THESIS

ENVIRONMENTAL EFFECTS OF THE 1978 SUNNYSIDE MINE FLOOD

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ABSTRACT

ENVIRONMENTAL EFFECTS OF THE 1978 SUNNYSIDE MINE FLOOD

In 1978, the pillar of rock and sediment between Lake Emma and the Sunnyside Mine collapsed, draining 5-25 M gallons (19-95 ML) of water and sediment through the mine and the American Tunnel within a few hours (Thompson, 2018). This caused a major flood in Cement Creek, a tributary of the Animas River north of Silverton, Colorado. Although work has been done on the geochemistry of mine outwash in the same drainage from the 2015 Gold King Mine spill, the material from the Sunnyside Mine flood has not been extensively studied previously. This study aims to determine whether the 1978 Sunnyside Mine flood had significant geochemical and geomorphic effects and continues to affect the environment today.

Likely flood deposits were identified approximately fifteen centimeters above the typical spring flood level based on sediment characteristics, interviews with witnesses to the flood and community stakeholders, as well as newspaper articles and photographs from shortly after the flood. Cement Creek sediment samples from flood and non-flood deposits were analyzed with VNIR spectroscopy for mineralogy. Sediment samples from the Sunnyside flood contained vermiculite, iron smectite, zeolites, gypsum, and secondary copper minerals, while most stream sediment included ferrihydrite, K-illite, and vermiculite. Sediment samples were also analyzed for their bulk elemental geochemistry, which revealed that the Sunnyside flood sediments had lower concentrations of heavy metals than the other sediments in Cement Creek, but had 59% more iron and 518% more sulfur. It is not clear whether the increased iron and sulfur exist as unweathered sulfides or as sulfates, but if there are sulfides or secondary sulfate minerals present

in the flood sediment, then the flood sediment has significantly more acid generation potential than the other sediment in Cement Creek. Additionally, the average Fe/Cu ratios of the flood sediment is higher than the non-flood sediment, which indicates that the material is either from a different source, or that the flood water had lower pH than the water in Cement Creek when the other sediments were deposited.

The significant difference in the minerals present and the elemental geochemistry, as well the continued preservation of flood horizon sediments, indicate that the Sunnyside Mine flood impacted the Cement Creek watershed. Understanding the impact that a major disaster like the Sunnyside Mine flood had on the area is important to have a better picture of a region that continues to face environmental impacts from mining activities.

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I acknowledge that the land this field work was conducted on is the traditional and ancestral homelands of the Navajo, Pueblo, and Ute Nations and recognize, with respect, the Indigenous peoples as original stewards of this land.

Research for the project could not have been completed without the assistance of Kirstin Brown, Terry Morris, Casey Carroll (Director of Archives at the San Juan Historical Society), Jake Kurzweil (Mountain Studies Institute), Jim Herron, Bill Jones, Beverly Rich, Scott Fetchenhier, and Bob Gallegos. I would also like to extend a special thanks to my field assistant, Adam Rang.

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1. INTRODUCTION

On the evening of Sunday, June 4, 1978, Lake Emma, which was above the Sunnyside Mine in Silverton, Colorado broke through the top of the mine. The entire contents (water and sediment) of the lake drained through the mine workings and the three-kilometer-long American Tunnel, into Cement Creek, and eventually into the Animas River, which supplies water to many downstream communities (figure 1). This study will use historical research, field observations, spectroscopy, and whole rock geochemistry to characterize the spill and compare sediment from the flood to other sediments in Cement Creek. This event is known both as the Sunnyside Flood and the Lake Emma Flood, and both of these names are used in this thesis.

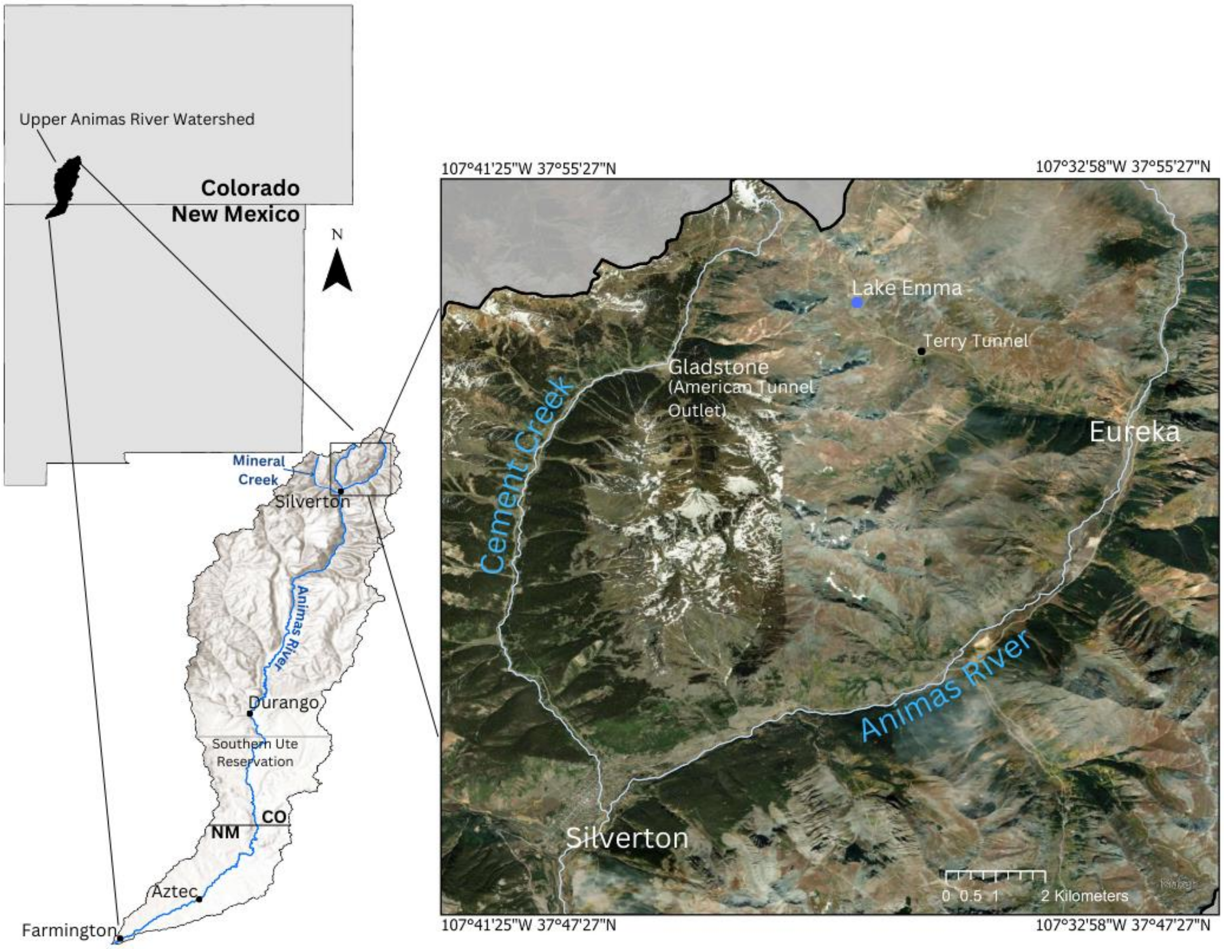


Figure 1: Reference map showing the locations of Lake Emma, the American Tunnel, Cement Creek, and surrounding communities.

1.1 Significance of study

This study is important to understanding the environmental geology of the Silverton, Colorado area. It is estimated that 5-25 million gallons (19-95 million liters) of outwash came from the Sunnyside Mine flood (Thompson, 2018). Firsthand accounts indicate the Sunnyside Mine flood had dramatic effects. The water drained quickly and moved fast enough to strip timber out of the mine shaft and flatten a train car in the mine (Bird, 1986). The outwash likely contained high amounts of heavy metals and a high acid content, which is known to have negative effects on wildlife, aquatic ecosystems, and human health (e.g., Simate & Ndlovu, 2014). Understanding the impact that a major disaster like the Sunnyside Mine flood had on the Cement Creek drainage is important to have a better picture of a watershed that continues to face environmental impacts from mining activities. Without constraining the effects of different events, it is difficult to accurately assess the risk that potential future hydrological events may pose to Cement Creek and the Animas River. This research will help illuminate the implications of the 1978 Sunnyside Mine flood.

1.2 Objective and Hypothesis

This study presents 1) historical research to determine the extent of the flood and the impact it had on the Cement Creek watershed and the town of Silverton, and 2) bulk sediment elemental geochemical analysis and spectroscopy to determine the mineralogical and geochemical signature of the flood sediments in relation to other sediments in Cement Creek. This provides novel information about the state of current sediments in the area and ongoing environmental concerns. The hypothesis of this study is that the 1978 Sunnyside Mine flood had extensive geochemical and geomorphic effects and continues to affect the environment today via a higher concentration of heavy metals in the stream and stream sediment and increased potential for acid generation.

2. GEOLOGIC HISTORY AND SETTING

2.1 Regional Geology

The study site is located in the western San Juan Mountains and extends from Silverton, Colorado to 11.5 km north, upstream along Cement Creek, ending at Gladstone. The regional bedrock is Precambrian amphibolite, gneiss, and schist, uncomformably overlain by Paleozoic and Mesozoic sedimentary units. These are followed by the Eocene Telluride conglomerate, which contains clasts of the Precambrian, Paleozoic, and Mesozoic units, as well as clasts from the onset of Tertiary volcanism.

In the mid-Tertiary, volcanic intrusions and extrusive tuffs and flows arose as part of the widespread ignimbrite flare-up throughout western North America. The San Juan Caldera deposited the Silverton Volcanics in 28.2 Ma, which are mostly preserved inside the boundary of the caldera (Yager & Bove, 2007). The Silverton Volcanics are extrusive flows of intermediate to felsic composition ranging from rhyolite to andesite (Luedke & Burbank, 2000). Along Cement Creek, the Burns Member of the Silverton Volcanics is exposed, which is comprised of massively interbedded tuffs, flows, and flow breccias containing mostly andesite and dacite. These rocks are hydrothermally altered, particularly on the west side of Cement Creek between Cement Creek and Mineral Creek (Luedke & Burbank, 2000).

At 27.6 Ma, the Crystal Lake tuff erupted, forming the Silverton caldera. While minimal Crystal Lake tuff remains as outflow, there is none preserved within the Silverton caldera, where the focus of this study is. However, the ring fracture caused by the collapse of the Silverton caldera is highlighted by erosion along the fracture zone by Mineral Creek and the Animas River. After the caldera formed, at 26.6 Ma, the ring fracture zone experienced felsic intrusions and dikes, as well as significant hydrothermal alteration forming low grade porphyry deposits. The area between the San Juan and Silverton calderas experienced resurgence and extensional fracturing, which created the Eureka Graben in between the calderas (Yager & Bove, 2007). The Toltec and Sunnyside Faults that form the edges of this graben later became heavily mineralized with a N 40° E trending polymetallic vein system with vein-related quartz-sericite pyrite alteration, and the Sunnyside Mine was built to mine ore along them. Alteration of this type generally follows caldera-related structures, formed 18-10 Ma, and is the source of most of the ore in the Silverton area (Bove et al., 2007). There are also smaller polymetallic veins throughout the area (Yager & Bove, 2007). A full description of the Sunnyside ore and its origin can be found in section 2.4.

Throughout the region, there is significant alteration due to the extensive volcanic and hydrothermal activity. Most rocks in the area are affected by propylitic alteration caused by the formation of the San Juan and Silverton calderas. This alteration did not create significant ore mineralization, but is characterized by chlorite, epidote, calcite, and illite (Bove et al., 2007). The other alteration types present in the study area are minimal weak sericite-pyrite, and vein-related quartz-sericite-pyrite. Within the Animas River watershed there are areas of acid-sulfate alteration and quartz-sericite-pyrite alteration, both of which are highly mineralized and have high acid-generating potential. Neither of these types of alteration outcrop in the area of this study, but sediments derived from rocks outside the study area likely exist in Cement Creek from Red Mountain and Ohio Peak, which are both to the west of the creek but feed its tributaries. The acid-sulfate alteration is characterized by quartz-alunite and quartz-pyrophyllite mineral assemblages (Yager & Bove, 2007) and occurred 23 Ma. The alteration in the Red Mountain area hosts silver-copper-lead mineralization of economic importance, while the Ohio Peak area does not have many significant economic mineral deposits.

Following the Tertiary volcanic period, the region experienced significant erosion throughout the Neogene, likely due to extensional tectonics and vertical displacement between the San Juan Mountains and the nearby Rio Grande Rift. (U.S. Geological Survey, 2007). This erosional period was followed by extensive glaciation in the Pleistocene. Except for the highest mountain peaks, the entire area was covered by an ice cap, with over thirty glaciers flowing into every valley that drains the central mountain range (Atwood & Mather, 1932). Eureka Gulch, where Lake Emma sits, and the canyon where Cement Creek is now were both heads of the Animas Glacier, which covered an area of approximately 1000 km^2 and reached all the way to Durango, nearly 100 km away. Glaciation changed the shape of the Cement Creek Valley from a V-shaped valley to a U-shaped valley, and carved the cirque where Lake Emma later formed. Radiocarbon dating shows that glaciers retreated from Lake Emma in the early Holocene (Elias et al., 1991). Glacial retreat created unstable slopes in the San Juan Mountains, resulting in landslide and talus deposits in the late Quaternary (U.S. Geological Survey, 2007).

2.2 History and Effects of Mining

Silverton and San Juan County have a long history of mining. Mineable gold was discovered in 1871 and mining lasted until the Sunnyside Mine closed in 1991 (Bird, 1986). Throughout this time, mining was the primary industry and economic driver in Silverton (Marshall & Zanoni, 1996). However, mining practices and waste management have changed significantly over that time. Although stream pollution from tailings was outlawed in Colorado in the 1890s (Thompson, 2018), most mill waste in San Juan County was still deposited in surface water until 1935 (USGS, 2007). This resulted in an estimated 8.6 million short tons (7.8 billion kilograms) of tailings ending up in the Animas River (Jones, 2007). While most ore came out of relatively large mines like Sunnyside and Shenandoah-Dives, the vast majority of mined sites in the area are small claim productions, of which there is often little to no record, and which can cause major environmental impacts when abandoned.

As ore grades decreased, milling became more common, and some small stamp mills were built in the 1870s and 1880s. Additionally, after the invention of the gravity mill in 1899, even small mining operations often had on-site mills rather than sending ore to a larger, consolidated location, so unaccounted for mill waste also causes lasting impacts in the county (Jones, 2007). There are nearly 5,400 identified inactive mine, mill, and prospect sites in the Animas River watershed area inventoried by the USGS (Church et al., 2007 b). Active remediation efforts have been ongoing in Silverton and surrounding areas since the 1990s by Sunnyside Gold, the Bureau of Land Management, the San Juan Resource and Conservation District and others, and was tracked by the Animas River Stakeholders Group (Finger et al., 2007) until the group disbanded in 2019 (Romeo, 2019). Some of these remediation activities include inventorying inactive and abandoned mines, removing tailings deposits and mine-waste dumps, plugging mine adits, collecting and diverting acid mine drainage away from streams, treating ponds and tunnels with limestone to reduce acid generation, and creating hydrologic controls that prevent surface runoff from travelling over or through mine dumps and tailings deposits (Finger et al., 2007). The Bonita Peak Mining District, which includes Cement Creek, Mineral Creek, and the Upper Animas River drainages, was designated a Superfund site by the EPA in 2016, after the Gold King blowout in 2015. The EPA built an Interim Water Treatment Plant at Gladstone to treat discharge from the Gold King Mine, which has improved the water quality of Cement Creek (EPA, 2022). The original water treatment plant built in 1979 was closed in 2004 after liability and leasing issues (Bonita Peak Mining District CAG, 2016).

2.3 Cement Creek

Cement Creek is a mountain stream with a mean basin elevation of 3,488 m, and is in a canyon surrounded by steep slopes. The drainage area of the basin of Cement Creek is 52.1 km^2 and receives 103 cm of precipitation a year (https://streamstats.usgs.gov/ss/?gage=09358000&tab=info). This study specifically focuses on the section of Cement Creek downstream of the confluence with the South Fork of Cement Creek at Gladstone, until the confluence with the Animas River in Silverton, since the Sunnyside flood entered the creek via the American Tunnel, which outlets at Gladstone. Sediment is added to the stream from erosion of the slopes above, mostly as talus deposits, as well as dust from the dirt road that runs next to the creek. The surficial deposits in Cement Creek were mapped by Blair and Yager in 2002, and that map was refined by Vincent, Stanley, and Wirt (2007). A longitudinal profile was also surveyed by Vincent et al. (2007) as part of a project to understand the formation of ferricrete throughout Cement Creek's history. During this mapping, they noted that many of Cement Creek's active floodplains and gravel bars had evidence of Lake Emma sediment, which they describe as "pebbles and granules supported in a silt matrix containing sand and clay" that is poorly sorted. They also identified debris such as mine ventilation pipes that they interpreted to be from the Lake Emma flood.

Overall, the alluvial sediments in Cement Creek are coarse grained, with minimal silt or clay (Vincent et al., 2007), although there are some deposits in the creek that do not follow that pattern. The morphology of Cement Creek is heavily affected by alluvial fans from the tributaries entering the creek, which often coincide with the gradient of Cement Creek changing from shallow to steep (Vincent et al., 2007). A major bend in the creek coincides with a large, inactive landslide deposit on the east side of the creek, which has not been dated but may have formed during or shortly after glacial retreat (Vincent et al., 2007). While this large landslide and the morphology of Cement Creek appear related, the landslide deposit does not show an obvious effect on the longitudinal profile of Cement Creek. In some places the creek incises an abandoned terrace deposit that extends between 1.5-3.5 m above the current stream level, which is made of interbedded gravel and peat that are very similar to current floodplain deposits along the creek (Vincent et al., 2007).

A distinctive feature of Cement Creek, which likely inspired the name, is extensive ferricrete deposits along the creek. Ferricrete is a formation in which precipitated iron oxides and hydroxides from the evaporation or neutralization of groundwater cement clasts into erosion-resistant sheets (Widdowson, 2003). There are active iron bogs and wet ferricrete currently forming on the flood plain, as well as cliffs of ferricrete that have been dated as at least 4,500 years B.P. (Vincent et al., 2007). Since ferricrete is resistant to erosion, it helps stabilize channel morphology even during major flow events that might otherwise have a larger impact on the stream. The highest annual flows are a result of snowmelt, but summer rainstorms also contribute to spikes in the flow regime (Conyers, 2011).

