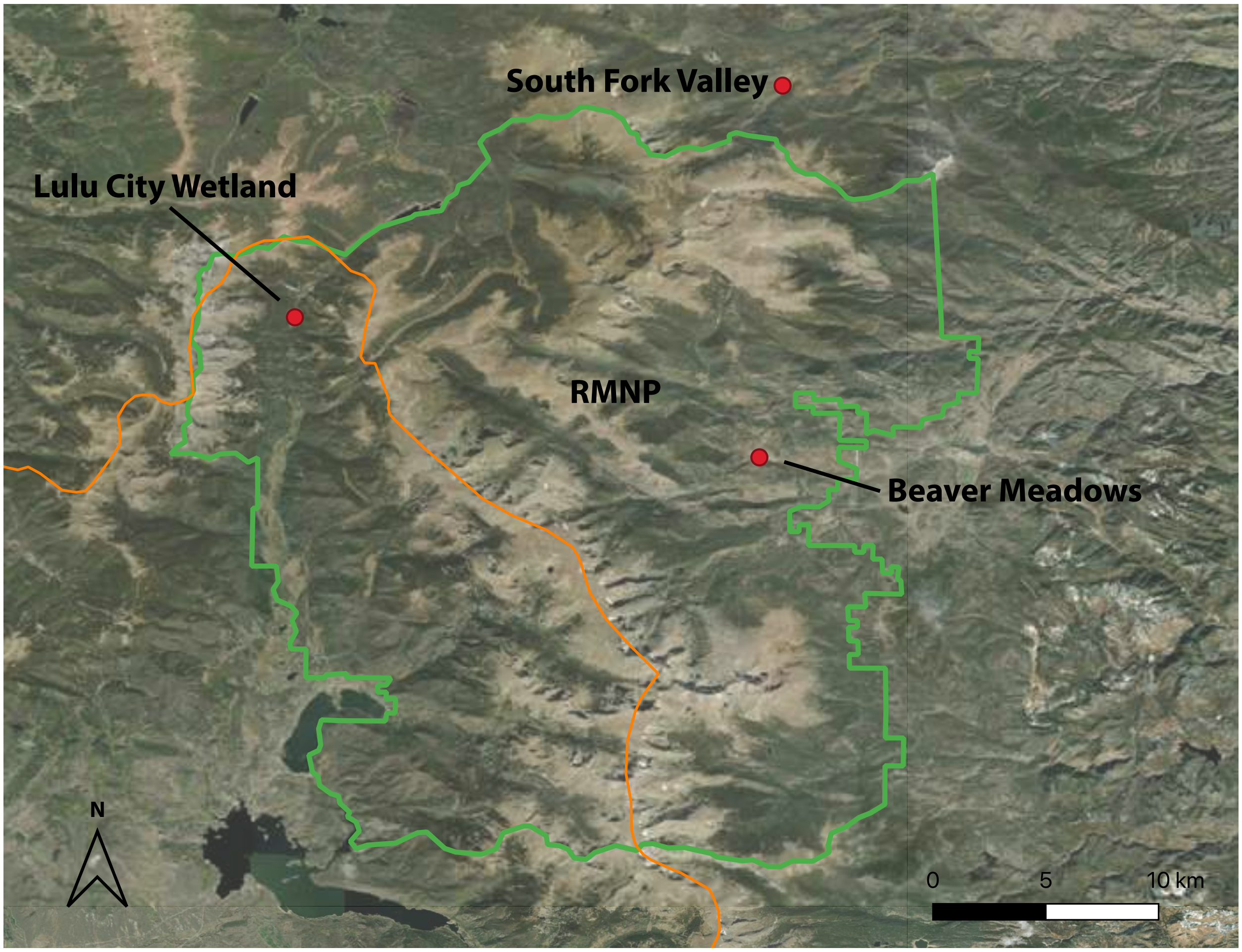


Figure 15: Location map of comparison studies. Outlines of Rocky Mountain National Park (green) and the Continental Divide (orange) are plotted for reference.

Rubin et al. (2012) found that debris flow deposition, peat accumulation, and overbank deposition were the primary drivers of aggradation over the last ~4 ka in the Lulu City Wetland. GPR, coring, and trenching were used by Rubin et al. (2012) to examine the subsurface, but no method could consistently examine deeper than ~4 m. The base of alluvial deposits in the Lulu City wetland was not constrained. Cross valley radargrams showed extensive areas of horizontal, continuous reflectors on the east side of the Lulu City Wetland, and significant high-energy deposition associated with debris flow deposition on the west side of the study area (Rubin et al., 2012). This study area differed markedly from the South Fork Valley, with thicker Holocene alluvial deposits, different depositional processes, and asymmetric valley bottom stratigraphy documented at Lulu City. The valley bottom stratigraphy of the Lulu City Wetland is significantly influenced by hillslope sedimentation due to highly altered volcanic bedrock and anthropogenic activities along an earthen ditch (Rathburn et al., 2013). Holocene sediments in the South Fork Valley are no more than 2 m thick, and primarily formed by vertical accretion of fine-grained sediment on the floodplain. No debris flow deposition was identified in the South Fork Valley, and valley bottom stratigraphy showed similar processes occurring on both sides of the valley. Cross valley stratigraphy was roughly symmetrical, with 5–10 m thick outwash sediments on both valley sides, and 1–2 m of Holocene sediments inset within outwash terraces. Polvi and Wohl (2011) and Kramer et al. (2012) showed that beaver ponding was an important process of sediment deposition in Beaver Meadows, with 30–50% of alluvium in the valley deposited via ponding. Beaver ponding of sediment in Beaver Meadows likely deposited more sediment than in-channel processes of deposition (Polvi and Wohl, 2011). Alluvial deposits in Beaver Meadows were generally less than ~6 m thick and beaver pond sediments were less than 3 m thick (Kramer et al., 2012). GPR surveys of valley bottom substrates revealed buried beaver dams, characterized by continuous, horizontal reflections grading onto small areas of chaotic reflections. Sedimentation in Beaver Meadows showed more similarities to the South Fork Valley than the Lulu City Wetland. Sediment dynamics at Beaver Meadows and the South Fork are strongly influenced by relict glacial topography and limited hillslope connectivity. Beaver Meadows and the South Fork Valley have experienced periods of valley bottom aggradation and incision following the LGM. Outwash sediments in the South Fork Valley are thicker than alluvial sediments in Beaver Meadows, yet the late-Holocene sediment regime of the South Fork is similar to that of Beaver Meadows. Finally, though the importance of beaver ponding was not explicitly evaluated in the South Fork Valley, vertical accretion deposits on the floodplain and fluvial terrace may be associated with beaver in addition to overbank deposition.

Comparison of these three subalpine valleys indicates that the sediment dynamics of these valleys are strongly modulated by hillslope-channel connectivity and the preexisting glacial geomorphology of the study sites. All sites effectively store post-glacial alluvial sediments despite evolving under different conditions. High hillslope sediment delivery to the Lulu City Wetland is due to strong hydrothermal alteration of the surrounding volcanic bedrock and anthropogenic influences; this supply of sediment from the hillslopes has driven preferential aggradation through the Holocene. Conversely, the South Fork Valley and Beaver Meadows have low rates of aggradation and have experienced periods of aggradation and incision in the Holocene. The deposition of a large volume of outwash sediments in the South Fork is not documented elsewhere, and likely reflects the different glacial histories of the South Fork and upper Colorado River valleys, and the lack of LGM glaciation at Beaver Meadows.

