RECONSTRUCTING THE HOLOCENE AND ANTHROPOCENE STRATIGRAPHIC HISTORY IN FOURMILE CANYON, COLORADO

By: Maneh Kotikian

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Department of Geology and Geography
Mount Holyoke College
South Hadley, MA 01075

Advisor: Alan Werner
Committee: Alan Werner, Steve Dunn, Lauret Savoy
Department Chair: Steve Dunn

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ABSTRACT

Fourmile Canyon is located in the Front Range in Colorado with Fourmile Creek at its base that flows eastward from Niwot Ridge, discharging into Middle Boulder Creek. In 2013, erosion from a 50-year flood exposed numerous bank exposures revealing the canyon fill deposits (Henson, 2013). This provides an opportunity to document the stratigraphy and to interpret the canyon's history. The exposed stratigraphy includes deposits associated with floods, wild fires, slope erosion and human activity and reveals the sedimentation history and changes in patterns of canyon aggradation and degradation over time. Carbon-14 dating is used to determine the wild fire history and to provide limiting ages for other stratigraphic units. Five exposures were located using LiDAR data and field exploration. Each stratigraphic layer was described at the exposures and layers containing charcoal were sampled. Charcoal from two exposures was dated (Carbon-14 AMS) to provide an age control for the outcrops as well provide a fire reoccurrence interval. Field observations combined with grain size analysis and textural characterization were used to interpret the depositional setting of individual stratigraphic units classifying them as slope deposits, fluvial deposits, or Anthropocene deposits based on the size and shape of the grains. Surprisingly, the oldest canyon deposits date to the late Holocene (c. 3300 yr BP); evidence of older deposits was not found and suggests the older deposits, if they did exist,

were eroded prior to the late Holocene. The occurrence of late Holocene deposits in the canyon suggests a period of prolonged canyon aggradation presumably due to a drier climate. Most of the canyon fill represents slope deposits that interfinger with fluvial deposits. The pattern of flood deposition was determined based on overbank sand deposits in otherwise slope deposit dominated areas (Knox, 2000). The record of two floods appears in the stratigraphy at Woodmine and the record of one flood appears in the stratigraphy at Downstream Woodmine. Slope deposits with large clasts following a wildfire suggest an increased size in sediment deposited due to stronger soil water repellency from higher intensity fires (Benavides-Solorio and Lee, 2005), and dated charcoal layers in the stratigraphy indicates a recurrence interval for wildfires in the two localities dated (6 fires since ~3200 yr BP at the Beebee Site and 8 fires since ~2200 yr BP at the Woodmine exposure). By understanding the sedimentation patterns during the Holocene, the geologic processes and environmental history and changes can be reconstructed.

INTRODUCTION

The goal of this study is to characterize and interpret the canyon fill stratigraphy exposed by the 2013 Fourmile Canyon flood to reveal the processes that have led to canyon fill aggradation.

Fluvial deposits show how Fourmile Creek behaved and indicate flood occurrences in the canyon. Charcoal layers are dated and used to provide an age control for the canyon fill and to reconstruct the fire history at two exposures. The Anthropocene impact on the canyon will be analyzed from the stratigraphy to find changes in aggradation, flood occurrences and fire history as humans change the environment.

This study reconstructs the available stratigraphic history of Fourmile Canyon at five exposures studied along Fourmile Creek to determine changes in sediment aggradation and flood and fire occurrences with respect to changes in the environment.

BACKGROUND

Location

Fourmile Creek in Fourmile Canyon begins at Niwot Ridge near the Continental Divide, on the eastern slopes of the Rocky Mountains. Fourmile Canyon is located in the Front Range near the cities of Nederland and Boulder, CO (Fig. 1). Fourmile Creek flows eastward and discharges into Middle Boulder Creek at the junction of Country Road 118 and State Highway 119, west of the city of Boulder. Fourmile Canyon's water shed is 63 km^2 and has steep slopes of an average of 20°. The elevation of the start of the canyon at Niwot Ridge is 2900 m and drops to 1600m at the junction of Fourmile Creek and Middle Boulder Creek (Graham et al., 2012).

Stream

Fourmile Creek has multiple tributaries, the main ones including Banana Gulch, Emerson Gulch, and Gold Run Creek. The discharge of Fourmile Creek is heavily influenced by seasonal snowmelt and intense summer thunderstorms (Fig. 2). Flash floods are common in this region. The average gradient of the creek is 37m per km (Graham et al., 2012; Purinton, 2013). The discharge is highest during March through July due to snowpack melt waters upstream and it is typical for discharge to spike throughout the summer months from June to September due to flash floods (Fig. 2).

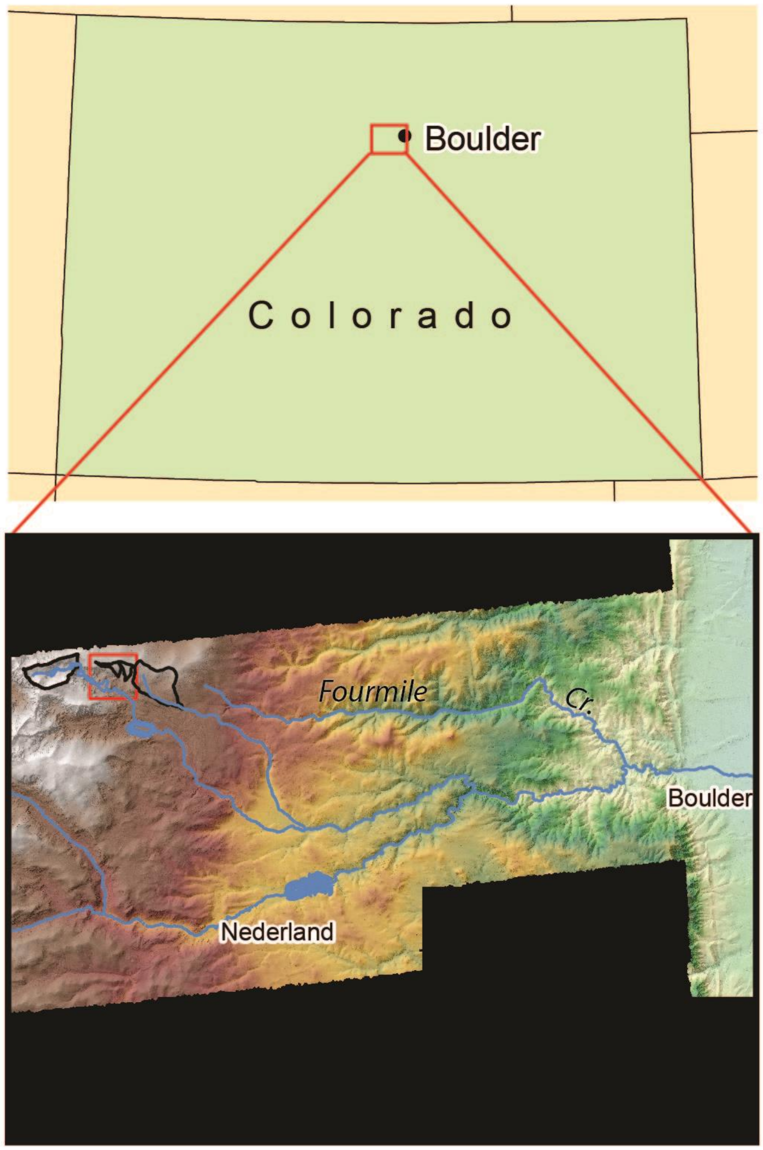


Figure 1: Topographic relief map of Fourmile Creek within Fourmile Canyon with respect to Nederland and Boulder and the location in Colorado (Image from: D. Dethier).

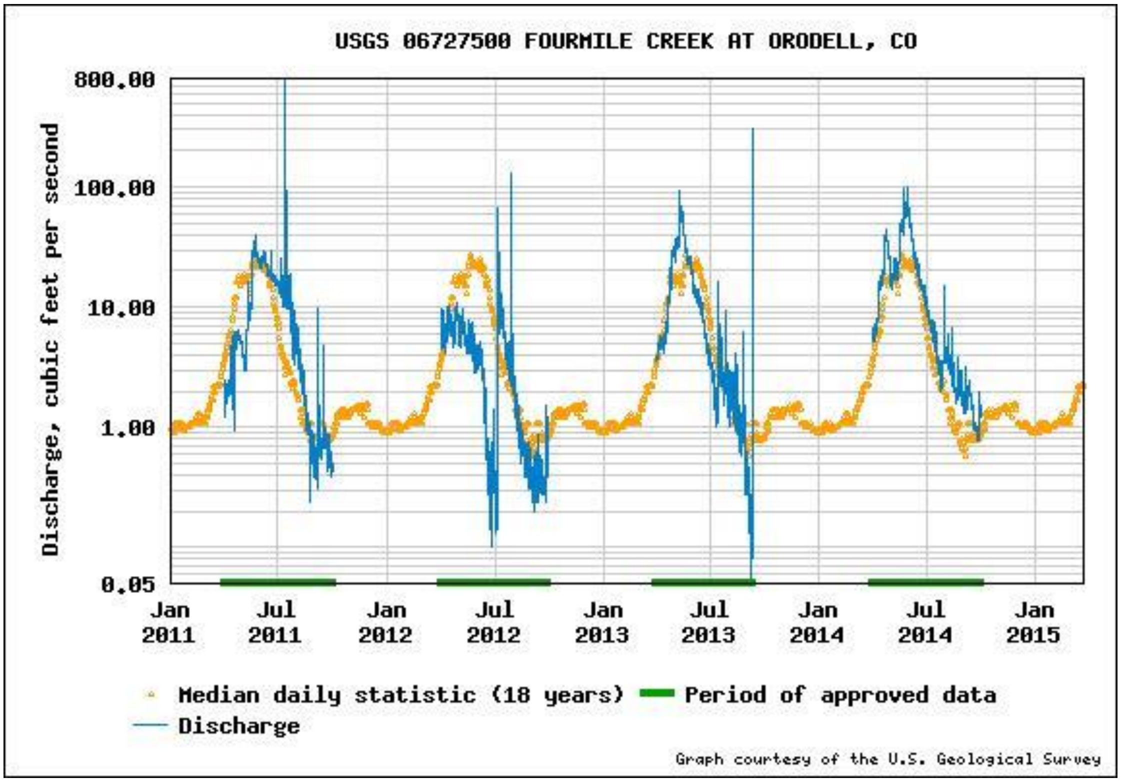


Figure 2: Hydrograph of Fourmile Creek at Orodell, CO, showing fluctuations in discharge (blue), and the mean daily statistic (yellow) from 2011 to 2015. The hydrograph was washed away during the 2013 flood (Graph from: USGS, 2015).

Climate and Vegetation

The climate in this region is classified as semi-arid with the majority of the vegetation consisting of coniferous forest between 1830 m and 3475 m elevation (Coe et al., 2014). At higher elevation near Niwot ridge, the land cover changes to alpine tundra above 3475m (Coe et al., 2014). Tree line at Niwot ridge occurs at 3345m elevation (NRLTES, 2015).There is a higher tree-density on the North facing slopes than the South facing slopes (Fig. 3) (Marr, 1961). North facing slopes are typically more densely vegetated and wetter due to less direct sunlight. South facing slopes are under direct sunlight and often have less tree cover and dryer soils (Shoshany, 2002).

Figure 3: This satellite photo shows the difference in vegetation cover on the north slope versus the south slope in Fourmile Canyon (Image from: Google Maps, 2015).

This region is impacted by the North American monsoon that occurs during the summer months from July to early September. The monsoon forms convective storms when moisture from the Gulf of Mexico moves into the southwestern United States. The average annual rainfall is 533mm per year (Murphy et al., 2000) with most precipitation falling as snow during the winter months. At Niwot ridge, the annual average precipitation is 930mm (NRLTERS, 2015).

During the middle Holocene, climate was warmer than it is today because the timberline was higher (Benedict et al., 2008; Madole, 2012). The timberline began to recede as the climate cooled around 4500 yr BP during Neoglaciation (Benedict et al., 2008). Warmer climate results in precipitation in the form of rain instead of snow therefore the cooling of climate resulted in precipitation in the form of snow during the winter months.

Geologic History and Structure

The Front Range formed during the Laramide orogeny (Dickinson et al. 1988). Orogenic uplift created the mountains due to regional compression from the Late Cretaceous to the early Tertiary (Dickinson et al. 1988). The canyons and ridges in the Front Range have been created by subsequent erosional processes (Murphy et al., 2000). The oldest rocks in the Front Range date to the middle Proterozoic. The bedrock in Fourmile Canyon consists of the Boulder Creek Granodiorite (Ebel et al., 2012). There have been three major phases of geologic history as described by Kellogg et al (2008).

Precambrian

The Colorado province, the core of the Front Range, is an Early Proterozoic Terrain that was formed during a long orogeny 1,790 Ma. The

Colorado province consists of quartz-feldspar gneiss, amphibolite, biotite schist, and partial-melt migmatite (Kellogg et al., 2008). These Proterozoic rocks in the Front Range are complexly folded and interlayered and are interpreted to be marine sediments and mafic and felsic volcanic rocks that were metamorphosed to amphibolite grade as well as calc-alkaline granitic rock intrusions (Kellogg et al., 2008). These rocks are divided by multiple discontinuous en echelon shear zones that trend northeast.

Paleozoic and Pre-Laramide Mesozoic

During the early Paleozoic Era, shallow seas existed over the region which deposited thin continental-shelf sequences of quartz-rich sands and carbonates. Uplift of the Ancestral Front Range caused the erosion of the lower Paleozoic sedimentary cover (Kellogg et al., 2008). As a result, no sedimentary strata older than Pennsylvanian is preserved. The Front Range continued to erode and by the Middle Jurassic it was eroded to a low relief mountain range (Kellogg et al., 2008). In the early Cretaceous, over 2 km of marine shale and small amounts of sandstone and limestone were deposited during transgressive events of the western interior seaway over the entire Front Range (Kellogg et al., 2008).

Laramide Orogeny

At the end of the Cretaceous Period (69 Ma), the western interior seaway began to recede and the Rocky Mountains rose from the sea eroding over 2 km of upper Paleozoic and Mesozoic sedimentary rock from the core of the range. The Laramide orogeny marked a 20-m.y. period of crustal compression, uplift, faulting and igneous activity (Kellogg et al., 2008).

Colorado Mineral Belt

The Colorado Mineral Belt runs from the Four Corners region to the Front Range and is a belt of Laramide intrusives with associated gold, silver, copper, and molybdenite deposits. The belt follows a northeast trending ductile shear zones which have been interpreted to be older zones of weakness. The gold mined in Fourmile Canyon comes from a hydrothermal system of gold-bearing pyrite-quartz veins along this belt (Kellogg et al., 2008).