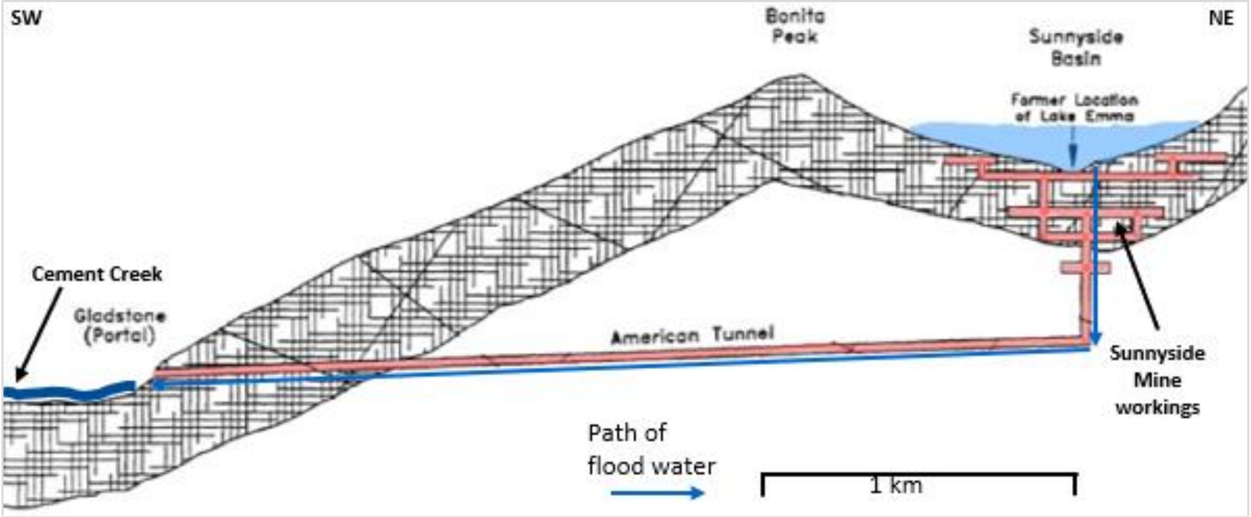
2.3.1 Geochemistry of Cement Creek

While the geochemistry of the Lake Emma flood has not been extensively researched, previous work has been conducted on the geochemistry of Cement Creek’s water and sediment. The water in Cement Creek was acidic, iron-rich, and undrinkable prior to mining (Rhonda, 1876). Blair and Yager (2002) mapped surficial deposits in the Animas River Basin, including Cement Creek, and identified terraces that likely preserved pre-mining sediment deposition. The terrace they analyzed had sediment with iron above 10 weight percent and elevated concentrations of ore-associated trace elements. They interpret this to mean that altered rock was weathering into Cement Creek and that there were likely acidic waters present before mining (Blair & Yager 2002).

Johnson et al. (2007) sampled surface and groundwater and conducted stream tracer dilution studies in Cement Creek between Gladstone and Fairview Gulch, as well as in Prospect Gulch, which is a tributary of Cement Creek. Their report investigates the relationship between groundwater and surface water geochemistry in order to calibrate a groundwater-flow model and thoroughly describe the hydrogeochemistry of Prospect Gulch. However, their study extends into the main stem of Cement Creek as well, in the upper reaches covered by this thesis. Groundwater geochemistry does not show distinct spatial trends within their study area. For surface water, they determined that unlike many mining-affected streams, the pH of Cement Creek decreases downstream, while conductivity and instream metals increase. This is especially true for the samples taken in Cement Creek at the mouth of Prospect Gulch due to water with low pH and high conductivity entering the stream from Prospect Gulch. The geochemical trends in Cement Creek are different than some other mining-affected streams because there are inputs of metals and acid-generating minerals throughout the stream from tributaries and groundwater, rather than input from a single mine. Generally, the influence of a single input source decreases downstream, causing the pH to increase and the metal loading to decrease, so having multiple sources of contamination disrupts the trend.

2.4 Sunnyside Mine

The Sunnyside lode was originally prospected in 1875 and was mined intermittently from then until its most recent closure in 1991 (Ransome, 1901; Marshall & Zanoni, 1996). Over its lifetime, the mine produced 800,000 ounces of gold and 14 million ounces of silver (Bove et al., 2007) and was the most productive mine in San Jaun County. In 1977 (shortly before the flood), the mine was an underground mine that miners accessed via a portal called the Terry Tunnel, which outlets in Eureka Gulch. The older levels of the mine were in the hillside above Lake Emma, but most of the mine was in the mountain beneath it. Starting in 1962, ore was lowered with gravity to the lowest level of the mine and then transported out via the two mile (3 km) long American Tunnel, which let out at the Gladstone Portal, next to Cement Creek (figure 2) (Marshall & Zanoni, 1996).



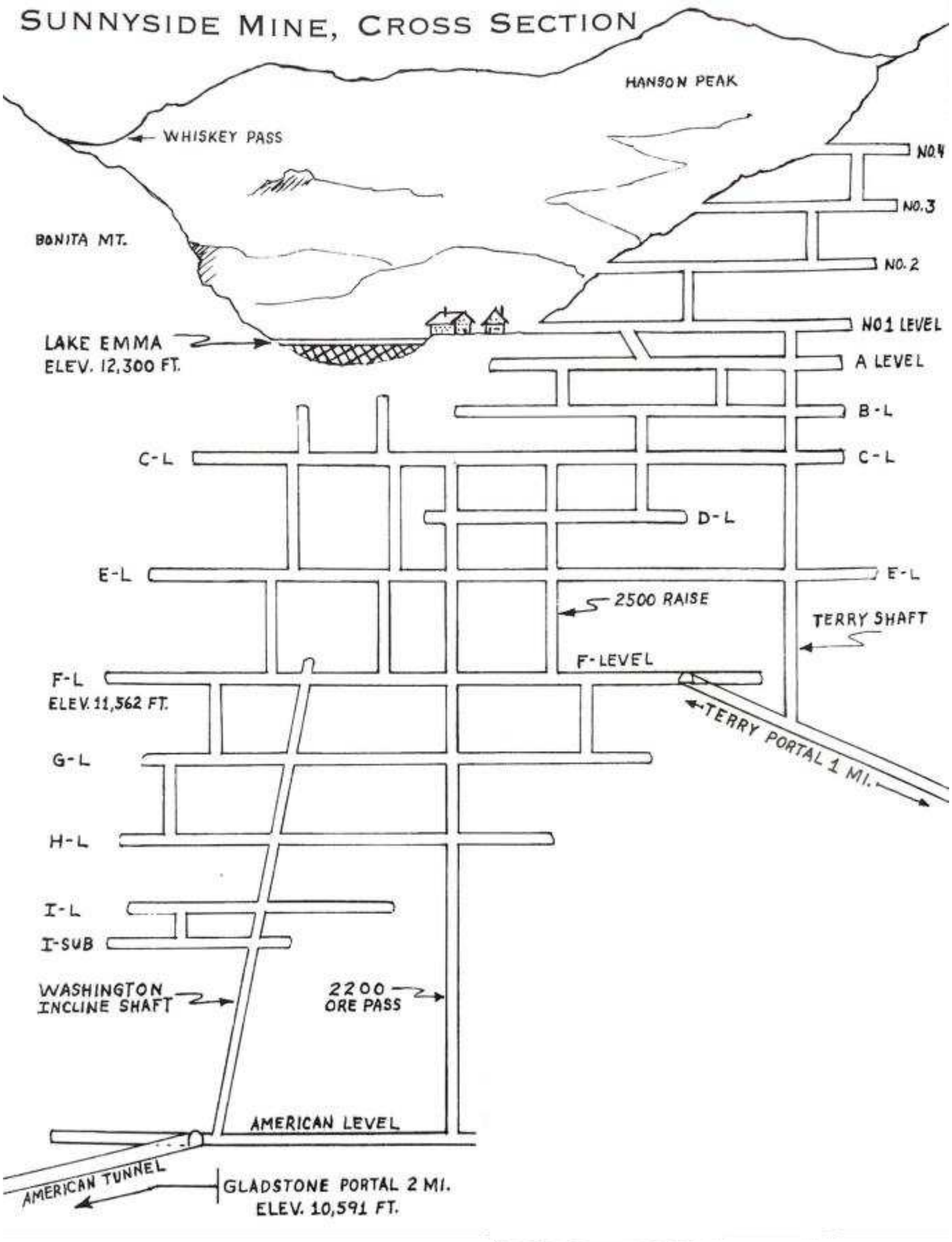


Figure 2: A) Schematic profile of the Sunnyside Mine workings as they relate to Lake Emma, the American Tunnel, and Cement Creek. Modified from Thompson, 2018. B) Schematic drawing (not to scale) of the interior of the Sunnyside workings, Marshall & Zanoni, 1996.

In the late 1970s, the inner workings of the mine extended vertically 610 m and laterally 2,100 m, mining an extensive network of veins which strike dominantly northwest in vertical to subvertical faults associated with the formation of the Eureka Graben (Casadevall & Ohmoto, 1977). The ore grades in the mine fluctuated widely over the life of the mine but the typical grades were 0.16 oz/T (5.2 ppm) gold, 1.6 oz/T (52 ppm) silver, 0.2% copper, 2.0% lead, and 3.0% zinc (Bartos, 1993). Multiple stages of mineralization lead to different mineralogy in different areas of the mine, both as ore and gangue (table 1).

Table 1: Mineralogy of Sunnyside Mine Ore, adapted from Geology Staff, Sunnyside Gold Corporation, 1988.

Ore Type	Mineralogy
Quartz-Pyrite/ Pyrrhotite	Quartz, pyrite, pyrrhotite
Banded Quartz-Sulfide	Quartz, pyrite, sphalerite, galena, chalcopyrite, sulfosalts
Massive Sulfide	Sphalerite, galena, pyrite, chalcopyrite, quartz, hematite
Gold	Quartz, gold, petzite, calaverite
Manganese	Pyroxmangite, quartz, friedelite, rhodochrosite, pyrite, galena, sphalerite, chalcopyrite, helvine, tephroite, huebnerite, alabandite, anhydrite, hematite
Quartz-Fluorite-Carbonate	Quartz, calcite, fluorite, pyrite, galena, sphalerite, chalcopyrite, rhodochrosite, gypsum

At the time of the flood, Standard Metals Corporation owned and operated the Sunnyside Mine, but they filed for bankruptcy in 1984 (UPI, 1984). In 1985, Sunnyside Gold Corporation (SGC) was founded to buy the mine and rejuvenate it so that it was in compliance with Colorado's environmental regulations and Sunnyside's mining permits, so that they could continue to mine (Lange, 2018). At the time, SGC was a subsidiary of Echo Bay Mines, Inc., a Canadian mining company (Frodeman, 2003). Sunnyside Gold Corporation became a subsidiary of Kinross Gold Corporation in 2003 when Kinross, TVX Gold, and Echo Bay merged under the Kinross name (Canadian Mining Journal Staff, 2002).

Since the mine's closure in 1991, SGC has conducted reclamation activities in the Silverton area, including in Cement Creek, at Gladstone, and in Eureka Gulch. This reclamation included consolidation and impoundment of historic mine waste, bank stabilization of mining affected creeks, and reseeding land where the vegetation has been affected by mining. Additionally, likely the most impactful remediation effort by SGC was the construction of bulkheads in the American Tunnel and other Sunnyside Mine portals to keep water from the interior of the mine from running directly into the Animas, as well as a water treatment plant at Gladstone. This significantly decreased metal loading and improved water quality in Cement Creek (Lange et al., 2019). Sunnyside Gold Corporation was released from their remediation obligations in 2003 after meeting several standards set by the Colorado Department of Public Health and Environment, and while the bulkheads remained in place, the Gladstone water treatment plant stopped operating in 2004. However, after the Gold King blow-out in 2015, the EPA resumed water treatment at Gladstone, and has maintained metal loading below the CDPHE's target levels in Cement Creek (Lange et al., 2019).

2.5 Summary of Disaster

The Sunnyside Mine Disaster occurred on the evening of Sunday, June 4, 1978, when a pillar made of rock and sediment separating Lake Emma from the stopes below gave way, draining the lake through the mine within a few hours (Marshall & Zanoni, 1996). In the days before the flood, miners reported an increase in water draining through the mine and had concerns for their personal safety (Marshall & Zanoni, 1996).

There is some controversy over the cause of the flood, but the prevailing theory is that when the area was glaciated, a fracture in the bedrock of the lakebed was filled with glacial sediment that subsequently became permafrost. As the miners followed the vein up toward the bottom of the lake, the permafrost melted, and the sediment washed out, allowing the lake to drain (Jones, 2007). Between five million and twenty-five million gallons (19-95 million liters) of water, and up to up to one million tons (900 million kg) of lake sediment washed through the mine tunnels and out of the American Tunnel, into Cement Creek and eventually the Animas River (Thompson, 2018). The exact time of the breakthrough is not well constrained, but the San Juan County sheriff, Virgil Mason, stated that reports of the flood reached Silverton by 7:00 p.m. Sunday evening (Marshall & Zanoni, 1996).

The Sunnyside Mine had two portals: the American Tunnel and the Terry Tunnel. The Terry Tunnel outlet is in Eureka Gulch rather than Cement Creek. The Terry Tunnel is also at a higher elevation than the American Tunnel, which would lead to a lower difference in hydraulic head between the outlet and the draining lake, likely lessening the effects of the flood. However, the Terry Tunnel was blocked by mud and debris early in the flood, so very little flood water exited the mine through that portal. This forced most of the flood out the American Tunnel instead (personal communication, Terry Morris, 2023).

Firsthand accounts indicate the flood had dramatic effects. The water drained quickly and moved fast enough to strip timber out of the mine shaft and flatten a train car in the mine (Bird, 1986). Black sediment from the lake was visible in the Animas more than 110 km downstream, and elevated levels of lead and zinc were reported in the water in Durango (Jones, 2007). The crater left where Lake Emma had been was reportedly 330 m wide and 150 m long (Bird, 1986). There are some reports that early mill tailings from Sunnyside were deposited in Lake Emma, but metal loading likely came primarily from waste rock from early levels of the mine that was dumped in Lake Emma as well as natural lake sediments and sediment washed from the interior of the active mine (Jones, 2007). This assessment is based on typical tailings disposal practices in 1883 to 1890, when the mill next to Lake Emma was operating (Weise-Alexander, 2021). During this time, tailings were likely dumped directly into Eureka Gulch and the South Fork

Animas River. After that point, the Midway Mill, also called the Sunnyside Mill (1897 map), operated in Eureka Gulch, approximately 2.5 km northwest of Eureka, near the confluence of the South Fork Animas River with the unnamed tributary that flows south from Lake Emma.

Church et al. (2007 a) analyzed the trace element data of sediment from terraces and the modern streambed of Cement Creek to try to determine a pre-mining geochemical baseline. In this study, they also identified sediment deposited by the Lake Emma flood preserved near the mouth of Prospect Gulch. Their analysis showed elevated levels of Pb in the sediment, but low concentrations of both Zn and Mn, which are prominent in the Sunnyside ore. They conclude that there was likely little ore in the sediment from the flood, but that the Pb likely came from galena dust picked up from inside the mine as the mud washed through. However, their analysis only considers one sample of Lake Emma sediment, so it does not depict any geochemical variation that may have been present in flood sediments.

3. METHODS

3.1 Historical Research

The first phase of this project was an investigation of characteristics of the flood from historical sources. These sources were used to obtain information on the amount and speed of water, the material it transported, and duration of the flood, as well as the geomorphic and human impacts it had on the town of Silverton and the communities downstream. Historical sources such as interviews, newspapers, and photographs are valuable sources of information, but must be treated slightly differently than typical scientific sources, especially in the case of oral histories and firsthand accounts that are not recorded immediately after the event in question. Human memory can be unreliable, and people (typically unintentionally) construct histories to fit with their existing biases and opinions. Even sources created immediately after an event are typically created for a specific purpose and audience that must be considered (Bombaro, 2012). However, these sources are immensely valuable to understand and contextualize past events.

Preliminary research included assessing oral histories of Silverton miners conducted by the Colorado Division of Reclamation and Mining Safety (CO DRMS, 2023), and photographs and accounts compiled in Mining the Hard Rock in the Silverton San Juans (Marshall & Zanoni, 1996), and Silverton Gold (Bird, 1986). There are few primary and contemporary secondary sources regarding the Sunnyside flood available online, so most research was done in person in Silverton and at the Durango Public Library. DPL hosts the archives of the Durango Herald, a daily newspaper published in Durango, CO. Photographs and shareholder reports from Standard Metals (the company that owned the Sunnyside Mine at the time of the flood) were collected from the San Juan County Historical Society (SJCHS). Informal interviews were conducted with former miners and community members who witnessed the flood and its aftermath, outlined in table 2. These interviews were recorded in writing during the interviews, and particularly poignant or informative quotes were written word for word and indicated as such. Terry Morris and Bill Jones also provided personal photographs and newspaper articles from shortly after the flood.

Table 2: Community members interviewed about the Lake Emma flood

Name	Credentials
Terry Morris	Miner at Sunnyside
Beverly Rich	Silverton community member, former chair of SJCHS
Scott Fetchenhier	Miner at Sunnyside, San Juan County Commissioner
Bob Gallegos	Miner at Sunnyside, witnessed flood during hunting trip
Bill Jones	Standard Metals assayer, SJCHS board member

Unfortunately, the archives of the Silverton Standard and the Miner, Silverton's newspaper, are not digitized or cataloged due to budget and staffing constraints at the SJCHS, and therefore most years are not available for public research. I attempted to make contact with Louis Girodo, who led the county crew that cleared mud and debris from the Sunnyside flood from the roads in Cement Creek but did not receive a reply. Some newspaper articles from shortly after the flood reference water testing conducted by the Colorado Department of Public Health, but those data were not available.

3.2 Field Observations and Sample Collection and Preparation

Sample localities were selected based on descriptions of Sunnyside flood deposits and conversations about where flood sediment was likely to be preserved based on the characteristics of the flood and the geomorphology of Cement Creek. Sampling sites were selected to represent both deposits from the flood and from other depositional events, as well as representing different reaches of Cement Creek between Gladstone and the confluence with the Animas River. (figure 3) Sediment samples of approximately 30 cm^3 were collected via trowel or sediment auger from identified sites along Cement Creek. Multiple samples were collected at each locality, and the sediment was examined and split by depth at notable changes in character. A total of 46 samples were collected from 27 sites across six localities. At each sample location the height above the creek's current water level was recorded, as well as GPS coordinates and photographs of each site and the surrounding area. Despite reports that flood material also came out of Terry Tunnel into Eureka Gulch, no samples were collected there due to extensive remediation work by the EPA and Colorado DRMS, which changed the character of the area. After returning from the field, samples were air-dried in a sediment oven and their color, grain size, and notable features such as organic material were cataloged. Clasts larger than fine pebbles were separated from the samples, and a portion of approximately 10 g of each of the finer grained portions was placed in a glass vial and mailed to Activation Laboratories, Ltd. for elemental analysis (see also section 3.4).