5.4 Management Implication of Findings

While this research was not inspired by any pressing management questions in the South Fork Valley, there are several key takeaways from this research which pertain to the management of the water and sediment in this formerly glaciated valley. This is particularly relevant as the headwaters of my study site, and of many post-glacial valleys in the southern Rockies, lie on National Forest lands, where resource managers may need to evaluate requests for new diversions or other flow regulation projects. Development pressure from water resource infrastructure is evident elsewhere in the South Fork headwaters, with several reservoirs located less than 5 km from my study site. Additionally, my investigation of post-glacial valley bottom sediments may inform land managers of the implications of increased building of cabins, roads, or other development in formerly glaciated valleys.

1. Valley width promotes resistance to disturbance. At the Mountain Campus, valley width and lack of tributary inputs mitigate the effect of local landscape disturbances (e.g., wildfire, hillslope mass wasting) on the sediment dynamics of the South Fork River. Despite recent fires burning the valley walls, sedimentation on the floodplain has been minimal. Recent field observations suggest that little to no hillslope sedimentation is occurring in response to the Cameron Peak Fire (S. Rathburn and S. Dunn, personal communication, October 2021), and I did not recognize any large deposits of hillslope sediment in the valley during field work in summer 2021. Further, hillslope-channel connectivity is limited in the valley, and if hillslope sedimentation were to increase in the valley, sedimentation would occur on the outwash terraces and the effect on the channel would be small. Only one tributary, Fall Creek, consistently flows from the surrounding slopes to the South Fork channel, and is the only external source of sediment to the valley besides the mainstem channel.

2. Modern changes to the South Fork Channel occur slowly because of the geomorphic setting. Channel change in the last ~80 years, as observed by analysis of aerial images, occurs slowly under the current flow and sediment regime. As mentioned in the previous management observation, the amount of sediment delivered to the valley is unlikely to change rapidly due to disturbance on the landscape, removing a potential natural driver of channel change. Rapid incision of the South Fork channel is unlikely to occur due to the local base level control associated with the terminal moraine immediately downstream of the studied reach. The presence of significant riparian vegetation on the channel banks and the floodplain makes the channel less susceptible to rapid changes. These observations suggest that grade control measures and hillslope sediment retention practices are not necessary in the South Fork Valley. Changes to the system that could produce channel change in the South Fork Valley include 1) significant local sedimentation to the channel associated with construction or other anthropogenic addition of sediment to the system, or 2) decreased streamflow in the South Fork River due to diversion of water. Both changes could increase the accumulation of sediment along the channel and potentially affect floodplain maintenance.

3. Long term storage of sediment in glacial valleys. Results presented here indicate that the South Fork Valley has been able to store large volumes of sediment deposited in the late Pleistocene throughout the Holocene. Though channel incision and lateral erosion has removed material across the area of the floodplain and low terraces, high terraces cover a large area of the valley floor (36.2% of the study site), and store over 10 m of post-glacial sediments in places. The modern channel flows through the center of the floodplain, and in only a few locations does the channel flow proximal to an outwash terrace. This suggests that the channel can only entrain sediments from these terraces in a few locations and implies that these deposits will experience little geomorphic change associated with channel processes. Additionally, if the development of late Holocene fluvial terraces is due to small scale incision in the last ~1000 years, these outwash terraces will become further disconnected from the channel and even less likely to experience change.

5.5 Future Research

Important additional research regarding the post glacial alluvial dynamics and landscape response of the South Fork River that could substantiate and/or leverage the efforts discussed herein include the following topics.

1. Increase the amount of direct observation of the subsurface throughout the South Fork Valley. Well logs from the two deep wells and shallow coring of fine-grained deposits were essential for interpreting GPR signals and characterizing the sediments and stratigraphy of the South Fork Valley. Despite these observations, at many locations where GPR data were collected there was no subsurface control. Increasing the number of observations of the subsurface would help to improve interpretations of geophysical data and allow for more robust conclusions about the processes responsible for the accumulation of sediments in the valley.

2. Improve geochronologic constraints on valley evolution. I was able to leverage a few radiocarbon ages of valley bottom sediments to constrain the timing of phases of aggradation and incision, but many questions remain unanswered. A lack of carbon in outwash sediments limited my ability to effectively date older valley bottom sediments. Floodplain and fluvial terraces in the valley are composed of organic-rich sediment and could easily be dated via bulk radiocarbon samples. Ages of samples collected on the floodplain and Holocene terrace could substantiate ages discussed in this work or show spatial patterns of the timing of aggradation across these surfaces. More radiocarbon ages could also allow researchers to calculate rates of aggradation observed on these surfaces with greater certainty.

Findings of this work could also be used, in conjunction with additional research, to answer other important questions about water and sediment in the South Fork Valley. Two ideas for additional research are as follows.

1. Examining interactions between alluvial stratigraphy and surface-subsurface water exchange. Water level data from the monitoring network at the Mountain Campus and data from this work, in addition to isotope data, are currently being studied to address how alluvial stratigraphy affects the storage and exchange of water in the shallow subsurface (M. Ronayne, personal communication, July 2021). This research will have important implications for understanding surface-subsurface water exchange and storage, and for floodplain and channel restoration practitioners to inform the design of floodplains in restoration projects. Results may also provide important information about how channel and floodplain evolution affect hyporheic exchange.

2. Connecting geomorphic response to climate signal. Collecting local paleoclimate data in the South Fork Valley could tie valley geomorphic change to a climate signal and examine the importance of climatic conditions on the alluvial behavior of the South Fork River. Numerous kettles in the South Fork terminal moraine are prime sites for coring and paleoclimate reconstructions using sediment stratigraphy, palynology, and radiocarbon analyses.

6. CONCLUSIONS

In this study, I examine the alluvial stratigraphy and geomorphology of the South Fork Cache la Poudre Valley and use these records to test hypotheses regarding the processes and timing of post-glacial fluvial landscape changes in the valley. I used surficial geologic mapping, sediment coring, ground-penetrating radar, radiocarbon geochronology, and analysis of historical aerial images. Results indicate that the dominant processes of sediment accumulation include bar migration, channel fills, and over bank deposits. Three primary periods of valley alluvial dynamics occurred since the LGM, including a period of over 10 m of aggradation occurring at 16.8 ka, likely shortly after deglaciation, a period of 5–8 m of fluvial incision beginning prior to 7.8 ka, and 1–2 m of aggradation occurring since ~2.1 ka. Valley stratigraphy suggests that lateral accretion of sediments via bar migration and channel filling were important processes during the initial period of aggradation. Aggradation of the valley ceased, and the channel began to incise into these sediments prior to 7.8 ka. Incision following the initial period of aggradation has removed 5–8 m of sediment across the extent of the floodplain and low terraces. The accumulation of sediment in the South Fork Valley likely resumed by ~2.1 ka, with a low terrace downstream of the Mountain Campus forming between 2.1 and 1.3 ka. At the Mountain Campus, the floodplain has formed over at least the last 500 years. Late Holocene sedimentation in the South Fork Valley has produced 1–2 m of aggradation and is primarily driven by vertical accretion of sediments via overbank deposition. Analysis of valley change over time indicates a net removal of sediment from the South Fork Valley through the Holocene, yet many of the sediments deposited in the two outwash terraces are preserved in the valley. The relict glacial topography of the valley likely promotes the storage of sediment and provides a strong geomorphic influence on the behavior of the South Fork channel at the Mountain Campus. The low valley gradient, held up by the local base level of the terminal moraine, a wide valley to store sediments, and limited hillslope and tributary connectivity in the valley are the most likely controls on sediment storage. As a result of the post-glacial valley evolution of the South Fork Valley, the current valley bottom changes slowly and is largely buffered against the effects of disturbances.