Soils

Canyon slopes consist of oxidized granitic rock, syenite, schist, and felsic intrusive rocks that now comprise the saprolite, thin soils and grus (Dethier and Bove, 2011; Kellogg et al., 2008). The Boulder Creek Granodiorite, the dominant basement rock exposed in Fourmile Canyon, weathers into sandy loam soils: Lamellic and Typic Haplustalf type (Ebel et al., 2012). Where slopes are <30°, a thin cover of colluvial debris covers the slopes and local bedrock outcrops exist (Schildgen, 2002). The debris is often grussified and extremely weathered.

Forest fires are common in the Front Range and recent studies have shown that fire severity influences soil water repellency and increases sediment yield in catchments (Benavides-Solorio and Lee, 2005; Morris and Moses 1987). When water repellency is high, rainfall induced runoff is capable of mobilizing larger clasts than usual increasing erosion in the canyon and aggradation in the canyon fill (Benavides-Solorio and Lee, 2005).

Climate Change

Following full glacial conditions 21000-18000 yr BP, the Front Range was warmer and dryer during the Holocene climatic optimum until Neoglaciation between 5000 yr BP and 3000 yr BP (Benedict 1973). Colder climate, glacial advance and greater snow cover occurred in the region 1505 yr BP to 955 yr BP, followed by high river discharges due to snowpack meltwater (Benedict, 1973). Fourmile Canyon is not a glacially eroded area and glacial meltwater did not flow down the canyon, however, glaciers did exist in different regions of the larger watershed Fourmile is within. Based on preserved timber found in a melting ice patch in the Front Range above the tree line by Benedict et al. (2008), it appears that Neoglaciation began affecting the trees causing them to die around 4200 cal. yr BP due to the colder climate (Benedict et al., 2008). This cooling lowered the alpine tree line to where it is today (Benedict et al., 2008).

Anthropocene History

Mining

Placer gold mining in Fourmile Canyon began in 1859 and marked a sharp increase in human impact and landscape change associated with the Anthropocene. Extensive placer mining involved excavating creek deposits for gold by separating sediment from the deposit to sift for gold (Fig. 4). Entire creek banks were demolished during these processes and large amounts of sediment was displaced. The shift to vein-hosted gold mining in 1860 resulted in over 200 companies building mills to process ore in the surrounding counties (BCPOS, 2012). The discovery of rare, tellurium gold led to more mining operations, over 50 just at Gold Hill, with eight mills for processing in Fourmile Canyon (BCPOS, 2012). The impact of the mining history can be seen today with large mine shafts, exploration pits and waste piles dotting the hillslopes of the Fourmile watershed and tailings pond sediment at historic mill sites along Fourmile Creek (Fig. 5).

Figure 4: Photograph of placer mining in Fourmile Canyon c. 1860 (Image from: D. Dethier).

Figure 5: Photograph of mine tailings pond deposit at Salina, a historic mill site in Fourmile Canyon. Person for scale (Image from: W. Ouimet).

Railroad

Multiple times between 1870 and 1920, a canyon railroad existed within Fourmile Canyon to transport recovered ore. The railroad had to be re-built when floods destroyed parts of the tracks. Following the flood in 1894, almost the entirety of the railroad was destroyed and needed to be rebuilt. The railroad had 65 bridges and climbed the canyon at an average grade of 190 feet per mile (BCPOS 2012). The blocks used to build the railroad bridges can easily be located today. The train carried an average of 100 tons of ore per day to the mills in Boulder and Denver during the mining boom (BCPOS 2012). The railroad was built on top of a distinctive road-bed fill to flatten the railway surface adjacent to Fourmile Creek (Fig. 6).

Figure 6: Example of railroad fill (boulders in stratigraphy) and grade (flat area where the boat is parked) at Copper Rock exposure. Author is photographed recording the stratigraphy of the exposure sitting on flood deposits from the 2013 Fourmile Canyon flood (Image from: W. Ouimet).

Fires

Wildfires are common along the semi-arid Front Range. Multiple fires have burned parts of Fourmile Canyon since the mining boom. Large fires do not occur frequently in this area because of the ability of firefighters to gain control over fires quickly. Humans and lightning are the main causes of fire. Fourmile Canyon experienced a large fire in September 2010, which burned for eleven days until it was contained consuming 169 houses (Fig. 7) (BCPOS, 2012). This was the largest fire in the canyon's recorded history burning a total of 16.5 km^2 (23% of the Fourmile watershed) (Purinton, 2013).

Floods

A major five-day rainfall event occurred in September 2013 causing a 50-year flood (Henson, 2013). This rain event caused 1,138 debris flows in the Front Range in a 3,430 km^2 area and heavy erosion in the canyons, including Fourmile (Coe et al., 2014). Prior to this flood, notable floods occurred in 1883, 1890, 1891, 1894, 1895, 1896, 1909, 1919 and 1969 (BCPOS, 2012). Of these floods, the most severe flood was the one in 1894 which washed out the railroad, roadways, and homes after 60 hours of rain (BCPOS, 2012). The 2013 flood's impact can be seen in the canyon with numerous cut banks as well as areas where sediment load was deposited (Fig. 8). Flash floods are common in the canyon and generally occur during the summer months during the monsoon season.

Figure 7: Photograph taken in the field of 2010 Fourmile Canyon burn area.

Figure 8: Flood deposit near Beebee Site. The high water mark is apparent in the tree bark. The large boulders closest to the water are placed by residents to provide bank stability. Behind these boulders is the flood deposit with lots of sand and boulders.

Previous Work

Slope Deposits

Slope deposits include colluvium and alluvium that are deposited on the canyon slopes down to the canyon floor primarily by sheetwash and sometimes small, temporary channels (Madole, 2012). Slope deposits typically have angular grains and are generally not as well sorted as fluvial deposits. Sediment accumulation is indicative of the extent of erosion on the slopes (Leopold and Völkel, 2007).

Fluvial Deposits

Fluvial deposits are found on the canyon floor consisting of sediment reworked by creek water. Fluvial deposits tend to be better sorted than slope deposits and contain more rounded grains and imbricated clasts. Wetlands and bog environments where water is abundant but is moving slow enough to deposit silt leave a depositional layer that is dark in color due to abundant organic material and contains mostly fine grains (Madole, 2012).

Fluvial Energy and Grain Size

High peak flows result in the deposition of large clasts and the suspension of smaller grains in the channel. Large clasts and gravel with an abundance of finer-grained material indicate higher peak flows compared to places that have finer grained deposits (Madole, 2012). Low stream discharge results in the deposition of finer grains. Extremely low stream discharge are found in wetlands where the peak flow is low enough to deposit silt and clay.

Climate and Fluvial Energy

Madole (2012) interpreted gravel deposition in the Roaring River Valley in the Front Range (almost 45 km to the north of Fourmile Canyon) to be a result of increased fluvial energy lasting from 3800-2450 yr ago and another interval of increased fluvial energy from 1630-1200 yr ago which was less intense than the first. The first interval of increased fluvial energy occurred during regional Neoglacial cooling. Madole (2012) concluded that if a creek discharge depends on snowmelt, as the climate warms, the snowpack will decrease causing finer grains to be deposited which will in turn be deposited especially where the stream gradient is flatter (Madole, 2012; Benedict et al., 2008).

Slope Deposit Aggradation and Climate

Slope deposits are transported to the canyon floor primarily by sheetwash from rainfall events. Neoglacial cooling resulted in precipitation shifting from rain-dominated to snow-dominated 3500 yr ago (Benedict et al., 2008; Anderson, 2011; Madole, 2012). Although snow is now the predominant form of precipitation, the area still experiences intense summer thunderstorms which produce large, short-lived, rainstorms causing slope deposits to accumulate on the canyon floor. A wet climate is necessary to move colluvium in substantial quantities (Madole, 2012); however, a field study by Benavides-Solorio (2003) observed that when soil water repellency is high (after a forest fire) indicating hyper-dry soils, it will induce a hydrophobic effect resulting in increased levels of runoff capable of aggrading more sediment in the canyon. Hyper-dry conditions increase runoff by greatly restricting rainwater infiltration into the ground (Ebel et al., 2012).

Fluvial Deposition and Climate

Snowmelt is the principal source of water in Fourmile Canyon and a wetter and colder climate has been related to increased snowmelt in the creek (Madole, 2012). Where boulder and cobble supported fluvial gravel is present indicates high peak flow due to the lack of smaller sized sediment. As discharge increases, larger sediment is transported resulting in the deposition of only larger clasts (Madole, 2012). Changes in the grain size of fluvial deposits indicate changes in peak flow. Fluvial deposition can also be in the form of an overbank deposit by floods of large magnitudes that result from long duration rainfall events (Knox, 2000).

Degradation is caused by an increase in fluvial energy capable of eroding the canyon fill. Fluvial energy is determined by stream discharge and gradient. If discharge increases, fluvial energy also increases allowing the creek to carry a larger sediment load than usual. Likewise, if the creek gradient increases, fluvial energy will also increase. However, if sediment of different sizes are found in the same place, it indicates changes in fluvial energy because the energy levels are controlled by discharge and not by change in creek gradient (Madole, 2012).

Aggradation and Degradation during the Anthropocene

The Anthropocene is defined as the start of modern human settlement. Sediment production is accelerated during the Anthropocene due to disturbance of the geologic processes occurring such as land clearance, hydraulic mining and road construction (James, 2013). Degradation is likewise accelerated by Anthropogenic impact due to increased surface runoff increasing overall fluvial energy.

METHODS

Field Methods

Exposure Locations

Exposures were located by following Fourmile Creek on foot and by driving alongside it looking for cut banks. LIDAR images were also used to identify large cut banks exposed by the 2013 flood. Many small erosion features were observed, however five were found that were large enough to warrant study. Characteristics of the variations in stratigraphy in the exposures held evidence of environmental and geological changes in the canyon and were recorded to link to other exposures.

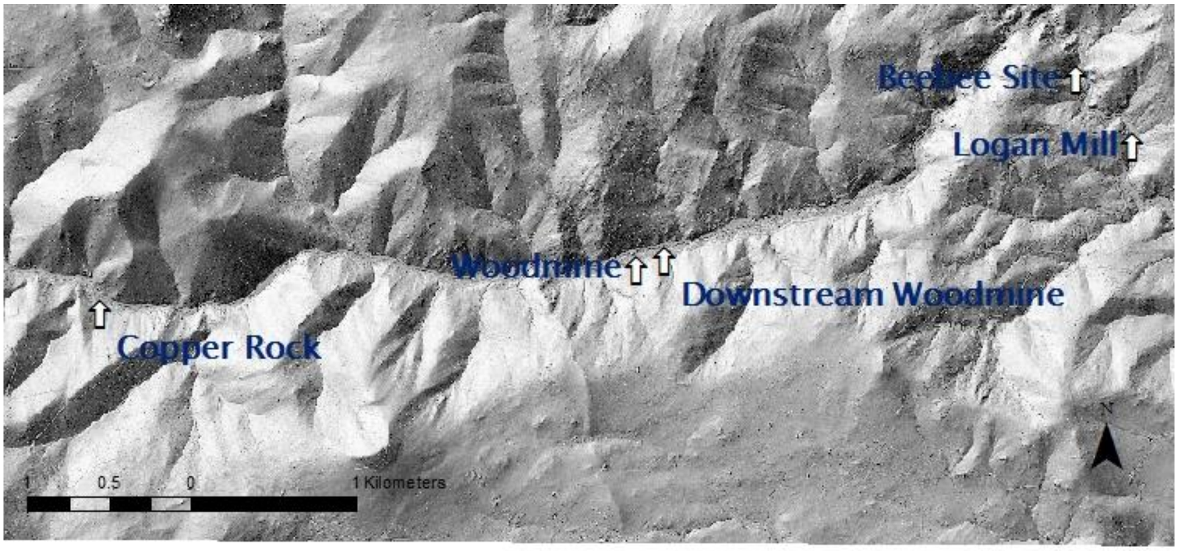


Figure 9: LiDAR map of exposures. Creek flows from west to east

Description of Exposures

Once an exposure was identified, its location was documented and the face was cleaned using shovels and trowels to neatly show all the stratigraphy. Thicknesses and descriptions were recorded of each stratigraphic layer and photographs of the column and exposure were taken. Descriptions noted the color, size, and texture of the sediment as well as any other prominent observations.

Field Classification of Stratigraphy

Depositional environments were interpreted for most stratigraphic layers. Layers with mine tailings were obvious with orange, blue, gray and white layers of fine clay (Fig. 5). The “railroad layer” was also easy to characterize because of the residual debris (soot, charcoal, and coal) deposited. Brick pieces and at times, metal pegs holding the tracks in place can also be found in the railroad layers. If coal was in a dark sooty layer with charcoal, it was immediately characterized as a railroad deposit since coal does not occur naturally in this region. The railroad fill lying below the railroad layer was characterized by having large blocks of angular boulders stacked and filled with sediment (Fig. 6). Its structure is recognizably man-made. Layers containing small angular pieces of granite were characterized as gruss and are interpreted to be of hillslope origin. Charcoal layers had ash and charcoal pieces in them. They were often on the order of centimeters wide and looked black in color and are interpreted to represent deposition after a forest fire at the location deposited. Fluival deposits contained imbricated clasts and rounded grains.

Sampling of Exposures

I focused primarily on collecting material from layers containing charcoal that could be dated in order to provide deposition ages. I also collected material that could help distinguish the depositional setting of the exposure. I sampled bottommost layers first and topmost layers were collected last. Layers containing charcoal were collected as well as some layers in between that appeared to have either a fluvial, alluvial or colluvial origins. In layers containing large cobbles and boulders, only the matrix was sampled and the presence of larger rocks were noted (Fig. 10).

Sample Collection

Charcoal fragments were individually dissected using a trowel and occasionally shovel to remove whole pieces. For charcoal layers, I focused on collecting the actual pieces and less on the collection of a representative matrix. The other stratigraphic layers whose origin was unknown were sampled using a trowel and shovel and put in sample bags. Stratigraphic layers of known depositional setting were collected in the same way to be compared to the samples of unknown depositional setting. Sample bags were filled based on availability of sediment and each sample weighs between 50 and 800 grams.

Figure 10: The author recording the stratigraphy at the Logan Mill 2013 flood deposit (Image from: W. Ouimet).

Lab Methods

Grain Size Analysis

Grain size analysis was done by dry sieving each sample collected. Sieve sizes used are 16 mm, 4mm, 2mm, 1.18mm, 0.5mm, 0.25mm, 0.063mm and the bottom pan. These sizes were chosen using Folk's method for grain size analysis because they represent the major grain size boundaries (Folk, 1980). Each sample was weighed to the nearest one tenth of a gram on an Ohaus® pan balance before sieving. Once weighed, the samples were emptied into the sieve stack and were placed in a ro-tap for 10 minutes. After shaking the samples with the ro-tap, samples collected from each sieve were weighed and recorded.