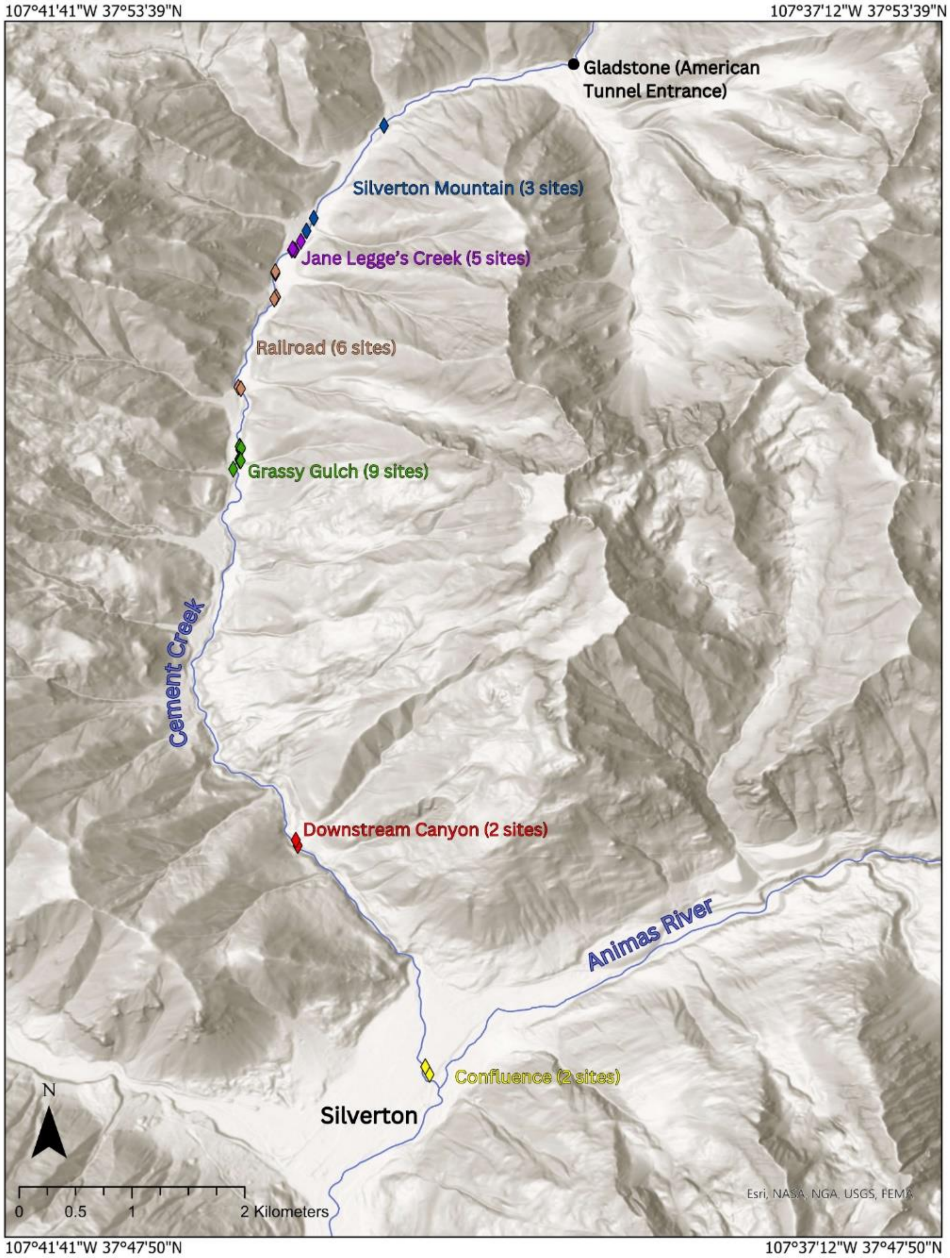


Figure 3: Map of Sampling Locations

3.3 Spectroscopy

Each sample was analyzed with an ASD TerraSpec HALO™ to collect visible light, near infrared and short-wave infrared spectra to determine the clay and hydroxide mineralogy. The primary minerals reported by the TerraSpec were recorded. Any sample that returned a "no match" result for some mineral was retested to confirm accuracy. The reflectance data were then exported from Panalytical's proprietary software into Excel for analysis. Spectra were plotted as wavelength vs. reflectance, and different localities were compared to each other. Sample sites that included well preserved flood horizons were plotted to analyze the difference with depth, and all identified flood samples were compared to identified non-flood samples. Additionally, the mineralogy reported by the TerraSpec was compared between the Lake Emma flood sediment and the other stream sediment samples to identify commonalities and differences.

3.4 Elemental Analysis

At ActLabs samples were sieved to 177µm and digested by aqua regia partial digestion, which uses a combination of hydrochloric and nitric acids to dissolve the samples, and then analyzed with ICP-MS. Two duplicate samples with alternative sample numbers were sent for quality control. Additionally, duplicates of eight samples were dissolved using 4-acid near total digestion, which uses a combination of hydrochloric, nitric, perchloric and hydrofluoric acids, and then analyzed with ICP-MS. These duplicates were to compare results, as each digestion method is better for certain elements. Aqua regia digestion does not reliably dissolve some minerals, including barite, zircon, monazite, sphene, chromite, gahnite, garnet, ilmenite, rutile and cassiterite. However, 4-acid digestion erratically volatilizes arsenic, antimony, chromium, uranium, and gold. Due to the analytical importance especially of arsenic and antimony, aqua regia was determined to be the best method for this study.

The trace element data were normalized against the North American Shale Composite (NASC) from the Geochemical Earth Reference Model (GERM) and Rollinson and Pease's *Using Geochemical Data* (2021), as well as the USGS National Uranium Resource Evaluation (NURE) Hydrogeochemical and Stream Sediment Reconnaissance (HSSR) database. For elements that had multiple values listed in the GERM NASC, the intermediate value was used, and for elements that had only two values, the concentration from the more recent study was used for normalization. Elements that were not listed in the GERM database but were listed in Rollinson & Pease (2021) were normalized by the Rollinson & Pease NASC values. For the remaining elements that were not included in any NASC database, the NURE HSSR data were averaged, and the results from this study were normalized to that average. All normalization concentrations can be found in Appendix F. Averages, medians, and quartiles were calculated for every element for all of the samples, and separate statistics were also calculated for flood vs non-flood samples in order to compare populations. In addition to comparing the suites of samples to each other, they are both also compared to sediment representing the Colorado River basin from Martin & Meybeck (1979), Canfield (1997), and Shumilin et al. (2002). They were also compared to the chemistry of Lake Emma sediment reported in Church et al. (2007 a). Unfortunately, sulfur was not represented in any databases available for normalization, so sulfur concentrations are compared as unnormalized values in weight percent.

Elemental concentrations throughout the Upper Animas River basin were mapped based on this study's samples and data collected for the USGS NURE HSSR project in ArcGIS Pro. Symbology was adjusted to represent relative concentrations of specific elements. Concentration scales are relative, with the lowest concentration value for each element acting as the minimum, and the highest concentration value from the dataset acting as the maximum.

Additionally, the Fe/Cu ratios of sediment as well as the pH and dissolved Cu content of water from Cement Creek were compiled from the NURE HSSR database (Smith, 2006), USGS Stream Gauge site 09358550 (Cement Creek at Silverton, CO), and Johnson et al. (2007). The Fe/Cu ratio of each sample was plotted against both the pH and dissolved Cu from the same collection time and site in order to fit a regression equation to the data that is specific to the relationship between these variables in Cement Creek. This analysis follows the method of Nimick et al. (2009). The Fe/Cu ratios of the sample in this study that were identified as Lake Emma flood sediment were then entered into the regression equation to interpret what the likely pH and dissolved Cu were in the flood water.

The Fe/Cu ratios of the identified Lake Emma flood sediments were compared with the other stream sediments from this study using a frequency distribution to identify potential differences in the aqueous geochemistry during deposition. The bins for the frequency distribution histograms were determined using the minimum and maximum Fe/Cu ratios represented in data from Cement Creek in Smith (2006), USGS Stream Gauge 09358550, and Johnson et al. (2007).

4. RESULTS

4.1 Historical Research

Data were collected from a variety of historical sources to determine characteristics such as height of flood waters, character and location of sediment, and timing of the flood.

4.1.1 Newspapers

Much of the broader historical context of the Lake Emma flood and its effects throughout the Animas watershed can be found in articles from The Durango Herald. The effects on surrounding communities extended for at least a week after the flood (which occurred in the evening on Sunday, June 4). According to Herald articles, the water at the mine portal was 5-6 feet (1.5-2 m) high and filled with mine timbers and debris, and as the flood came into town the water was 8-10 feet (2.5-3 m) high (although other eyewitness accounts contradict this height) (Durango Herald, 6/6/78).

The La Plata County Basin Health Unit discouraged citizens in Durango from drinking water from the Animas, and reported that water samples from the mine portal had 414 ppm Zn and 117 ppm Pb (Durango Herald, 6/7/78) and that water samples taken at Bakers Bridge in Durango had 12.6 ppm Zn and 4.0 ppm Pb (Durango Herald, 6/8/78). While the acting director of the Basin Health Unit at the time, Bob Ballinger, is quoted as saying water with more than 0.05 ppm of total metal content was unsafe to drink (Durango Herald, 6/8/78), the EPA currently has no regulations on Zn content, but recommends that drinking water be no higher than 5 ppm (US EPA, 2009). The EPA does not have an enforced maximum contaminant level for Pb, but the recommended maximum contaminant level goal for Pb is zero due to its adverse health effects on children (US EPA, 2016). Domestic water use from the Animas was cut off in Durango, CO, Aztec, NM, and Farmington, NM on Tuesday, June 6, but by Thursday, June 8, contaminant levels were lowering (Durango Herald, 6/8/78).

The Herald also quoted Marshall Fisher of the EPA enforcement division that "'the EPA and the state's Water Quality Control Board are carrying on a joint investigation into the water situation'" but Steve Jones, a lawyer for the EPA predicted that the investigation and any associated tests would be for an “internal report” and not made public (Durango Herald, 6/23/78).

While the Herald and the Rocky Mountain News out of Denver reported on the EPA investigation and the cleanup of the mine, no remediation within Cement Creek was mentioned, except for the installation of settling ponds and a water filtration system that was installed to prevent contamination of Cement Creek from digging mud out of the mine (Durango Herald, 7/5/78). The Colorado Department of Public Health mandated that settling ponds be built at Gladstone and Terry Tunnel (the other mine portal) before more solid material was removed from the mine to prevent excess metals from entering the Animas River. The CDPH gave Standard Metals until July 27 to construct the ponds, and mine manager Jerry Ott is quoted as saying that the company did not think settling ponds would be sufficient to meet CDPH’s water quality standards and that they planned to build a water treatment plant at Gladstone once the necessary equipment arrived in August (Durango Herald, 7/5/78). According to a timeline developed by the Bonita Peak Mining District Community Advisory Group with information from the Animas River Stakeholders Group and Silverton Standard archives, a water treatment plant was built to treat discharge from the American Tunnel in the fall of 1978 and updated in 1988 (Bonita Peak Mining District CAG, 2016).

4.1.2 Interviews

Personal interviews with Silverton community members were extremely valuable for estimating the size of the flood, the kind of material it was carrying, the geomorphic effects it had on Cement Creek, and the impact it had on the town of Silverton. These interviews are summarized below.

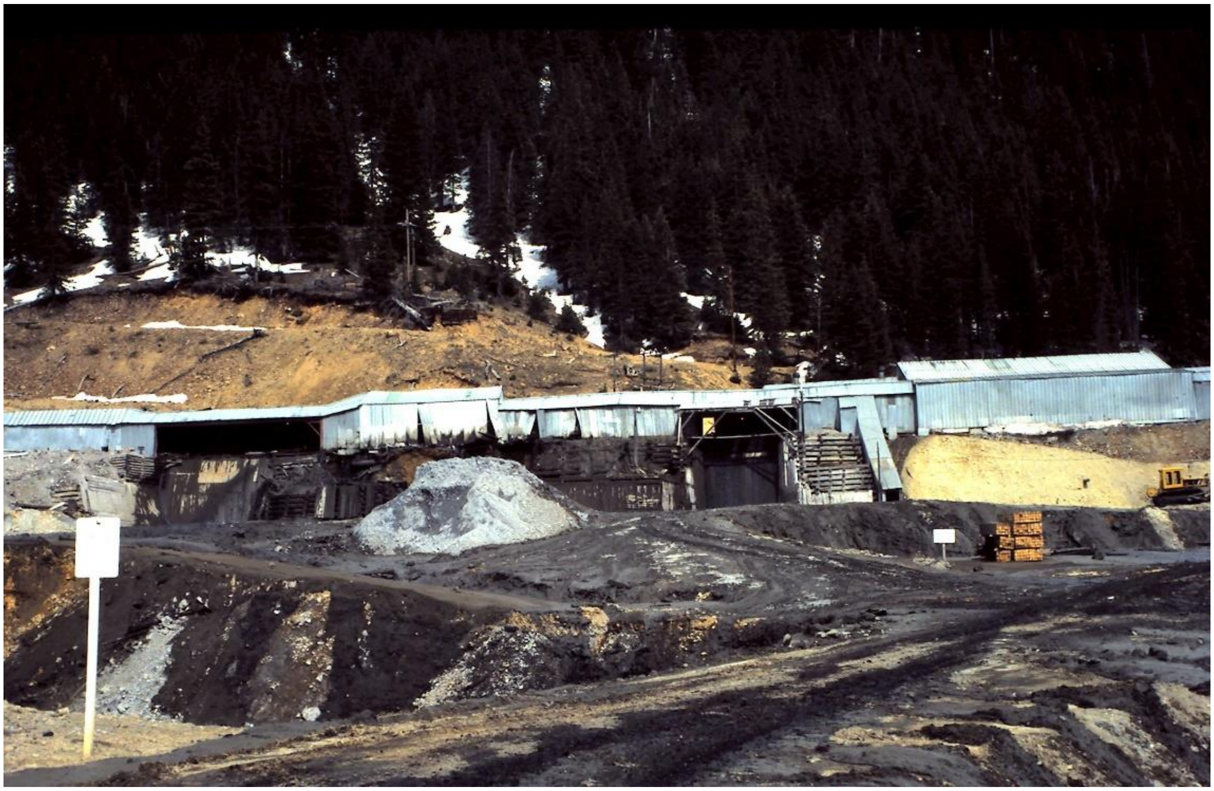
Terry Morris, former miner at Sunnyside explained that the culverts and bridges in Cement Creek where the road crosses the stream were dammed by mine timbers and debris, allowing flood sediment to pool behind them and start to settle, and reported that mud from the flood remained in thick deposits for a long time after the flood. He predicted that preserved flood sediment could be found at such sites.

Beverly Rich described watching the flood waters come into town and pass closely under the bridge next to the Historical Society (this bridge has since been replaced, so could not be used to estimate the water level in town during the flood).

Scott Fetchenhier is a prominent community member and served as the San Juan County Commissioner when Silverton and the surrounding area was added to the National Priorities List as the Bonita Peak Mining District. While not a direct witness to the flood, Fetchenhier was helpful directing me to other resources. He also reported that there continued to be smaller floods through the mine associated with spring melting draining through the former Lake Emma throughout the 1980s.

Bob Gallegos is a tour guide at the Old Hundred Mine and was in the canyon of Cement Creek on a hunting trip when the flood occurred. He reported that the water rapidly changed color to a dark black and a “windstorm started” from the rushing water.

Bill Jones, former Standard Metals assayer and author of Chapter C of USGS Professional Paper 1651 (2007), was in town when the flood occurred. He reports watching the sheriff (Virgil Mason) go “screaming out of town” at approximately 6:15 pm. Jones was waiting for a SJCHS meeting to start at 7 pm, and another member of the historical society reported that there was a flood warning in Bertramville, a neighborhood approximately 0.5 km north of the SJCHS building (which is on the northeast end of Silverton, closest to where Cement Creek enters the town) (Vandeberg, 1978). Jones recalled watching the flood come into town from the courthouse and said that the water was only a foot below the bridge that crossed Main Street, which typically had several feet of clearance. The water was carrying 8’ by 8’ mine shaft timbers, was filled with black mud, and smelled like diesel fuel and sulfur. Between 8:30 and 9 pm, Sheriff Virgil Mason returned to town. According to Jones, Seriff Mason was typically very calm, but the magnitude and severity of the flood made him a “shaking nervous wreck.” Jones also shared his experience of going up to Gladstone and Lake Emma in the week after the flood. He said that the bridge 1.5 miles (2.5 km) downstream of Gladstone had been washed out by the flood waters. He also took photographs of Gladstone, Cement Creek, and the site where Lake Emma used to be (Figure 4, Appendix A). Photographs taken in the days after the flood show a significant amount of damage, including the deposition of mud and some erosion of channel banks at Gladstone just below the entrance to the American Tunnel (figure 4).



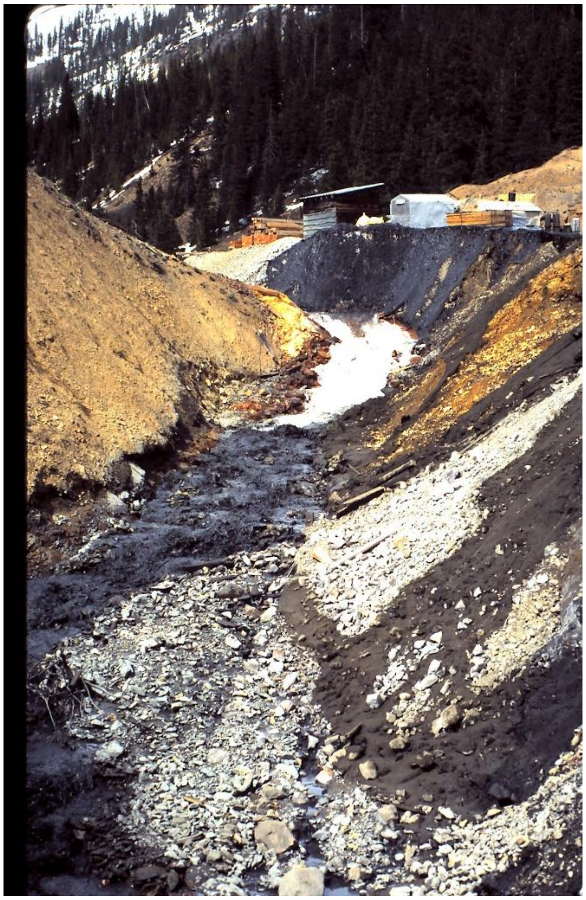


Figure 4: Photos taken at Gladstone and the American Tunnel the day after the flood. A) mine structures were damaged and a large amount of black mud was deposited. Photo is taken from immediately west of the American Tunnel entrance facing upstream. B) Gravel and black mud were deposited and a channel was sharply incised just downstream of the mine. Photo is taken looking downstream toward the entrance of the American Tunnel. Photographs courtesy of Bill Jones.

