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INTRODUCTION

In 2010, a wildfire burned through parts of Fourmile Canyon in the Front Range of Colorado. Three years later in 2013, a 50-year flood event caused extensive erosion in the canyon exposing the canyon-fill stratigraphy. The exposed cut banks along Fourmile creek reveal the geomorphologic history of different parts of the canyon and are useful for understanding the different period of environmental change, past events such as floods and wildfires, and human impacts that have occurred in the canyon. This study documents the exposed Holocene and Anthropocene canyon stratigraphy and provides an interpretation of its origin and age.

BACKGROUND

Setting

Fourmile Creek (65 km²) begins at Niwot Ridge near the Continental Divide and discharges into Middle Boulder Creek at the junction of Country Road 118 and State Highway119. The canyon is characterized by steep slopes and discharge is heavily influenced by seasonal snowmelt and intense summer thunderstorms. The Front Range, where Fourmile Canyon is located, formed during the Laramide orogeny (Dickinson et al., 1988). Canyon slopes are comprised of oxidized granitic rock, saprolite, syenite, schist, felsic intrusive rocks, thin soils and grus (Dethier and Bove, 2011; Kellogg et al., 2008). Following deglaciation 21000-18000 yr BP, the Front Range was warmer and dryer during the Holocene climatic optimum until Neoglacial 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 (Benedict, 1973).

Historical Record

Placer gold mining in Fourmile Canyon began during 1859 and marked a sharp transition of human impact and landscape change associated with the Anthropocene. The shift to vein-hosted gold mining resulted in over 200 companies building mills to processes ore (BCPOS, 2012). The impact from the mining history can be seen today with large mine shafts, exploration pits and waste piles dotting the hillsides of the Fourmile watershed and tailings pond sediment at historic mill sites along Fourmile Creek. Multiple times between 1870 and 1920, a canyon railroad existed within Fourmile valley to transport recovered ore. The railroad was built on top of a distinctive road-bed fill to flatten the railway surface adjacent to Fourmile Creek.

Wildfires are common along the semi-arid Front Range. Fourmile Canyon experienced a large fire in September 2010, which burned a total of 16.5 km² (23% of the Fourmile watershed). A major five-day rainfall event occurred in September 2013 causing a 50-year flood. This rain event caused 1,138 debris flows in the Front Range in a 3,430 km² area and heavy erosion in the canyons, one of which was Fourmile (Coe et al., 2014).
METHODS

Field Methods

**Exposures:** Exposures were located along Fourmile Creek using a 1-m resolution Digital Elevation Model from LiDAR data (light detection and ranging) or by hiking the canyon. The LiDAR used was taken after the 2013 flood (Anderson et al., 2012). The location of each exposure was recorded using a GPS (Fig. 1) and each exposure was cleared with shovels and trowels to freshly expose the stratigraphy. The stratigraphy was then photographed, sketched to document the major stratigraphic units, described, and measured.

**Sampling of exposures:** Samples were collected at the exposures for subsequent lab analysis and dating. Layers containing charcoal were sampled in order to provide age control for the associated stratigraphies and to estimate wild fire recurrence intervals. The main stratigraphic units were sampled to determine depositional environments. In layers containing large cobbles and boulders, only the matrix was sampled. Samples of the charcoal were collected for radiocarbon dating therefore the emphasis was on collecting the largest pieces of charcoal, not the matrix.

**Lab Methods**

**Grain size analysis and characterization:** Grain size analysis was done by dry sieving using a Ro-Tap shaker. The sieve sizes used include 16 mm, 4mm, 2mm, 1.18mm, 0.5mm, 0.25mm, 0.063mm and less than 0.063 mm and were chosen to represent the primary grain size boundaries (Folk, 1980). A representative amount (200g to 600 g) of each sample was weighed and sieved for 10 minutes. The samples collected by each sieve were weighed and recorded. Samples containing charcoal fragments in the matrix were run without separating charcoal out. A dissecting microscope was used to characterize the angularity and composition of each collected sample. Clast sphericity and angularity were classified using a particle shape chart (Miller and Henderson, 2010).

**Particle size statistics:** Particle size statistics were calculated using GRADISTAT version 8.0 (Blott and Pye, 2001). Grainsize distribution, mean, sorting, skewness, and kurtosis values were calculated for each sample and all samples were plotted on a gravel-sand-mud diagram using GRADISTAT.