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APPENDIX A

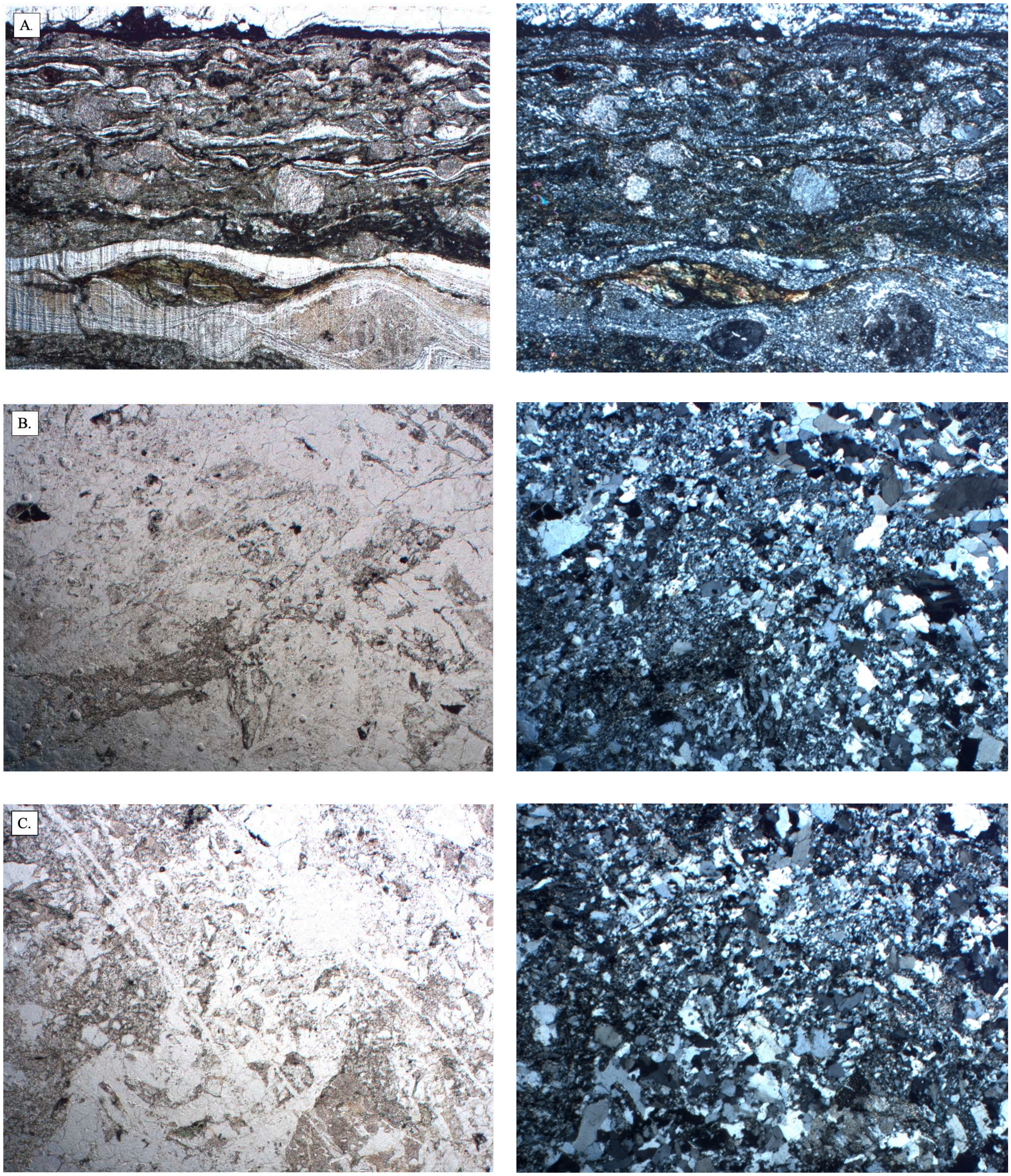


Figure A1: Photomicrographs of three selected bedrock samples collected from mapped shear zones in the South Fork Valley. All thin sections were imaged at 2.5 x magnification. Plane-polarized images are on the left, cross-polarized images on the right. A. Mylonite or ultramylonite with prominent brittle-plastic strain; quartz grains exhibit bulging and sub-grain rotation. Local cataclasis is possible with epidote veins appearing to be involved in brittle deformation. B. Highly silicified rock; 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 in this sample has been obscured by silicification. C. Cataclastic texture (angular, fragmented grains of various sizes); some discrete fractures across quartz display subgrains or bulging (fracturing likely near brittle-ductile transition).