4.1.3 Standard Metals Internal Documents

Standard Metals was a mining and milling company that owned the Sunnyside Mine along with other assets in the late 1970s. They sent regular reports to their shareholders, along with news releases whenever there were major developments that would affect their business. While their public communications obviously have a spin to reassure their shareholders and secure more funding for their activities, these documents are enlightening. Standard claimed that there was a large quantity of crushed ore on the floor of the mine at the time of the flood. Specifically, they estimated that up to 85,000 tons (77,000 metric tons) of crushed ore were potentially in the mine during the flood (Standard Metals Corporation, November 1, 1978). They included this detail to assure shareholders that there was money still in the mine, the ore affected by the flood was a small percentage of the ore available, and it was worth the time and money the cleanup efforts were taking. However, this report also indicates that it is very likely that ore material, not just waste rock and incidentally dissolved minerals, were included in the flood sediments. Additionally, while there is no evidence of cleanup in Cement Creek, the cleanup of the mine tunnels was a major project that required many years and the investment of a large amount of capital. Standard Metals was also involved in multiple lawsuits shortly after the flood, including suing their insurance companies who were attempting to claim that Standard was negligent in their operation of the Sunnyside, causing the flood. Their original insurance coverage reported to their shareholders in June 1978 was $9.5 million, with an additional $500,000 that could be paid to other parties who suffered damages (Standard Metals Corporation, June 6, 1978). On December 26, 1979, they announced that a jury determined that their insurance companies collectively had to pay $8,220,000, but they did not mention the half million dollars that could be paid to other parties. After appeals by their insurance companies, the parties settled on the sum of \$5.8 million in addition to the \$1.6 million already paid out, for a total insurance payout of \$7.4 million (Standard Metals Corporation, January 7, 1980).

4.2 Field Observations of Flood Sediments

Likely flood deposits were identified between approximately ten to twenty centimeters above the typical spring flood level at a number of sites along Cement Creek. Where preserved, the flood horizon is marked by layers of dark brown silt and bright orange silt to clay. Both layers are not visible at all sampling sites throughout the flood horizon, and the dark brown to black layer is present and identifiable more often than the orange clay layer. The thickness of flood deposit remaining is variable but was observed up to 8 cm thick (figure 5).

Figure 5: Lake Emma flood horizon preserved in Grassy Gulch at sampling site GG2. A layer of dark, organic rich, fine grained sediment is overlain by a bright orange clay layer. The sediment above these layers is sandy and similar in character to sediment throughout the Cement Creek watershed.

Support for the interpretation of flood deposits is based on eyewitness descriptions that the Lake Emma flood sediment was fine grained and organic-rich, as well as the approximate height of flood deposits from photographs taken shortly after the flood.

Flood deposits were preserved at Silverton Mountain, Railroad, Grassy Gulch, and Downstream Canyon sampling localities (figure 3), but were not clearly preserved at Jane Legge's Creek or the Confluence with Animas River. Most non-flood samples are composed of light brown sand, though grain size includes variation from silt to cobbles. While there were flood sediments preserved in several localities, they were best preserved and thickest where Cement Creek has a wide natural floodplain and where witnesses report pools forming during the flood due to drainages dammed by debris (figure 6).

Figure 6: Photographs of the second bridge upstream from Silverton in Cement Creek. Top photo was taken when sampling sites at the “Railroad” locality. Bottom photo taken by Terry Morris in the week after the Sunnyside flood.

A full description of each sample, as well as sampling method and field notes can be found in Appendix B. Photos of sample sites are located in Appendix C.

There is also some non-sediment evidence of the Sunnyside flood visible in the creek, though it is difficult to definitively confirm that it did not come from some other source at some other time. For example, the flood horizon at Grassy Gulch had pieces of an old fence buried in it that could only have been moved by fast moving water. Old railroad tracks, a corrugated steel culvert pipe, and probable mine timbers over a meter long can be found in the Downstream Canyon reaches and, except for the railroad, appear to have been carried there by the creek, which supports the likelihood that the sediment found in those areas are truly deposits from the flood.

There was no sediment identifiable as deposits from the Gold King Mine spill present in Cement Creek. The outwash from the Gold Kings event was 3 million gallons (11,000 m^3) over the course of one day, lower than even the most conservative estimates of Lake Emma flood discharge (Thompson, 2018). In 2017, Kathleen Sullivan, a scientist with the EPA, spoke at the Conference on Environmental Conditions of the Animas and San Juan Watersheds, and said that sediment from the Gold King spill was reworked and carried downstream, likely depositing in a diluted state in Lake Powell (Grover, 2017). As the Gold King spill is the largest flood that has occurred in the Cement Creek watershed since the Lake Emma flood, this further supports that the presence of a clear flood horizon indicates the preservation of flood sediment.

4.3 Spectroscopy

Sediment samples from the Lake Emma flood contain ferrihydrite, vermiculite, iron smectite, zeolites, gypsum, and secondary copper minerals, while most non-flood stream sediment includes ferrihydrite, K-illite, and vermiculite. The reported mineralogy for every sample is included in Appendix D. Many sampling locations showed differences in mineralogy with depth, especially between sediment identified as being from the Lake Emma flood and sediments from other depositional events (figure 7). Additionally, the different layers (black organic rich layer and orange clay layer) of the Lake Emma flood horizon had different mineralogy (figure 8) even though they are from the same event, leading to variability in the flood sediments overall. As a whole, the sediment samples from the Lake Emma flood have much more variability in their spectra, while the non-flood sediment samples are very consistent with one another. The non-flood sediments also have sharper troughs at approximately 1400 nm and 1900 nm, indicating that hydroxide minerals are more crystalline than the hydrated minerals in the flood sediments (figure 9).

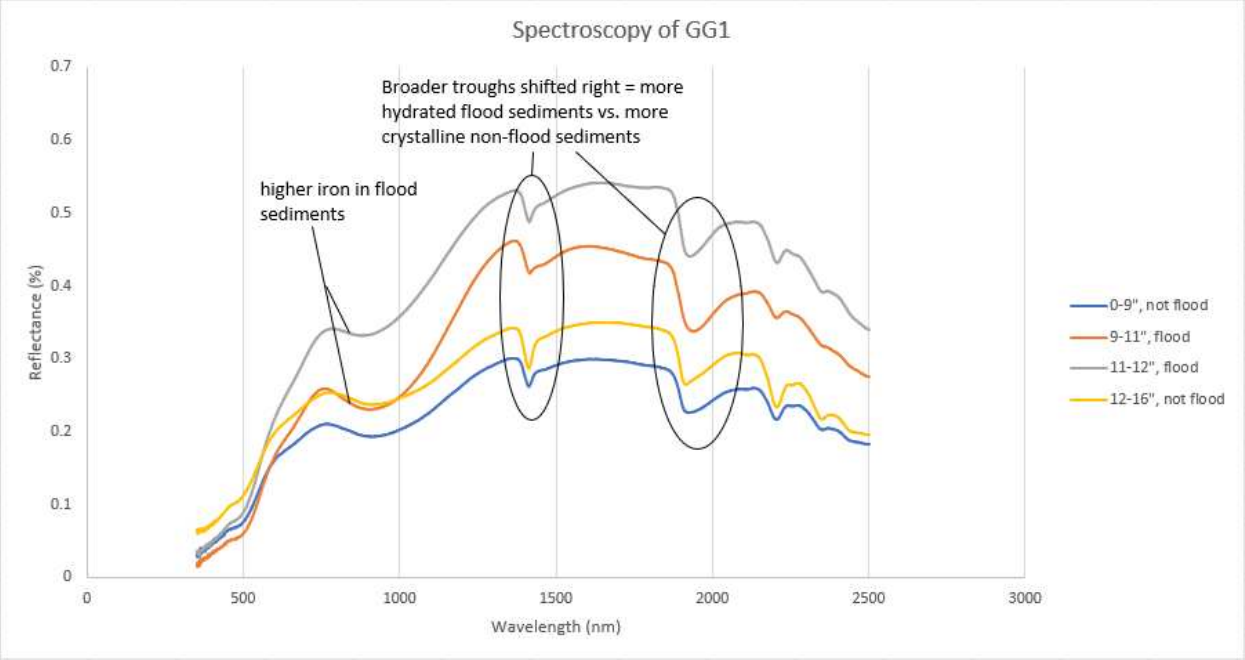


Figure 7: Wavelength vs. Reflectance spectroscopy plot of Grassy Gulch sample GG1, which shows a change in character with depth. The top 0-9” and the bottom section (12-16”) are very similar, containing ferrihydrite, rectorite, and phengite and ferrihydrite, k-illite, and vermiculite respectively, and have been identified as flood sediments, while the samples of 9-11” depth and 11-12” depth do not have vermiculite, instead containing ferrihydrite and smectite/illite and ferrihydrite and rectorite.

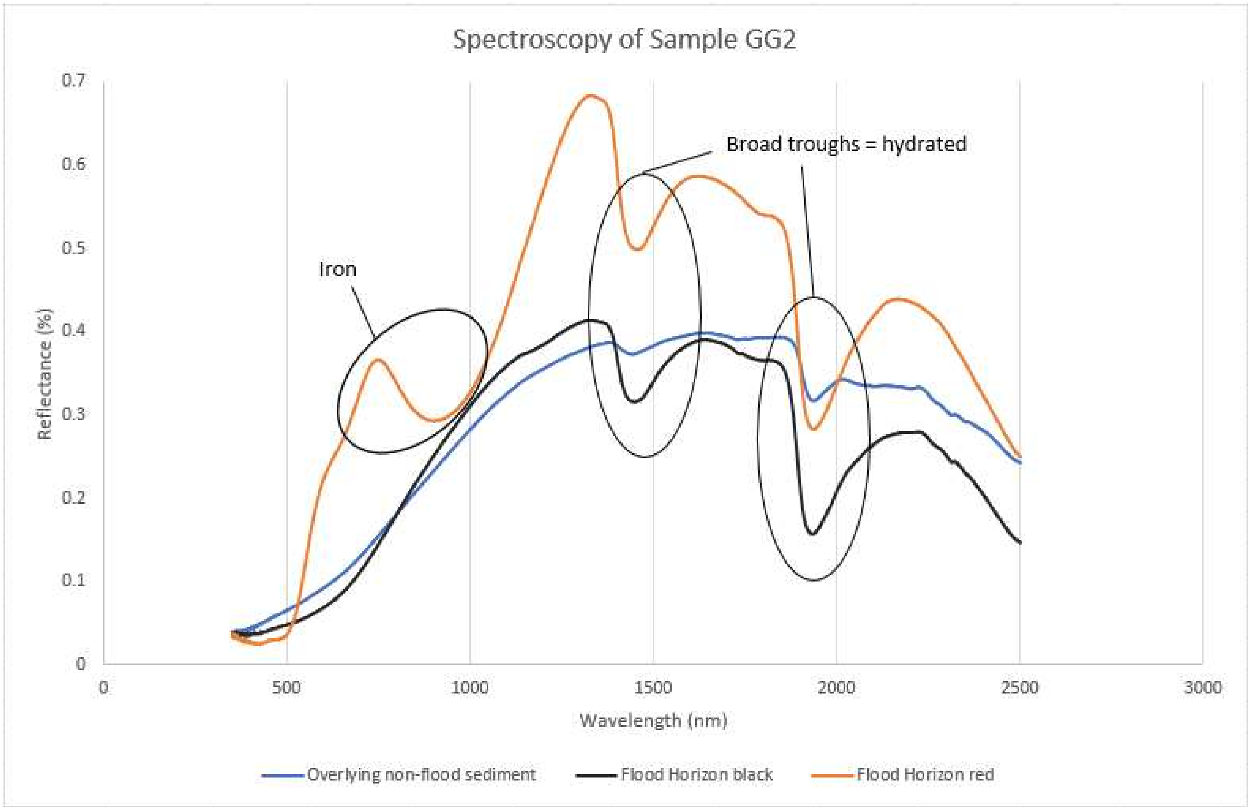


Figure 8: Site GG2, in Grassy Gulch, has three distinct types of sediment evident with depth. Figure 5 in section 4.2 shows these layers. The top layer (0-1”) is identified as laumontite, a calcium zeolite, while the black, organic rich layer identified as the top of the 1978 flood horizon is identified as chabazite (a zeolite), gypsum, and dioptase, and the orange layer below, interpreted as the bottom of the flood horizon, is interpreted as thomsonite-Ca, vermiculite, and iron smectite.

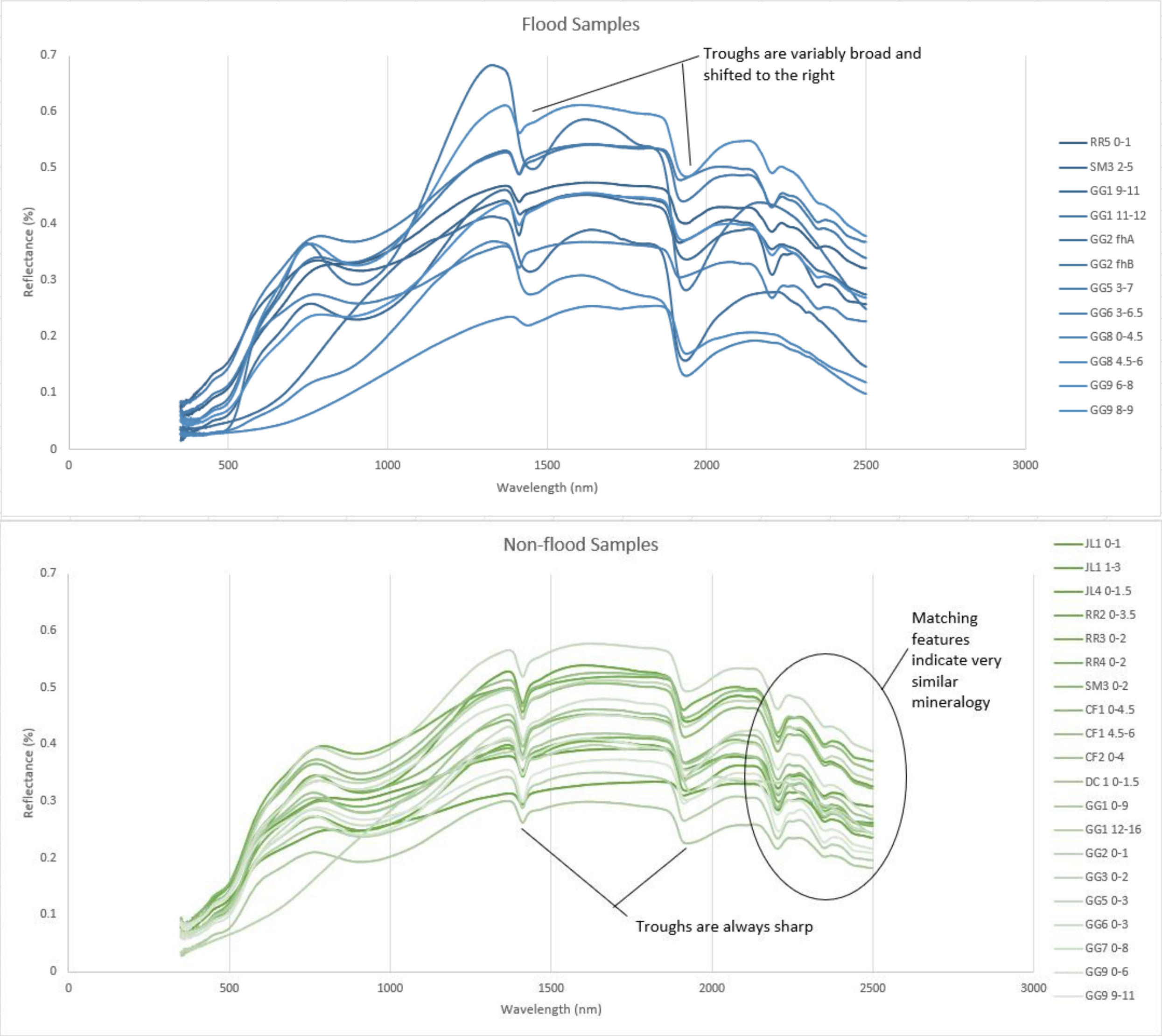


Figure 9: Plot of reflectance vs. wavelength from spectroscopy of samples identified as A) sediment deposited in the Lake Emma flood and B) sediments that were not deposited in the Lake Emma flood. Overall, there is more variability in the flood sediments, and sharper troughs at approximately 1400 nm and 1900 nm indicate that the clay minerals in sediment that is not from the Lake Emma flood are more crystalline, while the flood sediment contains clay minerals that are more hydrated.

4.4 Whole Rock Element Geochemistry

4.4.1 Comparison of Aqua Regia vs. 4 Acid Total Dissolution

While concentration values were similar between aqua regia and 4 acid total dissolution, there was significant variation in some elements. Aqua regia results showed higher concentrations for antimony, as expected, as well as for zinc, silver, cadmium, cobalt, nickel, germanium, and tellurium. However, most elements that are not associated with ore formation have lower reported concentrations in aqua regia than in 4-acid total dissolution, indicating that aqua regia was not fully dissolving and analyzing the minerals hosting those elements. However, the ore-related elements that are most important to this study were not as affected as other elements (figure 10). Additionally, four acid total dissolution analysis does not report values of gold, mercury, phosphorus, sulfur, or titanium. Based on these limitations as well as the cost of analysis, aqua regia was determined to be the best method for this study.