Preparing Samples for Sieving

Some sediment had hardened into clumps and required disaggregation prior to sieving. Clumps were gently broken up using a mortar and pestle to disaggregate the particles. The pestle was tapped on the clumps to break them and was not used to smear the clumps against the walls of the mortar. Extremely cemented samples were dampened with water to break apart the pieces and then slowly dried at 60 degrees Celsius while being constantly monitored to ensure that the particles did not clump together again.

Sampling of Material for Carbon-dating

In order to remove charcoal to be dated, the sample was spread out into a large bowl before the sieving process and macroscopic charcoal pieces were picked out using tweezers. Most samples had abundant charcoal quantities not requiring further separation. Once all easily collectable charcoal was removed, the sample was sieved. Accelerator Mass Spectrometry (AMS) Carbon dating of 6 charcoal samples was done at Woods Hole Oceanographic Institute. Prior to dating, the outer surface of the charcoal was cleaned and then leached in heated acid-base-acid leaches to remove any modern surface contaminants. Carbon dioxide was produced from the charcoal sample and reacted with an Fe-catalyst to form graphite which was then pressed onto targets that were analyzed using AMS. The samples' calibrated calendar ages were obtained using the Fairbanks0107 conversion (NOSAMS, 2014).

Particle Size Statistics and Sample Comparison

Particle size statistics were calculated using GRADISTAT© version 8.0 (Blott and Pye, 2001). Values were calculated for grainsize distribution, mean, sorting, skewness, and kurtosis and graphs were made showing grain size distribution, gravel- sand- mud diagrams as well as a cumulative grain size plot (microns). Plots and values were calculated for each sample and all samples were plotted on a gravel- sand- mud ternary diagram.

A dissecting microscope was used to characterize the angularity and composition of each collected sample. Clast sphericity and angularity of a representative assortment of grains were classified using a particle shape chart (Fig. 11) (Miller and Henderson, 2010). This data was used in conjunction with the particle size statistics to determine depositional setting (fluvial or slope deposit) of sediment sampled.

Additional samples from the Woodmine exposure were provided by Will Ouimet for grain size and textural analysis. These samples were taken from stratigraphic layers that showed distinct changes in depositional setting (fluvial or slope deposit) (Fig. 12).

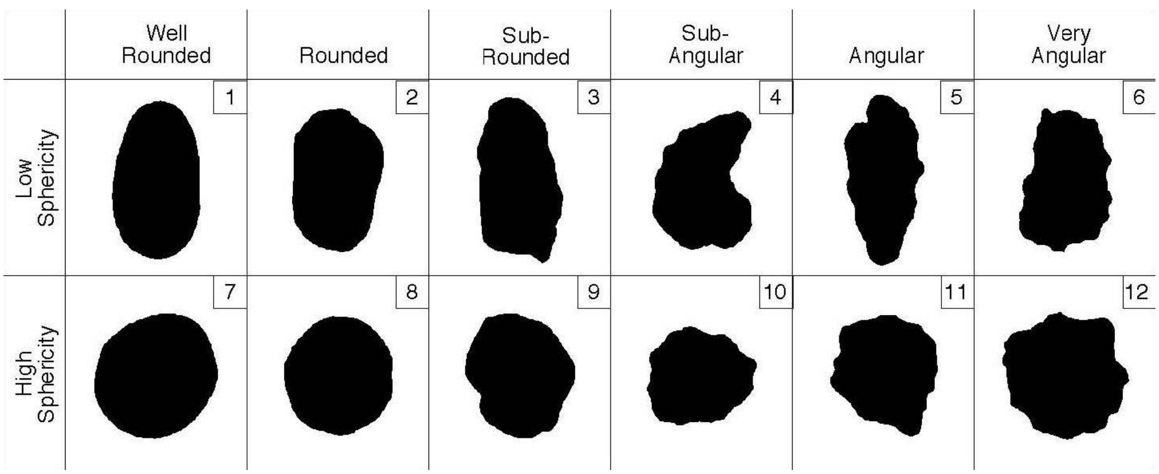


Figure 11: Clast sphericity and angularity chart (Image from: Miller and Henderson, 2010).

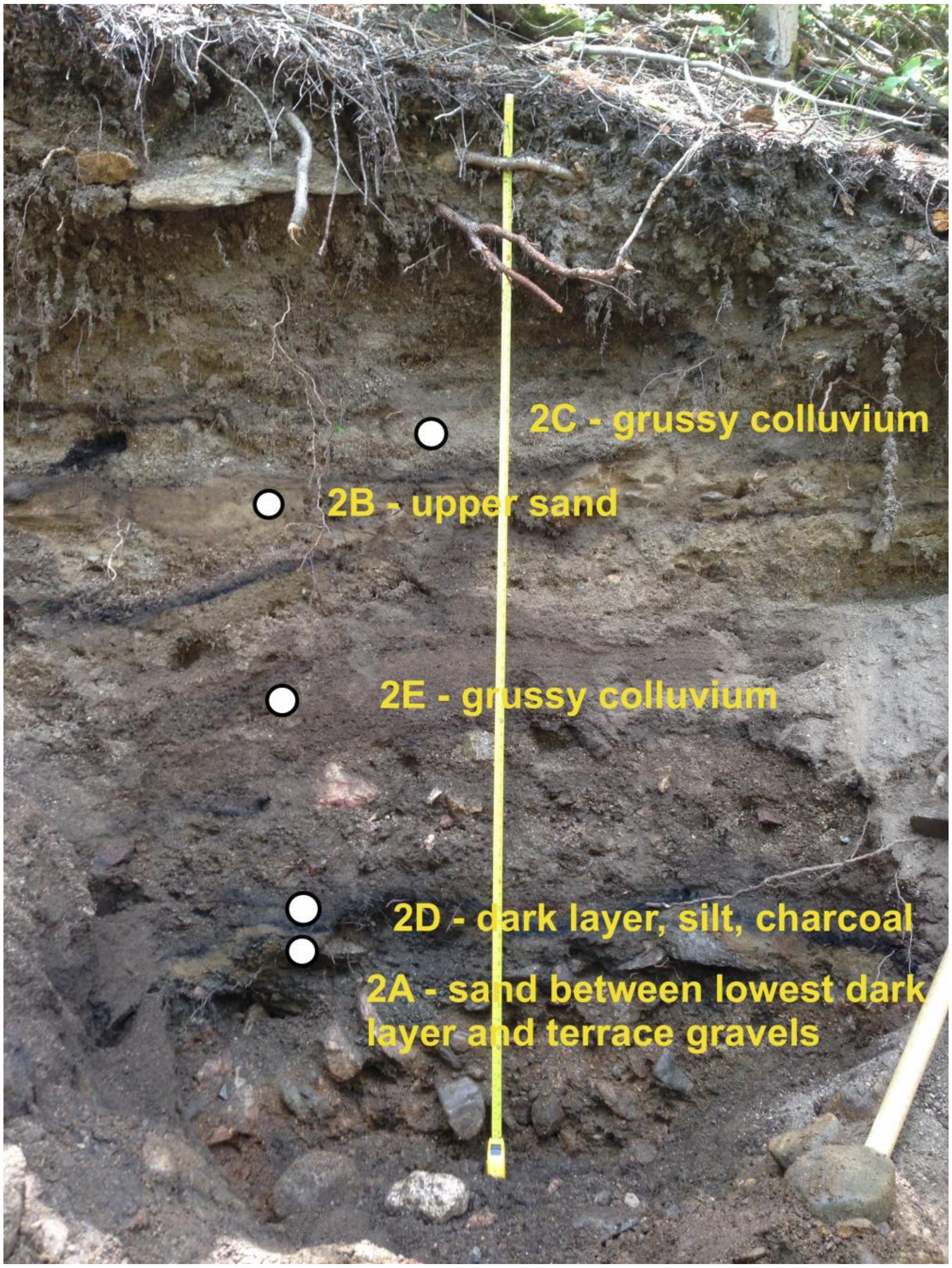


Figure 12: Location of W. Ouimet's samples in Woodmine exposure with descriptions (Image from: W. Ouimet).

RESULTS

Exposure Stratigraphy

Sampling sites are spread along approximately 4 km of Fourmile Creek.

Woodmine

The Woodmine exposure (Fig. 9; Fig. 13) is located at the base of a hillslope and contains two main parts: the main face and the upper section (Fig. 14). The main face has a height of 200 cm and the upper section has a height of 400 cm. This exposure was revealed by the 2013 flood in Fourmile canyon. The railroad grade is in close proximity to the outcrop but the exposure does not have railroad coal or other man-made materials in the stratigraphy. The base of this outcrop has large clasts that are imbricated (up-canyon) and overlain by sand and multiple charcoal rich layers.

At the main face, layers containing charcoal occur at 162 cm (MK-14-03), 135 cm (MK-14-04), 80 cm (MK-14-05), and 51 cm (MK-14-06) below the surface of the ground (Fig. 13).

The upper section of this exposure contains four additional charcoal layers at depths of 123 cm (MK-14-07), 150 cm (MK-14-08), 140 cm (MK-14-09), and 90 cm (MK-14-10). Because MK-14-09 and MK-14-10 are located above MK-14-08, it can be inferred that they are in chronologic order and are therefore younger than MK-14-08. The stratigraphic layer MK-14-05 was collected from at the Main Face can be traced to the upper section's stratigraphy providing a clear connection between the two faces (Fig. 14).

Beebee Site

The Beebee site (Fig. 9) lies behind an abandoned house next to the property of Mr. Robert Beebee and is located at the base of a hillslope that was exposed by the 2013 flood (Fig. 9). The exposure is at the base of a slope with multiple charcoal layers and shows no sign of fluvial interactions. Coal pieces found at the top indicate recent deposition from the Anthropocene (Fig. 15). This exposure contained six charcoal layers at depths of 320 cm (MK-14-16), 260 cm (MK-14-17), 235 cm, 180 cm (MK-14-18), 140 cm, and 70-80 cm (MK-14-19) below the surface. Some charcoal layers are overlain by slope deposits with large clasts towards the contact of the charcoal (Fig. 15).

Copper Rock

The Copper Rock site is surrounded by slopes but is located in a wide, flat area of the canyon (Fig. 9). The 2013 flood created this exposure revealing the railroad fill with preserved stratigraphy below (Fig. 16). Beneath the railroad fill separated by 50 cm of sediment was a sand-rich deposit 30 cm thick that was dark in color from the organics and charcoal it contained (MK-14-21) and above it was a dark sand and mud deposit (MK-14-22). Charcoal was not dated from this exposure; however, the railroad fill indicates that the sediment below predates the Anthropocene. It is possible that the stratigraphy below the railroad fill has been altered by the addition of railroad fill above or has sediment missing due to the construction of the fill.

Downstream Woodmine

The Downstream Woodmine exposure (Fig. 9) contained clear evidence of human activity in the region. It contained both placer mine tailings as well as sediment from a tailings pond. Thirty centimeters beneath the mine tailings pond deposit was a gray, mud-rich charcoal deposit (MK-14-13) stratigraphically overlying a terrace with large imbricated clasts (Fig. 17). Placer mine tailings can be found behind the exposure and continue at the surface of the ground from the bank to the base of the slope up to the railroad-graded surface. This outcrop is representative of the strong anthropogenic impact in Fourmile Canyon (top 130 cm of sediment). Separating the mine tailings pond deposit and the placer mine tailing deposit is a 30cm thick sand deposit indicating a disturbance in human related sediment deposition.

Logan Mill

The Logan Mill site is a flood deposit from the 2013 flood (Fig. 9). The mound I dug into was 140 cm high and contained multiple distinct layers from the different stages of the 2013 flood. Sample MK-14-14 was collected from 110 cm below the surface and was taken from a section of darker sediment in the matrix of the layer. The layer had large (>25 cm) rocks with a fine-grained matrix (Fig. 18).

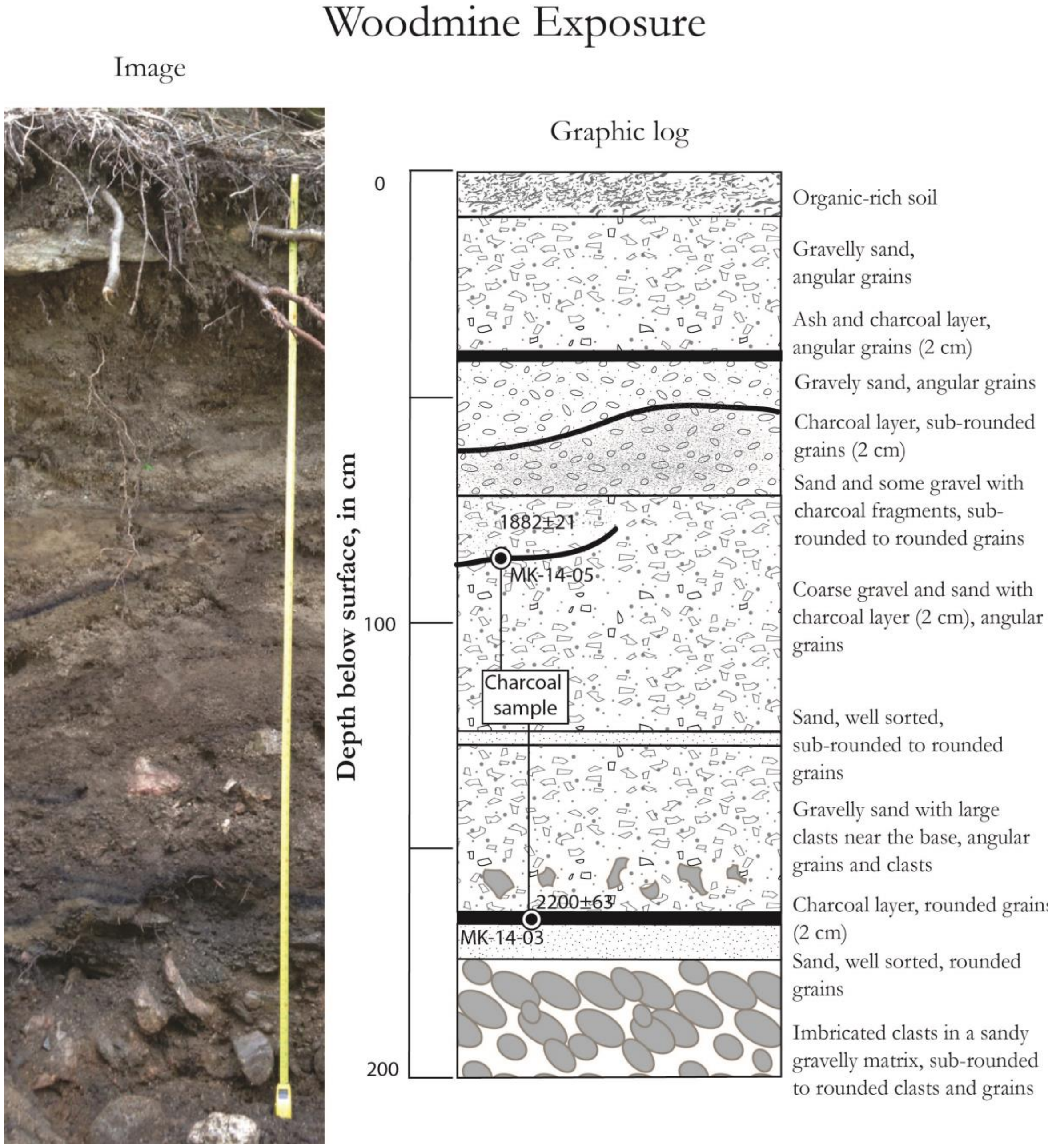


Figure 13: Graphic log with photo of the Woodmine exposure. Stratigraphic units and brief descriptions are provided. Charcoal dates are labeled from the unit they were collected from.