APPENDIX B

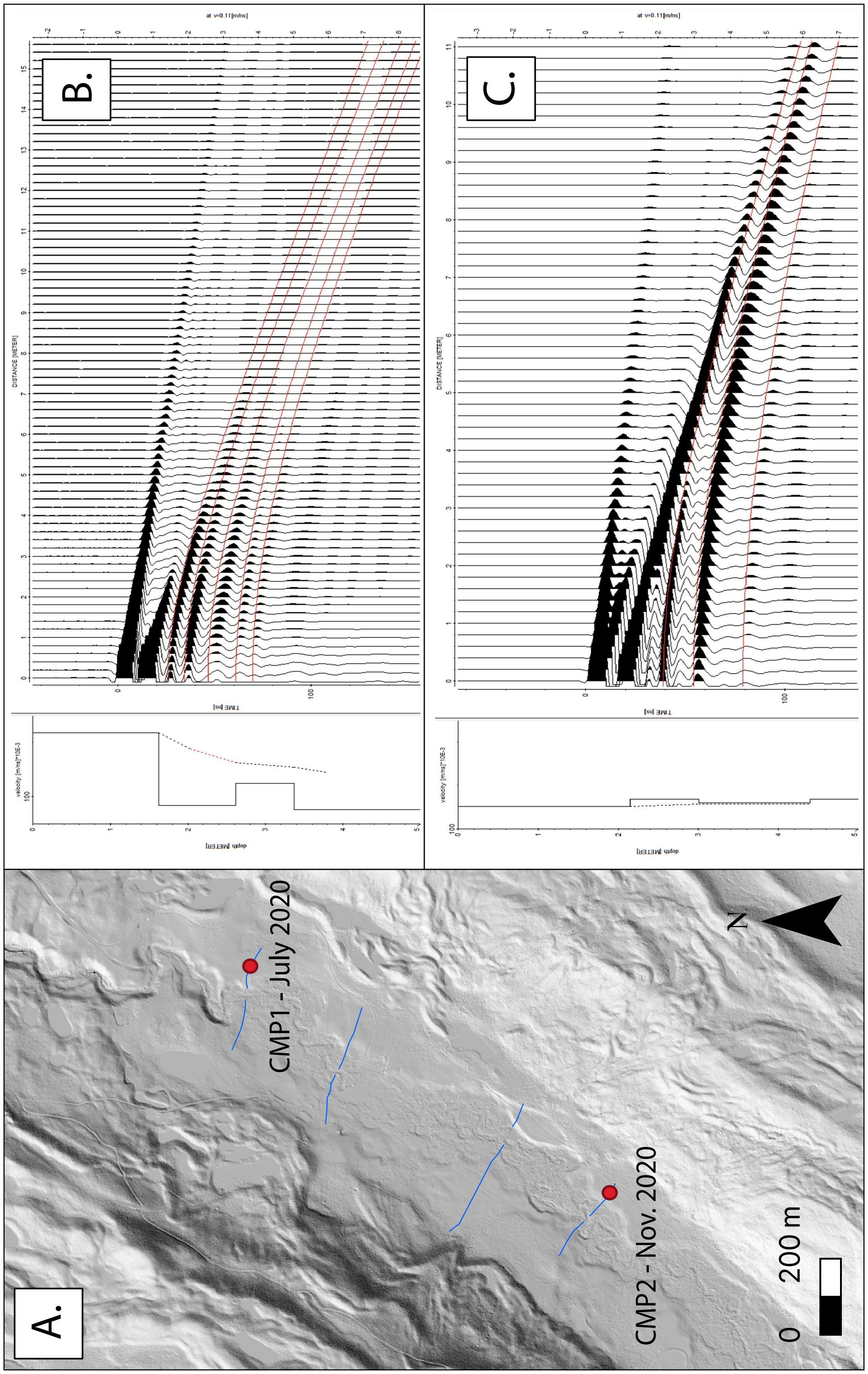


Figure B1: Radar velocity models developed from CMP surveys conducted at two sites in the South Fork Valley. A. The location of the CMP surveys are shown as red dots. Blue lines represent common offset profiles discussed in the text. B. Velocity model and data from CMP1 (July 2, 2020). C. Velocity model and data from CMP2 (Nov 6, 2020).

APPENDIX C

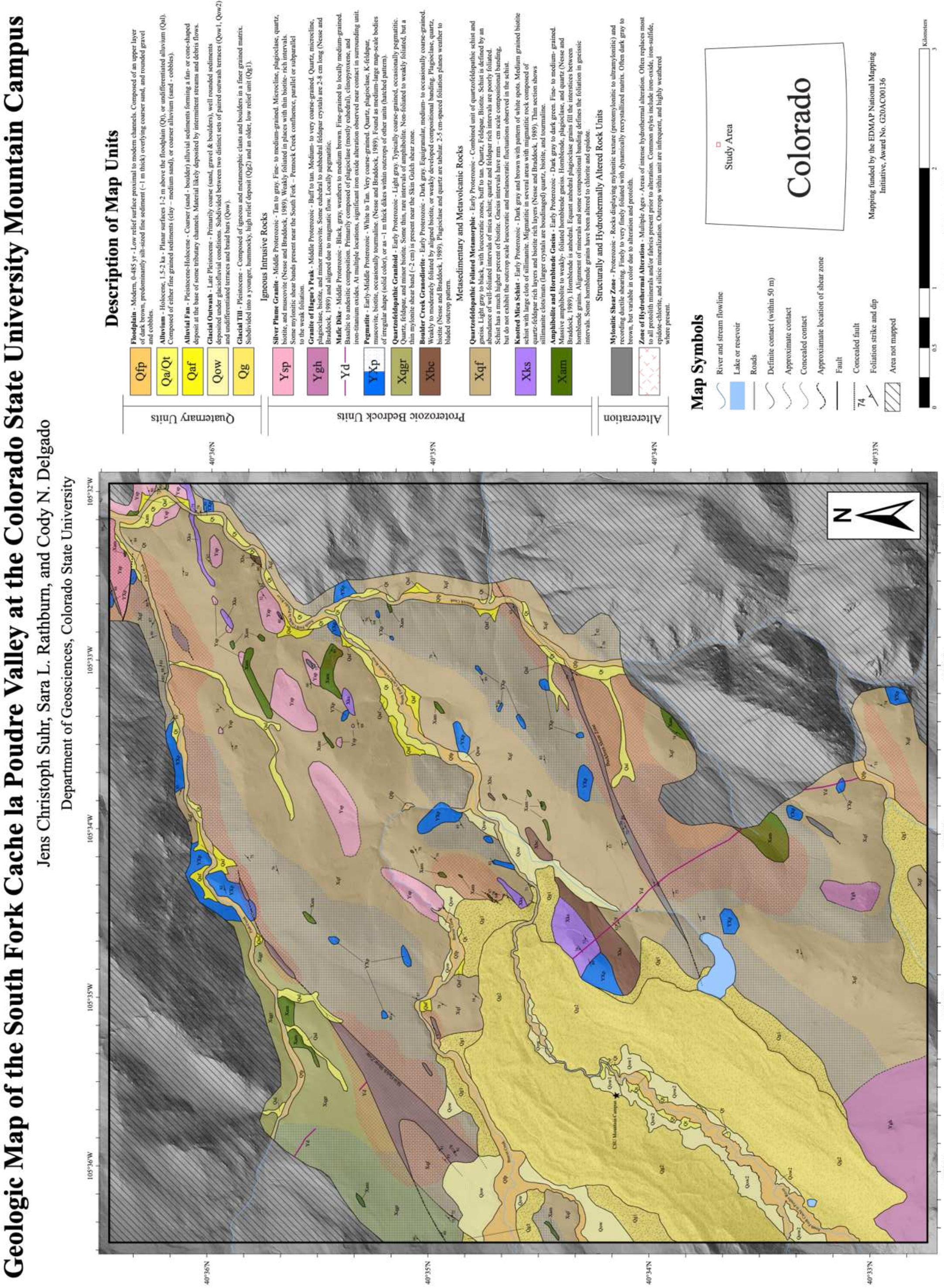


Figure C1: Geologic Map of the South Fork Cache la Poudre Valley completed for 2020 EDMAP award to S. Rathburn. The technical report titled "Remapping a Portion of the Pingree Park Quadrangle, Colorado, to Provide Insights Regarding the Development of Unconfined Valleys in Mountains" (Rathburn et al., 2021) accompanies the map.