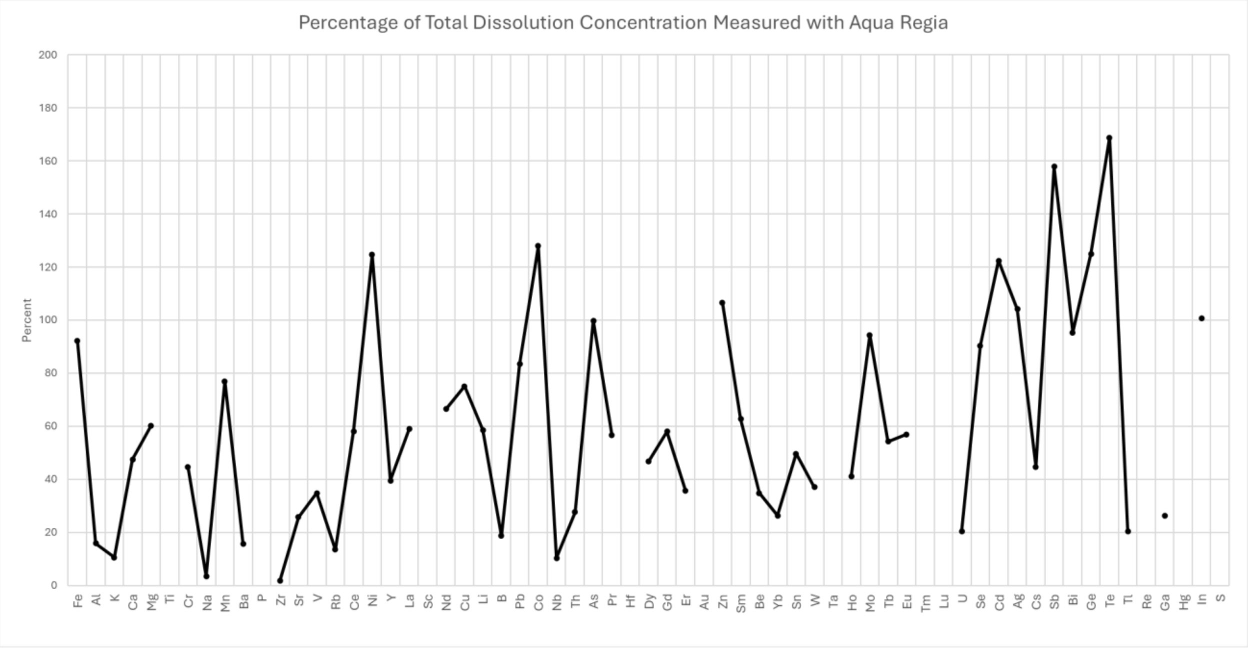


Figure 10: Plot showing the percentage of the average concentration measured by 4-acid total dissolution analysis that is measured on average by aqua regia analysis ((AR/TD) · 100) for the tested elements. Gaps in the line show elements that four acid dissolution does not test for or elements where values were consistently below the detection method of aqua regia, so no differences could be calculated.

4.4.2 Trace Elements

The elemental geochemistry of the samples for the most part is not significantly different between sediment from the Lake Emma flood and sediment from other deposition. All samples are enriched in the suite of chalcophile elements that are associated with ore mineralization in the area (figure 11). The analysis of Lake Emma sediment and published values for the Colorado

River basin do not include many of the elements considered in this study, so a full comparison is difficult. However, both the Lake Emma flood and non-flood sediments collected from Cement Creek in this study follow some similar patterns to the Colorado River basin as a whole, but do not match exactly, nor do any of the samples match well overall with the Lake Emma sediment analyzed in Church et al., 2007 a (figure 12).

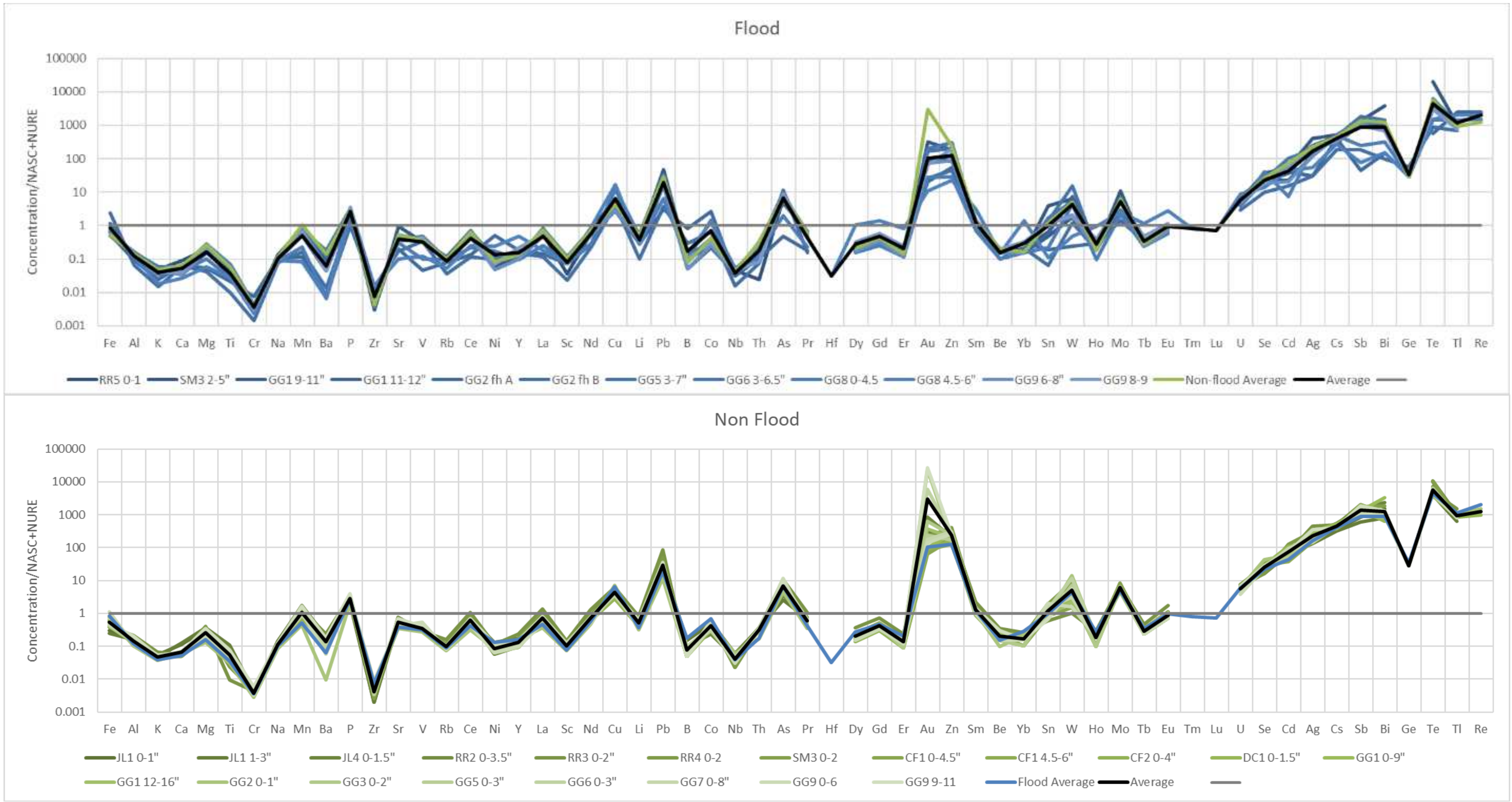


Figure 11: A) plot of trace element values in sediments that were deposited in the Lake Emma flood and B) sediment that was not deposited during the Lake Emma flood. Results have been normalized to the North American Shale Composite (NASC) with supplemental normalization values from the National Uranium Resource Evaluation (NURE) for elements not represented in the NASC (see section 3.4 and Appendix F). Elements are in order of greatest to least abundant in the normalization set. Gaps in data series indicate an element that was below the detection limit in that sample.

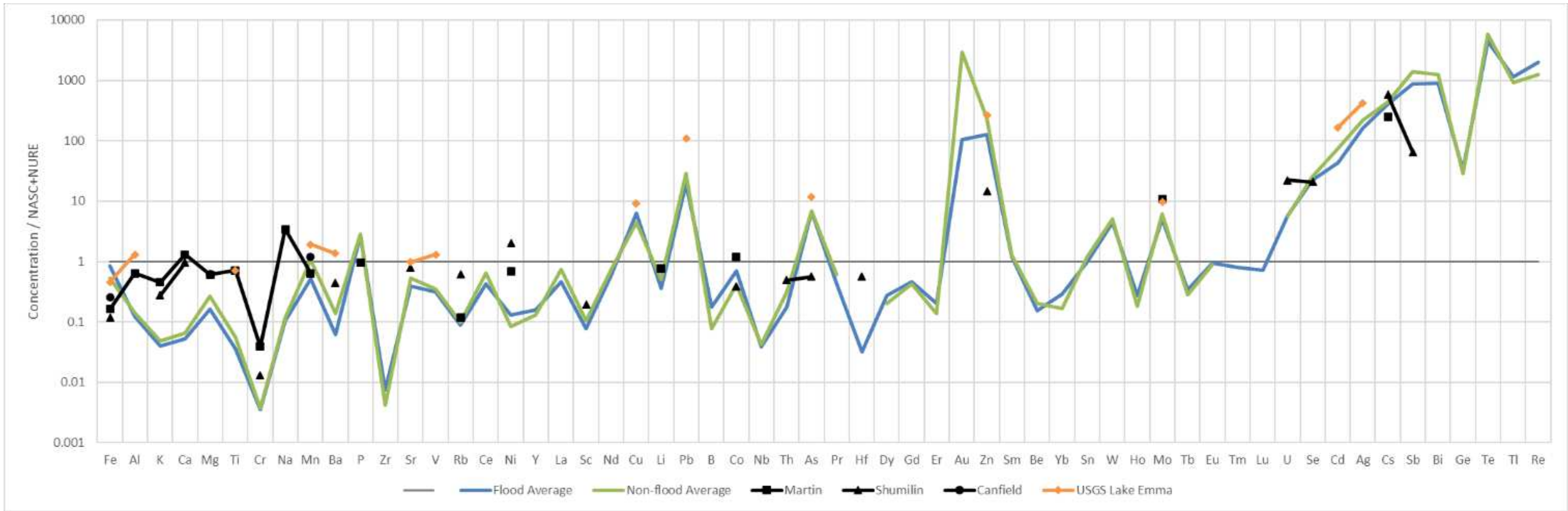


Figure 12: Normalized quantities of trace elements, showing the average elemental content of flood samples, non-flood samples, and the reported values of Colorado River sediment from Martin & Meybeck (1979), Shumilin et al. (2002), Canfield (1997) and the Lake Emma sediment analyzed by the USGS (Church et al., 2007 a).

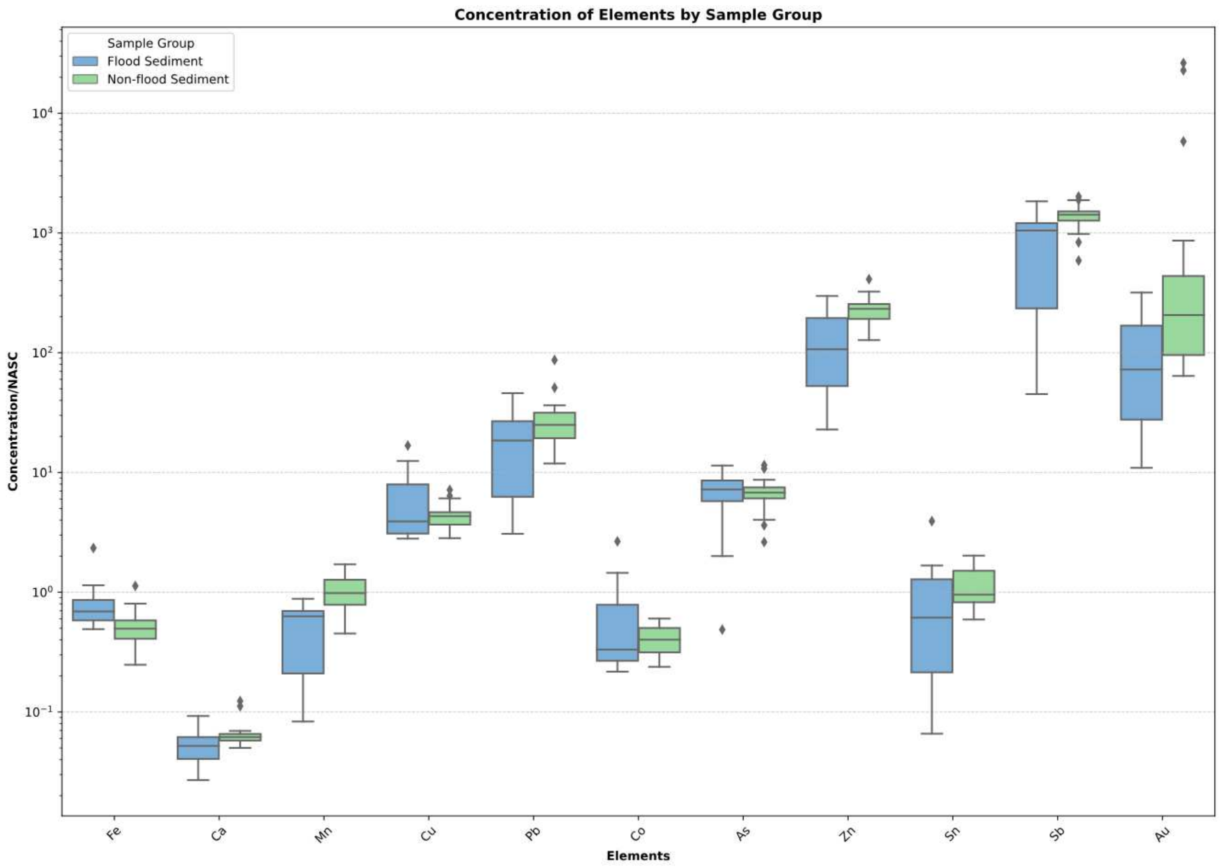


Figure 13: Ranges of notable elements in flood and non-flood sediments. Concentrations are normalized in order to better visualize trends across elements with very different concentrations. The elemental makeup in flood deposits has greater variability than other deposits.

While the difference in elemental concentrations is minor, the Lake Emma flood sediment typically has slightly lower average concentrations of most elevated elements than the normal stream sediment. However, that is not the case for iron. Although most samples are depleted in iron compared to the NASC normalization, the Lake Emma sediment has 59% more iron than the non-flood sediment on average (figure 13).

Since sulfur could not be normalized using the NASC, it is not included in the above diagrams. However, sulfur concentrations can be compared between the two suites of samples without normalization. As with many other elements, the Lake Emma flood sediment had a much wider range of sulfur concentrations than the other sediment did. The weight percent sulfur was also much higher on average in the Lake Emma flood sediment (figure 14).

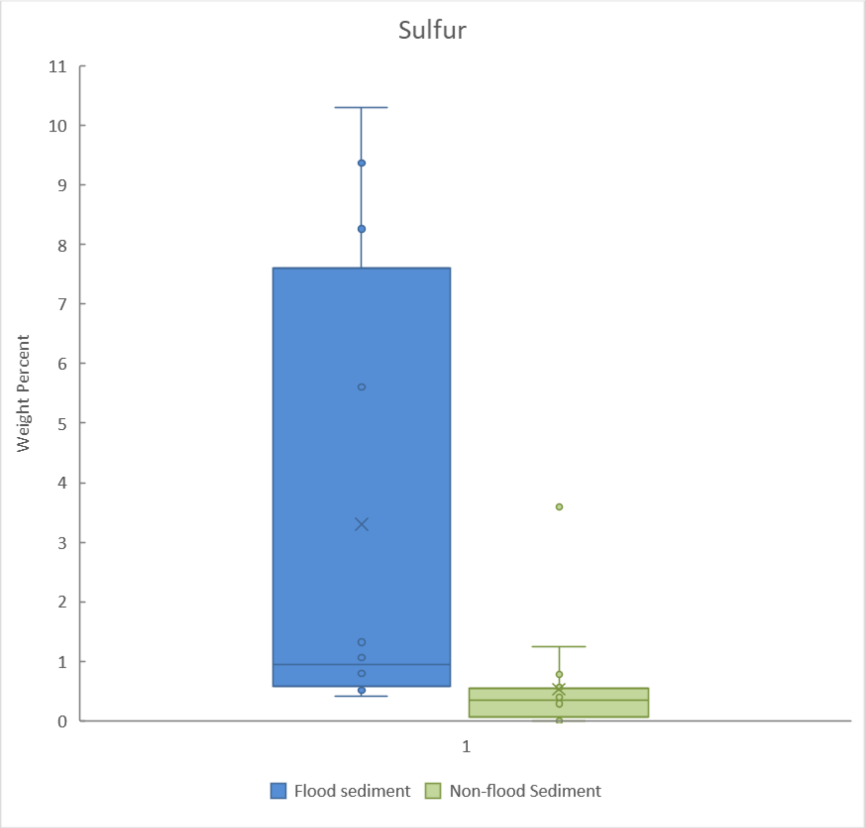
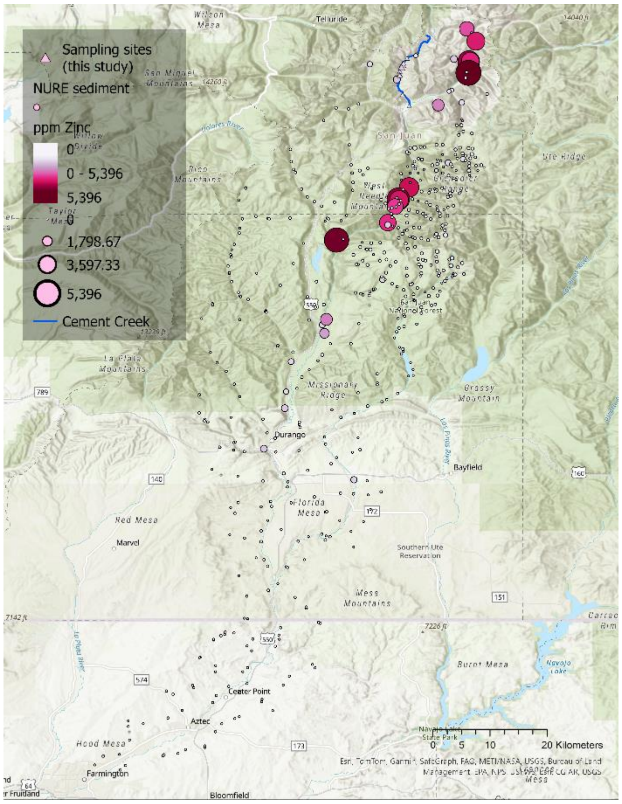
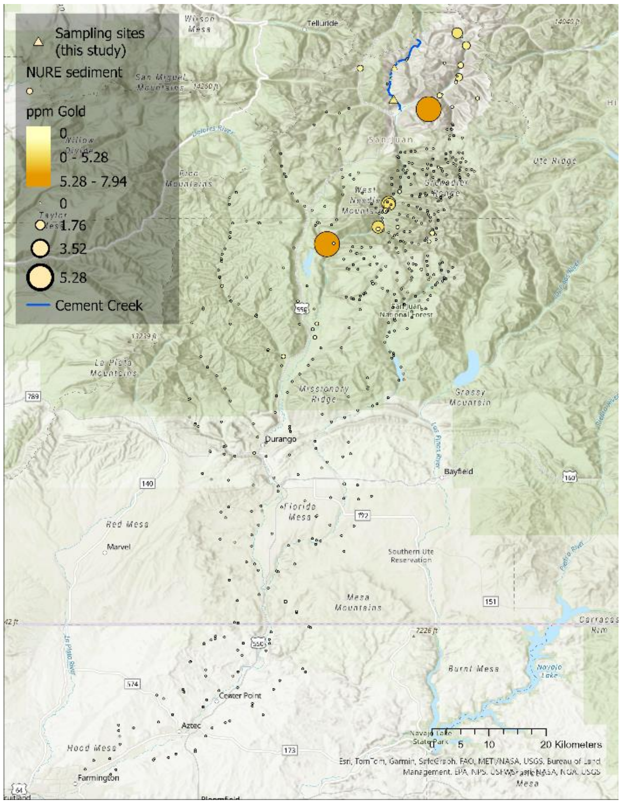


