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Anthropocene Landscape Change and the Legacy of Nineteenth- and Twentieth-Century Mining in the Fourmile Catchment, Colorado Front Range

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Human impacts on earth surface processes and materials are fundamental to understanding the proposed Anthropocene epoch. This study examines the magnitude, distribution, and long-term context of nineteenth- and twentieth-century mining in the Fourmile Creek catchment, Colorado, coupling airborne LiDAR topographic analysis with historical documents and field studies of river banks exposed by 2013 flooding. Mining impacts represent the dominant Anthropocene landscape change for this basin. Mining activity, particularly placer operations, controls floodplain stratigraphy and waste rock piles related to mining cover >5% of hillslopes in the catchment. Total rates of surface disturbance on slopes from mining activities (prospecting, mining, and road building) exceed pre-nineteenth-century rates by at least fifty times. Recent flooding and the overprint of human impacts obscure the record of Holocene floodplain evolution. Stratigraphic relations indicate that the Fourmile valley floor was as much as two meters higher in the past 2,000 years and that placer reworking, lateral erosion, or minor downcutting dominated from the late Holocene to present. Concentrations of As and Au in the fine fraction of hillslope soil, mining-related deposits, and fluvial deposits serve as a geochemical marker of mining activity in the catchment; reducing As and Au values in floodplain sediment will take hundreds of years to millennia. Overall, the Fourmile Creek catchment provides a valuable example of Anthropocene landscape change for mountainous regions of the Western United States, where hillslope and floodplain markers of human activity vary, high rates of geomorphic processes affect mixing and preservation of marker deposits, and long-term impact varies by landscape location. *Key Words: Anthropocene, human impacts, landscape change, LiDAR, mining.*

人类对于地表过程和物质的冲击, 对于理解提出的人类世时期而言相当关键。本研究检视十九与二十世纪在科罗拉多州的四里溪流域採矿的程度、分布与长期脉络, 并将空中 LiDAR 製图分析与历史文件以及 2013 年洪泛所暴露的河岸之田野调查进行配对。採矿的冲击, 呈现出人类世在此一流域中的支配性地景变迁。採矿活动, 特别是砂矿床的作业, 控制了洪泛平原的地层, 而与採矿相关的废弃沙石堆, 则覆盖了流域中百分之五以上的山坡地。源自採矿活动 (探测、採矿以及建筑) 的山坡表面扰动之总比率, 至少超过十九世纪之前五倍。晚近的洪泛与人类冲击的套印, 使得全新世的洪泛平原演化纪录黯然失色。地层关系显示, 四里溪谷底在过去两千年中竟增高达两公尺, 而砂矿床的重整、侧蚀或微小下切侵蚀, 自全新世晚期主宰至今。砷与金集中于山坡土壤、採矿相关沉积与河流沉积的细粒部分, 作为该流域採矿活动的地理化学标记; 降低洪泛平原沉积物中的砷与金价, 将需耗费数百年至上千年。总体而言, 四里溪流域提供了美国西部山区的人类世地景变迁之宝贵案例, 其中坡地与洪泛平原的人类活动印记不尽相同, 高比率的地形形成过程影响了标记物沉淀的混合与保存, 而长期的影响则随着不同的地景区位而有所不同。 *关键词: 人类世, 人类冲击, 地景变迁, LiDAR, 採矿。*

Los impactos humanos sobre los procesos y materiales superficiales de la tierra son fundamentales para entender la época antropocénica propuesta. Este estudio examina la magnitud, distribución y contexto a largo plazo de la minería de los siglos XIX y XX en la cuenca del Fourmile Creek, Colorado, acoplando el análisis topográfico aéreo LiDAR con documentos históricos y estudios de campo de las bancas del río que la inundación de 2013 dejó expuestas. Los impactos de la minería representan el paisaje de cambio dominante en esta cuenca durante el Antropoceno. La actividad minera, en particular las operaciones tipo minería de placer, controla la estratigrafía de la planicie inundable y los amontonamientos roca

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residual que cubren >5% de las laderas de la cuenca. Las tasas totales de perturbación superficial en las laderas debidas a la actividad minera (prospección, minería y construcción de vías) exceden las tasas anteriores al siglo XIX en por lo menos cincuenta veces. Las recientes inundaciones y la sobrecarga de impactos humanos oscurecen el registro de la evolución de la planicie de inundación en el Holoceno. Las relaciones estratigráficas indican que el fondo del valle del Fourmile era por lo menos dos metros más alto en los pasados 2.000 años y que el trabajo de minería de placer, la erosión lateral, o la menor erosión de profundidad, dominaron desde el final del Holoceno hasta el presente. Las concentraciones de As y Au en la fracción fina del suelo de las laderas, los depósitos relacionados con minería y los depósitos fluviales sirven como un marcador geoquímico de la actividad minera en la cuenca; reducir los valores de As y Au en los sedimentos de la planicie de inundación puede tomar desde cientos de años hasta milenios. En general, la cuenca del riachuelo Fourmile provee un valioso ejemplo del cambio del paisaje en el Antropoceno para las regiones montañosas del oeste de los Estados Unidos, donde los marcadores de actividad humana en ladera y planicie de inundación varían, las altas tasas de los procesos geomórficos afectan la mezcla y preservación de los depósitos de marcación y el impacto a largo plazo varía según la localización del paisaje. *Palabras clave: Antropoceno, impactos humanos, cambio del paisaje, LiDAR, minería.*

Humans are efficient and potent geomorphic agents capable of affecting earth surface processes, redistributing large volumes of earth surface materials that linger in watersheds and modifying and creating landforms (Hooke 1994, 2000; Merritts 2011; Hooke, Martín-Duque, and Pedraza 2012; Tarolli and Sofia 2016). Quantifying human impacts in a landscape is necessary for differentiating human-induced change from background geological processes (Certini and Scalenghe 2011; Perroy et al. 2012; Erlandson 2014; Fraser, Leach, and Fairhead 2014; Ma et al. 2014; Waters et al. 2014; Edwards 2015; Streeter et al. 2015). Detailed studies of changes in earth materials and rates of surface processes are fundamental to defining the proposed Anthropocene epoch, which postulates that landscapes and the environment have been measurably affected by humans (Crutzen and Stoermer 1999; Steffen, Crutzen, and McNeill 2007; Chin et al. 2013; Edwards 2015; Finney and Edwards 2016; Waters et al. 2016). As a geologic time period of global significance, the onset of the Anthropocene is debated, with competing definitions ranging from *early* (beginning 8,000–5,000 years BP in association with early agriculture and measurable greenhouse gas increases), *middle* (beginning ~200–150 years BP in association with the industrial revolution), and *the great acceleration* (beginning ~1950 in association with nuclear testing and widespread plastics; Ruddiman 2003, 2013; Edgeworth et al. 2015; Zalasiewicz et al. 2015; Zalasiewicz et al. 2016). Regardless of which time frame is discussed globally, stratigraphic markers of human processes vary regionally due to a variety of factors, including the timing, magnitude, and type of anthropogenic activity and background rates of geomorphic processes, which determine the transport and preservation potential of sedimentary deposits associated with human activity. Detailed studies in local settings are particularly crucial where contaminants are involved (e.g., from mining and other industrial activities), posing potential threats to the health of forest and human ecosystems.

Humans began to inhabit the Colorado region more than 13,000 years ago, similar to other regions in North America, and were responsible for a range of measurable ecological changes throughout the Holocene (Wohl 2001). Westward expansion of settlers, traders, and trappers in the 1800s drove dramatic human-induced geomorphic and ecological change in the region. The discovery of gold in Colorado in the 1850s accelerated population growth and initiated widespread mining activity throughout the Colorado mineral belt, which extends from the southwestern corner of the state near Durango to Boulder County, northwest of Denver (Tweto and Sims 1963). During the high-intensity mining era (1859–1942), landscape disturbance in Boulder County, including the Fourmile Creek catchment, took various forms, including (1) prospecting, mining, and milling that deposited crushed subsurface rock as unconsolidated material on the surface; (2) placer mining that excavated and washed channel, floodplain, and toeslope deposits from depths as much as 4 m below the surface; (3) railroad, road, and trail building that excavated linear platforms in mainly steep terrain, digging into and locally covering native materials over a depth range of 2 to 4 m; and (4) logging for fuel, charcoal, structures, and mine timbers (Veblen and Donnegan 2005). In other mountain valleys in the Western United States, the amount of sediment displaced by vein and placer mining and by the milling of gold ore exceeds long-term Holocene sediment production by several orders of magnitude (James 1989; Vincent and Elliott 2007).

At present, flooding and channel change are long-term concerns in mountain communities where the legacy of nineteenth- and twentieth-century mining activity and recent land-use alteration interact with short- and long-term effects of climate change and water-use policy (see Madole 2012). Wildfire, flooding, sediment transport, and local debris flows threaten structures built on mining claims patented in the nineteenth century and in areas subdivided and developed since the mining era, as well as downstream areas. Locally, mining legacy sediment impairs downstream water quality (Murphy et al. 2015).

This article couples LiDAR topography analysis with historical documents and field studies to investigate the legacy of mid-nineteenth- to twentieth-century mining and stratigraphy exposed by severe flooding in 2013 in the Fourmile Creek catchment, Colorado Front Range. We address the following specific questions:

1. What are the magnitude, type, and spatial distribution of mining impacts along lower Fourmile Creek?
2. What is the relationship between mining impacts and the Holocene geologic history of the canyon, which also was exposed by the flooding?
3. How does the long-term legacy of mining sediment vary on hillslopes compared to adjacent river valleys?
4. What are the implications of mining impacts for Anthropocene studies?

Human impacts, topographic changes, and potential threats studied here are characteristic of mountainous mined regions of the Western United States and highlight the impact of mining on longer term hillslope and channel change. Mining-affected areas have been studied previously (Lewin, Davies, and Wolfenden 1977; Knox 1987; James 1989; Knighton 1989; Lecce and Pavlowsky 2001; Marcus, Meyer, and Nimmo 2001; Coulthard and Macklin 2003; Lecce et al. 2008; Singer, Aalto, and James 2008), but the introduction of high-resolution LiDAR analysis permits expanded and specific quantification of mining impact on hillslopes and channels. Overall, this article adds to the sparse record of Holocene hillslope change and channel evolution in the Colorado Front Range. We examine the geomorphic overprint of human impacts (Brown et al. 2013) between 1859 and 1942, particularly mining and road building, which represent the dominant Anthropocene landscape changes for the lower Fourmile Creek catchment, associated with both erosion and obscuring of the record of Holocene floodplain evolution.