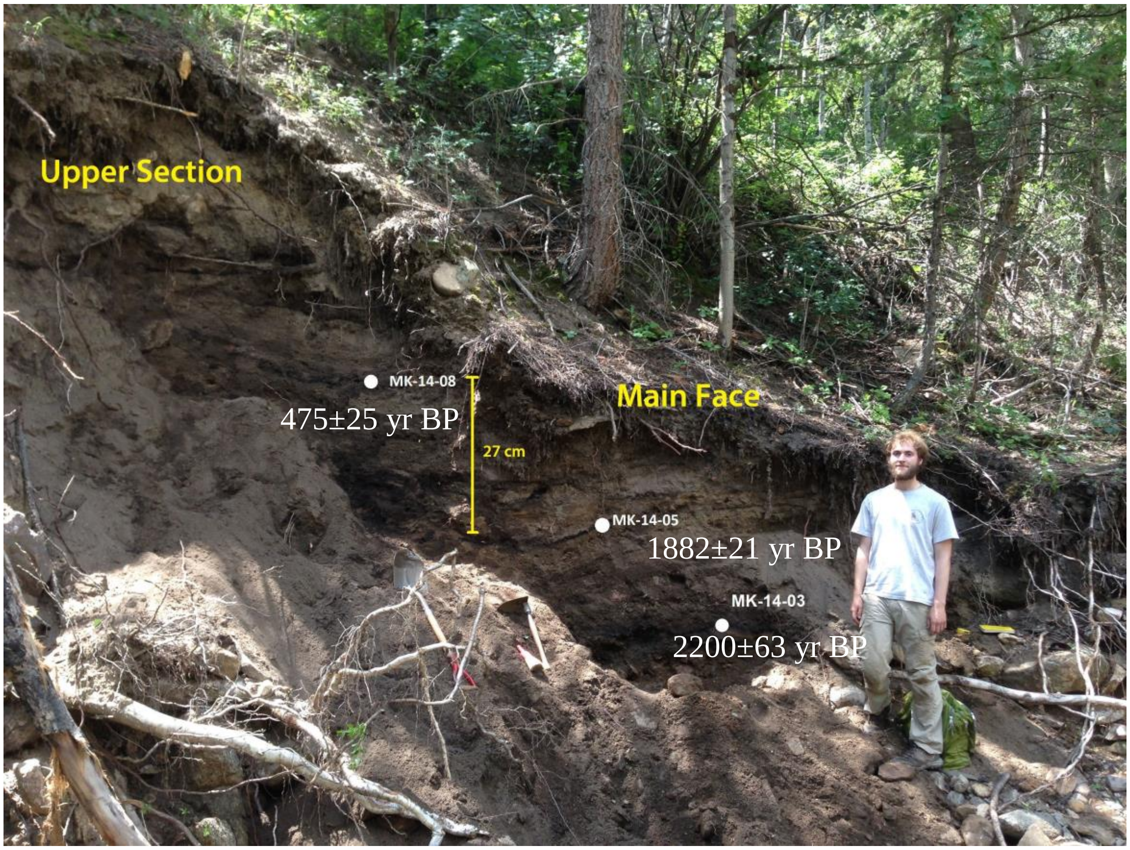


Figure 14: A photograph of the main face and upper section of the Woodmine exposure with person for scale.

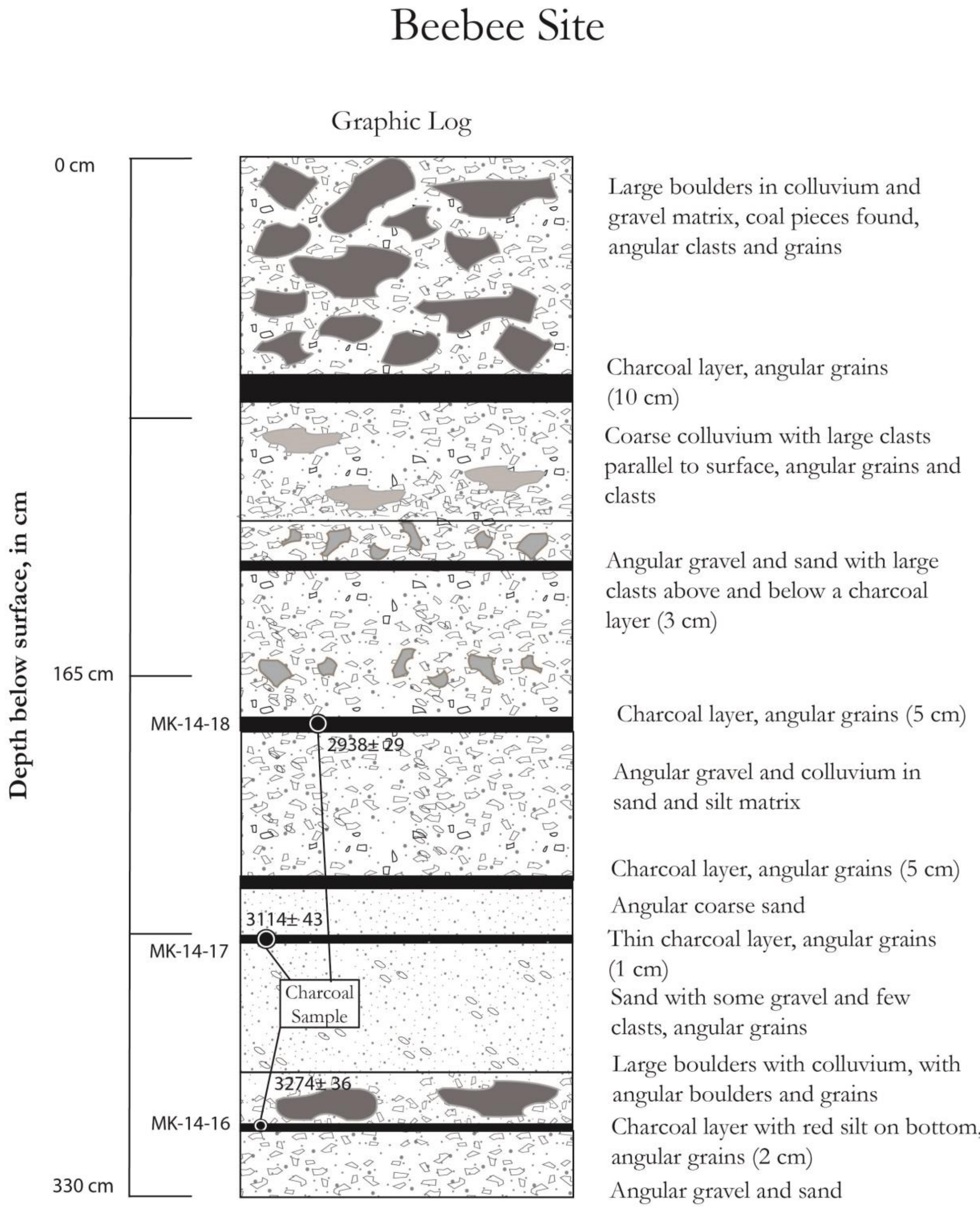


Figure 15: Graphic log of Beebee site with descriptions of stratigraphic units.

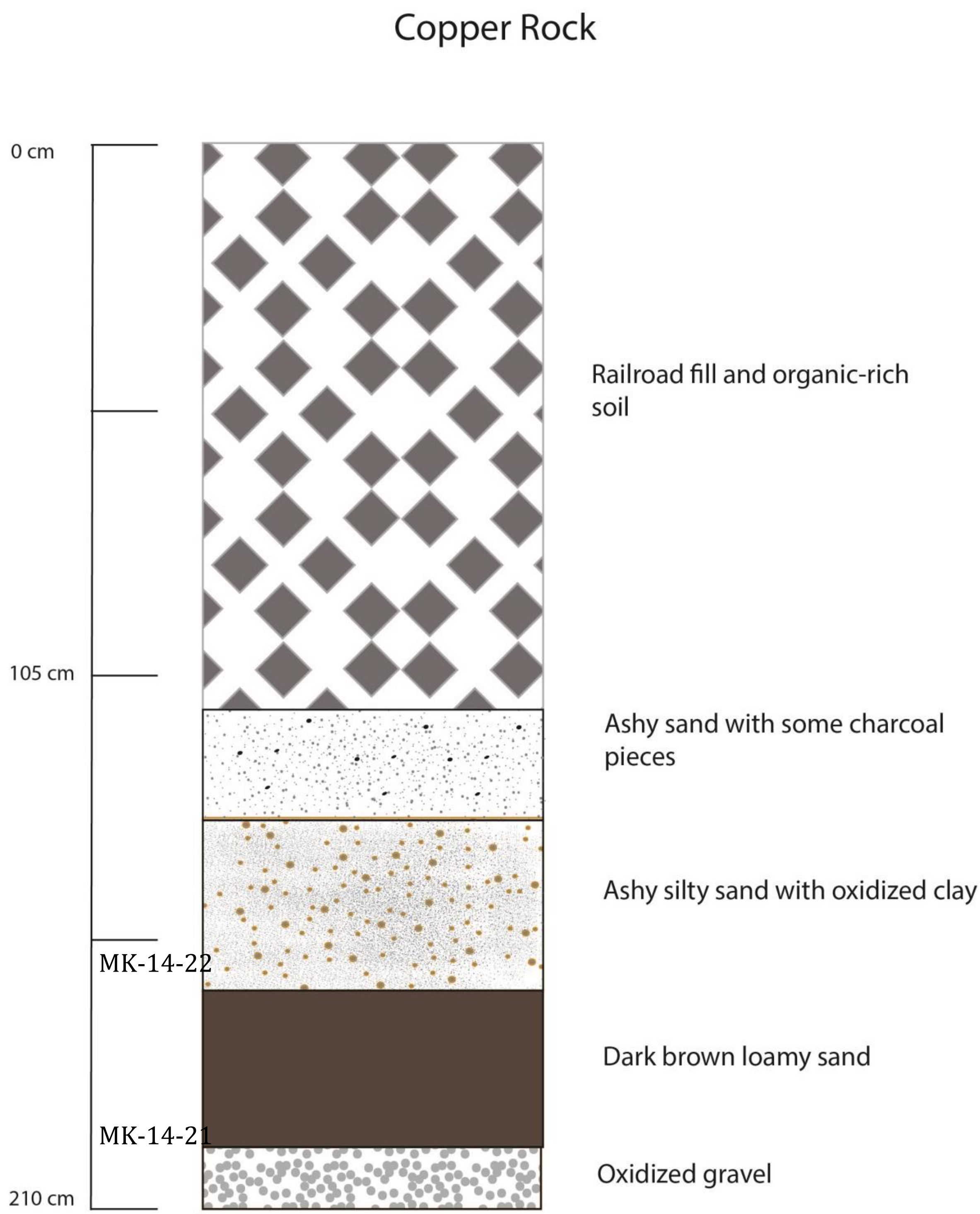
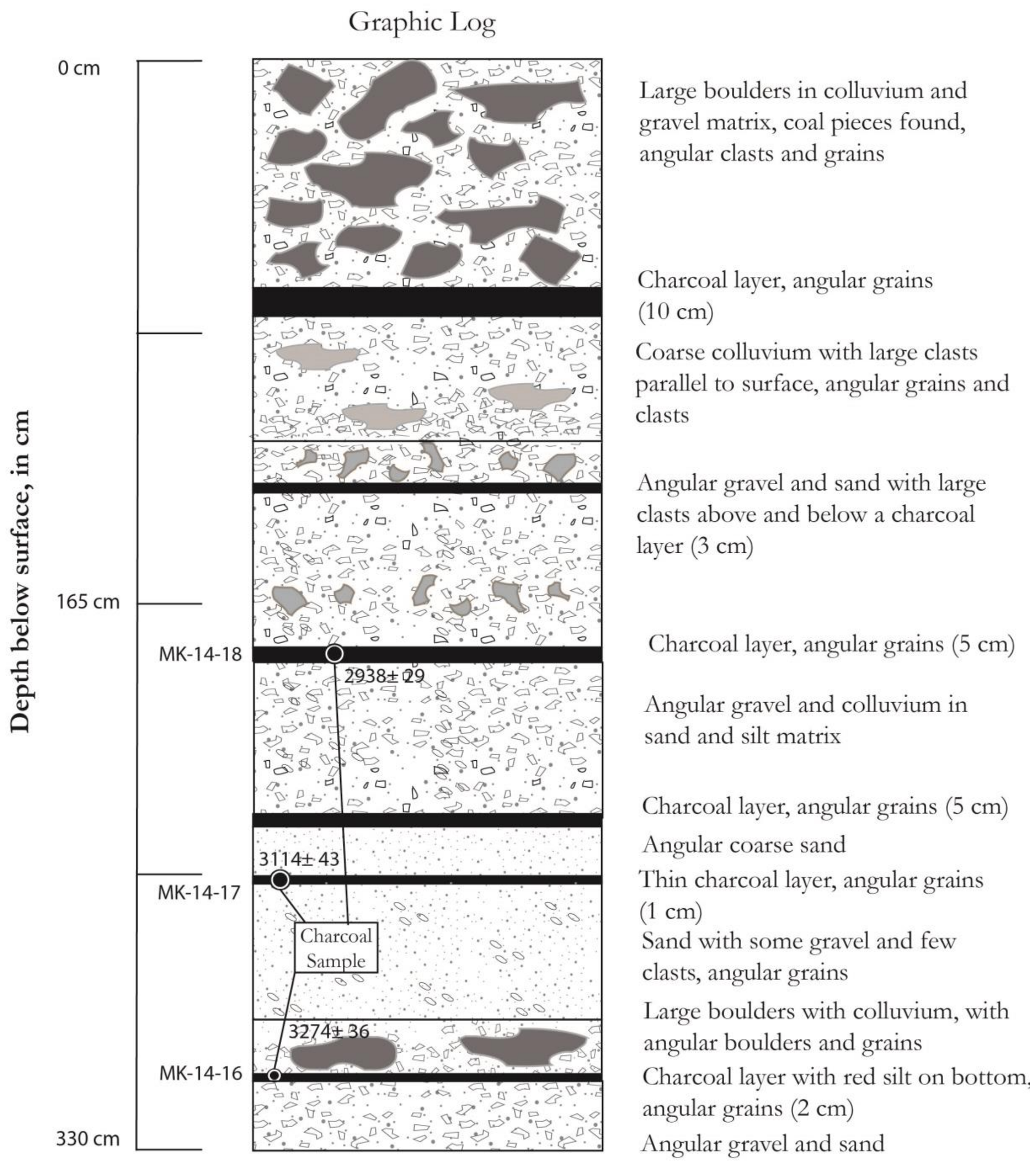


Figure 16: Graphic log of Copper Rock exposure with descriptions.