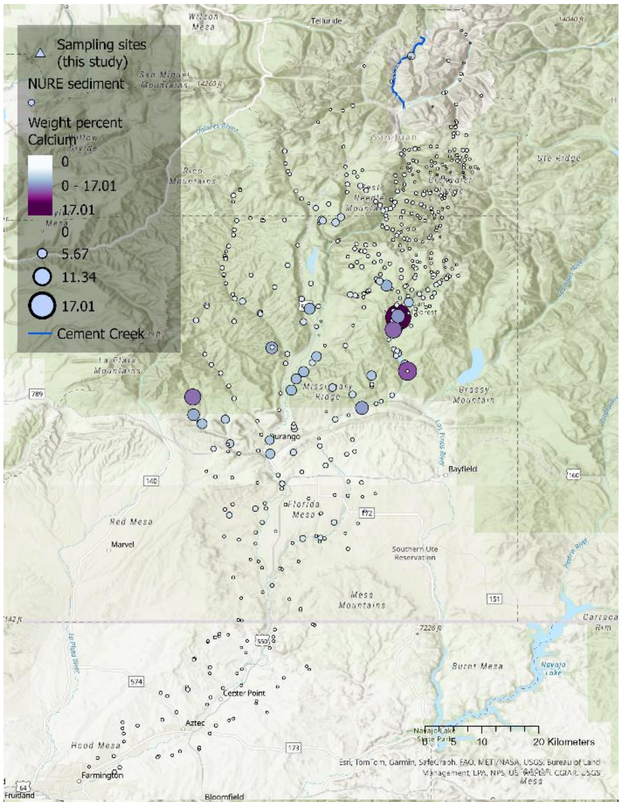
Figure 14: Comparison of weight percent sulfur in Lake Emma flood sediments (blue) and other Cement Creek sediments (green). There is a wider range of concentrations in the Lake Emma sediment, but overall, the Lake Emma sediment has higher concentrations of sulfur.

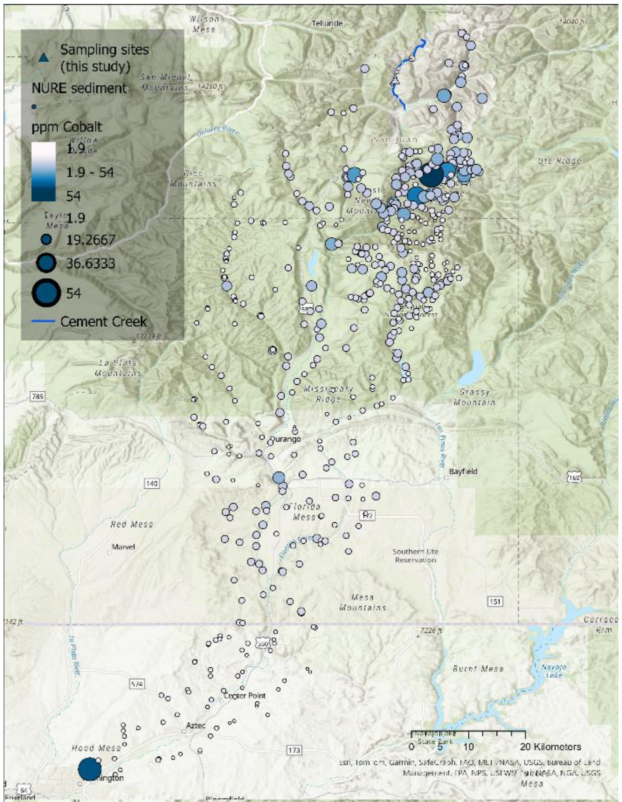
4.4.3 Maps of Elemental Concentrations

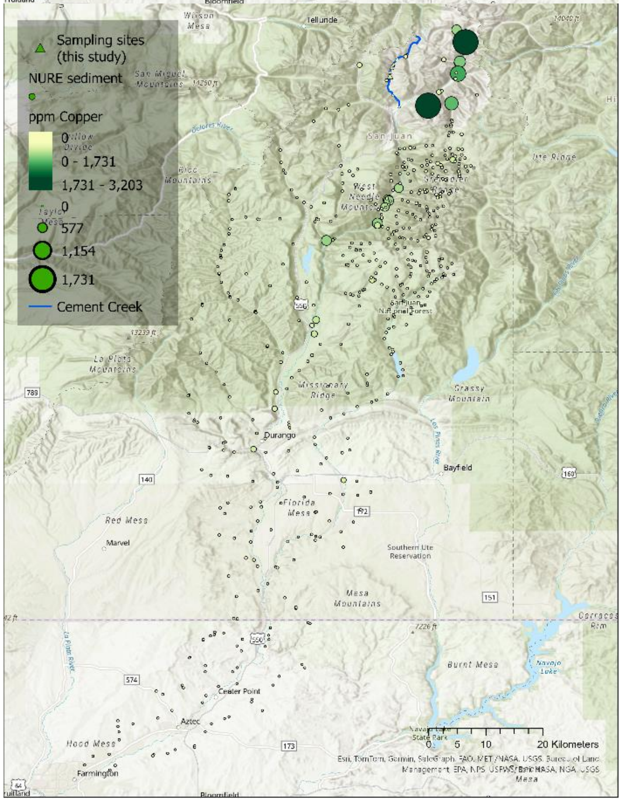
Significant elements within this study were mapped in comparison with elemental concentrations within the rest of the Upper Animas watershed (figure 15). The trend visible in all of these maps is that the sites from this study are enriched in heavy metals relative to the watershed as a whole, but are in most cases not the most significantly enriched area. The entire watershed is heavily mineralized and mining affected, so element concentrations are often elevated, especially in the headwaters. Most elements have especially high concentrations along the main stem of the Animas River, but Ca, Co, Sn, and As are more enriched along other tributaries in the watershed. The only element for which the samples collected in Cement Creek for this study have significantly higher concentrations than other sampling sites in the Upper Animas River watershed is iron.

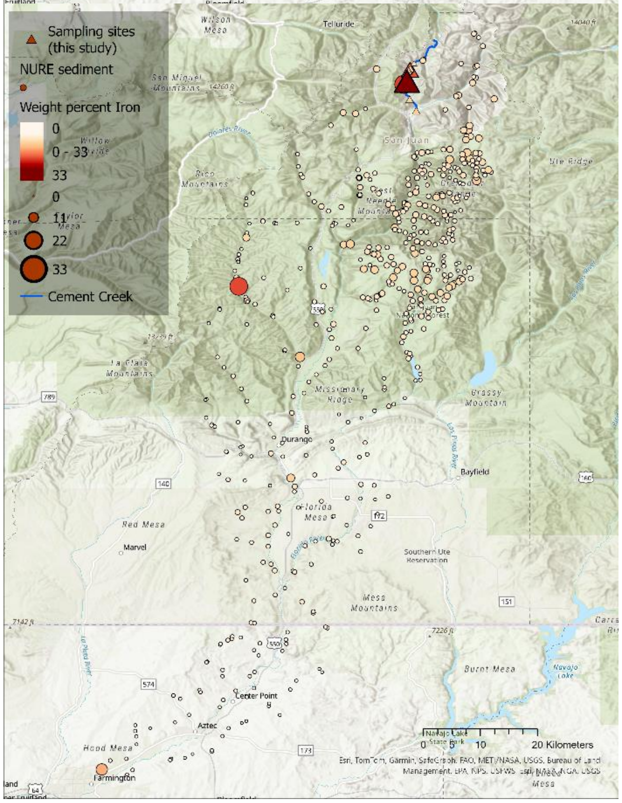





Sampling sites (this study)
NURE sediment
Weight percent Calcium
0
0 - 17.01
17.01
0
5.67
11.34
17.01
Cement Creek
Telluride
Durango
Bayfield
Farmington
Aztec
Center Point
0 5 10 20 Kilometers


Sampling sites (this study)
NURE sediment
ppm Cobalt
1.9
1.9 - 54
54
1.9
19.2667
36.6333
54
Cement Creek
Telluride
Durango
Bayfield
Farmington
Aztec
Center Point
0 5 10 20 Kilometers


Sampling sites (this study)
NURE sediment
ppm Copper
0
0 - 1,731
1,731 - 3,203
0
577
1,154
1,731
Cement Creek
Telluride
Durango
Bayfield
Farmington
Aztec
Center Point
0 5 10 20 Kilometers


Sampling sites (this study)
NURE sediment
Weight percent Iron
0
0 - 33
33
0
11
22
33
Cement Creek
Telluride
Durango
Bayfield
Farmington
Aztec
Center Point
0 5 10 20 Kilometers

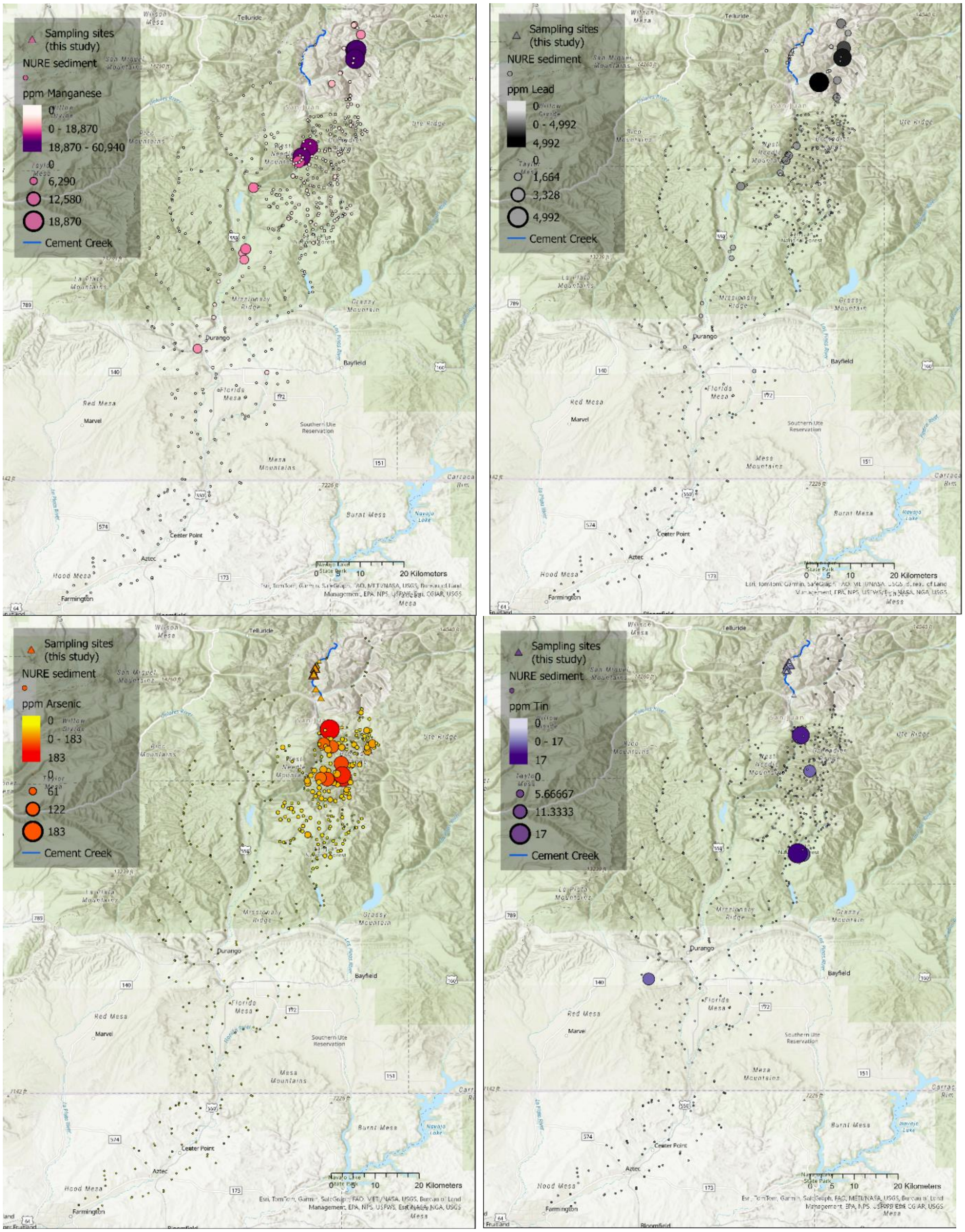


Figure 15: Maps showing the relative concentrations of elements throughout the Upper Animas River Watershed. Round points are data from the NURE database, while triangular points indicate samples from this study. Samples from this study include both flood and non-flood sediment. Cement Creek is highlighted in blue.

4.4.4 Calculation of Water Quality and Assessment of Fe/Cu Ratios

When metals are in an aqueous solution, the precipitation of metal ions from that solution is strongly dependent on pH (Stumm & Morgan, 1996). When Cu binds to an iron hydroxide, the amount of Cu in the precipitate will change the ratio of Fe/Cu. Therefore, the Fe/Cu ratio within a sample is dependent on the pH of the solution and the concentration of aqueous Cu that is available for precipitation. However, there are other factors that can influence the precipitation of Cu onto Fe precipitates (and therefore Fe/Cu ratios), such as competition with other metals, sorbate/sorbent ratios of the system, and specific surface area (Nimick et al., 2009).

Plotting the Fe/Cu ratios in Cement Creek samples (both sediment and unfiltered water) collected by the USGS (Smith 2006, USGS Stream Gauge 09358550, and Johnson et al., 2007) versus the pH and the dissolved Cu (in filtered water) from the same samples using the method of Nimick et al., 2009 did not show meaningful trends. The pH in Cement Creek falls consistently between 3.5 and 5. The only outliers are the data from the NURE database, which have pH measurements of 7.1 and 6.3. However, the Fe/Cu ratios of the samples vary by multiple orders of magnitude, with most data falling between 20 and 1,000 (figure 16).

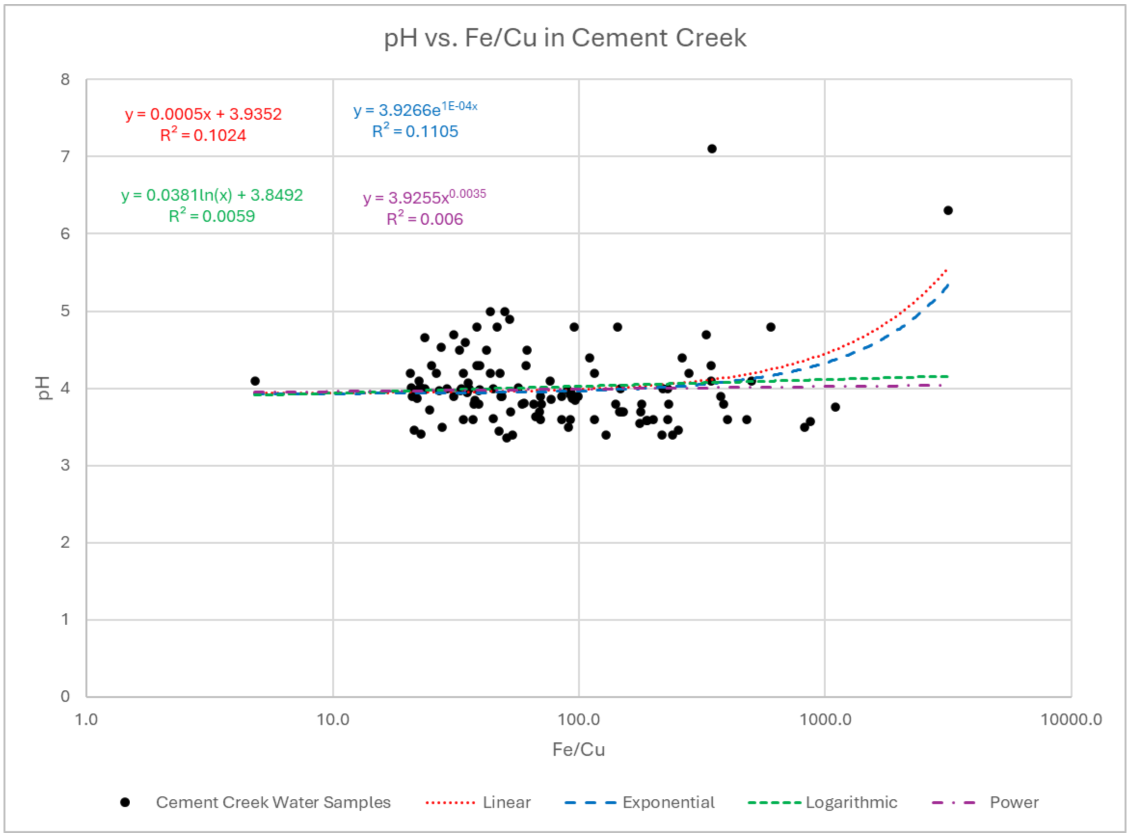


Figure 16: pH vs. Fe/Cu ratios of samples collected in Cement Creek from the HSSR NURE database (Smith 2006), USGS Stream Gauge 09358550 (Cement Creek at Silverton, CO), and Johnson et al., 2007. pH is consistently between 3.5 and 5, while Fe/Cu ratios vary widely. Therefore, no regression equations provide a good fit for these data.