Setting

The study catchment is cut into the rolling upland of the Front Range west of Boulder, Colorado, and is drained by Fourmile Creek, which originates in a subalpine headwater area and includes numerous small, steep tributaries (Figure 1). The Fourmile Creek catchment has an area of 63 km^2 upstream of the U.S.

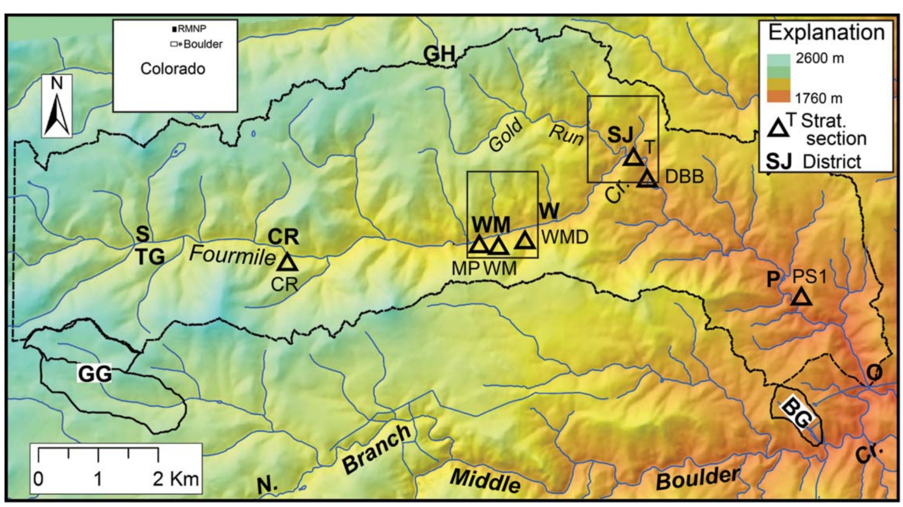

Figure 1. Map of the lower Fourmile Creek catchment (50.3 km^2) showing location of selected stratigraphic sections (CR, MP, WM, WMD, T, DBB, PS1) and place names described in the text: GG = Gordon Gulch; BG = Betasso Gulch; S = Sunset; TG = Todd Gulch; CR = Copper Rock; MP = Metals Production mill; WM = Wood Mine; WMD = Wood Mountain mill; T = Tailings at Salina Junction; DBB = Downstream Bee Bee; PS1 = Poorman; W = Wallstreet; GH = Gold Hill; SJ = Salina Junction; P = Poorman; O = Orodell. The dashed line outlines the lower Fourmile catchment; solid lines delineate Gordon Gulch and Betasso Gulch catchments. Rectangles delineate the extent of Figures 3A and 3B. Inset map shows location of Rocky Mountain National Park. (Color figure available online.)

Geological Survey stream-gauging station Fourmile Creek at Orodell, Colorado (06727500), which is located 0.4 km upstream of its confluence with Boulder Creek. The catchment has an average slope >20° and an elevation range from 1,600 to 2,900 m (Graham et al. 2012). In early September 2010, the Fourmile Canyon fire burned 2,600 hectares (23 percent of the Fourmile catchment) and destroyed more than 160 homes. Burn severity ranged from low to severe (trees charred; soil organic matter burned) in mainly forested terrain (Murphy, Writer, and McCleskey 2012). The wildfire reexposed mining-disturbed areas on slopes that had been revegetating for seventy years or more and decreased the threshold of rainfall intensity required for flooding and sediment mobilization from hillslopes (Murphy et al. 2015). Widespread flooding and local debris flows in September 2013 extensively reworked channel and floodplain areas (Coe et al. 2014; Moody 2016), exposing mining legacy and Holocene sediment along the valley floor.

To help understand the alluvial record in areas less affected by mining activity and recent fires and to test the influence of catchment scale, we also collected data from two adjacent drainages (Figure 1): Betasso Gulch (0.45 km^2) and Gordon Gulch (3.5 km^2). The geomorphology of both catchments has been analyzed in detail as part of the Boulder Creek Critical Zone Observatory research (e.g., Foster et al. 2015).

Climate, Hydrology, and Holocene Channel Change

Present mean annual precipitation in the Fourmile area is ~530 mm, including a significant fraction that falls as snow in winter months (Murphy et al. 2003). Summer rainfall occurs mainly in July and August, associated with convective storms that might produce intense downpours (Ebel, Moody, and Martin 2012) and higher peak discharges than the annual snowmelt flood. Surface runoff from convective storms mobilized large amounts of sediment from burned Fourmile slopes in July 2011 and July 2012 (Murphy et al. 2015) and limited amounts in July 2013, but an extended period of moderate to heavy precipitation produced catastrophic flooding along lower Fourmile Creek in September 2013. Discharge at the Orodell gage peaked at ~70 $m^3 s^{-1}$ (Kimbrough and Holmes 2015) and exceeded bankfull for ~120 hours; the high flows exported ~60,000 to 193,000 m^3 of sediment from the catchment (Wicherski, Dethier, and Ouimet 2017). Anecdotal accounts and historical images show that extensive areas along Fourmile Creek flooded in 1894 and circa 1919; the flood of 1894 is thought to be the largest event since settlers arrived in the Colorado Front Range in the 1850s.

Climate and hydrology are not well documented before the twentieth century. Palynology and fire history studies in the Colorado Front Range and adjacent ranges provide an outline of climate change in those areas during the Holocene and suggest general aspects of changes in temperature and precipitation. Timberline rose rapidly in the early Holocene to elevations above present values, likely peaking before 6,000 years BP, implying warmer and drier conditions (Benedict et al. 2008; Madole 2012). Timberline lowered around 4,500 years BP during Neoglaciation (Benedict et al. 2008), suggesting conditions that were slightly cooler and more moist than at present. Vegetation (Sherriff et al. 2014), slope stability, and stream flow likely responded to these changes in effective precipitation and snowpack, but peak flows and sediment transport also might reflect monsoonal moisture, convective storms during the summer months, or strong El Niño years.

The stratigraphic record of late Quaternary channel change in the Colorado Front Range is sparse and inconsistent, suggesting that late Pleistocene glacial deposits and Holocene climate, as well as catchment elevation and size, could influence the record of hillslope sediment delivery and channel transport. The Fourmile Creek catchment was not glaciated in latest Pleistocene time. Madole (2012) interpreted a postglacial alluvial record (Figure 2) from the Roaring River (a high-elevation headwater catchment in Rocky Mountain National Park) in terms of fluctuating climate emphasizing the texture of alluvial deposits as a proxy for snowmelt intensity and duration. Madole hypothesized that the absence of early-middle Holocene alluvium implies low sediment supply under conditions of relative warmth and a high snow line, a paleoclimate interpretation consistent with other regional studies (Muhs and Benedict 2006; Benedict et al. 2008). Along the Roaring River, deposition of coarse alluvium occurred mainly after about 5,000 years BP, driven by periods of increased snowmelt but punctuated by extended warmer, drier periods. Schildgen et al. (2002) showed that Middle Boulder Creek, an area of glaciofluvial aggradation during late Pleistocene time, cut down through 5 to 10 m of those deposits and locally into bedrock after about 10,000 years BP and fluctuated near its current level in late Holocene time. Downstream along major Front Range drainages, long-term stratigraphic records suggest that deep incision into High Plains sedimentary fill occurred only during the warmest part of extended interglacials, when sediment supply was low (Duhnforth et al. 2012).

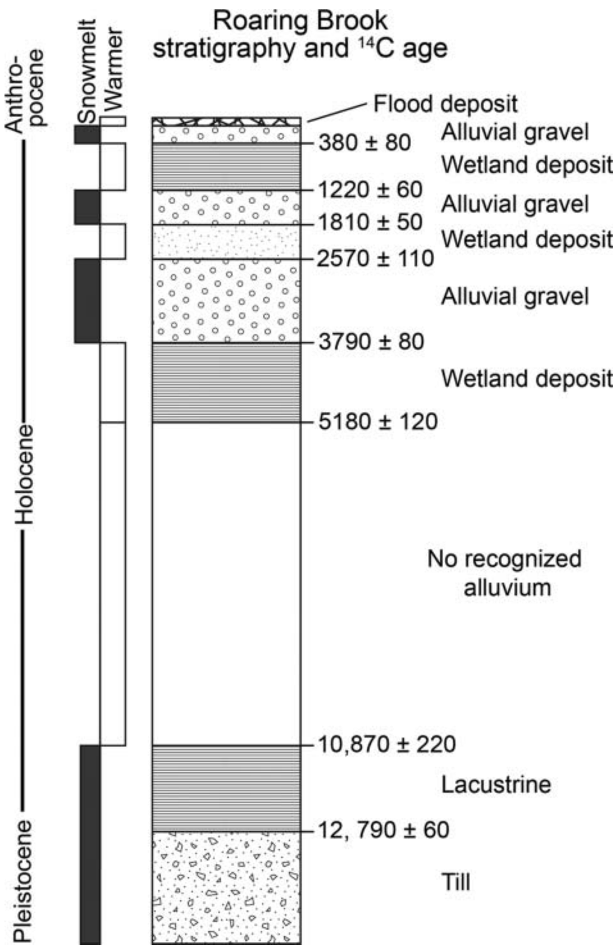

Figure 2. Late Pleistocene and Holocene alluvial record from the unglacierized Roaring River catchment, located in Rocky Mountain National Park (RMNP), some 30 km northwest of the lower Fourmile catchment (see Figure 1). Deposits are interpreted as reflecting periods of stronger or weaker snowmelt runoff (modified from Madole 2012, figure 5).