Beebee Site



Graphic Log
Depth below surface, in cm
0 cm
165 cm
330 cm
MK-14-18
2938± 29
MK-14-17
3114± 43
MK-14-16
3274± 36
Charcoal Sample
Large boulders in colluvium and gravel matrix, coal pieces found, angular clasts and grains
Charcoal layer, angular grains (10 cm)
Coarse colluvium with large clasts parallel to surface, angular grains and clasts
Angular gravel and sand with large clasts above and below a charcoal layer (3 cm)
Charcoal layer, angular grains (5 cm)
Angular gravel and colluvium in sand and silt matrix
Charcoal layer, angular grains (5 cm)
Angular coarse sand
Thin charcoal layer, angular grains (1 cm)
Sand with some gravel and few clasts, angular grains
Large boulders with colluvium, with angular boulders and grains
Charcoal layer with red silt on bottom, angular grains (2 cm)
Angular gravel and sand

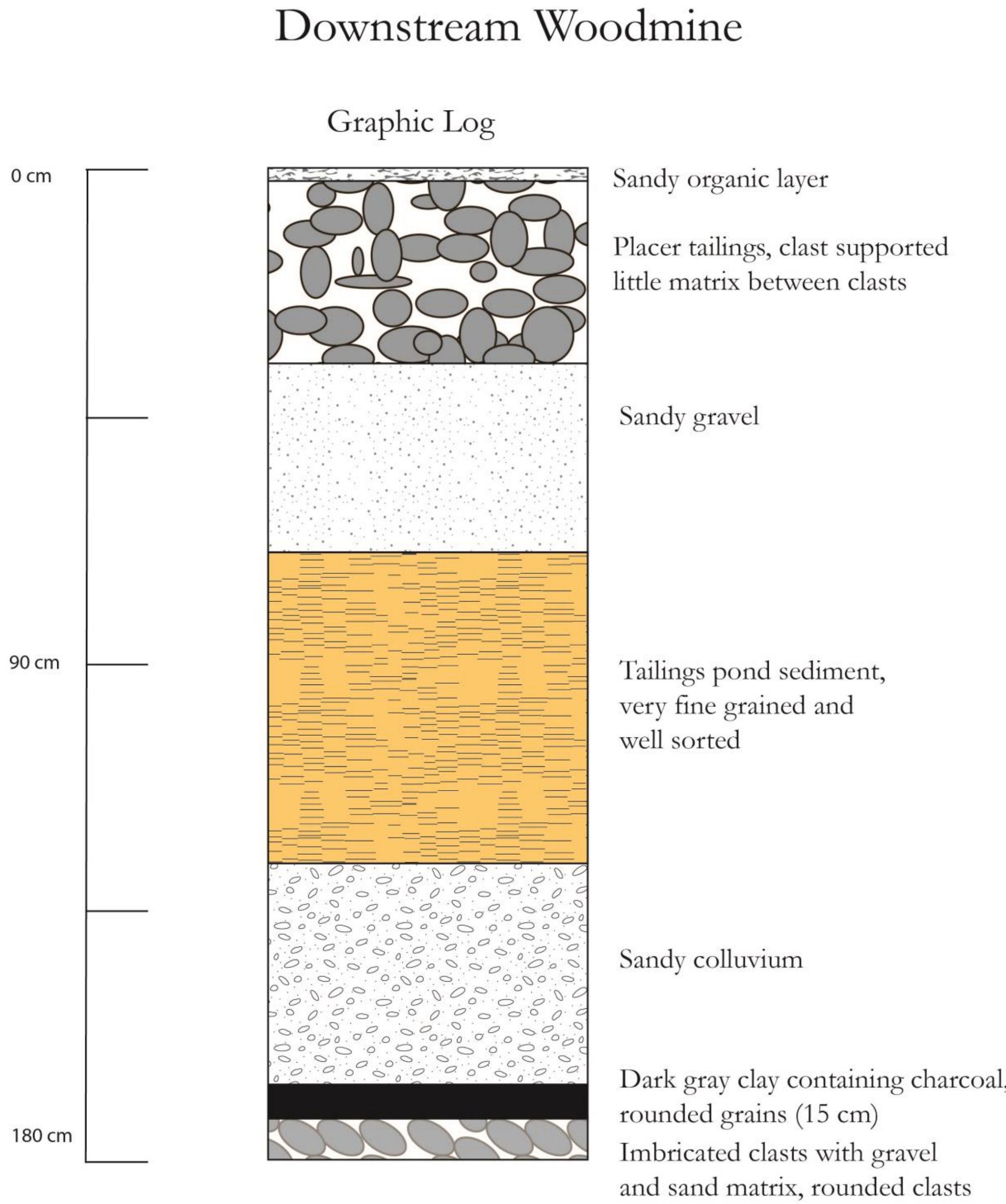


Figure 17: Graphic log of Downstream Woodmine exposure with descriptions.

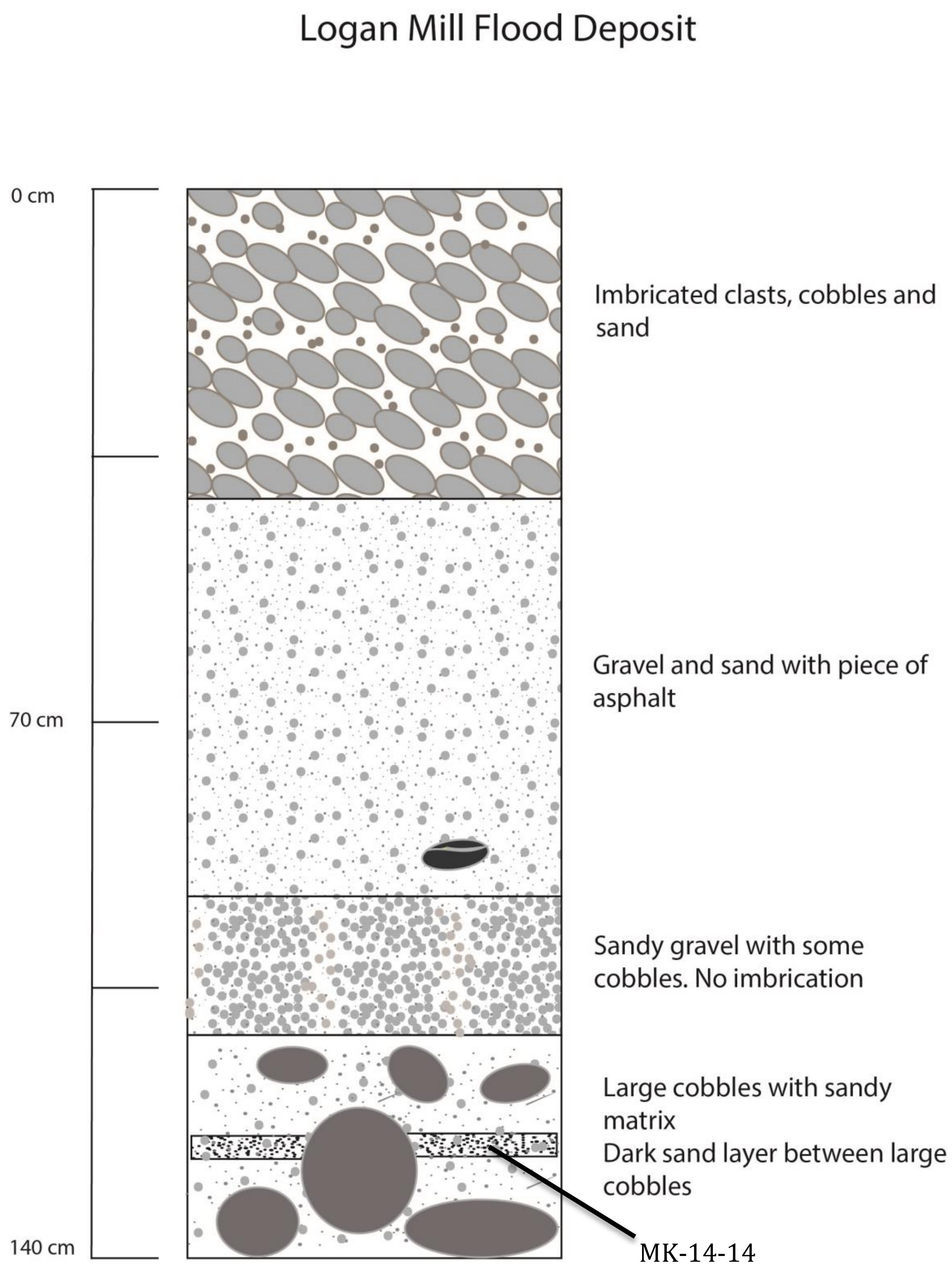


Figure 18: Graphic log of Logan Mill exposure with descriptions and sample location.

Charcoal Dates

Age control for the exposed stratigraphy at the Woodmine and Beebee sites is provided by AMS C^{14} ages on charcoal fragments picked from discrete charcoal layers or dispersed fragments within the exposure stratigraphy. The charcoal dates are thought to provide close limiting ages for the exposure stratigraphies and provide the timing of past forest fires. The concentration of the charcoal in the layers dated indicates that the fires occurred at the location sampled. The oldest (3247±36 yr BP) charcoal layer (MK-14-16) dated was from the Beebee Site and was sampled at a depth of 320 cm below the present-day ground surface (Table 1). The youngest (475±25 yr BP) charcoal sample dated (MK-14-08) was collected at the upper section of the Woodmine exposure from a depth of 150 cm from the top of the upper section (Fig. 14)

Sample Name	Depth (cm)	Exposure	14 C Age	Age Error	Calibrated Calendar Age			Δ13 C	Δ14 C
					Age	Standard Deviation	Calibration Version		
MK-14-3	162	Woodmine	2180	20	2200	63	Fairbanks0107	-23.79	-243.4
MK-14-5	80	Woodmine	1940	20	1882	21	Fairbanks0107	-26.31	-220.83
MK-14-8	150	Woodmine	390	15	475	25	Fairbanks0107	-21.88	-54.76
MK-14-16	320	Beebee Site	3050	20	3274	36	Fairbanks0107	-23.6	-321.52
MK-14-17	260	Beebee Site	2950	20	3114	43	Fairbanks0107	-21.77	-312.67
MK-14-18	180	Beebee Site	2840	20	2938	29	Fairbanks0107	-23.34	-303.19

Charcoal Dates in Years B.P.

Table 1: Charcoal date results.

Woodmine

Samples MK-14-03, MK-14-05, and MK-14-08 were dated from the Woodmine exposure and their ages are in stratigraphic order with the oldest, sample MK-14-03 at the base of the exposure, and the youngest sample, MK-14-08, above the other two dated units. MK-14-03 was dated to 2200±63 yr BP (Fig. 14). This sample was collected 162 cm below the surface of the main face of the exposure. MK-14-05 was collected 80 cm below the surface of the main face of the exposure and dated to 1882±21 yr BP. MK-14-08 was collected from the upper section of the Woodmine exposure and was dated to 475±25 yr BP. The associated stratigraphic layer is not traceable to the main face of the exposure. However, the stratigraphic unit that MK-14-05 was collected from can be traced from the main face to the upper section of the exposure and from this point, MK-14-08 is 27 cm above the stratigraphic unit of sample MK-14-05 (Fig. 14)

This separation indicates that 27 cm of sediment was deposited in a span of 1400 yrs. This is significantly different from the 80cm of aggradation that occurred between MK-14-03 and MK-14-05 over around 320 yrs. From where MK-14-08 was collected, 150 cm of sediment has been deposited since around 475 yr BP.

Beebee Site

Samples MK-14-16, MK-14-17 and MK-14-18 were collected from discrete charcoal layers in the Beebee stratigraphy. The charcoal ages were in stratigraphic order with the oldest sample (MK-14-16) dating to 3247±36 yr BP, the next oldest (MK-14-17) dating to 3114±43 yr BP, and the youngest sample (MK-14-18) dating to 2938±29 yr BP (Table 1). Sample MK-14-16 was collected from the base of the exposure 320 cm below the surface. Between sample MK-14-16 and MK-14-17, the canyon aggraded 60 cm over around 130 yrs. Between sample MK-14-17 and MK-14-18, the canyon aggraded 110 cm over around 150 yrs. From sample MK-14-18, the 180 cm of sediment was deposited from 2938±29 yr BP to present (Fig. 15). These ages show the fire history at the base of the exposure, document timing of these events, and also provide insight on the amount of aggradation occurring in the canyon over time.

Grain Size, Shape, and Maturity Analysis

Grains size analysis was performed on collected sediment samples to characterize the texture of the stratigraphic units identified in the field and to assess the potential to use textural difference to differentiate fluvial and slope deposits in the exposure stratigraphy based on the matrix of samples collected.

Grain Size Analysis

The grain size data show that all the canyon fill samples collected have relatively low mud content and were categorized as sandy gravel and gravelly sand (Fig. 19). Two samples, MK-14-22 and OC-14-2B were categorized as slightly gravelly sand and OC-14-2A and MK-14-13 were classified as sand and slightly gravelly muddy sand, respectively. There was only one distinct clustering of data points identified in Figure 19 along the boundary of gravelly sand and slightly gravelly sand including the samples from sand and slightly gravelly muddy sand categories. This cluster contains the samples with higher sand content based on the sand to gravel ratio.

Textural Maturity

Microscopic analysis of samples from the Woodmine, Downstream Woodmine, and Copper Rock sites found in Cluster A suggests that all of these samples had rounded to sub-rounded grains indicating transport by water which was consistent with field observations. Therefore it was determined that these samples were all fluvial deposits since each sample had rounded to sub-rounded grains and in the field they were all classified as fluvial deposits because of their rounded clasts and visibly better sorting containing more sand.