APPENDIX D

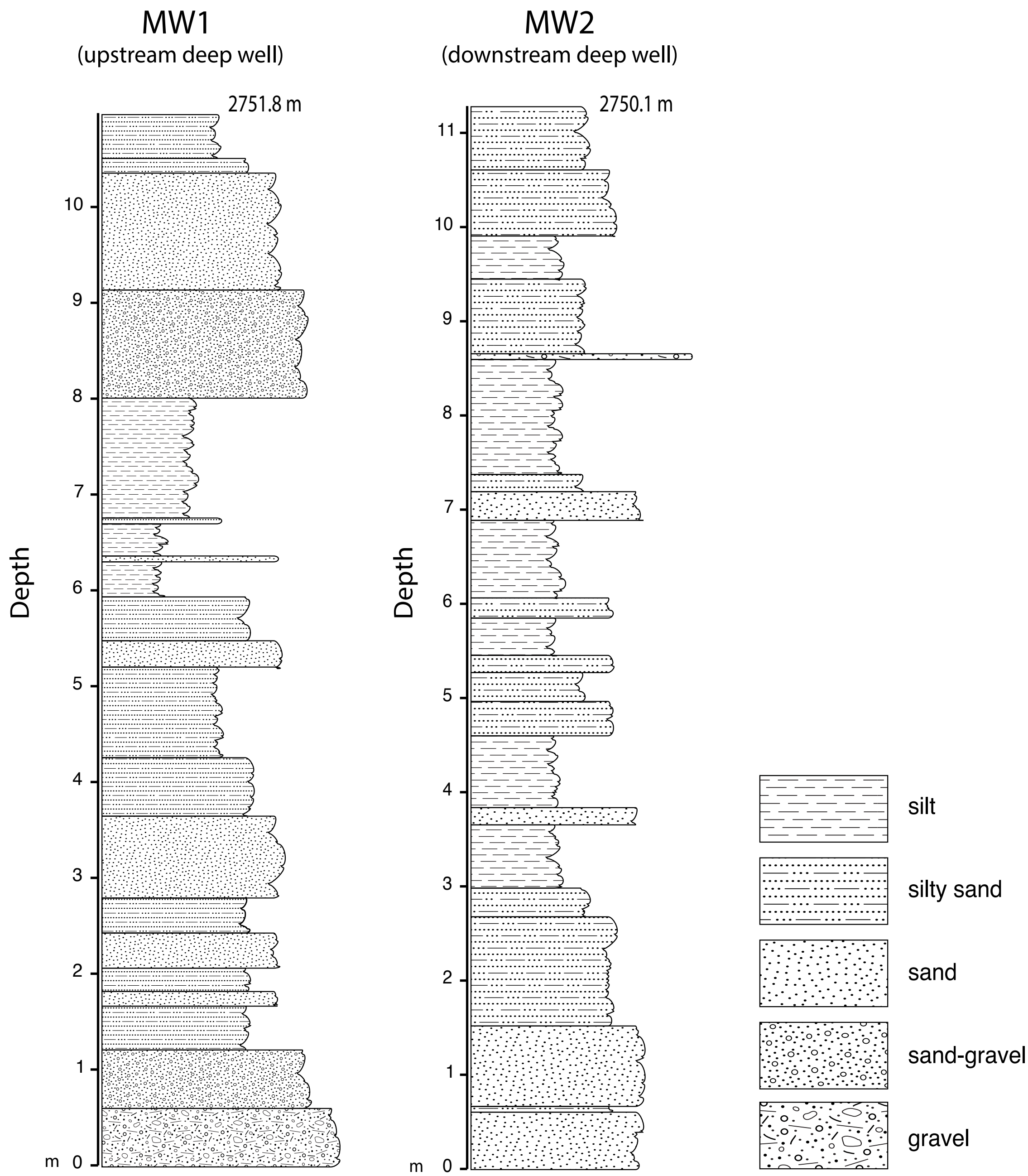


Figure D1: Stratigraphic columns developed from cores of two ~10 m deep ground water wells at the CSU Mountain Campus. The elevation of the ground surface at the top of each well is included for each column. The widths of sediment packages in this figure correspond to the grain size of the sediments.

APPENDIX E

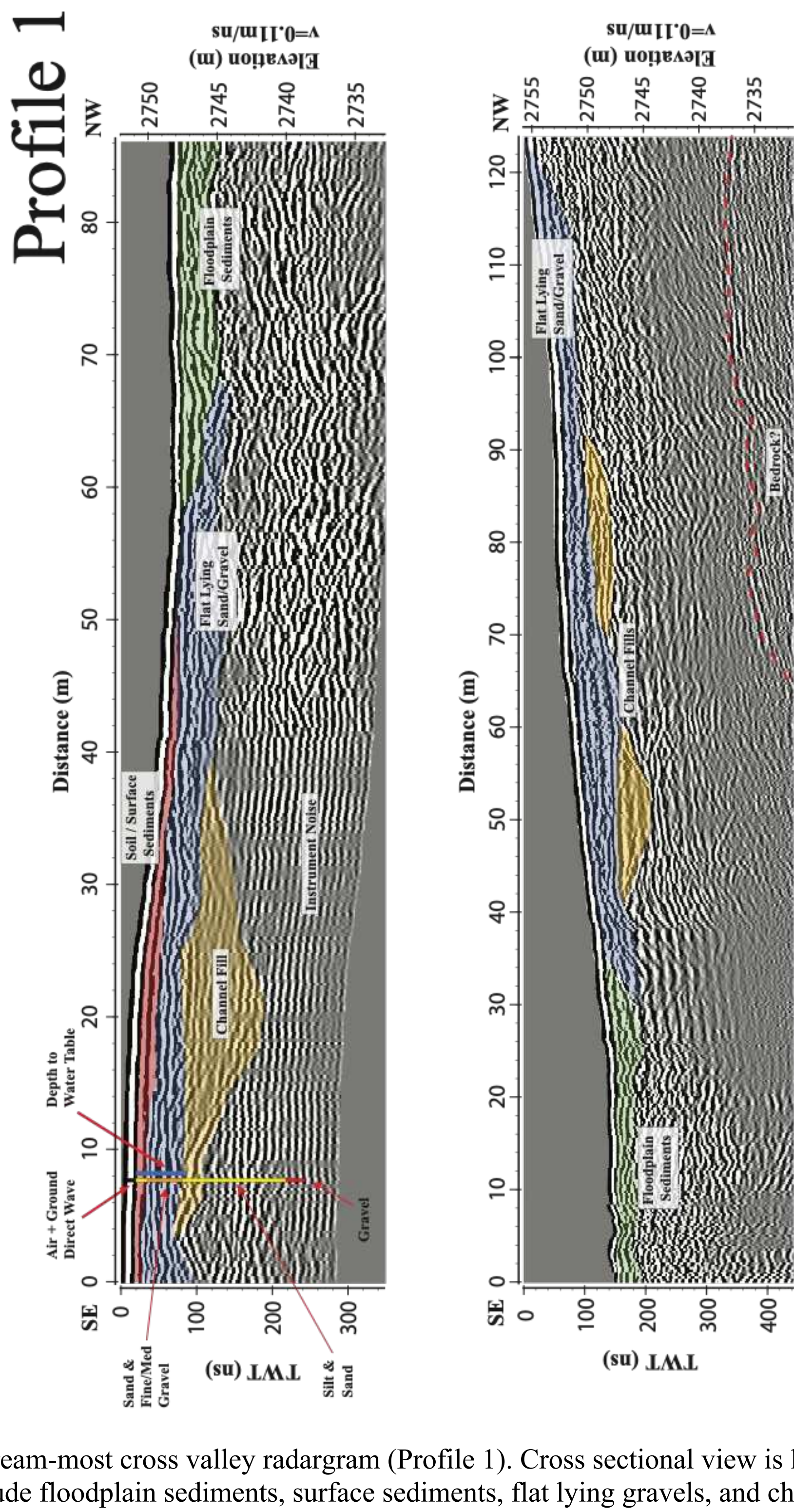


Figure E1: Upstream-most cross valley radargram (Profile 1). Cross sectional view is looking upstream. Radar facies include floodplain sediments, surface sediments, flat lying gravels, and channel fills. Channel fills and gravels are the most extensive radar facies. Facies interpretations are correlated with a simplified stratigraphic column from well MW1 (top left). Till may be present near the surface at the far left, but the reflection pattern is not clear. A deep reflector may represent bedrock, but this is uncertain.