Geology and Mining History

Fourmile Creek and adjacent catchments are developed primarily in felsic gneisses and schists (~1.8 Ga), intruded in the lower basin by Boulder Creek Granodiorite (~1.7 Ga) and Longs Peak Granite (~1.4 Ga; Cole and Braddock 2009). Porphyritic dikes (60–30 Ma) of varying composition cut the older rocks. Mineralization, mainly gold tellurides and local pyrite, galena, and sphalerite, occurs with quartz veins 0.1 to 5 m wide in northeast-trending fractures and within northwest-trending silicified zones known as reefs.

The mining history of the Gold Hill and Sugarloaf Districts, which include most of the Fourmile Creek catchment, is typical of gold rushes in the Western United States and across the globe; sediment from gold rush activities provides a convenient local marker for the beginning of the widespread redistribution and concentration of earth materials by human activity. Gold was discovered near Gold Hill in 1859 and as many as 5,000 prospectors dug small surface mines on the principal veins and established placer operations along Fourmile Creek and its main tributary, Gold Run (Twitty 2007). Free gold from oxidized, near-surface regolith was soon exhausted, but the recognition of gold telluride minerals and, eventually, the ability to extract gold from pyritic and telluride ores led to extensive underground mining and episodic placer mining in the next eighty years (Lovering and Goddard 1950). Silver, lead, and zinc were significant to minor by-products at a few mines. A narrow-gauge railroad, built for the mining industry along Fourmile Creek and completed in 1883, supplemented an extensive network of roads and paths that connected mines, mills, and small towns. The flood of 1894 washed out extensive areas of the railroad, which was rebuilt in 1898, only to be washed out again in 1919 (Twitty 2007). Individual mining and milling operations generally were short-lived, controlled by the limited extent of most veins, the difficulty of extracting gold from the ore, logistical challenges, and external economic factors that controlled gold and silver prices. Overall, patented lode claims were established on much of the upland area and more than 70 percent of the Fourmile Creek floodplain above Salina Junction was covered by patented placer claims and mill sites; many of these claims became building sites as the population of Boulder Country grew (Twitty 2007). Gold mining peaked in 1892; vein and placer production was limited from World War I until 1934, when federal policy increased the price of gold and many mines operated again until 1942, when World War II rules shut most of them permanently (Murphy 2006). Mining history in Fourmile Canyon was typical of mineralized areas at the northern end of the Colorado mineral belt, where moderate production between 1865 and 1965 came mostly from underground mining of Au-bearing and base metal veins and lodes of limited vertical and lateral extent (Koschmann and Bergendahl 1968). Gold production from placer operations was relatively minor but produced extensive channel disruption (Lovering and Goddard 1950).

Methods

We coupled LiDAR analysis of surface disturbance (e.g., James et al. 2012) and historical photos of mining activity with field studies of stratigraphic exposures and sediment transport (Wicherski, Dethier, and Ouimet 2017). Widespread bank erosion during the September 2013 flood along Fourmile Creek and some tributaries locally exposed Holocene and mining legacy deposits; extensive channel and floodplain reworking during the flood provides a good model for the geomorphic effects of infrequent events. Studies of latest Pleistocene and Holocene deposits in adjacent headwater catchments (from Betasso and Gordon gulches and summarized in Leopold et al. 2011; Shea et al. 2013; Foster et al. 2015) provide context for results from Fourmile Creek.

LiDAR Analyses and Related Field Measurements of Mining Legacy Sediment

This study took advantage of digital elevation models (DEMs) derived from two airborne LiDAR missions, one flown in August 2010 immediately before the Fourmile Canyon Fire with ~10 points m^{-2} (S. P. Anderson, Qinghua, and Parrish 2012) and the other flown in November 2013 after the September 2013 flooding, with 2 to 5 points m^{-2} (S. W. Anderson, Anderson, and Anderson 2015). In a 50.3-km^2 area of the 63.3-km^2 Fourmile catchment (we excluded the upper reaches because they were not included in all of the LiDAR coverage; we refer to the 50.3 km^2 area as the lower Fourmile Creek catchment) we used the 1- and 2-m DEMs as a base to manually digitize topography disturbed by historical prospecting and mine-related activity. We used a screen view of 1:1,500 as a digitizing window. Prospect pits smaller than ~2 m in diameter and historical placer operations could not be resolved consistently on the LiDAR DEMs, but we mapped roads and trails as narrow as 1.5 m in most areas. We also digitized the location of the railroad grade where it could be distinguished from roads that locally follow the alignment of the grade. Along Fourmile Creek, we measured raster difference between the 2010 and 2013 DEMs to compute erosion and deposition changes in the floodplain area.

We did not conduct a systematic field study of mining legacy deposits in the lower Fourmile catchment, but we measured deposit areas and estimated thicknesses locally using field surveys as we mapped exposures and sampled deposits. Measurements allow us to estimate the impact of vein mining-related activities on hillslopes, a subject mainly neglected in previous work. LiDAR elevations were used to measure the maximum thickness of sixty-one mine waste deposits at adits and shafts in the heavily mined Gold Run and adjacent catchments and we field checked fourteen of those sites as we sampled their geochemistry. In the adjacent Gordon Gulch catchment, we surveyed prospect pit volumes at fifty-one sites. On hillslopes near Wood Mine and Wall Street, we used the LiDAR DEMs to measure diameters and rim-to-pit depths and an assumption of 30° pit slopes to calculate volumes at ~115 sites, in areas where we also mapped and sampled soil catenas. We estimated the thickness of railroad and mine road fills based on the volume of material removed for the mean tread width and an average value of 30° for basin hillslopes.

Historical Photos and Records of Mining Activity

High-resolution historical images in the collection of the Carnegie Branch Library for Local History (http://nell.boulderlibrary.org/) in Boulder, Colorado, portray placer, mining, and milling activity and channels in the Fourmile catchment and adjacent areas. We downloaded property boundary maps (http://www.bouldercounty.org/gov/data/pages/gisdldata.aspx) for the area between Orodell and Sunset (Figure 1), sorted the records for parcels that included patented placer claims, and plotted them on our geographic information system base. Finally, we searched published research for historical mine, mill, and placer locations; records of crude ore and waste production; and formal and anecdotal accounts of mining and milling activities in the region (Cobb 1999; Twitty 2007; Anstey and Thomas 2013). Estimating crude ore and waste rock production from historical figures was challenging; individual mines did not keep long-term records, but values can be approximated from data in Henderson (1926) and in Lovering and Goddard (1950).

Stratigraphic Studies in the Fourmile Creek Catchment and Adjacent Areas

After examining sites of bank and toeslope erosion along an ~18-km reach of Fourmile Creek in October 2013 and June 2014, we surveyed and sampled in detail those sites that best exposed stratigraphic relations in the floodplain, on adjacent hillslopes (Figure 1), and in the numerous prospect pits that punctuate the landscape. Along Fourmile Creek, most channel and floodplain exposures are <2 m thick. Charcoal fragments at two Fourmile sites (Wood Mine and Downstream Bee Bee; sites WM and DBB in Figure 1) were submitted to the AMS laboratory at

Woods Hole Oceanographic Institute for ^{14}C dating. ^{14}C calendar ages were calibrated to years BP using the Fairbanks0107 calibration curve (Fairbanks et al. 2005). In two areas (Copper Rock and Wood Mine), we used shallow geophysical techniques to study subsurface stratigraphy and the depth to bedrock. In Betasso and Gordon gulches, deeper cuts mapped by Leopold et al. (2011) and Shea et al. (2013) expose alluvial and colluvial deposits of latest Pleistocene and early Holocene age in an area of limited mining-related sediment.

Elemental Analyses of Floodplain Sediment

From 2011 to 2014, we sampled hillslope, mine and mill-waste deposits, and tributary and floodplain deposits in the Fourmile Creek catchment from Sunset to near Orodell (Figure 1); we include three samples of suspended sediment collected during postwildfire flood events in 2011 and 2012, as described in Murphy et al. (2015). After oven-drying at 80°C for twenty-four hours, we separated samples using a 150-μm sieve and submitted ~20 g of the <150-μm fraction to Acme Analytical Laboratories in Vancouver, British Columbia (now Bureau Veritas Minerals; see vmininfo@ca.bureauveritas.com), for complete elemental analysis by inductively coupled plasma-mass spectrometry and instrumental neutron activation analysis techniques.

Results

LiDAR DEM studies and analysis of historical photos and documents help us to estimate the volume of mining legacy sediment and provide a context for field studies of the 2013 flood event and fresh exposures it revealed. Large volumes of mining legacy sediment and some Holocene toeslope sediment remain in storage. Placer mining beginning in 1859, large floods in 1894 and 2013 (Anstey and Thomas 2013), smaller floods, and the annual snowmelt flood have reworked and resurfaced much of the lower Fourmile Creek floodplain and those of its major tributaries. Gravels displaced by placer operations are interfingered with flood deposits and extend along Fourmile Creek from Sunset to the confluence with Boulder Creek. Patented placer claims indicate the main areas of disruption; historical photos and documents allow us to estimate the reworking depth for floodplain and toeslope deposits. The fine fraction of mining legacy deposits, tributary, and floodplain sediment along Fourmile Creek is enriched in As, Au, and other metals compared to upstream sediment and hillslope soils.