Combined Grain Size and Textural Maturity

Samples MK-14-03, MK-14-05, OC-14-2A, OC-14-2B, OC-14-2D were collected from the Woodmine deposit and were in Cluster A, indicating fluvial deposition. Grain size analysis, field descriptions, and textural analysis showed the presence of slope deposits as well as fluvial deposits at Woodmine (Fig. 13).

Sample MK-14-13, from Downstream Woodmine was likewise determined to be fluvial based on field observations of the seemingly well sorted layer, textural analysis and grain size analysis. Likewise, the thick, organic-rich layer and the sandy organic-rich layer from which MK-14-22 and MK-14-21, respectively, were collected from were determined to be fluvial deposits (Copper Rock exposure). Examination under the microscope determined that these layers were dark due to charcoal bits as well as decayed organics and not the sediment composition.

At the Beebee site, all samples had angular clasts of a similar texture and no samples from this exposure were within the boundary of Cluster A suggesting the samples were not fluvial samples. This characterization is consistent with field interpretations. I conclude that all samples at the Beebee site are slope deposits because of the high angularity of grains as well as the unsorted nature of the colluvium.

Grain size analysis of the Logan Mill exposure, a deposit from the 2013 flood in Fourmile Canyon, showed that although the sediment was transported by water, the grains from the base of the deposit remained sub-angular and were not in the boundary of Cluster A. However, since this sample was collected from the base of the exposure, it could indicate it originated very locally therefore was not transported far to round the grains.

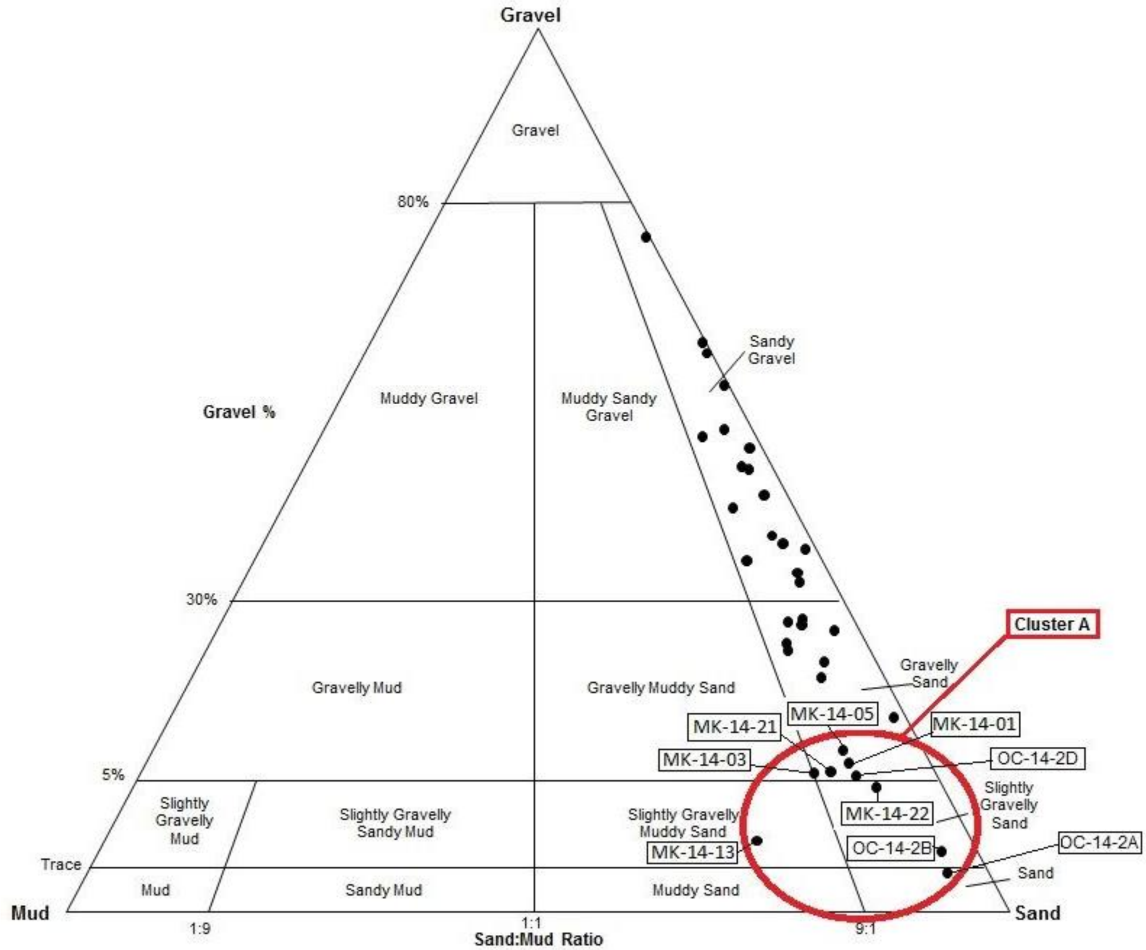


Figure 19: Gravel - sand - mud ternary diagram with Cluster A labeled.

INTERPRETATIONS

The main goal of this project has been to interpret the origin and age of the canyon fill deposits exposed in recently eroded river banks. Using field observations, sediment characterization and AMS C^{14} dating, the canyon fill is interpreted to be largely slope deposits that interfinger at some localities with over-bank flood deposits associated with Fourmile Creek. Dated charcoal within the exposures constrains the age of the canyon fill and documents past forest fires.

Woodmine

Stratigraphy

The Woodmine exposure stratigraphy consists primarily of slope deposits with interbeds of fluvial sands, typically well-sorted and texturally mature (i.e. rounded grains) (Fig. 13). The interbedding of slope and stream deposits are interpreted as infrequent storm events that erode the accumulation of slope deposits depositing sand as overbank deposits. The resulting sand deposits are probably quickly buried by subsequent slope deposits. The resulting interfingering represents an interplay between slope deposits building into the canyon and fluvial processes reworking the sediment downstream. In this exposure, there are three fluvial sand units in the 2m exposure. At the base of the exposure (163-200cm below the surface), the first two stratigraphic layers are interpreted to be of fluvial origin based on the occurrence of imbricated clasts at a depth of 170-200 cm. This cobble and boulder gravel is capped by 7 cm of rounded sand grains. This sand unit likely represents the waning flow conditions of the creek bed. Overlying the basal fluvial unit is a slope deposit (125-163 cm) based on poor sorting and the presence of angular cobbles in one portion of the layer as well as angular grains throughout. A thin sand unit (123-125 cm) indicates a younger canyon flood event. The event that could have caused this change in depositional characteristics is likely an overbank flood; it resulted in the deposition of 2 cm of sandy fluvial deposit before shifting again to more gravelly slope sediment deposition. At 80-123 cm depth, slope deposits dominate followed by 10 cm of fluvial sediment deposition at 70-80 cm depth. This was the last fluvial deposition and the exposure consists of slope deposits from 70-0 cm below the surface. Interfingering of channel sediment and slope deposits with the pattern described represents a primarily slope depositional setting with occasional periods of fluvial deposits (Knox, 2000).

I interpret that the base of the outcrop is the old creek bed. The large imbricated clasts found here are similar to the current creek bed, which has large clasts that are likewise well imbricated. The fluvial deposits found in the exposure thereafter are not thicker than 10 cm. In order for slope deposition to be overlain by a fluvial deposit, there must first be lateral erosion followed by overbank fluvial sediment. It is possible that the canyon fill was aggrading and the creek was further away not affecting the sediment accumulation. This allowed the sediment to drape towards the water forming a bank once reaching the creek which would continue to cut through the new sediment cutting the bank. During floods or periods of higher water level the creek would have topped its banks, depositing sand. The water in the creek would have high discharge and once it rose above the banks, it would lose energy and deposit the sand and finer grains it was carrying. This pattern was observed during the 1894 and 2013 flood. As the creek rose above its banks, the water pooled above the banks and deposited sand. Each of these fluvial deposits interfingered with the slope deposits are likely deposited in a similar manner. It is important to understand the origin of the fluvial deposits in order to determine if they were a result of the creek bed aggrading or if short-lived events, such as overbank floods cause the sediment to be deposited.

The upper section and the main face of Woodmine are significantly different in height (Fig. 14). The upper section is 2 m above the main face. The stratigraphy at the main face connects to the stratigraphy on the upper section indicating the upper section accumulated after 1882±21 yr BP. Sample MK-14-08 (475±25 yr BP) is separated by sample MK-14-05 (1882±21 yr BP) by 27cm indicating a decrease in aggradation rate. MK-14-08 is near the contact of the upper section with the main face, which could indicate a change of depositional setting that allowed sediment to accumulate on the upper section but not the main face. It’s also possible that an erosional event that created the distinction between the upper section and main face of Woodmine by erosion causing a lowering of the surface of the main face. From 475±25 yr BP to present, the canyon fill of the upper section has aggraded more sediment than the main face of the Woodmine exposure shows. This could be due to its height difference with the creek and the lack of fluvial interplay.

Chronology

The charcoal ages provide important age controls for the stratigraphy as well as documenting the timing of past forest fires. The three charcoal dates taken at this exposure constrain the age of the canyon fill 2 m (MK-14-03) to 80 cm (MK-14-05) below the surface at the main exposure and an additional charcoal date taken from the upper section of the exposure 50 cm (MK-14-08) above MK-14-05 at 80 cm depth at the main face. The oldest charcoal date is 2200±63 yr BP and was located above the basal unit with the large imbricated clasts.

The oldest date provides a minimum limiting age for the basal fluvial unit. If the overlying sand is associated with the terrace, it is likely to be of a similar age. If on the other hand, it is a separate fluvial deposit it could be much younger. The age determined at 80 cm below the surface (MK-14-05) suggests that the main face of the Woodmine exposure is older than 1882±21 yr BP but younger than 475±25 yr BP. Sample MK-14-08 located on the upper section, 27 cm above MK-14-05, dates to 475±25 yr BP providing a minimum age for the upper section of Woodmine however, the layer is discontinuous to the main face of the exposure and therefore cannot be used as an age reference for the main face of the

Woodmine exposure. Considering the Woodmine exposure as a whole, the three charcoal dates constrain the age of the canyon fill between 2200±63 yr BP and 475±25 yr BP.

At least eight forest fires have occurred at this locality from 2200±63 yr BP to present-day, three of them occurring after 475±25 yr BP. Five fires at this exposure fall between 2200±63 yr BP and 475±25 yr BP. The first known forest fire at this exposure occurred at 2200±63 yr BP (MK-14-03) the next fire occurring at 1882±21 yr BP (MK-14-05). Two more fires preceded the one in 1882±21 yr BP and their exact age is only broadly known because they were not dated. The stratigraphic units of these fires continue from the upper section of the exposure and are located below MK-14-08 indicating they occurred between 1882±21 yr BP and 475±25 yr BP. One other forest fire occurred before 475±25 yr BP but the charcoal did not continue into the main face of the exposure and was only found in the upper section below sample MK-14-08. Two fires occurred after 475±25 yr BP.

The first fluvial deposit is identified above the terrace of imbricated clasts and sand (163 cm depth). Its close proximity to the terrace indicates it was likely a result of the creek migrating away and not an overbank flood deposit because the bank did not exist (Knox, 2000). The fluvial deposit occurred before 2200±63 yr BP therefore it is older than the charcoal layer above it but there is no other age constraint. From 2200±63 yr BP and 1882±21 yr BP, one flood event is interpreted. Due to the similarity of the two ages, the canyon must not have aggraded much during this time. The thin fluvial deposit (2 cm thick) indicates water had pooled above the creek terrace depositing sand. It is likely that an overbank flood was the cause of the water topping the creek bank (Knox, 2000). Following the forest fire that dated 1882±21 yr BP, another fluvial deposit accumulated. This fluvial deposit is 10 cm thick and occurs 120 cm above the base of the old creek bed. It is interpreted as an overbank deposit because the slope deposits beneath it indicate this was not where the creek flowed and must have been the terrace (Knox, 2000).

Beebee Site

Stratigraphy

The stratigraphy at the Beebee site consisted only of slope deposits, there were no fluvial deposits recognized at this site. The lack of fluvial deposits indicates this exposure was far enough from the creek that it was not directly affected by it. Coal from the railroad was found at the top of the exposure however, there is no indication that the Anthropocene has altered the underlyingstratigraphy. The lowest charcoal layer was 320 cm below the surface and was a thin deposit (2 cm thick). Immediately above this charcoal layer (310 cm depth) is a coarse-grained slope deposit with large angular clasts. This increase in size of grains of a slope deposit is typical for post-fire burned areas.

The soil water repellency strength increases with fire severity and has been shown to increase runoff and induce mobilization of larger clasts (Benavides-Solorio and Lee, 2005). Increased runoff due to hyper-dry conditions causes more sheet-flow on the slopes during high volume rain events, common in the Front Range during monsoon season (Ebel and et al., 2012). The resulting increase in runoff is enough to move clasts that are larger than if soil water repellency had been low and the rain water was being partially absorbed by the soil (Benavides-Solorio and Lee, 2005). This pattern of coarser deposits over charcoal is consistent with four out of the six fire events identified at the Beebee exposure. Charcoal occurring at 320 cm, 180 cm, 140 cm, and 70 cm below the surface, all had large clasts immediately above charcoal layers relative to the grains and clasts deposited afterwards. If the charcoal layer thickness is indicative of the severity of the forest fire, it would suggest larger clasts would be found in the stratigraphic layer following thickest charcoal layers. The thickest charcoal layer in this exposure is 10 cm thick (70 cm depth) and has the highest concentration of large clasts in this exposure that continues from 70 cm below the surface to the present surface of the exposure at 0 cm. This increase in large clasts is because of high burn intensity but could also be a result of Anthropocene slope remobilizing due to railroad construction or mining uphill. Coal from the railroad was found in this layer indicating the railroad and its associated construction was nearby (BCPOS, 2012).

Two fire events at 260 cm and 235 cm below the surface did not exhibit large clasts or coarser grained deposits following the burn layers. It is possible this occurred because the forest fires were of low severity and did not increase the soil water repellency enough to cause enhanced runoff capable of moving larger grains and clasts (Benavides-Solorio and Lee, 2005), or the associated rainfall events were relatively small.

Chronology

Charcoal at this exposure was collected from three layers and dated to 3247±36 yr BP (320 cm below the surface), 3114±43 yr BP (260 cm below surface), and 2938±29 yr BP (180 cm below surface). Between 3247±36 BP and 3114±43 yr BP, 60 cm of slope deposit accumulated. From 3114±43 yr BP to 2938±29 yr BP, 80 cm of slope deposit accumulated with one other undated forest fire occurring in between. The remainder of the exposure (180 cm) accumulated from 2938±29 yr BP to present which is confirmed by the coal pieces found in the topmost unit (0-70cm below the surface), indicating the canyon fill was aggrading during this period because of the positive net change in sediment accumulation. This is a notable change in fire frequency: from 3247±36 yr BP to 2938±29 yr BP four forest fires are documented during a span of 316 - 302 yrs, and from 2938±29 yr BP to present, only two forest fires are recorded.