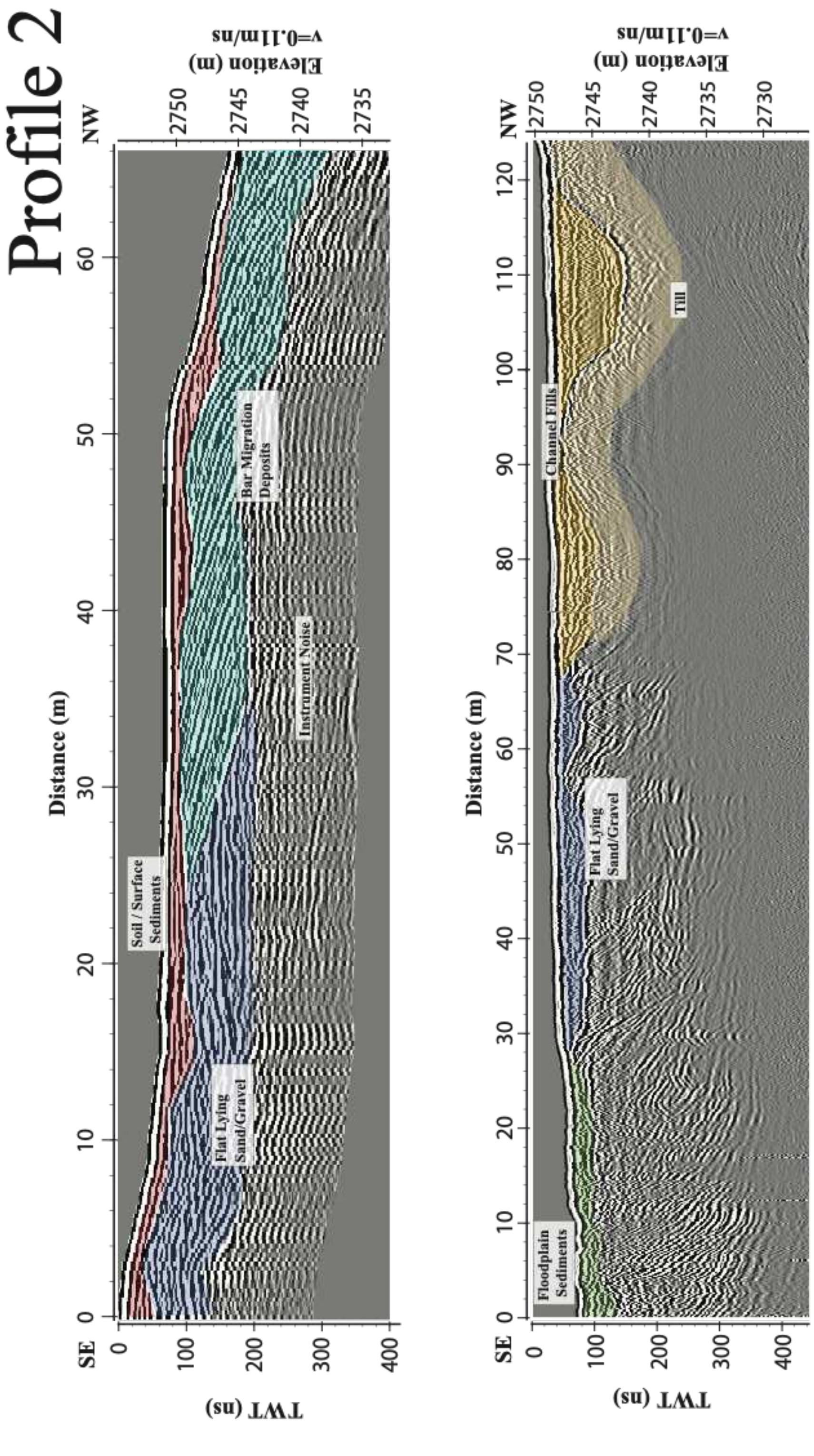


Figure E2: Second from upstream-most cross valley radargram (Profile 2). Cross sectional view is looking upstream. All radar facies are identified in this cross section. Lateral accretion deposits and flat lying gravels are the most common reflection pattern. Channel fills are clearly identified overlying till (bottom right).

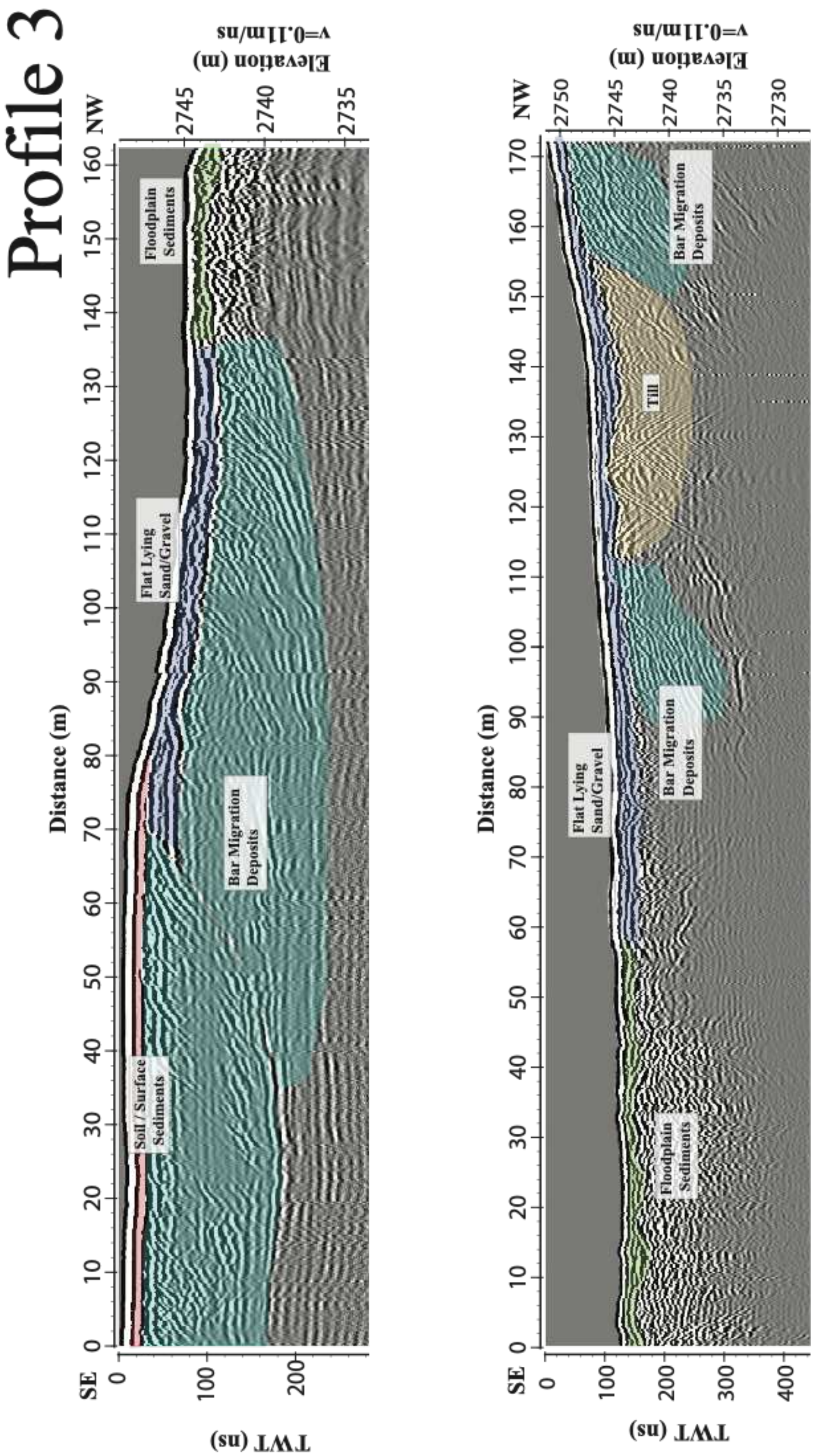


Figure E3: Third from upstream-most cross valley radargram (Profile 3). Cross sectional view is looking upstream. Dipping reflectors are most common in this cross valley radargram and appear to be both concave up and concave down in the upper panel. Dipping reflectors appear to converge at a strong horizontal reflector at depth.