Imprint of Mining on the Fourmile Creek Landscape

Our results document the profound influence of mining, road, and railroad construction on hillslopes and the floodplain in the Fourmile catchment. Road and railroad construction disrupted and locally buried toeslope areas and helped to recycle large volumes of waste rock from mining and milling as fill material. Many mine shafts and adits were located on hillslopes or in upland areas away from the valley floor, but most mills and some mine tunnels were near channels or close to the railroad. Prospect pits, mine waste dumps, and roads and paths on hillslopes are well defined on the 1- and 2-m DEMs (Figure 3), particularly where the 2010 wildfire thinned or removed the canopy. The Gold Hill district, including most of the lower Fourmile Creek catchment, produced an estimated ~706,300 tons of crude ore valued at ~$8.5 million between 1904 and 1944; total production is not known but might have been $12 million to $14 million (Lovering and Goddard 1950) or about 10^6 tons. By way of comparison, the upper Animas/Silverton District in southwestern Colorado might have produced about 18.1 $\times$ 10^6 tons of crude ore, much of it from wide veins rich in lead and zinc sulfides (Church et al. 2007). Waste rock in the Fourmile area originated from unmineralized shafts, tunnels, levels, and vein margins and likely ranged from 15 percent to 80 percent of crude ore volumes, depending on tunnel size and vein and stope width. It was common practice to fill overhand stopes with waste material as veins were mined from the bottom up (e.g., Ransome 1901; Hoover 1909). Such waste material likely came from stope margins but could have originated elsewhere in the mine or from previously milled rock. If we assume a mean stope width of ~1.3 m and tunnel and shaft cross sections of ~3.3 m^2, we can locally estimate the proportion of waste rock from mining. Detailed maps of the Ingram Mine (Lovering and Goddard 1950, Plate 27), which operated episodically for sixty years, show that 30 percent to 40 percent of the ~22,000 m^3 of mined rock was from tunnels and shafts. The value was ~15 percent at the Slide Mine (Lovering and Goddard 1950, Plate 24), which mined the largest and richest veins in the district. Measured values thus suggest that mining removed at least 1.25 $\times$ 10^6 tonnes of rock from the subsurface of the Gold Hill area, producing >10^6 m^3 of legacy waste rock. Local milling of the crude ore likely exceeded 50 percent of the total ore removed from the subsurface, adding to the volume of fine-grained waste

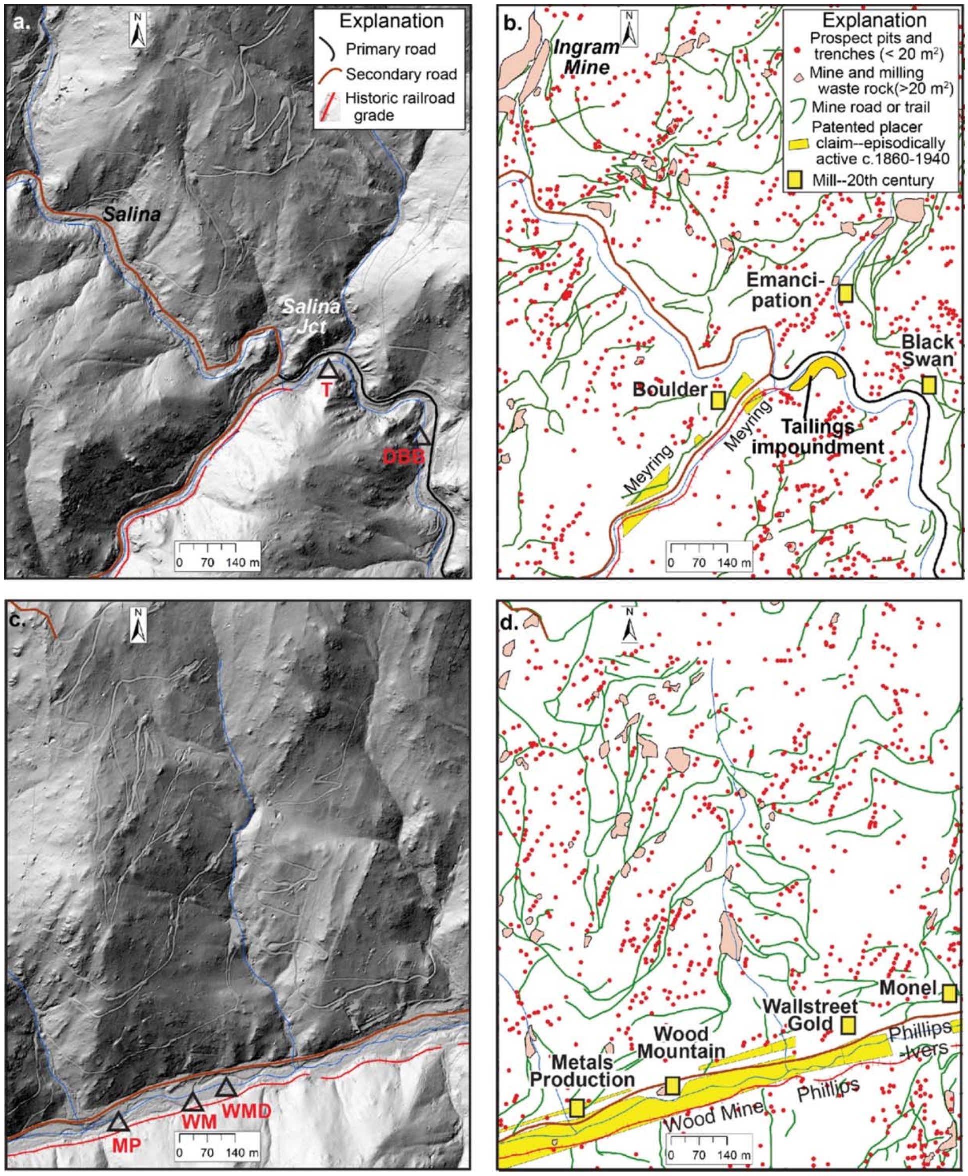

Figure 3. LiDAR hillshade and interpreted images showing place names and digitized features and areas of surface disruption related to historical mining activity: roads and trails (black, brown, and green); historical railroad grade (red); placer claims (yellow); historical gold mills (yellow rectangles); stratigraphic locations described in the text (black triangles). A and B show the area near Salina Junction. C and D show the area between Wood Mine and Wallstreet (see Figure 1). (Color figure available online.)

material in the catchment; at least some of the mill waste was dumped directly into Fourmile Creek or Gold Run (Murphy 2006).

Placer operations, mill sites, and historical tailings ponds in the floodplain generally were difficult to distinguish on DEMs but were locally exposed in the field and are noted in historical and geological accounts (Lovering and Goddard 1950; Twitty 2007). Placer operations (Figure 4) and milling activities altered the channel and floodplain between Copper Rock and Salina Junction and between the Poorman area and Orodell (Figure 1). Historical images of placer mining show that operations locally extended at least 5 m below the surface in alluvial and colluvial debris and reworked the entire floodplain, probably several times in some areas. Tailings were dumped into the channel until the 1930s and waste rock was used for roads and the railroad and locally filled portions of the floodplain, as well as parts of many tributary valleys and gulches. Deposits remaining from prospecting, mining, and road building in the lower Fourmile Creek catchment (Table 1) thus represent a minimum value for production of these legacy sediments. Extended storms like that in 1894 reworked or altered most of the Fourmile Creek floodplain; local

Figure 4. Historical photographs of Fourmile Creek placer operations. (A) View downstream (east) across Wood Mountain placer operations toward Wood Mountain Mine and mill, circa 1900. Note narrow gauge railroad and extensive embankment along base of north-facing slope (on right). *Photo Credit*: Carnegie Branch Library for Local History Photo S-1816. (B) View of Wood Mountain Placer near Wallstreet. *Photo Credit*: Carnegie Branch Library for Local History Photo 219.10.3, taken between 1878 and 1901 by J. Collier and labeled "Wallstreet."

devastation produced by flash floods and the collapse of tailings impoundments in the 1930s are noted in historical summaries (e.g., Cobb 1999).

Holocene to Present Stratigraphy along Fourmile Creek

The stratigraphic record of alluvial and toeslope change is fragmentary along Fourmile Creek, obscured and reworked by nineteenth- to early twentieth-century activities related to mining, and by major floods. Flood deposits from 2013 near stratigraphic section DBB (see Figure 1) are rich in asphalt clasts. Floodplain deposits locally contain artifacts (e.g., brick and tile fragments, cinders) mobilized by mining and related railroad and road activity. We did not map any exposures of early Holocene age along Fourmile Creek or its tributaries, but the ~10 m thickness of alluvium

Table 1. Characteristics of surfaces disturbed by mining-related activity in lower Fourmile Creek catchment (50.3 km^2), measured and estimated from LiDAR DEM images

Category	Number	Length (km)	Min width (m)	Max width (m)	Thickness (m)	Area (km^2)	Volume (m^3)
Railroad[a]		28.76	4	8	2	0.17	3.45E + 05
Major roads[b]		15.56	9	12	3	0.16	4.90E + 05
Local roads[b]		48.7	6.5	9	2	0.38	7.55E + 05
Roads and trails[c]		431	1	6	1.5	1.51	2.26E + 06
Mine dumps (>40 m^2)[d]	459				4	0.40	1.60E + 06
Placer claims[e]	15				4	0.71	2.84E + 06
Prospects/small mine dumps[f]	18,002		2	6	2	0.23	4.52E + 05
Tailings impoundment (Salina Jct.)					4	<0.01	1.30E + 04
Total mine dumps and prospects						0.63	2.05E + 06
Total disrupted area						3.56	8.75E + 06

Note: DEM = digital elevation model.
[a]Length and width measured from LiDAR DEMs; thickness of disrupted material estimated from mean road and railroad widths and average hillslope values of ~30°; fill thickness checked in field exposures in 2013 and 2014.
[b]Designation and standard dimensions from http://www.bouldercounty.org/gov/data/pages/gisdldata.aspx; thickness of disrupted material estimated from mean road widths and average hillslope values of ~30°; fill thickness checked locally in field exposures in 2013 and 2014.
[c]Thickness of disrupted material estimated from mean road and trail widths measured on LiDAR DEMs and average hillslope values of ~30°.
[d]Areas measured from LiDAR DEMs, thickness estimated as LiDAR measurement of maximum thickness × 0.5, based on field measurements near Salina, Wallstreet, and Wood Mine.
[e]Area measured from patented placer claims (http://www.bouldercounty.org/gov/data/pages/gisdldata.aspx) and historic accounts. Depth of placer mining estimated from images, historic accounts of Fourmile placer mining, and descriptions of Colorado placer mining techniques in Henderson (1926).
[f]Prospect dimensions estimated from field measurements ($n = 51$) in Gordon Gulch and LiDAR measurements of depth ($n = 112$) in the lower Fourmile catchment. Most small mine dumps are >2 m thick.

imaged beneath the floodplain near Copper Rock and Wood Mine (Wicherski, Dethier, and Ouimet 2017) probably includes pre-late Holocene deposits. Deposits exposed by lateral erosion in the 2013 flood include modern and older alluvium (Figure 5), placer debris, tailings and mine waste rock, railroad and road subgrade, and local areas of thick toeslope colluvial debris. We describe and illustrate each of these stratigraphic settings next.