**Carbon-14 dating:** Two exposures exhibited charcoal for Carbon-14 dating (Woodmine and Beebee). Charcoal from six samples was picked using tweezers to be dated at Woods Hole Oceanographic Institute using AMS carbon dating. Prior to dating, the outer surface of the charcoal was cleaned and then leached in heated acid-base-acid leaches to ensure no additional carbon or organic material remained.
Carbon dioxide was produced from the charcoal sample and reacted with a Fe-catalyst to form graphite which was then pressed onto targets that were analyzed using accelerator mass spectrometry. The samples’ calibrated calendar ages were obtained using the Fairbanks0107 conversion (NOSAMS, 2014).

RESULTS

Summary of exposures

The exposures reveal different periods of time into the history of the canyon from the Holocene through the Anthropocene. The Woodmine exposure (Fig. 1) is located at the base of a hillslope and contains two main parts: the main face, and the upper section (Fig. 2). The main face has a height of 200cm and the upper section is 200cm taller than the main face. 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 indicating no Anthropocene related sediment deposition. The base of this outcrop has large clasts that are imbricated with a thin layer of sand on top as well as multiple charcoal rich layers (Fig. 3).

The Beebee site lies behind an abandoned house next to the property of Mr. Robert Beebee and is located at the base of a hillslope and was exposed by the 2013 flood (Fig. 1). The exposure is a slope deposit with multiple charcoal layers and shows no signs of fluvial interactions however coal pieces were found at the top indicating some Anthropocene modified deposits (Fig. 4A).

The Copper Rock site is surrounded by slopes but is located in a flattened area of the canyon (Fig. 1). The 2013 flood uncovered this exposure revealing the railroad fill with preserved stratigraphy below. Beneath the railroad fill was a mud-rich deposit 40cm thick that was dark in color from the organics it contained (sample MK-14-22).

The Downstream Woodmine exposure (Fig. 1) was indicative of the effect of the Anthropocene related activity in the region. It contained both placer mine tailings as well as sediment from a tailings pond. 30 cm beneath the mine tailings pond deposit was a gray, mud-rich charcoal deposit (MK-14-13) on top of a terrace with large imbricated clasts (Fig. 4B). Placer mine tailings continue behind the exposure and further back towards the base of the slope is the railroad graded surface.
Grain Size, Shape, and Maturity Analysis

The grain size analysis showed that all samples had relatively low silt/clay contents with only one apparent clustering of data points, Cluster A (Fig. 5). This cluster contains samples with a higher sand content based on the sand to gravel ratio. Analysis of samples from the Woodmine, Downstream Woodmine, and Copper Rock sites found in Cluster A suggests that all of these samples were fluvial due to their rounded to sub-rounded grains. At Woodmine, some layers contained rounded grains and had less gravel (Fig. 5) while other layers at the same locality contained only angular grains. These results are shown with the associated stratigraphic column at Woodmine (Fig. 3). At the Beebee site, all samples had angular clasts of a similar texture (Fig. 4A).

Charcoal Dates

Age control for the exposed stratigraphy at Woodmine and the Beebee site is provided by charcoal dates that ranged from 3274 yr BP to 475 yr BP (Table 1). Samples MK-14-03, 05, and 08 are from the Woodmine exposure and their ages are in stratigraphic order with the oldest, 2200 yr BP, at the bottom of the exposure (Fig. 3). Samples MK-14-16, 17 and 18 are from the Beebee site had charcoal ages come back in
Charcoal Dates in Years B.P.

<table>
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<th>Sample Name</th>
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<th>Age Error</th>
<th>Calibrated Calendar Age</th>
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<tr>
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<td>2938 29 Fairbanks0107</td>
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stratigraphic order with the oldest, dating to 3274 yr BP, at the base of the exposure (Fig. 4A).

**INTERPRETATIONS**

**Woodmine**

Fluvial deposits at Woodmine are interfingered with colluvial deposits in outcrop. This makes sense because the exposure is located in contact with the base of the slope and the creek. Mapped exposure at Woodmine is 200cm – the upper 70cm is dominantly colluvial and the bottom 50cm is dominantly fluvial with a 50cm thick section of interfingering when clear fluvial sand has clear colluvium directly above and below (Fig. 3). Variations in stratigraphy suggest a change in the pattern of deposition which could be caused by environmental change, such as climate or human interactions that change the way sediment naturally accumulates.

The charcoal dated at Woodmine was in stratigraphic order from distinct layers suggesting that the charcoal was not a result of slope processes but was probably created at that location or in close proximity to where the samples were collected. Radiocarbon dated wildfires occurred during 2200 yr BP, 1882 yr BP, and 475 yr BP (Table 1). Sample MK-14-08 was dated from the upper section of the Woodmine exposure adjacent to the main face in order to compare the ages of stratigraphic units to determine the cause of the change in shape between the main face and the upper section. MK-14-08 is only 475 yr BP whereas MK-14-05 (main face) was 1882 yr BP (Fig. 2). With a height difference of 27cm between these two samples, it is possible that the upper section is younger than the main face of the exposure indicating that the top of the main face was eroded away.