Comparing the fire ages dated from the Woodmine exposure and the Beebee site, it is apparent that forest fires have occurred in both localities. Since the dated charcoal shows the Beebee Site is older, it is possible that undated charcoal from fires higher in the stratigraphy is from the same fires as those in Woodmine.

Copper Rock

Unlike the Beebee site, the Copper Rock site is located along the main canyon in a wide part of the canyon and contains evidence of both slope and fluvial deposition. No distinct charcoal layers occur at this site although charcoal was found in the slack water deposit and no evidence of flooding exists in the stratigraphy.

Stratigraphy

The slack water deposits have been attributed to beaver activity or a local landslide that created a local dam (Madole, 2012). There is no apparent layering in the slack-water deposit indicating a depositional event that did not occur in intervals or was destroyed via bioturbidation (Ely and Baker, 1985). The stratigraphy at this exposure is primarily fluvial with the exception of the Anthropocene railroad fill (0-110 cm below surface) and has no evidence of interfingering with slope deposits. The oxidized gravel at the base of the exposure (210 cm below the surface) indicates a higher energy deposit which likely represents creek channel deposits. The abrupt transition to the slack-water deposit indicates a quick change in environment that lasted long enough to deposit 30 cm of mud. The most likely possibility of such a quick change in depositional environment is a dam in the creek at this location. Since this layer occurs stratigraphically below the railroad-fill, it was not a result of Anthropocene activity. After accumulating, the slack-water deposit transitioned to sand which is visible at 170 cm below the surface.

It is possible that at this point, the beavers had left the area and the dam failed or the pond had filled up breeching the dam. This would cause an increase in discharge resulting in the drainage of slack water and the restoration of the distinct creek. Conversely, if a landslide had occurred damming the stream, the constant inflow of water from the head of the creek might have caused a failure in the dam allowing water to drain more slowly. This would allow the slack water to drain, increasing the discharge of the creek, which would then lead to suspension of finer grains such as clay and silt. The suspension of finer grains would result in downcutting but it is possible the creek was located at another part of this area and the sediment in this exposure was not eroded.

As the sand is intermixed with the mud from the slack water deposit, it suggests an increase in fluvial energy allowing it to suspend the finer grains it once could not support. The stratigraphy shows the creek was depositing more sorted sand which indicates the constant increase in energy.

Chronology

The railroad grade provides an age constraint for the exposure. Since it caps the stratigraphy, it is determined that the underlying sediment is older than the railroad grade. The Anthropocene impact in this area is high and as a result, the complete stratigraphic history of this site is unknown because the processes in which the railroad road grade is built is invasive and it is possible that other layers of stratigraphy existed at this location before the railroad was constructed.

Downstream Woodmine

Stratigraphy

Besides the fluvial deposits at the base of the outcrop and between the mine tailings (30-60 cm below the surface), the outcrop is interpreted as exclusively slope deposits and Anthropocene deposits. It is interpreted that the creek once flowed here until slope deposits began to aggrade and displaced the stream.

The tailings pond and placer mining tailings in the exposure indicate that this region was heavily impacted by mining practices. Placer mining occurred at the creek banks and a tailings pond was created in close proximity to the creek. The extent of the placer mining is expansive stretching out for meters behind the exposure. It seems extremely likely that the original stratigraphy at this site was destroyed during the Anthropocene and that the exposure represents an incomplete record of this part of the canyon. The mine tailings pond sediment deposition indicates that large amounts of anthropogenic activity occurred at this location. This would include human foot traffic, mill construction, the transportation of rock to the mill, and the actual tailings, which were a slurry of ground rock and water (BCPOS, 2012).

Chronology

One peculiar aspect of this site is that the placer mine tailings occur stratigraphically above the mine tailings pond deposit. Historical records indicate that placer mining occurred during 1859 and was not revisited after that period due to the opening of pit mines (BCPOS, 2012). This deposit suggests the opposite. It is possible that individuals performed placer mining independently after the formation of the tailings pond, but it is also possible that placer mining was done at the base of the slopes, further from the creek and has slumped down to cap this exposure over the years. This would explain why the placer mine tailings continue meters behind the creek, up to the base of the slopes. It is recorded that a large flood occurred in Fourmile Canyon in 1894 that was so strong that it washed out the railroad, including the railroad grade, tracks and bridges, destroyed the road, and wiped away entire towns in Fourmile Canyon (Lambrecht, 2008). It is possible that the thick deposit of sandy gravel (30 cm depth) is an overbank deposit from when the 1894 flood swept through the canyon. The occurrence of the tailings pond could have possibly created a flat are to trap the water allowing it to deposit as much sediment as it did. This is suggested because of the close proximity of the tailings pond to the creek. Unfortunately, a sediment sample was not collected from this sandy stratigraphy layer to analyze for grain size and angularity.

Logan Mill

Stratigraphy

The Logan Mill deposit was formed during the 2013 Fourmile Flood and was exposed by digging vertically into the flood deposit to reveal the stratigraphy. Although the deposit formed during the flood, the sediment deposited by the flood can be used to make predictions on the fluvial energy of the water and the fluctuations in energy based on the size of the sediment being deposited to compare to other stratigraphy units thought to be created by floods. It is known that the entire deposit was deposited by the 2013 flood because trees burned by the 2010 fire were identified in this area by burned trunks rooted in the ground below the base of the deposit. There are large, basketball sized clasts which indicate high fluvial energy that are matrix supported which shows that the flood waters were saturated with sediment (140-90 cm below surface). There is a distinct shift to sandy gravel lacking imbrication and large clasts. Since it is known that this was deposited during a flood event, it is curious the gravel is not noticeably imbricated. This indicates the flood water at this interval of the flood was turbid and was not able to align the gravel and grains because the water was not flowing uniformly and in the same direction. However, the lack of large clasts and boulders in the middle of the stratigraphic section suggests the fluvial energy was not high enough to transport larger clasts.

The underlying layer (40- 90 cm below the surface) is the thickest deposit (50 cm thick) and consists primarily of gravel and sand. This layer was more gravel rich and contained a piece of asphalt near the base. The lack of imbrication suggests turbid water flow with the possibility of side-valley drainage which would have washed the asphalt piece in. Lower fluvial energy is probable due to the lack of large clasts and boulders in the exposure.

The upper-most layer contains imbricated clasts in a sandy matrix. This deposit acted like a cap protecting the stratigraphy below. It is likely that a deposit like this formed during a peak discharge event with high energy that carried the clasts from the debris flows and destruction that occurred during the span of the rain event (Fig. 10; Fig. 18).

DISCUSSION

In an effort to reconstruct the Holocene and Anthropocene history in Fourmile canyon, multiple creek banks exposed by the 2013 Fourmile Canyon Flood were studied. Chronology of two of the largest exposures is provided by radiocarbon dates on interbedded charcoal layers. The charcoal was also used to infer the timing of past forest fires. Holocene and Anthropocene stratigraphic history is crucial for understanding the geomorphologic processes, primarily erosion, that have occurred in the canyon shaping it to be the way it is today. By identifying the different geologic and environmental events that have occurred in Fourmile Canyon and interpreting the conditions, environmental and climatic, that led to these events, we can better understanding of the effect changes in environment by humans, climate, floods, and fires, have on the canyon fill stratigraphy.

Canyon Fill

During this study, canyon fill stratigraphy was studied at five sites and the largest exposures were dated. The oldest charcoal found in Fourmile Canyon was dated to 3247±36 yr BP (i.e. from the late Holocene). Sediment older than the late Holocene was not found. It is possible that it existed and simply was not exposed or that it was never deposited. One possible interpretation of the paucity of older deposits is that during the early Holocene there was lateral channel migration on canyon floor, which could have eroded the early Holocene canyon fill (Knox, 2000). Another idea that could explain the lack of early Holocene fill is that during the Holocene climatic optimum (Benedict et al., 2008), there was less snowfall and more precipitation in the form of rain. It is possible that the snow plays a significant role eroding the canyon and as a result the canyon slopes did not experience as many freeze-thaw cycles associated with temperatures below freezing that would accelerate sediment production and aggradation in the canyon fill (Henry, 2007). Madole (2012) found that in Roaring River Valley, sediment preceding the late Holocene was scarce and attributed it to greater peak flows. Therefore, it is a possibility that greater peak flows eroded the canyon fill in Fourmile Canyon during the early or middle Holocene.

It is curious that following the 2013 storm that caused the flood in Fourmile Canyon, many landslides and debris flows were recorded. Of the 5 stratigraphic sections investigated, there was no evidence of debris flows or landslides which could be indicating the slopes were more susceptible to these erosional events during the Anthropocene.

Flood Deposits

Fluvial deposits were found intercalated with slope deposits at the Woodmine exposure and at the Downstream Woodmine exposure. These fluvial units were interpreted as large magnitude flood deposits when the creek overflowed its banks and deposited a layer of sand. A similar pattern was observed during field work as well. The 2013 flood in Fourmile Canyon has been interpreted as a 50-year flood and at many sites along the creek; sandy deposits ranging in thickness from 2 cm to 20 cm were observed capping the adjacent banks. Flash floods commonly occur in Fourmile Canyon and because the climate has not changed much from the late Holocene (Madole, 2012), the likelihood of flash floods probably occurred with a similar frequency. Similarly, larger magnitude floods likely occurred less frequently than flash floods but left their mark in the canyon stratigraphy like the flood in 2013.

At the Downstream Woodmine site, the interpreted flood deposit from the 1894 flood was 30 cm thick which provides evidence for a large magnitude flood, such as a 50-year flood (Knox, 2000). If this deposit is from a flood, it occurred during the Anthropocene because it is bounded by mine tailings deposits.

Late Holocene flood deposits in the Roaring River Valley located in the Front Range have been interpreted as resulting from periods of increased snow melt leading to increased stream discharge between 3800 yr ago and 2400 yr ago and during 1630 yr ago and 1200 yr ago (Madole, 2012). Comparing these results to the Woodmine flood deposits yield that the ages of high melt in the Roaring River Valley do not correlate to the age constraints of the floods in Fourmile Canyon. The Woodmine exposure indicated one flood occurred before 2200±36 yr BP, one flood between 2200±36 yr BP and 1882±21 yr BP, and one flood after

1882±21 yr BP. Due to the lack of age constraints on the lower and upper parts of the exposure stratigraphy, it is possible that first and last flood at the Woodmine exposure fall into the time interval described by Madole (2012). The floods at Woodmine were either not caused by increased melt water flow or the climatic variations at Roaring River valley cannot be compared to the climatic variations in Fourmile Canyon even though both are located on the Front Range. Using the Neoglaciation date given by Benedict et al. (2008), and the model proposed by Madole (2012) it is inferred that a flood that occurred from 4500 yr BP to present, could be a direct result of increased stream discharge due an increase in snow melt or a long-duration rainstorm.

The past two floods in recorded history that were over bank floods occurred in Fourmile canyon after long-duration rainstorms during 1894 and 2013. The snowmelt fluctuations due to climatic changes may not have much of an impact on the magnitude of the flood since the volume of water is so high. The most important element in producing a large magnitude flood in the Front Range today is a high-volume rainstorm which is attributed to the North American Monsoon (Murphy et al., 2000). If these floods can be attributed to the North American Monsoon season, the flood deposits will provide evidence for the existence of these climatic patterns during the late Holocene.

Fire History and Impact

Wildfire deposits are very common in the Woodmine and Beebee exposures. In the main face of the Woodmine exposure, there are four fires preserved in the stratigraphy. At the Beebee site, there are six fires exhibited in the stratigraphy. The age of the charcoal units at the two sites were not similar suggesting that although forest fires did occur in the two areas they were not of regional extent but rather consisted of localized fires of limited extent. This is consistent with historical forest fires in the Front Range (BCPOS, 2012) and other studies that reconstructed fire histories in the Front Range. However, this does not necessarily indicate that a fire not dated in either exposure was not from the same event. The Beebee site exhibits stratigraphy significantly older than the Woodmine exposure. It is possible that fires seen in the top portion of the Beebee site could relate to fires in the Woodmine exposure if more charcoal was dated.

Immediately overlying some of the charcoal layers was coarse grained cobble gravel uncharacteristic of the general deposition of slope deposits at each exposure. This was exhibited at the Woodmine exposure at a depth of 163 cm, and at the Beebee site at depths of 320 cm, 180 cm, 140 cm, and 170 cm. It has been suggested that this pattern is a result of increased run-off and sheet-wash due to increased soil water repellency after a fire (Benavides-Solorio and Lee, 2005). Soil water repellency increases as fire severity increases and the severity of the fire can be understood by observing the stratigraphy immediately following a fire.

Morris and Moses (1987) studied 80 catchments in the Front Range and concluded that after forest fires, the sediment yield in catchments indicated that sediment flux rates are three times greater in burned areas than non-burned areas. Ebel et al. (2012) concluded that hyper-dry soil conditions result in very little rain infiltration. This can be compared with the study done by Benavides-Solorio (2003) about soil water repellency and burn severity. After fires, canyons aggrade at a faster rate and accumulate larger grains based on the severity of the burn (Morris and Moses, 1987; Benavides-Solorio, 2003; Ebel et al., 2012).

Anthropocene Impact

The 2013 rain event that caused the 2013 Fourmile flood mobilized many landslides and debris flows in Fourmile (Coe et al., 2014). The mine tailings piles are an example of accelerated erosion by humans and have caused a large sediment influx into the creek and from the slopes. The tailings piles reflect the amount of rock removed from within the mountains. By comparing the past flood history from the past to the present, a relationship can be seen. Floods occurred in Woodmine before 2200±63 yr BP, one between 2200±63 yr BP and 1882±21yr BP, and again once after 1882±21yr BP. Two overbank floods have been recorded in this exposure after 2200±63 yr BP and in Downstream Woodmine and Fourmile Canyon evidence that the 1984 and 2013 floods were overbank floods is found. Having access to more exposures that reveal the past flood history of the canyon is vital for understanding the frequency of large overbank floods in the region to further understand the changes that are occurring in the canyon that are promoting long-duration rains whether they are climatically induced (change in N. American monsoon patterns) or an increase in run-off due to hyper-dry conditions is causing more rain fall to flow directly into the creek (Ebel et al., 2012).

The most recent fire in Fourmile Canyon (the largest in the canyon's recorded history) was started by humans (Coe et al., 2014) and as this trend continues, there will likely be an acceleration of slope erosion and canyon fill aggradation directly related to these human caused fires (Knox, 2000; Morris and Moses, 1987). The change of the source of fires from environmental to human caused is an important change in the history of the canyon because the known effects of increased erosion and increased run-off post-fire are significant.