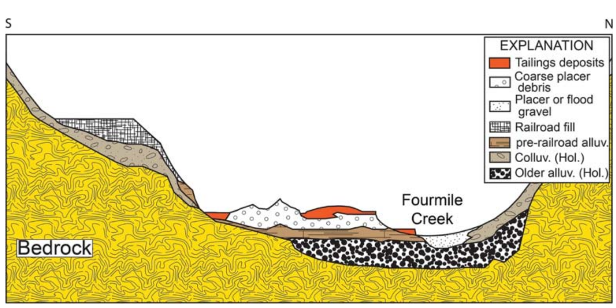

Figure 5. Schematic cross section of the Fourmile Creek valley west of Salina Junction showing stratigraphic and lateral relationships of mining era and premining (late Holocene) deposits. Valley-floor width is approximately 70 m. (Color figure available online.)

Holocene Deposits

Two exposures of colluvium demonstrate local accumulation in toeslope areas, beginning before ~3,400 years BP (Figures 6 and 7; Table 2) and extending into the mining era, which is marked by coal and slag fragments in the colluvium (DBB site). At the Wood Mine (WM) site, the highest dated charcoal layer (~475 years BP) in the section is 0.5 m below a layer of coarse, angular boulders likely derived from late nineteenth-century railroad construction. Charcoal layers and lenses at both sites imply that fires were common in late Holocene time. Gravelly sand encloses the oldest charcoal at the DBB site and overlies a red layer that likely formed during a fire; other charcoal-rich layers at the site appear to have been transported downslope, whereas those at Wood Mine might have been transported downslope and down the valley. The highest layer of alluvial sand at Wood Mine is about 1.4 m above the present channel and dated at ~1,880 years BP, which provides a minimum value for local channel aggradation in late Holocene time.

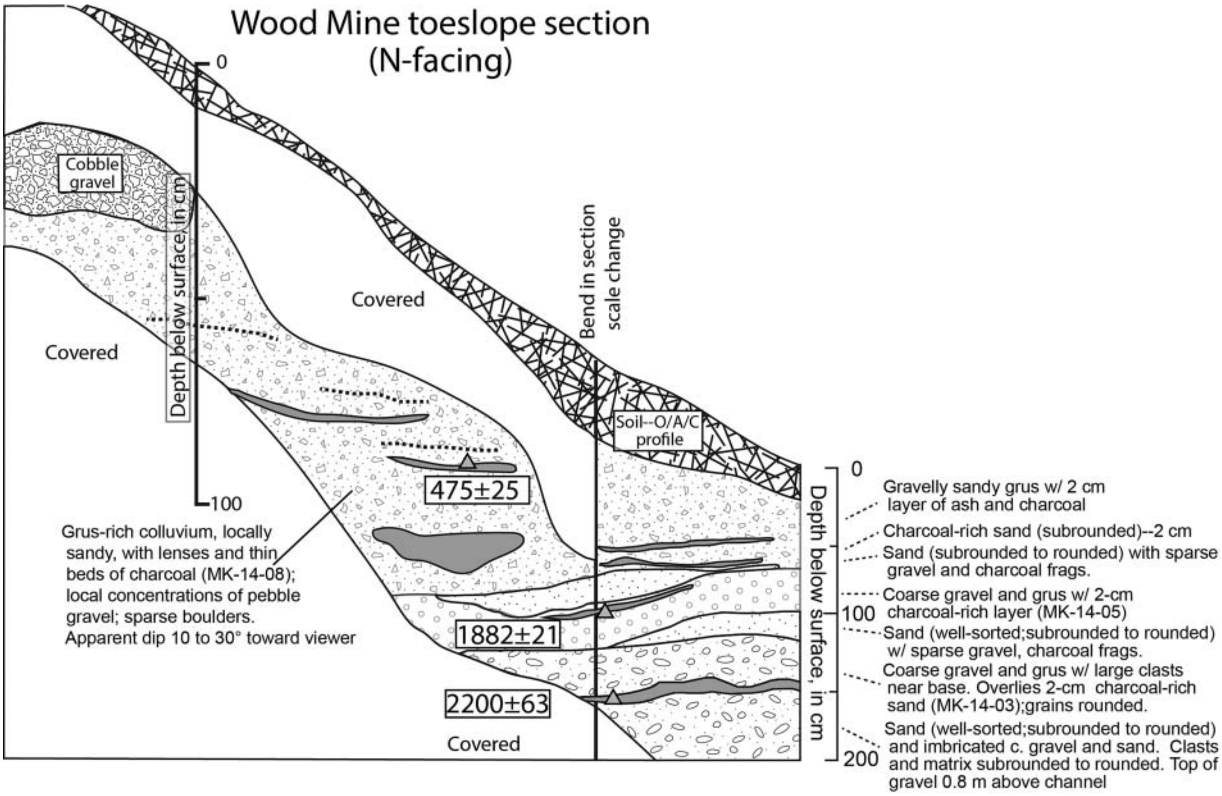

Figure 6. Composite stratigraphic section at Wood Mine colluvial site, located on a north-facing toeslope next to Fourmile Creek, downhill from the historical railroad grade. Section is ~ 6m wide; note that vertical scale changes at bend in section.

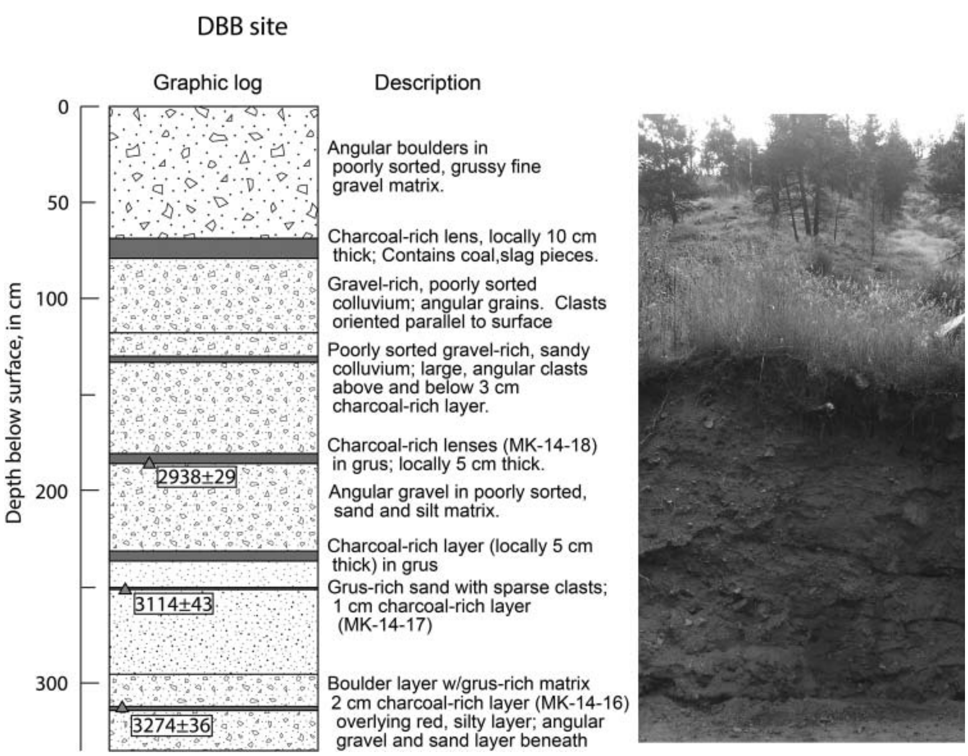

Figure 7. Stratigraphic section and image showing thick toeslope deposit at DBB site, 1 km downstream from Salina Junction. DBB = Downstream Bee Bee.

Table 2. ^{14}C ages and content for charcoal exposed at Wood Mine and DBB sites

Sample name	Location	Sample depth (cm)	Material	Age in years BP[a]	Calibrated age in years BP[b]
MK-14-8	WM	80[c]	Charcoal	390 ± 15	475 ± 25
MK-14-5	WM	100[d]	Charcoal	1,940 ± 20	1,882 ± 21
MK-14-3	WM	150[d]	Charcoal	2,180 ± 20	2,200 ± 63
MK-14-18	DBB	180	Charcoal	2,840 ± 20	2,938 ± 29
MK-14-17	DBB	260	Charcoal	2,950 ± 20	3,114 ± 43
MK-14-16	DBB	320	Charcoal	3,050 ± 20	3,274 ± 36

Note: DBB = Downstream Bee Bee.
[a] ^{14}C years BP.
[b] Based on Fairbanks0107 calibration curve (Fairbanks et al. 2005).
[c] Figure 6, left scale.
[d] Figure 6, right scale.

Nineteenth- and Twentieth-Century Deposits

Railroad and roadbed deposits, composed in many places of mine waste rock, are preserved above Salina Junction in several areas where they did not wash out in the 1894 flood, which eroded and reworked extensive areas of the floodplain and adjacent areas at least as far west as Copper Rock (Figure 8). Reconstruction of eroded roadbed was substantial, and at Salina Junction the new railroad yard nearly filled the floodplain in an area that later became the site of a tailings impoundment. In the steeper, narrow canyon downstream from Salina Junction, the modern highway is built on the old railroad grade in many locations; in other areas, repeated flooding from Fourmile Creek and tributary channels has removed all of the original trestles and cut locally into the railroad grade. Downstream, near Orodell, both houses and roads occupy the original right-of-way and the railroad fill has been repurposed locally as bank protection. Cutbank exposures at Poorman (Figure 9A; site PS1 in Figure 1) and at other nearby areas reveal railroad grade that was excavated into a steep hillside and built on at least 0.8 m of fill, which overlies a massive, poorly sorted deposit (fill); a sandy alluvial gravel; and adjacent sidecast material. At Copper Rock (Figure 9B; site CR in Figure 1), the road grade overlies angular, oxidized rock fragments, probably from an adjacent tunnel, and covers fine-grained, organic-rich alluvium.

One of the largest preserved gold milling deposits along the Fourmile Creek floodplain, a circa 1940 tailings impoundment, was built over the historical railroad yard and siding at Salina Junction (Figure 10; site T in Figure 1). Original volume likely was >15,000 m^3.