**Copper Rock**

The thick clay-rich deposit (MK-14-22) at Copper Rock beneath the railroad fill is interpreted to be a slack-water depositional setting because of the high organic matter content, the rounded clasts, and the thickness of the stratigraphic layer (30cm). It is likely that this represents ponding of water by a landslide, flood deposit, or beavers (Madole, 2012).

**Beebee Site**

The radiocarbon ages of the charcoal in the three layers’ dates at the Beebee site are 3274 yr BP, 3144 yr BP, and 2938 yr BP, respectively. The charcoal samples at this site were all slope deposits based on the texture of the associated sediment. The charcoal layers must have occurred from fires in close proximity to the outcrop because of their concentration. Although coal is found in the top-most layer, the Anthropocene impact did not affect the aggradation pattern of the site.

**Downstream Woodmine**

The clay rich layer just above the imbricated clasts shows a low energy depositional setting following a high energy fluvial event. Based on the stratigraphy between the Woodmine exposure and Downstream Woodmine, it appears that imbricated clasts of this size are not commonly occurring deposits of Fourmile creek. The mine tailings in the stratigraphy
at Downstream Woodmine indicate Anthropocene reworking of sediment. During 50 years that mining boomed in this region, 130cm of sediment has accumulated.

**DISCUSSION**

Fluvial aggradation occurs during waning flow conditions accumulating at the base of the creek raising the grade. When stream discharge is low, its capacity to carry a large load decreases resulting in sediment deposition (Bull, 1990). The same is true for slope deposits. When the system does not have enough energy to remove more than is being accumulated, there will be aggradation (Bull, 1990). Interfingering of slope deposits and fluvial deposits indicate times when both systems did not have enough energy to remove extra accumulation of sediment and deposited it as canyon-fill. The disappearance of glaciers after 3000 yr BP suggests less meltwater in the creek corresponding with fluvial aggradation. It is possible that periods of dryer climate led to the aggradation sediment which was followed by periods of wetter climate causing degradation of Fourmile Canyon. Samples in Cluster A (Fig. 3) are all interpreted to be of fluvial origin because of their rounded clasts and higher relative sand content. The missing sediment on the main face of the Woodmine exposure suggests that a large erosional event such as a flood or debris flow selectively wiped the top sediment away on that face leaving the upper section intact.

During 50 years that mining boomed in this region, Downstream Woodmine indicates that as much 130 cm of sediment (much of what the flood exposed) is directly associated with Anthropocene landscape change and human activity within the Fourmile floodplain. Closer to valley sides, such as expressed in Woodmine and Beebee, there is less indication of the Anthropocene. Overall, stratigraphic columns and descriptions show that railroad and mining related sediment associated with the human activity in the Anthropocene was deposited directly on top of older Holocene deposits and often consisted of reworking the older deposits (such as the placer deposits of Downstream Woodmine).

The oldest charcoal samples dated at Woodmine and at the Beebee site show that the accessible canyon-fill at Fourmile Canyon is young, dating exclusively to the late Holocene. Overall, during the late Holocene, sediment was aggrading in Fourmile Canyon. This is significant because during the Holocene, aggradation was not occurring at the rate it accumulated at during the Anthropocene. By understanding the Anthropocene impact in Fourmile Canyon, it is possible to further investigate the impact humans have on the erosion of slopes, the likelihood of more frequent fires and the severity of floods from increased run-off.

**CONCLUSION**

The stratigraphy exposed by the Fourmile Canyon Flood in 2013 provides evidence of past forest fires, periods of fluvial aggradation and slope deposition during the Holocene and the effects of human activity in the Anthropocene. The canyon fill contains interbedded charcoal and fluvial and slope deposits that can be differentiated confidently based on angularity and sand to gravel ratios. The dates on charcoal record times of localized forest fires and provide an age control for the canyon stratigraphy while giving an idea of fire occurrence intervals. The charcoal dates showed that the canyon fill dates to the late Holocene. The canyon-fill is young and may represent a time of canyon aggradation during an interval of increased aridity. The stratigraphy gives an insight on Holocene patterns of sediment accumulation as well as patterns of sediment accumulation during the Anthropocene and the changes in accumulation rates, forest fire occurrence intervals and the frequency of large erosional events.

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REFERENCES