The dissolved Cu concentrations in the USGS data have a stronger relationship with Fe/Cu ratios in unfiltered water samples than the pH does. However, while the general trend relationship is as expected, the trend is not strong enough to serve as an accurate predictor of dissolved Cu based on Fe/Cu ratios. The closest fit is an exponential regression, which has an R^2 of only 0.26 (figure 17).

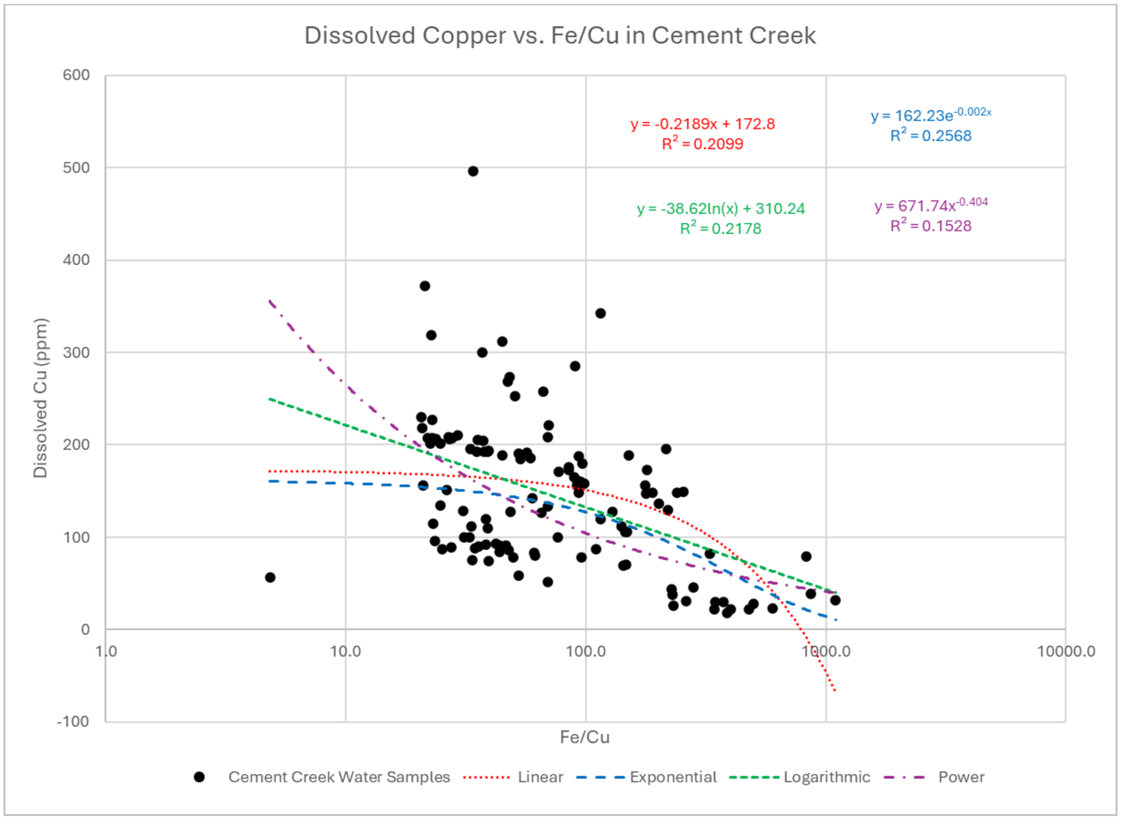


Figure 17: Dissolved Cu vs. Fe/Cu ratios of samples collected in Cement Creek from USGS Stream Gauge 09358550 (Cement Creek at Silverton, CO), and Johnson et al., 2007. There is a weak relationship between the variables, but there are no regression equations that fit well enough to meaningfully predict dissolved Cu concentrations based on Fe/Cu.

Although pH does not correlate well with Fe/Cu ratios of unfiltered water samples from previous studies in Cement Creek, analysis of the Fe/Cu of the sediments in this study can still provide insight. The Lake Emma flood sediment collected in this study has significantly higher average Fe/Cu ratios than the non-flood sediment, as well as a wider range of values (figure 18).

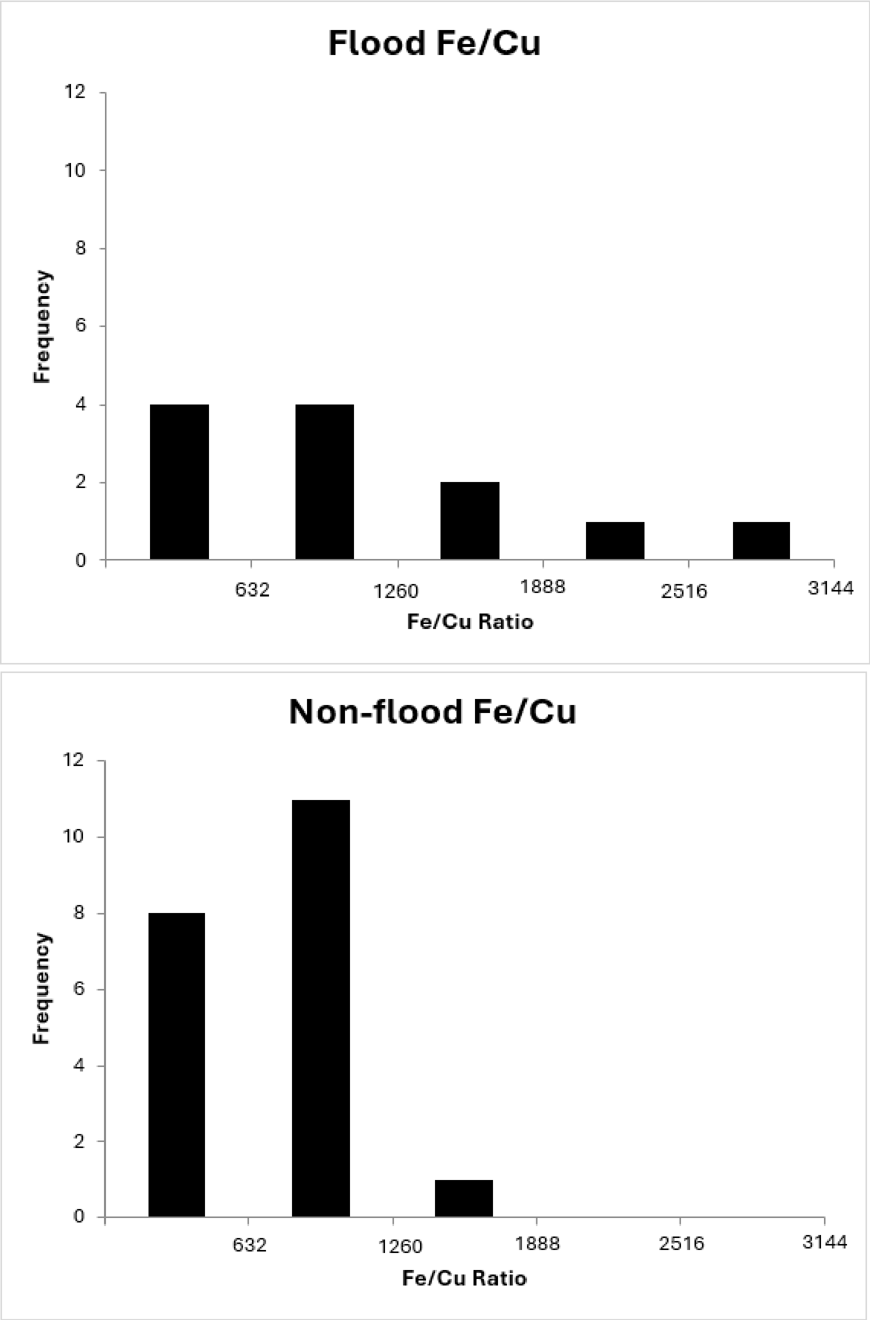


Figure 18: Frequency distributions of Fe/Cu ratios in the Lake Emma flood sediment and other stream sediment. The flood samples have a wider spread of ratios, but overall have higher Fe/Cu ratios than the other sediments.

5. DISCUSSION

5.1 Benefits and Drawbacks of Historical Research

Incorporating historical research such as newspapers, photographs, business documents, and interviews was instrumental to this project. For scientific investigations like this one, where there are few scholarly descriptions of the event being researched and a loss of evidence over time, looking at historical sources may be the only viable option. Another benefit to this project specifically is that the incorporation of historical sources prevented a blind search for preserved sediment deposits and characteristics of flood material when that knowledge already exists in the community. Having more background information from a variety of interdisciplinary sources makes research projects better and more efficient. While it may have been possible to identify Lake Emma sediment using published descriptions and localities such as Church et al. (2007 a), the extent of preserved sediment identified in this study is far greater than has been recognized in other studies. Using community knowledge and historical accounts aided field work substantially.

Additionally, in this study many people who were directly impacted by this tragic event still live in the community where this research was conducted. Including those individuals as community stakeholders can build goodwill towards scientific research in the area and lead to more community engagement in the future. Everyone contacted to assist with this historical research was willing to participate, and many expressed gratitude that their experiences were being considered.

However, there are some challenges to conducting historical research that arose during this study and could hinder other similar investigations. As discussed in section 3.1, personal accounts (both those offered in modern interviews and those that were recorded closer to the time of the event) are not always reliable sources of information. For example, eyewitness accounts of the height of flood water given in this study's interviews and historic newspapers ranged from three to ten feet (1-3 m) and were rarely related to a specific cross section of the stream. This makes calculating even a rough estimate of the discharge unreliable.

5.2 Presence of Lake Emma Flood Sediment in Cement Creek

While previous studies have alluded to the presence of Lake Emma flood sediments in Cement Creek and/or analyzed the sediment geochemistry, the preservation of the sediment is more extensive than earlier recognized. Lake Emma sediment is present where suitable depositional environments exist throughout the length of the stream and is found at every locality except the confluence with the Animas River and Jane Legge's creek. Both of these localities have had new infrastructure built since the flood (a bridge over culverts at JL and a walking path at CF) which may have impacted the ability to preserve older stages of deposition. Lake Emma flood sediments were identified based on eyewitness descriptions of fine grained, organic-rich sediment, which appeared in the field area as a layer of dark fine grained sediment bracketed by layers of orange clay-rich sediment. The orange sediment is likely the result of iron and sulfur rich minerals weathering, since it was observed surrounding the black sediment and no eyewitnesses reported red or orange colored sediment in the immediate aftermath of the flood.

The fact that so much Lake Emma flood sediment persists indicates that it has had a lasting effect on the creek. The flood deposited sediment on bars that are well above typical flood levels, and deposits were generally observed between ten and twenty centimeters above the yearly spring flood level. It is likely that the mud was deposited when the flood water was ebbing, rather than at the maximum height of the flood water. This likely lead to more sediment deposition in areas where the flood water pooled and moved more slowly. Because the sediment is still present in the system, it has the potential to continue to cause environmental effects such as metal loading and acid generation.

5.3 Cement Creek Geochemistry

5.3.1 Mineralogy vs. Whole Rock Geochemistry

The concentration of trace elements in the Lake Emma flood sediments and the other stream sediments are similar overall, (though there are some significant differences), but their NIR, SWIR, and Vis spectra are not. This indicates that the elements that compose this sediment are housed within different minerals. The Lake Emma sediments are more hydrated and are more commonly identified as hydrated clay minerals such as smectite. The clay minerals in sediments that are not from the Lake Emma flood are more crystalline and often identified to contain vermiculite, a clay mineral that typically contains less water. Clay minerals often form during weathering processes, so it is possible that this difference in mineralogy is due to different weathering conditions experienced by the sediment suites. The spectra collected by Kokaly et al. (2017) of precipitate from acid wastewater treatment at the Summitville gold mine in southwest Colorado also show broad troughs at 1400 nm and 1900 nm, which may indicate that hydrated clay minerals are common in acidic mine waste environments.

It is also necessary to consider whether the hydrated signature shown in the Lake Emma sediments' spectra are due purely to water, or if there are additional components in clay minerals such as organics in the system, as implied by the descriptions of the flood sediment as very organic rich. Hydration can indicate the presence of water in the chemical structure of a mineral, but organic cations can replace water in between the layers of clay minerals (Grim, 1968). The TerraSpec is not set up to identify any organic materials, and there are organic OH groups with spectra that overlap with water (Ben-Dor et al., 1997). It is possible that more contact with and adsorption of organic material caused the clays in the Lake Emma sediments to be less crystalline.

5.3.2 Implications of Similarities and Differences in Whole Rock Geochemistry

The bulk geochemistry of the Lake Emma flood sediments and other stream sediments is similar. The enrichment of both suites of samples in elements associated with ore minerals in the area indicates that the intense mineralization of the region is the predominant geochemical signature.

The differences that are present between the suites of samples can illuminate important distinctions between the sediments. The Lake Emma flood sediments have significantly lower concentrations of Mn, Zn, and Sb, and they have significantly higher concentrations of Fe and S. Results show that the Lake Emma flood sediments often are less enriched in heavy metals than the other stream sediments in Cement Creek, which does not confirm the hypothesis of this study that the flood continues to have environmental effects by increasing the metal content of the stream. Since the environmental impact from heavy metals from the other stream sediment is likely higher, the heavy metal impact of the flood is not significant. Historical research indicates that the sediment at the bottom of Lake Emma contained waste rock from an older era of mining, possibly a small amount of old tailings, and glacially deposited sediment that would predate mining activity. Eyewitness accounts also indicate that the flood passed through the Sunnyside Mine within a few hours. While fast moving water could pick up sediment from the mine, such a short residence time would not necessarily result in dissolution of ore-related elements from mine walls or larger pieces of crushed ore that were not mobilized by the flood. Therefore, it is possible that the lake-bottom sediments may have contained less mining-affected material than the surface sediments that are usually deposited in Cement Creek. Most ore-related elements may be less enriched in the Lake Emma flood deposits because the lake-bottom sediment diluted the signature of mine material. It is not known exactly how much sediment was at the bottom of Lake Emma before the flood. It also is not possible to quantify how much sediment was left in the Lake Emma basin after the flood, as the area has undergone reclamation and much of the basin has been recently filled with waste rock and rock removed from the mountainside next to the basin (personal communication, Morely Beckman, 2023).

The only elements that were significantly more enriched in the Lake Emma flood sediment were iron and sulfur. The flood sediments had on average 518% more sulfur, and 59% more iron than the other stream sediment. Pyrite, FeS_2, is a primary acid-generating mineral in acid mine/rock drainage due to the oxidation of sulfide during weathering (Evangelou & Zhang, 1995, Nordstrom & Alpers, 1999, etc.). Additionally, the sulfate mineral gypsum was identified in the Lake Emma flood sediments, indicating sulfide oxidation. However, no other sulfate minerals were identified, and the absence of soluble iron sulfate minerals indicates that the sediment has less acid-generating potential than it may have once had. Sulfate minerals were not identified in many flood sediment samples that have elevated S and Fe levels. The elevated levels of Fe and S indicate that the Lake Emma flood sediments may still have significant acid-generating potential in Cement Creek despite their relatively low heavy metal concentrations and the absence of iron sulfate minerals, if a significant proportion of the Fe and S remain in oxidizing sulfide minerals. This supports the hypothesis that the Lake Emma flood may continue to environmentally impact Cement Creek.

One possible cause of the higher Fe and S levels in the Lake Emma sediment is the presence of waste rock from the older levels of the Sunnyside Mine in the lake. Hydrothermally altered veins containing ore often have a pyrite alteration halo surrounding them. This halo would be considered waste rock, as pyrite is not an ore mineral. Therefore, the waste rock may have had a much higher concentration of iron and sulfur than the average for the region.

5.3.3 Implications of Fe/Cu Ratios

The Fe/Cu ratio of iron oxides and oxyhydroxides are based on how much Cu is able to precipitate or adsorb onto these iron minerals. More Cu precipitation leads to a lower ratio. As is the case for many metals, the solubility of Cu ions is highly dependent on the pH of the solution. Cu is more soluble (more likely to exist as ions in water than as a precipitate) at lower pH levels (Cuppett et al., 2006). The ability of Cu^{2+} ions to bind to the surface of ferrihydrite increases dramatically from 20% to 80% between pH levels of 4.5 and 5.5 (Stumm & Morgan, 1996). However, the amount of Cu precipitate is also highly dependent on the concentration of Cu in the aqueous solution, as well as the charge of surface minerals that copper would precipitate onto.

The Fe/Cu ratios of the Lake Emma sediment are overall higher than the Fe/Cu ratios of other stream sediment. Unfortunately, as the elemental concentrations are reported for each sediment sample as a whole, there is some uncertainty over the amount of iron and copper related to iron oxides and oxyhydroxides as opposed to clay minerals. However, if most of the iron is present as oxides and oxyhydroxides, this indicates that some aspect of the system in which these sediments formed must be different. Either the pH of the Lake Emma flood water was lower, causing more copper to stay in solution, or the water had lower copper concentrations overall, so there was not as much copper available to precipitate. Generally, precipitates in the same stream can be assumed to form from the same source, and therefore have the same available Cu concentration (Nimick et al., 2009). However, the water and sediment from Lake Emma would not have flowed into Cement Creek under normal conditions, because Lake Emma was in the South Fork Animas River watershed. Therefore, it is not possible to confirm whether the difference in Fe/Cu ratios is due to a lower pH or lower Cu concentration.

6. CONCLUSIONS AND IMPLICATIONS

The preservation of sediment from the Sunnyside Flood observed in this study is extensive, and more prevalent than previously known. Distinctive flood sediments were identified in favorable deposition settings in many reaches of Cement Creek. The continued presence of Lake Emma flood sediments in Cement Creek means that environmental effects the flood had on the area persist. While the Lake Emma flood was an abnormally large event, other mine water blowouts in similar areas likely also have lasting effects, which is important to consider during remediation and reclamation projects of mine lands. Additionally, when conducting research or planning reclamation projects, historical research and input from community members can be extremely valuable, as there are often sparse records of land use and what potential problems may exist, even when the people who have lived in the area are aware of issues and often have their own records and accounts of local history.

The higher Fe/Cu ratios of the Lake Emma flood sediments could reflect the possibility that the flood sediments were deposited from water with a lower pH but could also indicate that the sediment is from a different source than the regular sediment in Cement Creek, and that source has lower concentrations of copper. The hydrated nature of the clay minerals in the Lake Emma flood sediment could also indicate that the sediment involved in the flood had undergone different weathering processes than the sediment deposited in Cement Creek from other events, which could also point to the explanation that flood sediments are primarily different because they come from a source that under normal circumstances would not flow into Cement Creek. However, the hydration of the Lake Emma flood sediment clays could also reflect a higher amount of organics present in the system than the rest of the Cement Creek sediment.