Between about 1942 and 2012, much of the original impoundment had become revegetated, the protective cover of sandbags and flanking riprap had disappeared, and erosion had removed part of the deposit. During the 2013 flood, erosion cut deeply into the legacy deposits, revealing the remains of the underlying railroad yard. Lateral erosion by Fourmile Creek also exposed part of the wood frame that anchored the dam and eroded the adjacent highway in two places, undercutting the mine waste rock on which it was built. Raster difference calculations show that the 2013 flood eroded between 3,000 and 4,000 m^3 of the fine-grained tailings at this location. The U.S. Environmental Protection Agency removed the remaining tailings, which contained relatively high concentrations of As, Au, and Pb, to an offsite landfill in 2015.

Upstream from Salina Junction, we were able to identify remnants of tailings impoundments from the 1930s only near the Metals Production and Wood Mountain mills, respectively (Figures 11A and 11B; sites MP and WMD in Figure 1). Distinctive yellow tailings could be traced in alluvium for 150 m downstream from these impoundments and as local lenses in alluvial deposits for an additional 100 to 200 m. Field observations thus suggest that fine material typical of gold ore treated by milling and flotation is not preserved widely as discrete layers in the Fourmile floodplain. Tailings impoundments are mentioned in accounts of the 1930s mining boom (Twitty 1977); fine waste from earlier milling activity along Fourmile Creek and its larger tributaries likely flowed downstream and into Boulder Creek and beyond. Placer operations also would have sent fine sand, silt, and clay downstream as suspended load.

Discussion

Legacy of Nineteenth- and Twentieth-Century Mining in the Lower Fourmile Creek Catchment

Mining legacy sediment dominates floodplain surface stratigraphy, and deposits related to historical

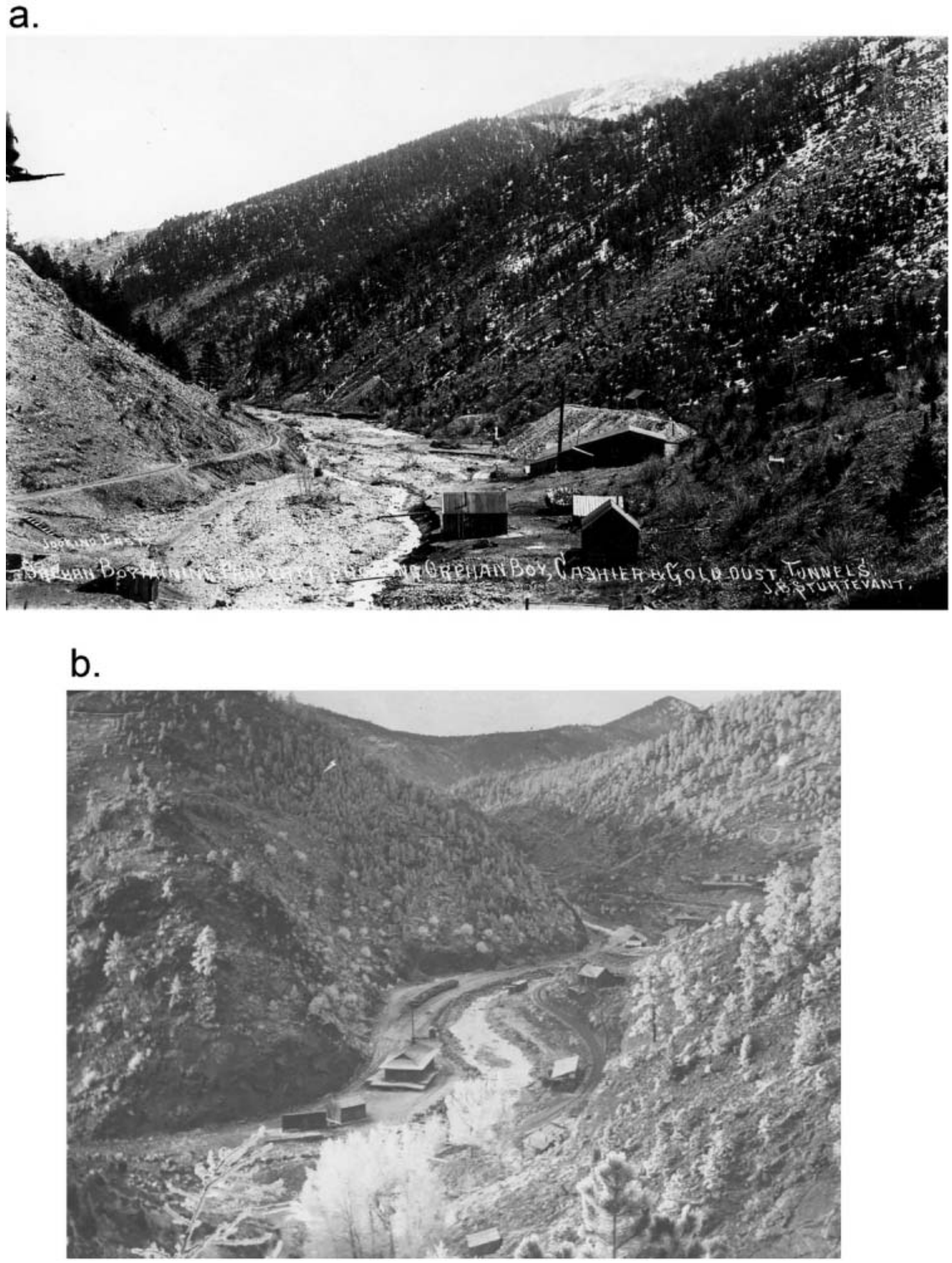

Figure 8. Historical views of the Fourmile Creek floodplain and adjacent steep hillslopes. (A) View downstream across Copper Rock mining camp between 1884 and 1910, showing disrupted channel and waste rock piles at the Orphan Boy and other tunnels. Photograph probably taken after the 1894 flood and before 1898, when the railroad was rebuilt. Large waste rock piles visible in this image have disappeared. *Photo Credit*: Carnegie Branch Library for Local History Photo 219-7. (b) View west across railroad yard, train station, and Fourmile Creek, Salina Junction, circa 1909–1913. Flat areas upstream and downstream from station formed the base of the 1930s tailings impoundment. *Photo Credit*: Carnegie Branch Library for Local History Bernard & Grace (Hoover) Meyring Virtual Photograph Collection, Photo 999-3-4.

mining cover >5 percent of hillslopes along the lower Fourmile catchment. Erosion and deposition related to placer reworking of the channel and to other mining activity, together with repeated flooding along Fourmile Creek, have removed or covered Holocene and late Pleistocene deposits. Mining legacy sediment on hillslopes is not well connected to the Fourmile Creek channel or to its principal tributaries. Large volumes of this sediment, much of it relatively coarse waste rock that accumulated in mine dumps between about 1860 and 1942, remain on the slopes of the Fourmile Creek catchment. Some of the $\sim 1.6 \times 10^6$ m^3 of sediment is stable, but many legacy deposits are in gullies or on slopes steeper than 20 percent and locally include

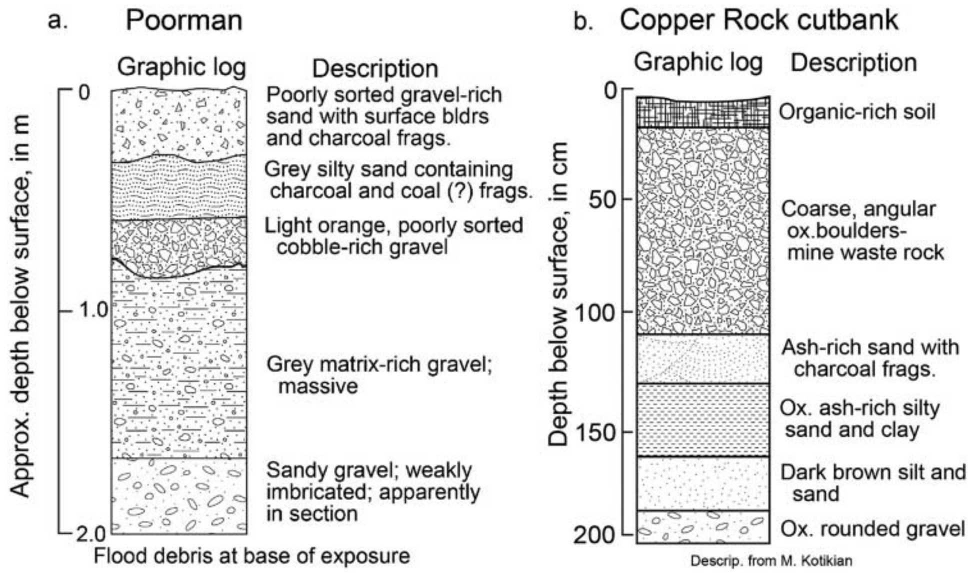

Figure 9. Stratigraphic section showing coarse fill exposed beneath historical railroad grade. (A) Poorman site and (B) Cutbank at Copper Rock site.

remnants of legacy deposits that eroded in response to storms after the 2010 wildfire. Deposits in lower Fourmile Creek subcatchments that have high erosion potential (Ruddy et al. 2010) could move downslope if changing climate produces more intense rainstorms that connect hillslope erosion with channels.

Several periods of placer mining and large floods reworked the lower Fourmile Creek floodplain after 1860, but fine sediment geochemistry continues to reflect the mining legacy. We did not recognize discrete pre-1933 gold milling deposits in our floodplain mapping and hypothesized that most fine material released by mining and milling was transported downstream or mixed with sediment unrelated to mining. Concentrations of As in the <150-μm fraction of floodplain sediment near the mouth of Fourmile Creek are five to ten times the concentrations measured at sites upstream of Copper Rock, and Au concentrations are at least two to four times higher (Figures 1 and 12). Sediment concentrations after the 2013 flood were similar to concentrations measured in the two years after the 2010 wildfire. The range of As and Au concentrations in sediment from tributaries is similar to that of samples from the Fourmile Creek floodplain; concentrations of soil collected from unmined hillslopes are two orders of magnitude lower. Because the volume of mine waste rock and tailings on Fourmile Creek hillslopes and gullies exceeds 10^6 m^3, concentrations of As and other contaminants in floodplain sediment are likely to remain high for hundreds of years to millennia, as suggested by studies in other areas where contamination in channel sediments continues to be supplied from other reservoirs in the catchment (Marcus et al. 2001; Dennis et al. 2009).