CONCLUSION

The stratigraphy exposed by the 2013 Fourmile Canyon flood show the processes that have led to canyon fill accumulation and can be used to understand past environmental events such as floods and fires. There was no canyon fill found dating older than the late Holocene indicating the older stratigraphy was simply not exposed or it had eroded away. If the older stratigraphy had been eroded, it would be a direct result of greater peak flows (Madole, 2012) during the Holocene Climatic optimum caused by precipitation in the form of rain rather than snow (Benedict et al., 2008).

Fluvial deposits at the Woodmine, Downstream Woodmine, Copper Rock, and Logan Mill exposures show that overbank floods either do not occur frequently in the canyon or are not preserved in the canyon fill stratigraphy.

At the Woodmine and Beebee sites, AMS C-14 dating provided an age control for the exposures and gave insight on the fire history at these sites. The resulting dates showed that the fires are of localized extent and are not regional. The stratigraphy immediately following the fire layers revealed the degree of burn severity by the increase in sediment size (Benavides-Solorio and Lee, 2005). Four out of six fires at the Beebee site had high burn severity and at Woodmine, one fire out of four had high burn severity. This pattern shows that fires of different intensities have occurred in Fourmile Canyon as demonstrated by the fires at these two exposures.

The human impact on Fourmile Canyon has included the removal and grinding of rock for ore, mines in the slopes, and human-caused fires. I conclude that the mine tailings piles are an example of accelerated erosion by humans and have caused a large sediment influx into the creek and off of the slopes. Fires caused by humans will occur more frequently than fires caused by environmental factors and as this trend continues, it is expected that there will be an acceleration of slope erosion and canyon fill aggradation directly related to fires (Morris and Moses, 1987; Knox, 2000). The change of the source of fires from environmental to human caused is an important change in the history of the canyon because the effects of increased erosion (three times as much sediment aggradation) and increased run-off post-fire (related to fire severity) are significant (Morris and Moses, 1987; Benavides-Solorio and Lee, 2005; Ebel et al., 2012).

BIBLIOGRAPHY

Adams, D.K., and Andrew C.C., 1997. "The North American monsoon." *Bulletin Of The American Meteorological Society* 78, no. 10:2197. *Academic Search Premier*, EBSCO*host* (accessed April 10, 2015).

Anderson, L., 2011. Holocene record of precipitation seasonality from lake calcite δ18O in the central Rocky Mountains, United States. *Geology*, *39*(3), 211-214.

Anderson, R.S., Riihimaki, C.A., Safran, E.B., and MacGregor, K.R., 2006. "Facing reality: Late Cenozoic evolution of smooth peaks, glacially ornamented valleys, and deep river gorges of Colorado's Front Range." *Geological Society of America Special Papers* 398: 397-418.

Anderson, S.P., Anderson, R.S., Tucker, G., 2012. Landscape scale linkages in critical zone evolution. C. R. Geosci. 344, 586–596.

Anderson, SP, von Blankenburg, F., and White, A.F., 2007: Mechanical-chemical interactions shape the Critical Zone and fluxes from it. Elements, 3: 315–319.

Anderson, S.P., Qinghua, G., and Parrish, E. G., 2012, Snow-on and snow-off LiDAR point cloud data and digital elevation models for study of topography, snow, ecosystems and environmental change at Boulder Creek Critical Zone Observatory, Colorado: Boulder Creek CZO, INSTAAR, University of Colorado, Boulder, digital media.

BCPOS (Boulder County Parks and Open Space). Fourmile Canyon Historical and Architectural Survey, 2012-2013. By Mary Therese Anstey and Adam Thomas. Compiled by HISTORITECTURE, L.L.C. Report no. Project CO-12-018. N.p.: n.p., 2013.

Benavides-Solorio, J. de D., 2003. "Post-fire runoff and erosion at the plot and hillslope scale, Colorado Front Range." *Fort Collins, CO: Colorado State University*.

Benavides-Solorio, J. de D., and MacDonald, L.H., 2005. "Measurement and prediction of post-fire erosion at the hillslope scale, Colorado Front Range."*International Journal of Wildland Fire* 14, no. 4: 457-474.

Benedict J.B., 1973. Chronology of cirque glaciation, Colorado Front Range. Quaternary Research 3: 584–600.

Benedict, J.B., Benedict, R.J., Lee, C.M., and Staley, D.M., 2008. "Spruce trees from a melting ice patch: Evidence for Holocene climatic change in the Colorado Rocky Mountains, USA." *The Holocene* 18, no. 7: 1067-1076.

Birkeland, P. W., Shroba R. R., Burns S. F., Price A. B., and Tonkin P. J., 2003. "Integrating soils and geomorphology in mountains—an example from the Front Range of Colorado." *Geomorphology* 55, no. 1: 329-344.

Blott, S.J., and Pye, K., 2001. "GRADISTAT: a grain size distribution and statistics package for the analysis of unconsolidated sediments." Earth surface processes and Landforms 26, no. 11: 1237-1248.

Bull, W. B., 1990. "Stream-terrace genesis: implications for soil development. "Geomorphology 3, no. 3: 351-367.

Carrara, P.E., 2011. "Deglaciation and postglacial treeline fluctuation in the northern San Juan Mountains, Colorado." *Professional Paper*.

Clow, D.W., 2010. "Changes in the timing of snowmelt and streamflow in Colorado: a response to recent warming." *Journal of Climate* 23, no. 9: 2293-2306.

Coe, J. A., Kean, J.W., Godt,J.W., Baum, R.L., Jones, E.S., Gochis, D.J., and Anderson, G.S., 2014. "New insights into debris-flow hazards from an extraordinary event in the Colorado Front Range." GSA Today 24, no. 10.

Colorado Water Conservation Board (CWCB): Fourmile Creek Watershed Master Plan. December 12, 2014.

Das, T, H. G. Hidalgo, D. W. Pierce, T. P. Barnett, M. D. Dettinger, D. R. Cayan, C. Bonfils, G. Bala, and A. Mirin., 2009 "Structure and detectability of trends in hydrological measures over the western United States." *Journal of Hydrometeorology* 10, no. 4: 871-892.

Davis, P. T., Birkeland P. W., Caine, N., and Rodbell D. T., 1992, "New radiocarbon ages from cirques in Colorado Front Range." *Geological Society of America, Abstracts with Programs;(United States)* 24, no. CONF-921058--.

Dickinson, W.R., Klute, M.A., Hayes, M.J., Janecke, S.U., Lundin, M.A., McKittrick, M.A., and Olivares, M.D., 1988, Paleogeographic and paleotectonic setting of the Laramide sedimentary basins in the central Rocky Mountain region: Geological Society of America Bulletin, v. 100, p. 1023–1039, doi: 10.1130/0016-7606(1988)100<1023:PAPSOL>2.3.CO;2

Dethier, D.P. and Bove, D.J., 2011: Mineralogic and Geochemical Changes from Alteration of Granitic Rocks, Boulder Creek Catchment, Colorado. Vadose Zone Journal 10: 858-866. DOI: 10.2136/vzj2010.0106

Ebel, B. A., Moody, J.A., and Martin, D.A., 2012. "Hydrologic conditions controlling runoff generation immediately after wildfire."*Water Resources Research* 48, no. 3.

Ely, L. L., and Baker, V. R., 1985. "Reconstructing paleoflood hydrology with slackwater deposits: Verde River, Arizona." *Physical Geography* 6, no. 2: 103-126.

Fenske, J., 2003. "Application of paleohydrology to corps flood frequency analysis." *Research Documents. U. S. Army Corps of Engineers, Hydrologic Engineering Center*: 34.

Folk, R.L., 1980 Petrology of Sedimentary Rocks. Austin, TX: Hemphill Publishing Company.

Graham, R., Finney, M., McHugh, C., Cohen, J., Stratton, R., Bradshaw, L., Nikolov, N., and Calkin, D., 2012, Fourmile Canyon Fire Findings: USDA Forest Service, General Technical Report RMRS-GTR-289, 110 p.

Greene, H. Gary, Donald L. Tiffin, and Chris O. McKee., 1986. "Structural deformation and sedimentation in an active caldera, Rabaul, Papua New Guinea." *Journal of volcanology and geothermal research* 30, no. 3: 327-356.

Google Maps. 2015. Fourmile Canyon. Satellite Map (Google Earth).https://www.google.com/maps/place/Fourmile+Canyon+Dr,+Boulder,+CO+80302/@40.0362962,105.4272245,662m/data=!3m1!1e3!4m2!3m1!1s0x876be9bc82f87139:0xb0bc02a32b1f3136

Henry, Hugh AL., 2007. "Soil freeze–thaw cycle experiments: trends, methodological weaknesses and suggested improvements." *Soil Biology and Biochemistry* 39, no. 5: 977-986.

Henson, Bob., 2013. "Inside the Colorado Deluge: How Much Rain Fell on the Front Range, and How Historic Was It? Retrieved March 10, 2014." .

James, L. Allan., 2013 "Legacy sediment: definitions and processes of episodically produced anthropogenic sediment." *Anthropocene* 2: 16-26.

Johnson, B. G., Eppes, M.C., Diemer, J.A., Jiménez-Moreno, G., and Layzell, A.L, 2011. "Post-glacial landscape response to climate variability in the southeastern San Juan Mountains of Colorado, USA." *Quaternary Research* 76, no. 3: 352-362.

Johnson, B. G., Jiménez-Moreno, G., Eppes, M.C., Diemer, J.A., and Stone, J.R., 2013. "A multiproxy record of postglacial climate variability from a shallowing, 12-m deep sub-alpine bog in the southeastern San Juan Mountains of Colorado, USA." *The Holocene* 23, no. 7: 1028-1038.

Kaste, J. M., Heimsath, A.M., and Bostick, B.C., 2007 "Short-term soil mixing quantified with fallout radionuclides." *Geology* 35, no. 3: 243-246.

Kellogg, K. S., Shroba, R.R., Bryant, Bruce, and Premo, W.R., 2008, Geologic map of the Denver West 30' x 60' quadrangle, north-central Colorado: U.S. Geological Survey Scientific Investigations Map 3000, scale 1:100,000, 48-p. pamphlet.

Knox, J. C., 2000. "Sensitivity of modern and Holocene floods to climate change." *Quaternary Science Reviews* 19, no. 1: 439-457.

Lambrecht, Mona, 2008. *Boulder, 1859-1919*. Arcadia Publishing.

Layzell, A. L., Eppes, M.C., Johnson, B.G., and Diemer, J.A., 2012 "Post-glacial range of variability in the Conejos River Valley, southern Colorado, USA: fluvial response to climate change and sediment supply." *Earth Surface Processes and Landforms* 37, no. 11: 1189-1202.

Leopold, M., and Völkel, J., 2007. "Colluvium: Definition, differentiation, and possible suitability for reconstructing Holocene climate data." Quaternary International 162: 133-140.

Leopold, M, Dethier, D., Völkel, J., Raab, T., Rikert, T.C., and Caine, N., 2008. "Using geophysical methods to study the shallow subsurface of a sensitive alpine environment, Niwot Ridge, Colorado Front Range, USA." *Journal Information* 40, no. 3.

Madole, R. F., 2012. "Holocene alluvial stratigraphy and response to climate change in the Roaring River valley, Front Range, Colorado, USA." Quaternary research 78, no. 2 : 197-208.

Marr, J. W., 1961. "Ecosystems of the east slope of the Front Range in Colorado." *University of Colorado Press*.

Mason, O. K., and Begét, J.E., 1991. "Late Holocene flood history of the Tanana River, Alaska, USA." *Arctic and Alpine Research*: 392-403.

Miller, N. A., and Henderson, J. J., 2010. "Quantifying sand particle shape complexity using a dynamic, digital imaging technique." Agronomy journal 102, no. 5: 1407-1414. FIGURE 1.

Moody, J. A., and Nyman, P., 2013. *Variations in Soil Detachment Rates after Wildfire as a Function of Soil Depth, Flow Properties and Root Properties*. No. SIR-2012-5233. United States Geological Survey.

Morris, S.E., and Moses, T.A., 1987. "Forest fire and the natural soil erosion regime in the Colorado Front Range." *Annals of the Association of American Geographers* 77, no. 2: 245-254.

Murphy, S.F., McCleskey, R.B., and Writer, J.W., 2012, Effects of flow regimes on stream turbidity and suspended solids after wildfire, Colorado Front Range, in Wildfire and water quality—Processes, impacts, and challenges, Conference in Banff, Canada, June 2012, Proceedings: Wallingford, Oxfordshire, U.K., International Association of Hydrological Sciences publication 354, p. 51–58.

Niwot Ridge Long-Term Ecological Research Site (NRLTERS). Accessed April 10, 2015. niwot.colorado.edu.

NOSAMS. "Radiocarbon Data and Calculations." National Ocean Sciences Accelerator Mass Spectrometry. Last modified November 4, 2014. Accessed March 6, 2015.http://www.whoi.edu/nosams/page.do?pid=40146.

Ouimet, W., Dethier, D., Bierman, P., Wyshnytzky, C., Shea, N., and Rood, D.H., 2015. "Spatial and temporal variations in meteoric 10 Be inventories and long-term deposition rates, Colorado Front Range." *Quaternary Science Reviews* 109: 1-12.

Purinton, B.J., 2013. "The Hydrologic and Geomorphic Impacts of the 2010 Fourmile Canyon Fire, Boulder Creek Watershed, CO". *Honors Theses - All*. Paper 1080, http://wesscholar.wesleyan.edu/etd_hon_theses/1080.

Ritter, D. F., 1975. "Stratigraphic implications of coarse-grained gravel deposited as overbank sediment, southern Illinois." *The Journal of Geology*: 645-650.

Saunders, S., Montgomery, C.H., Easley, T., and Spencer, T., 2008. *Hotter and drier: the West's changed climate*. Rocky Mountain Climate Organization.

Schildgen, T,. Dethier, D.P., Bierman, P., and Caffee, P., 2002. "26Al and 10Be dating of late Pleistocene and Holocene fill terraces: a record of fluvial deposition and incision, Colorado Front Range." *Earth Surface Processes and Landforms* 27, no. 7: 773-787.

Shoshany, M., 2002. "Landscape fragmentation and soil cover changes on south- and north-facing slopes during ecosystems recovery: an analysis from multi-date air photographs." *Geomorphology* 45, no. 1: 3-20.

Spillman, W. J., 1918. *Farm Science: A Foundation Textbook on Agriculture*. World Book Company.

USGS. Hydrograph. Illustration. USGS Current Conditions for the Nation. Accessed April 10, 2015.http://waterdata.usgs.gov/nwis/uv?