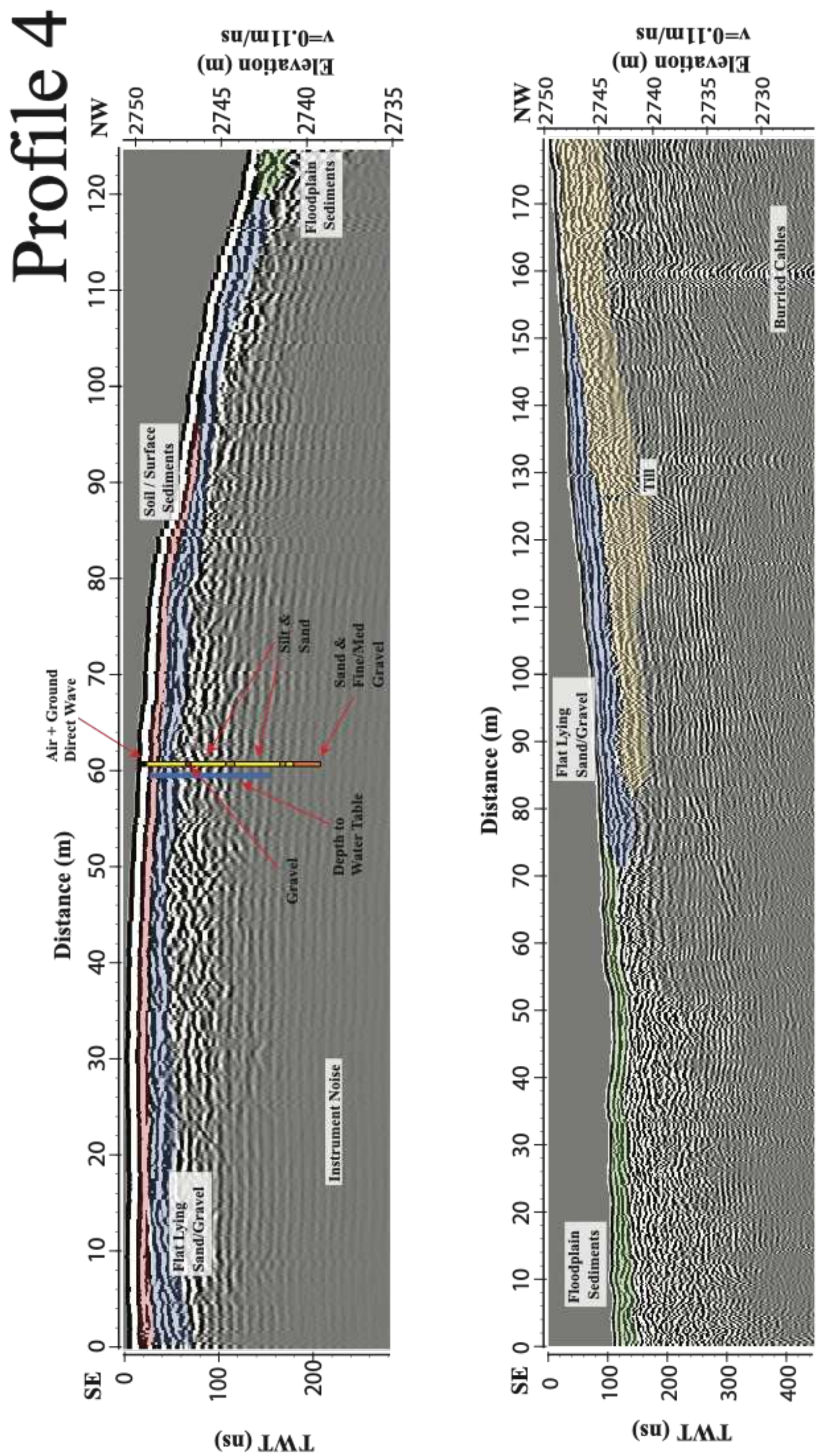


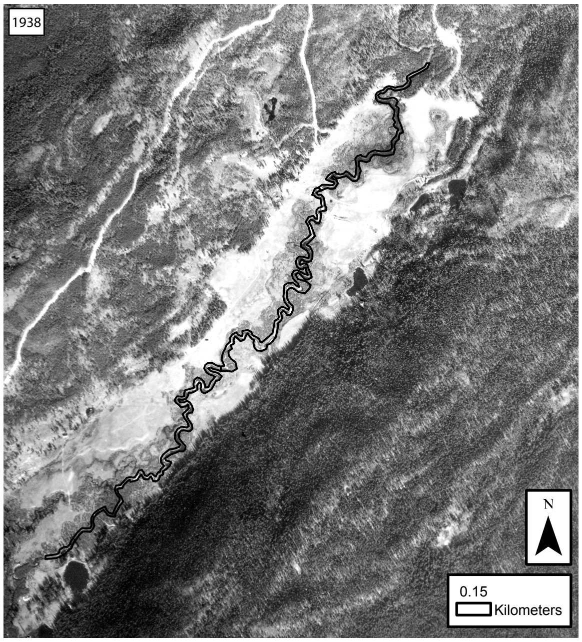
Figure E4: Fourth from upstream-most cross valley radargram (Profile 4). Cross sectional view is looking upstream. Till and vertical accretion deposits (on the floodplain and fluvial terrace) are most common facies in this radargram. The upper panel shows significant ringing at depth, obscuring signal. Facies interpretations are correlated with a simplified stratigraphic column from well MW2 (top left).

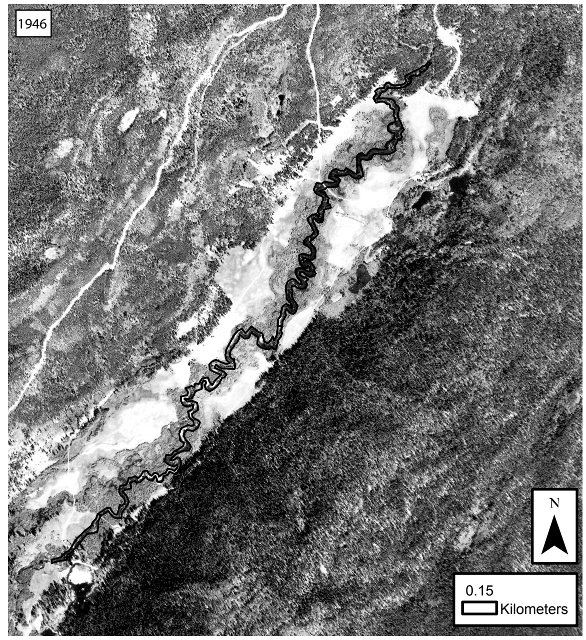
APPENDIX F

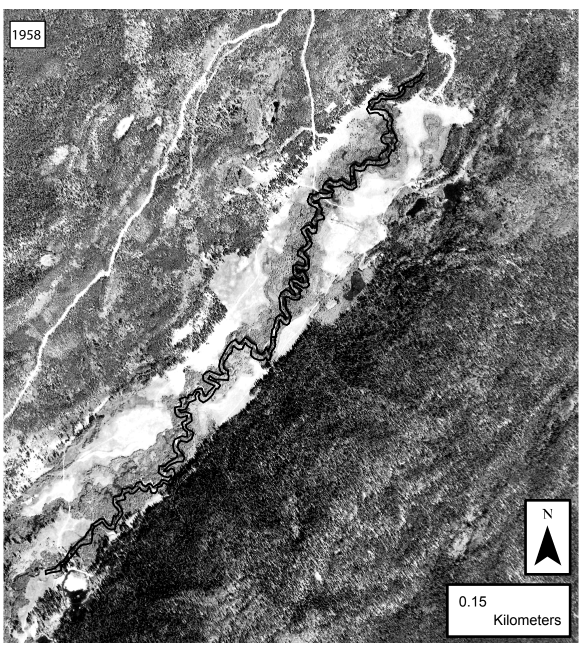
Table F1: Radiocarbon data tables provided from the DirectAMS laboratory in Washington State. The upper two rows of the table are samples submitted in spring 2020, the lower rows for samples submitted in summer 2020. Radiocarbon age and error were used to calibrate ages into calendar years before present.