Mining-related disturbance profoundly altered Fourmile Creek hillslopes and near-channel areas; episodic erosion has connected some mining deposits on hillslopes with tributary channels and the Fourmile Creek floodplain. During the mining era, vein mining added rock material from as deep as ~300 m below the surface at nearly 500 sites, locally filling gullies and creating steep-sided, mineral-rich mounds that cover >1.2 percent of the surface. Dirt roads, trails, and the railroad grade cover an additional 4 percent of the catchment. During the 2013 flood, two large debris flows in the Gold Run drainage transported >40,000 m^3 of slope material rich in mining debris to Fourmile Creek and >10,000 m^3 of sediment moved down other tributaries in smaller debris flows (Wicherski, Dethier, and Ouimet 2017). Mine waste rock from dumps and dirt roads also formed an important component of sheetwash, most of which flowed from heavily disturbed areas (Figure 3) that burned in 2010.

Long-Term Geomorphic Context of Historical Mining

The longer term alluvial record in the Fourmile area provides a context for analyzing late Holocene and mining-era channel and hillslope changes in the lower Fourmile Creek catchment. Before the mining era, the pace of downcutting along local channels and

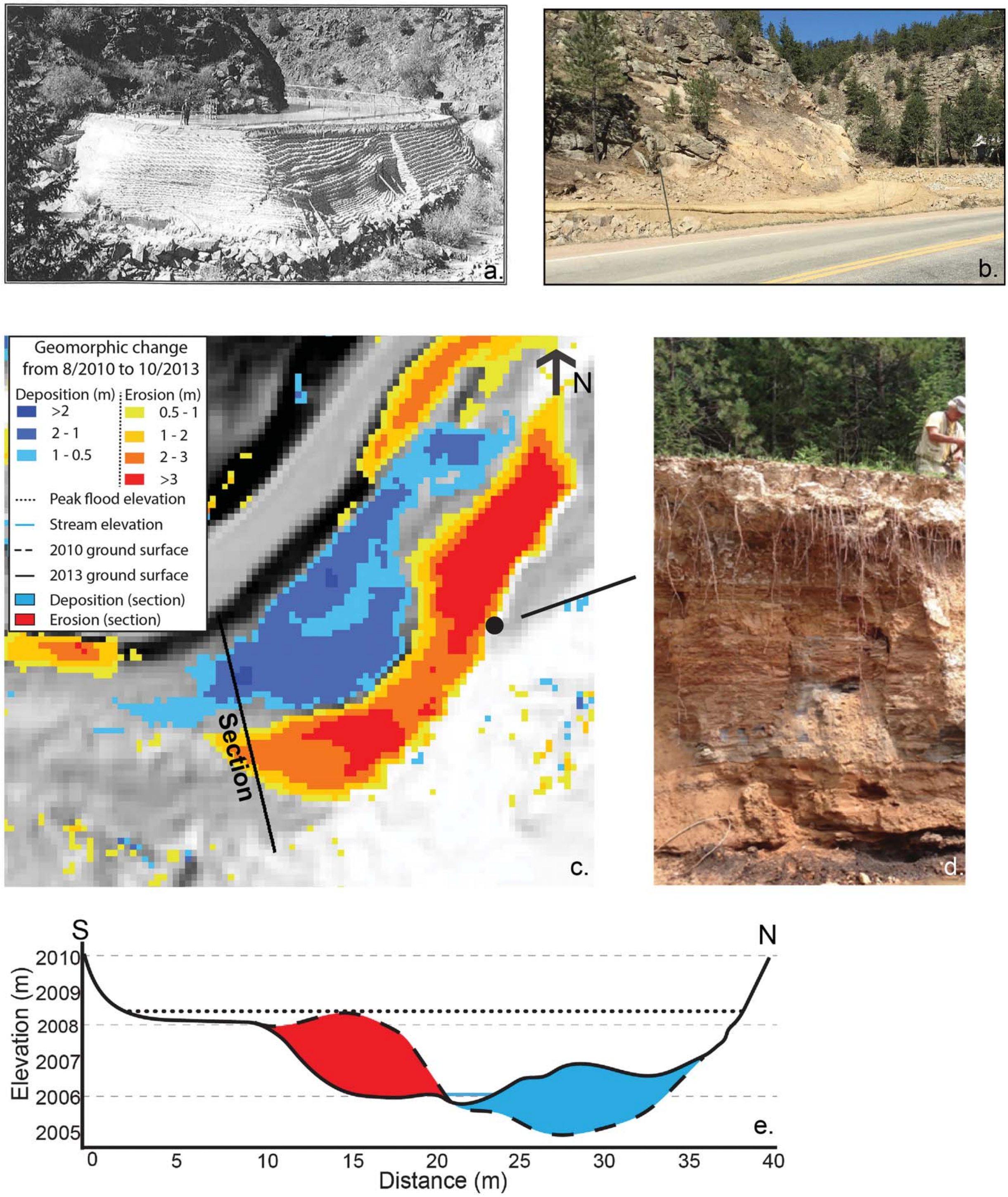

Figure 10. Images, plan view, and cross sections of the tailings impoundment area downstream of Salina Junction. (A) View (circa 1940) looking upstream at tailings impoundment. *Photo Credit*: Carnegie Branch Library for Local History, Boulder Historical Society Collection (213-Salina). (B) Image of the impoundment site after tailings were removed (28 March 2015). (C) Plan view of geomorphic changes in the impoundment area from 2010 to 2013, measured by raster difference. (D) Image showing eroded tailings (site T in Figure 1); dark material at base is coal-rich railroad debris. (E) Cross section of channel change in the 2013 flood, measured by raster difference and field surveys. (Color figure available online.)

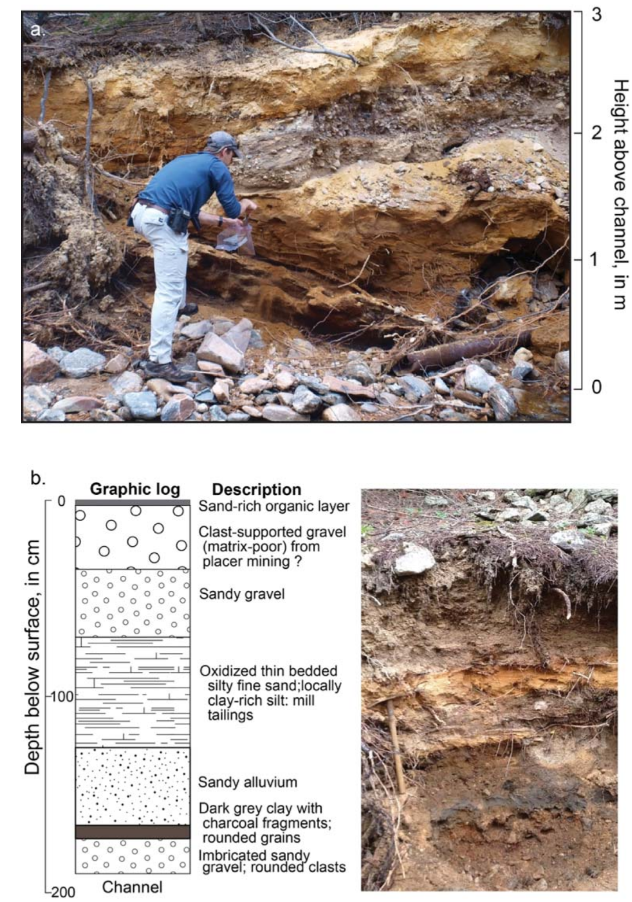

Figure 11. Exposure of eroded tailings deposits along Fourmile Creek. (A) Downstream from the Metals Production mill along near W. Emerson Gulch. (b) Stratigraphic section and image of eroded tailings deposit downstream from the Wood Mountain mill. (Color figure available online.)

floodplain changes likely reflected the volume of stored late Pleistocene sediment and peak stream power, controlled by the annual snowmelt flood and large storms, particularly those following wildfires (Murphy et al. 2015). Unlike Middle Boulder Creek and Roaring River, which preserve late Pleistocene glaciofluvial deposits beneath local terrace remnants, late Pleistocene deposits do not flank lower Fourmile Creek. Local evidence from hillslope studies and dated sections in Betasso Gulch and Gordon Gulch, both of which share a divide with the Fourmile Creek catchment (Figure 1), suggest that small headwater channels first eroded and then aggraded during late Pleistocene and early to at least middle Holocene time. In Betasso Gulch, a 4-m-thick exposure on a first-order tributary records filling of a gully cut through 4 m of saprolite with material eroded from nearby hillslopes, beginning before 18,000 years BP and continuing until after ~5,400 years BP (Leopold et al. 2011). In lower Gordon Gulch, alluvial fans draining north- and south-facing slopes aggraded over main channel alluvium from before 9,900 years BP until after 1,900 years BP, when small tributary channels cut down below the fan surfaces. Radiocarbon ages (1,110 ± 50 years BP and 1,520 ± 40 years BP) on wood from beneath two low stream terraces upstream from the fans imply that during the past ~1,100 years the channel has changed <1 m vertically (Shea et al. 2013). Upstream from the dated sites in both Betasso Gulch and Gordon Gulch, colluvium on toeslopes and alluvial fans is thick locally, suggesting that channel capacity has not been sufficient to transport all the sediment delivered from hillslopes in late Pleistocene and Holocene time.

The alluvial record from Gordon Gulch and Betasso Gulch, headwater catchments with a limited snowmelt flood at present, suggests that sediment transport in channels has balanced supply from hillslopes only in the past 1,000 years, locally preserving relatively thick deposits of late Pleistocene and Holocene sediment. In the Fourmile Creek catchment, however, the snowmelt flood dominates sediment transport in most years (except after wildfires; Murphy et al. 2015). Terrace remnants and alluvial fans are absent. Fill terraces might never have accumulated or might have been removed by placer mining or by late Holocene to present floods. Interlayering of channel alluvium with toeslope deposits indicates that lower Fourmile Creek was 1 to 2 m higher in the past 2,000 years but that lateral erosion or minor downcutting dominated late Holocene and nineteenth- and twentieth-century time, despite the large volumes of sediment mobilized by mining and road building. The 2013 flood produced net floodplain erosion of about 0.2 m (Wicherski, Dethier, and Ouimet 2017). The late Holocene and nineteenth- and twentieth-century record is thus broadly similar in the small headwater catchments, along Middle Boulder Creek and Roaring River, and along Fourmile Creek. In southwestern Colorado, where there was minimal placer mining and extensive milling of gold and lead and zinc ores, the braided channel of the upper Animas River was aggrading slowly when extensive mining activity began around 1900 and has aggraded since that time (Vincent and Elliott 2007).

Sediment transport related to mining, milling, and flood events in the Fourmile catchment and in other mineralized areas (e.g., Hancock et al. 2008) dwarfs steady-state measures of erosion and is comparable to

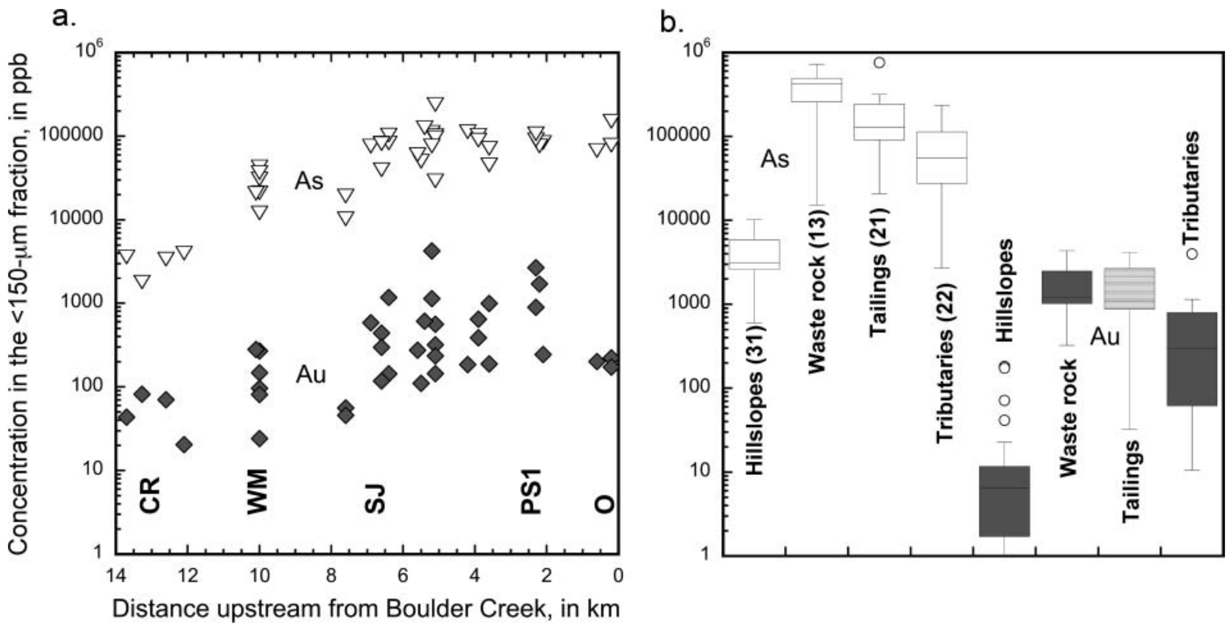

Figure 12. As and Au concentrations in the <150 μm fraction of Fourmile catchment deposits. (A) Downstream increase in concentration in floodplain sediment (collected in 2011–2014 [$n = 39$], including three samples of suspended sediment collected as described in Murphy et al. 2015). Place name abbreviations from Figure 1. (B) Hillslope, waste-rock piles, tailings, and tributary overbank deposits.

high transport rates measured in logging-disrupted areas of Northern California (Madej and Ozaki 2009). Erosion from contemporary logging activities and forest fires doubtless added to disturbance directly related to mining. Saprolite weathers to regolith at a rate of 2 to 2.5 mm per 100 years in the dry, relatively cool climate of the Front Range (Dethier et al. 2014). Averaged over the $\sim$50 km^2 lower

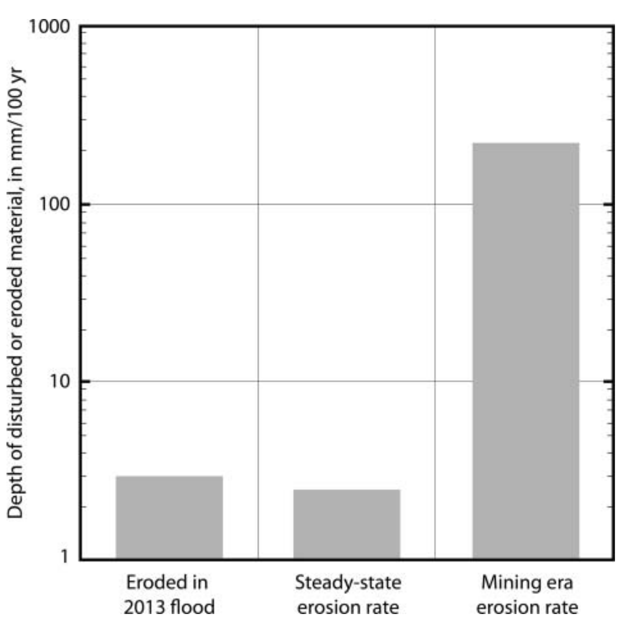

Figure 13. Comparison of disturbance or erosion depth, Fourmile catchment; the 2013 flood is assumed to be a 50- to 100-year event.

Fourmile Creek catchment, disturbance and mixing of the critical zone by mining-related activities reached an effective depth of >100 mm (Figure 13), exceeding pre-nineteenth-century rates by at least fifty times. Most of the mining-related disturbance took place during an eighty-year period between about 1860 and 1942. Some of the mining-legacy sediment will continue to erode until slopes and channels reach a steady state, however.

Erosion from the Fourmile Creek floodplain and slopes in the 2013 flood event was equivalent to hundreds of years of erosion at steady-state rates (Wicherski, Dethier, and Ouimet 2017), in an event for which the seven-day rainfall had an annual exceedance probability of <0.1 percent (Murphy et al. 2015) and channel flooding a recurrence interval of about fifty years (see http://www.bouldercounty.org/doc/flood/lowerbouldercreekmasterplan.pdf). Sediment yields from the Fourmile Creek catchment in the 2013 flood were similar to values reported by S. W. Anderson, Anderson, and Anderson (2015) for a large number of Front Range basins. Frequent large floods will rework and locally erode Fourmile channels, but transport of mining legacy sediment from hillslopes and tributaries by smaller events is likely to slow or prevent downcutting by Fourmile Creek and to supply sediment rich in As and Au to the floodplain, particularly when wildfire increases hillslope erosion rates as it did in 2010.

Conclusions and Implications for the Anthropocene

Results presented here demonstrate the pervasive influence of nineteenth- and twentieth-century mining along the floodplain and on the slopes of the lower Fourmile Creek catchment in Boulder County, Colorado. These widespread human impacts represent the dominant Anthropocene landscape change for this region, consistent with an onset of Anthropocene of ~150 years BP for the Colorado Front Range and perhaps much of the mined, mountainous regions of the Western United States. Our results also support the idea, however, that stratigraphic markers of anthropogenic activity vary regionally. The Anthropocene is a time-transgressive stratigraphic boundary, with significant variation around the globe. In the lower Fourmile Creek catchment, mining-related sediment represents a clear marker of anthropogenic activity. Even in this landscape, though, stratigraphic markers vary by type and timing (i.e., 1880s railroad debris and charcoal fragments, ~1900 matrix-poor placer gravels on Holocene colluvium, or 1930s to 1940s tailings on Holocene flood deposits). Anthropogenic activity is also erosional, associated with the reworking and local erosion of 1 to 4 m of Holocene valley deposits by placer mining and subsequent flooding.

Preservation of stratigraphic deposits associated with human activity depends on rates of background geomorphic processes. In the steep Colorado Front Range, wildfires and floods are common, and severe flooding such as that seen in 2013 can mobilize and transport fine-grained, metal-rich tailings that so clearly mark mining activity. Fluvial erosion of fine-grained material highlights how stratigraphic markers of the Anthropocene reflect the competition between the magnitude of human impacts and their preservation potential, time since activity, and subsequent erosion. There is no direct evidence of early Anthropocene (Ruddiman 2013) human impacts in the deposits studied along Fourmile Canyon. Either the intensity of premining human activity was not sufficient to leave clear stratigraphic markers or subsequent "background" geomorphic processes removed the evidence of previous activity. Preservation potential in the Mountain West is significantly different compared to legacy sediment in the mid-Atlantic region (Jackson et al. 2005; Walter and Merritts 2008; Merritts et al. 2011), where background erosion rates are lower. The scale of valley deposits is different, but so are the timescales of removal. Steep landscapes around the globe generally are more erosive and dynamic (landslides, floods, aggradation, erosion); therefore, the magnitude of human-induced changes needs to be greater to produce a significant, recognizable, long-term anthropogenic influence.

The generation and fate of Anthropocene sediment also can vary significantly from hillslopes to adjacent river valleys. Results presented here mainly are consistent with previous work in mining-impacted areas that show sediment transport in river valleys, with mine tailings forming a clear marker of such activity (Lewin, Davies, and Wolfenden 1977; Knox 1987; James 1989; Knighton 1989; Lecce and Pavlowsky 2001; Marcus et al. 2001: Coulthard and Macklin 2003; Lecce et al. 2008; Singer, Aalto, and James 2008). One new aspect of our work is the differentiation of valley versus hillslope impacts and legacy in relation to mining influence, with different duration (preservation) and susceptibility to wildfire-related debris flows and flood erosion. Recent (post-1950) floods along lower Fourmile Creek effectively reworked mining sediment within the floodplain, resulting in similar physical characteristics in young and older, pre-1850 sediment; however, their geochemistry is different. Many hillslope locations, though, have seen little natural modification or erosion and mining deposits are likely to remain in place much longer than floodplain sediments.

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