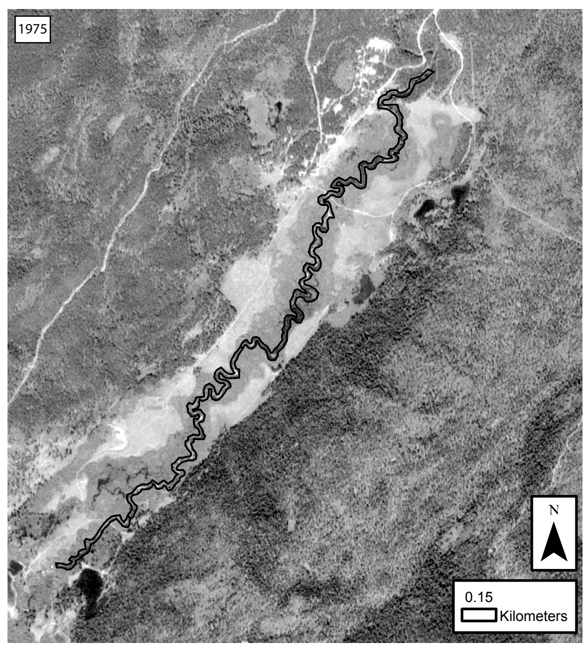
DirectAMS Code	Submitter ID	Sample Type	Fraction of Modern		Radiocarbon Age	
			pMC	1σ Error	BP	1σ Error
D-AMS 037842	MC_MW1_12/14	sediment (bulk)	17.80	0.13	13,865	59
D-AMS 037843	MC_MW2_24/26	sediment (bulk)	Insufficient carbon for analysis			
D-AMS 039502	MC_MW2_12/14	sediment (bulk)	Insufficient carbon for analysis			
D-AMS 039503	MC_MW2_16/18	sediment (bulk)	Insufficient carbon for analysis			
D-AMS 039503	MC_BP1_0.3-0.4	sediment (bulk)	41.93	0.17	6,982	33
D-AMS 039505	MC_BP1_0.8-0.9	sediment (bulk)	81.59	0.25	1,634	25
D-AMS 039506	MC_DSSW_0.95-1.03	sediment (bulk)	94.14	0.24	485	20
D-AMS 039507	LZD_FP_0.35	sediment (bulk)	83.41	0.22	1,457	21
D-AMS 039508	LZD_FP_1.1-1.2	sediment (bulk)	76.83	0.22	2,117	23

APPENDIX G


1938
N
0.15
Kilometers


1946
N
0.15
Kilometers


1958
N
0.15
Kilometers


1975
N
0.15
Kilometers

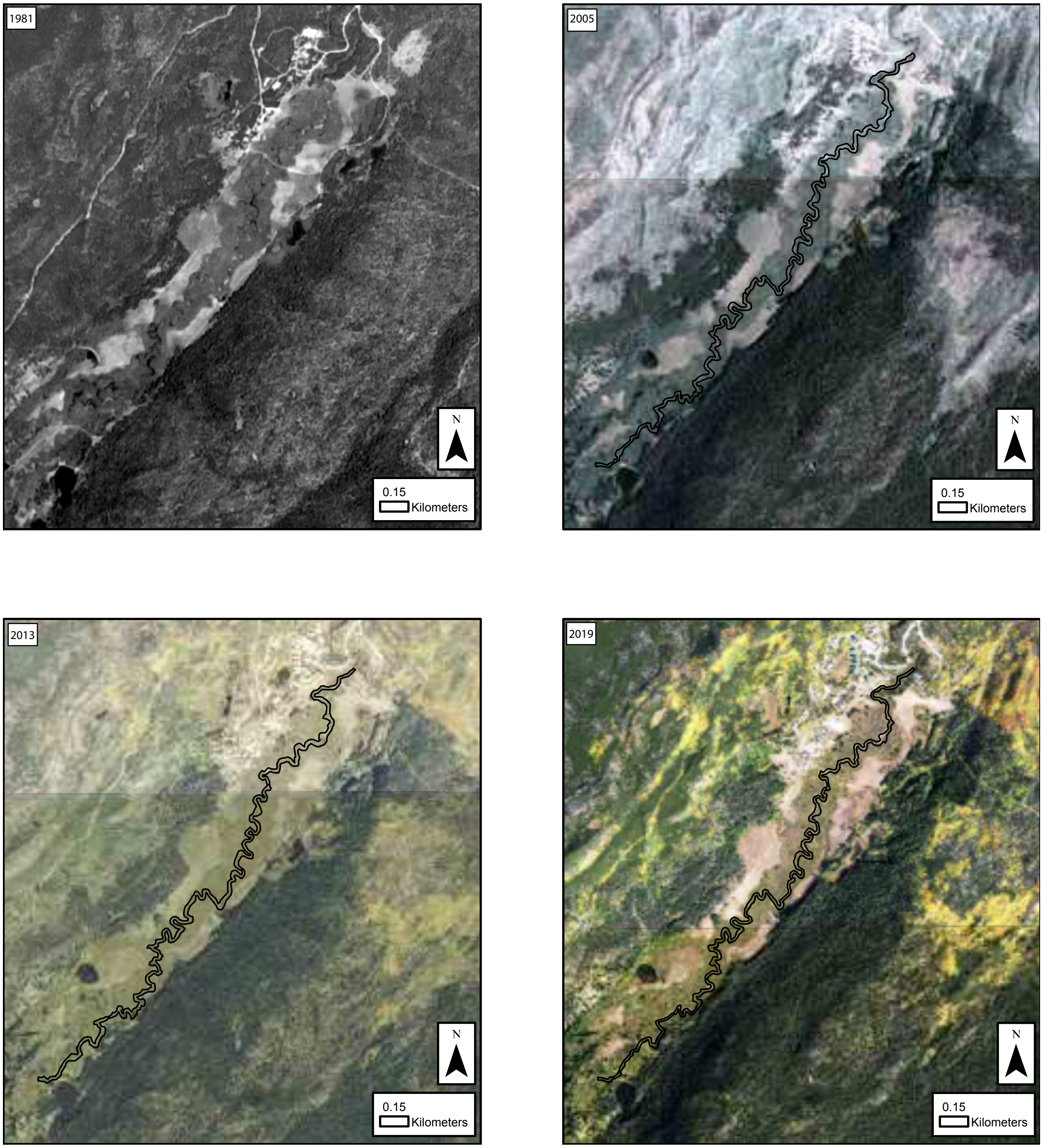


Figure G1: Orthorectified aerial images of the South Fork Valley from 1938–2019 (1938, 1946, 1958, 1975, 1981, 2005, 2013, 2019). All images are clipped to the same extent with the same scale. All images were used to digitize the bankfull channel of the South Fork at the Mountain Campus, except for 1981 due to poor image quality.