Overall, both the Lake Emma flood sediments and the other sediment in Cement Creek are enriched in ore-associated elements, and the mineralization of the region is the dominant geochemical signature. However, the Lake Emma flood sediments are less enriched in most heavy metals than the other stream sediments, possibly because the mining-affected sediments were diluted by glacially derived lake-bottom sediments that already existed in Lake Emma. The Lake Emma flood sediments were significantly more enriched in both iron and sulfur, which along with the presence of sulfate minerals identified by spectroscopy indicates they may have a much higher potential for acid generation from the flood sediments than the other sediment in the creek, which can have significant negative impact on the environment despite the lower quantity of heavy metals overall.

The hypothesis of this study was that the 1978 Sunnyside Mine flood had significant geochemical and geomorphic effects and continues to affect the environment today. While the exact impact that the flood has had on the environment is complex, the high potential for acid generation is a significant negative environmental impact that is likely to continue to impact the environment for many more years, supporting this study's hypothesis.

6.1 Potential Future Work

Further research is needed to fully characterize the sediment from the Lake Emma flood at the Sunnyside Mine. Mineralogy of the sediment, specifically the presence or absence of sulfide minerals and secondary acid sulfate minerals, should be determined. Additional work may be required to identify the source of iron and sulfur. This will help to ascertain how much acid generation potential the Lake Emma flood sediments continue to have. Searching for and analyzing areas where the sediment from the flood is less weathered would also be useful. Many samples in this study were taken from cut banks of Cement Creek, where the flood sediments are exposed to weathering, but they are likely present and less weathered below the surface at other places on the floodplain.

The flood sediments were described by eyewitnesses as dark, fine grained, and organic rich, and individuals report that the water smelled like sulfur and diesel fuel. To better understand the nature of the flood. It would be useful to determine if the organic material present in the flood sediment was naturally occurring organics from the bottom of Lake Emma or industrial material picked up by the water as it passed through the mine.

Geochemical methods similar to those used in this thesis could be used in studies to compare lasting environmental effects in Cement Creek to those that may exist in other areas. Additionally, while the draining of Lake Emma that caused this flood is a unique event that is unlikely to occur elsewhere, similar floods could be caused by blowouts, tailings dam failures, and large seasonal floods at other mines, both active and abandoned. Many of these events that happened in the past may have a similar gap in reliable records while community members have memories and personal records. Unfortunately, many individuals, especially those who are trained only in scientific research and not social science or history, may have difficulty making sense of and effectively utilizing contradictory historical sources. However, it is worthwhile for scientists to develop skills in historical research methods to make use of existing information when conducting research.

REFERENCES

Atwood, W. W., & Mather, K. F. (1932). *Physiography and Quaternary geology of the San Juan Mountains, Colorado* (No. 166; Professional Paper). USGS.

Bartos, P. J. (1993). Comparison of Gold-Rich And Gold-Poor Quartz-Base Metal Veins: Western San Juan Mountains, Colorado: The Mineral Point Area As An Example. *SEG Discovery*, *15*, 1–11. https://doi.org/https://doi.org/10.5382/SEGnews.1993-15.fea

Ben-Dor, E., Inbar, Y., & Chen, Y. (1997). The reflectance spectra of organic matter in the visible near-infrared and short wave infrared region (400–2500 nm) during a controlled decomposition process. *Remote Sensing of Environment*, *61*(1), 1–15. https://doi.org/10.1016/S0034-4257(96)00120-4

Besser, J. M., Finger, S. E., & Church, S. E. (2007). Impacts of Historical Mining on Aquatic Ecosystems—An Ecological Risk Assessment. In *Integrated Investigations of Environmental Effects of Historical Mining in the Animas River Watershed, San Juan County, Colorado*. U.S. Geological Survey. [Professional Paper 1651].

Bird, A. G. (1986). *Silverton Gold: The Story of Colorado's Largest Gold Mine*. Allan G. Bird.

Blair, R. W., & Yager, D. B. (2002a). *Surficial geology along Mineral and Cement Creeks in the Ironton quadrangle, Animas River watershed, San Juan County, Colorado* [Map]. U.S. Geological Survey. In No. DDS-71; Digital Data Series.

Blair, R. W., & Yager, D. B. (2002b). *Surficial geology along the Middle and South Forks of Mineral Creek, Mineral and Cement Creeks, and the Animas River in the Silverton quadrangle, Animas River watershed, San Juan County, Colorado* [Map]. U.S. Geological Survey. In No. DDS-71; Digital Data Series.

Blair, R. W., Yager, D. B., & Church, S. E. (2002). *Surficial geologic maps along the riparian zone of the Animas River and its headwater tributaries, Silverton to Durango, Colorado, with upper Animas River watershed gradient profiles* (No. DDS-71; Digital Data Series).

Blood, W. A. (1968). *Geology, History, and Economics of the Sunnyside Mine, Eureka Mining District, San Juan County, Colorado* [Doctoral Thesis, Colorado School of Mines].

Bonita Peak Mining District | Department of Public Health & Environment. (n.d.). Retrieved April 11, 2024, from https://cdphe.colorado.gov/hm/bonita-peak-mining-district

Bonita Peak Mining District CAG. (2016, February 25). The Long Road to Superfund. *Silverton Standard*. https://www.bonitapeakcag.org/wp-content/uploads/2019/10/Gladstone-Chronology-from-Silverton-Standard-reformatted.pdf

BONITA PEAK MINING DISTRICT Site Profile. (n.d.). EPA. Retrieved April 11, 2024, from https://cumulis.epa.gov/supercpad/SiteProfiles/index.cfm?fuseaction=second.Stayup&id=0802497#Stayup

Bove, D. J., Mast, M. A., Dalton, J. B., Wright, W. G., & Yager, D. B. (2007). Major Styles of Mineralization and Hydrothermal Alteration and Related Solid- and Aqueous-Phase Geochemical Signatures. In S. E. Church, P. von Guerard, & S. E. Finger (Eds.), *Integrated Investigations of Environmental Effects of Historical Mining in the Animas River Watershed, San Juan County, Colorado*. U.S. Geological Survey. [Professional Paper 1651].

Campbell, W. L., & Antweiler, J. C. (1980). Nomogram for converting units common in the precious metals industry. *Geology*, *8*(9), 450. https://doi.org/10.1130/0091-7613(1980)8<450:NFCUCI>2.0.CO;2

Canadian Mining Journal Staff. (2002, November 20). COMPANY NEWS Kinross, Echo Bay, TVX Delay Merger. *Canadian Mining Journal*. https://www.canadianminingjournal.com/news/company-news-kinross-echo-bay-tvx-delay-merger/

Canfield, D. E. (1997). The geochemistry of river particulates from the continental USA: Major elements. *Geochimica et Cosmochimica Acta*, *61*(16), 3349–3365. https://doi.org/10.1016/S0016-7037(97)00172-5

Casadevall, T., & Ohmoto, H. (1977). Sunnyside Mine, Eureka mining district, San Juan County, Colorado; geochemistry of gold and base metal ore deposition in a volcanic environment. *Economic Geology*, *72*(7), 1285–1320. https://doi.org/https://doi.org/10.2113/gsecongeo.72.7.1285

Church, S. E., Fey, D. L., Brouwers, E. M., Holmes, C. W., & Blair, R. (1999). *Determination of pre-mining geochemical conditions and paleoecology in the Animas River Watershed, Colorado* (Nos. 99–0038; Open-File Report). U.S. Geological Survey.

Church, S. E., Fey, D. L., & Unruh, D. M. (2007a). Trace Elements and Lead Isotopes in Modern Streambed and Terrace Sediment—Determination of Current and Premining Geochemical Baselines. In S. E. Church, P. von Guerard, & S. E. Finger, *Integrated Investigations of Environmental Effects of Historical Mining in the Animas River Watershed, San Juan County, Colorado*. U.S. Geological Survey. [Professional Paper 1651].

Church, S. E., Mast, M. A., Martin, E. P., & Rich, C. L. (2007b). Mine Inventory and Compilation of Mine-Adit Chemistry Data. In S. E. Church, P. von Guerard, & S. E. Finger (Eds.), *Integrated Investigations of Environmental Effects of Historical Mining in the Animas River Watershed, San Juan County, Colorado*. U.S. Geological Survey. [Professional Paper 1651].

Clark, R. N. (1999). Spectroscopy of rocks and minerals and principles of spectroscopy. In *Manual of remote sensing, Volume 3, Remote sensing for the earth sciences* (pp. 3–52). Wiley.

Clarke, L. (1981, August 30). Put to the test: Standard Metals makes a strong comeback from the Lake Emma Disaster. *Durango-Cortez Herald*.

Colorado Division of Reclamation, Mining, and Safety. (2023, July 5). *Silverton Miners' Oral Histories*. YouTube. https://www.youtube.com/playlist?list=PLB3JRydr2LBXbDw6VoVUjgBQhDAy2xq4a

Conyers, M. M. (2011). *The fluvial geomorphology of the Upper Animas River basin, Colorado* [Ph.D., Texas State University - San Marcos]. https://www.proquest.com/docview/927588677/abstract/7AEE2874258D46F5PQ/1

Cuppett, J. D., Duncan, S. E., & Dietrich, A. M. (2006). Evaluation of Copper Speciation and Water Quality Factors That Affect Aqueous Copper Tasting Response. *Chemical Senses*, *31*(7), 689–697. https://doi.org/10.1093/chemse/bjl010

Draper, E. (1994, January 9). Echo Bay reclaims Silverton gold mine. *Durango Herald*.

Elias, S. A., Carrara, P. E., Toolin, L. J., & Jull, A. J. T. (1991). Revised age of deglaciation of Lake Emma based on new radiocarbon and macrofossil analyses. *Quaternary Research*, *36*(3), 307–321.

EPA. (2022, February 22). *Bonita Peak Mining District Info Map Tool* [ArcGIS StoryMaps]. https://storymaps.arcgis.com/collections/e34d136ea58242f68ec12bd2a04acf8c

Evangelou, V. P. (Bill), & Zhang, Y. L. (1995). A review: Pyrite oxidation mechanisms and acid mine drainage prevention. *Critical Reviews in Environmental Science and Technology*, *25*(2), 141–199. https://doi.org/10.1080/10643389509388477

Finger, S. E., Church, S. E., & von Guerard, P. (2007). Potential for Successful Ecological Remediation, Restoration, and Monitoring. In S. E. Church, P. von Guerard, & S. E. Finger (Eds.), *Integrated Investigations of Environmental Effects of Historical Mining in the Animas River Watershed, San Juan County, Colorado*. U.S. Geological Survey. [Professional Paper 1651].

Frodeman, R. (2003). *Geo-logic: breaking ground between philosophy and the earth sciences*. State University of New York Press.

Gannett, H., Douglas, E. M., & Tweedy, F. (1897). *Colorado, Silverton Sheet* [Topographic]. U.S. Geological Survey.

Geochemistry of stream sediments in the US from the NURE-HSSR database by common geographic areas. (n.d.). Retrieved March 23, 2024, from https://mrdata.usgs.gov/nure/sediment/geo-inventory.php

Geology Staff, Sunnyside Gold Corporation. (1988). Structure & Ore Deposits of the Sunnyside Mine, Silverton, Colorado. In R. M. Hutchinson, *Epithermal Base-Metal and Precious-Metal Systems, San Juan Mountains, Colorado* (Vol. 3, pp. 60–73). Society of Economic Geologists. https://doi.org/10.5382/GB.03

GERM Reservoir Database -- Geochemistry of the North American Shale Composite (NASC) Reservoir. (n.d.). Geochemical Earth Reference Model. Retrieved April 11, 2024, from https://earthref.org/GERMRD/842/?n=842&n=842&n=842&n=842&n=842&n=842&n=842&n=842&res_id=842&database_name=germrd&search_start=main&sort=value%20desc

Grim, R. E. (1968). *Clay Mineralogy* (Second). McGraw-Hill, Inc.

Guido, Z. S., Ward, D. J., & Anderson, R. S. (2007). Pacing the post–Last Glacial Maximum demise of the Animas Valley glacier and the San Juan Mountain ice cap, Colorado. *Geology*, *35*(8), 739–742. https://doi.org/https://doi.org/10.1130/G23596A.1

Hayden, F. V. (1876). *[Eighth] Annual Report of the United States Geological and Geographical Survey of the Territories, embracing Colorado and parts of adjacent Territories: being a report of progress of the exploration for the year 1874*. Government Printing Office. https://doi.org/10.3133/70038932

Johnson, R. H., Wirt, L., Manning, A. H., Leib, K. J., Fey, D. L., & Yager, D. B. (2007). *Geochemistry of Surface and Ground Water in Cement Creek from Gladstone to Georgia Gulch and in Prospect Gulch, San Juan County, Colorado* (Open-File Report Nos. 2007–1004). U.S. Geological Survey.

Jones, W. R. (2007). History of Mining and Milling Practices and Production in San Juan County, Colorado, 1871–1991. In S. E. Church, P. von Guerard, & S. E. Finger (Eds.), *Integrated Investigations of Environmental Effects of Historical Mining in the Animas River Watershed, San Juan County, Colorado*. U.S. Geological Survey. [Professional Paper 1651].

Kimball, B. A., Runkel, R. L., Walton-Day, K., & Bencala, K. E. (2002). Assessment of metal loads in watersheds affected by acid mine drainage by using tracer injection and synoptic sampling: Cement Creek, Colorado, USA. *Applied Geochemistry*, *17*(9), 1183–1207. https://doi.org/10.1016/S0883-2927(02)00017-3

Kokaly, R.F., Clark, R.N., Swayze, G.A., Livo, K.E., Hoefen, T.M., Pearson, N.C., Wise, R.A., Benzel, W.M., Lowers, H.A., Driscoll, R.L., and Klein, A.J., 2017, USGS Spectral

Library Version 7: U.S. Geological Survey Data Series 1035, 61 p., https://doi.org/10.3133/ds1035.

Krauskopf, K. B. (1967). *Introduction to Geochemistry*. McGraw-Hill, Inc.

Lange, S. (2018). Remediation Helps Rescue a River. *Engineering and Mining Journal*, *219*(7), 26–31.

Lange, S., Fourie, A. B., & Tibbett, M. (2019). *Evaluating the effectiveness of Sunnyside Gold Corporation's reclamation, San Juan County, Colorado, USA* (pp. 1255–1266). Australian Centre for Geomechanics. https://doi.org/10.36487/ACG_rep/1915_99_Lange

Langmuir, D. (1997). *Aqueous environmental geochemistry*. Prentice Hall.

Luedke, R. G., & Burbank, W. S. (1964). *Geology of the Ironton Quadrangle, Colorado* [Map]. U.S. Geological Survey.

Luedke, R. G., & Burbank, W. S. (2000). *Geologic Map of the Silverton and Howardsville Quadrangle, Southwestern Colorado* [Map]. U.S. Geological Survey.

Marshall, J., & Zanoni, Z. (1996). *Mining the Hard Rock in the Silverton San Juans: A Sense of Place a Sense of Time* (2nd ed.). Simpler Way Book Company.

Martin, J.-M., & Meybeck, M. (1979). Elemental mass-balance of material carried by major world rivers. *Marine Chemistry*, *7*(3), 173–206. https://doi.org/10.1016/0304-4203(79)90039-2

Mast, M. A. (2018). *Calibration datasets and model archive summaries for regression models developed to estimate metal concentrations at nine sites on the Animas and San Juan Rivers, Colorado, New Mexico, and Utah*. https://doi.org/10.5066/P9THSFE0

Mine closure affects areawide economy. (1978, June 11). *Durango Herald*.

Mountain Studies Institute. (n.d.). *Animas River Monitoring*. Mountain Studies Institute. Retrieved January 11, 2023, from https://www.mountainstudies.org/animasriver

Nimick, D. A., Gurrieri, J. T., & Furniss, G. (2009). An empirical method for estimating instream pre-mining pH and dissolved Cu concentration in catchments with acidic drainage and ferricrete. *Applied Geochemistry*, *24*(1), 106–119. https://doi.org/10.1016/j.apgeochem.2008.11.007

Nordstrom, D. K., & Alpers, C. N. (1999). Geochemistry of Acid Mine Waters. In G. S. Plumlee & M. J. Logsdon (Eds.), *The Environmental Geochemistry of Mineral Deposits Part A* (Vol. 6A). Society of Economic Geologists.

Price, C. F. (1999). *Upper Animas Watershed (CERCLIS ID# CO0001411347) San Juan County, Colorado* [Analytical Results Report]. Colorado Department of Public Health and Environment Hazardous Materials and Waste Management Division.

Pruess, J., Wohl, E. E., & Jarrett, R. D. (1998). Methodology and Implications of Maximum Paleodischarge Estimates for Mountain Channels, Upper Animas River Basin, Colorado, U.S.A. *Arctic and Alpine Research*, *30*(1), 40–50. https://doi.org/10.1080/00040851.1998.12002874

Ransome, F. L. (1901). *A Report on the Economic Geology of the Silverton Quadrangle, Colorado* (USGS Numbered Series No. 182; Bulletin).

Rollinson, H., & Pease, V. (2021). *Using Geochemical Data: To Understand Geological Processes* (Second). Cambridge University Press.

Romeo, J. (2019, August 29). Animas River Stakeholders disband after 25 years of cleanup efforts. *The Durango Herald*. https://www.durangoherald.com/articles/animas-river-stakeholders-disband-after-25-years-of-cleanup-efforts/

Schemel, L. E., Kimball, B. A., & Bencala, K. E. (2000). Colloid formation and metal transport through two mixing zones affected by acid mine drainage near Silverton, Colorado. *Applied Geochemistry*, *15*, 1003–1018. https://doi.org/https://doi.org/10.1016/S0883-2927(99)00104-3

Shumilin, E. N., Carriquiry, J. D., Camacho-Ibar, V. F., Sapozhnikov, D., Kalmykov, S., Sánchez, A., Aguíñiga-García, S., & Sapozhnikov, Y. A. (2002). Spatial and vertical distributions of elements in sediments of the Colorado River delta and Upper Gulf of California. *Marine Chemistry*, *79*(3), 113–131. https://doi.org/10.1016/S0304-4203(02)00059-2

Simate, G. S., & Ndlovu, S. (2014). Acid mine drainage: Challenges and opportunities. *Journal of Environmental Chemical Engineering*, *2*(3), 1785–1803.

Smith, S. M. (2006). *Reformatted Data from the National Uranium Resource Evaluation (NURE) Hydrogeochemical and Stream Sediment Reconnaissance (HSSR) Program Version 1.40* (Open File Report Nos. 97–492). USGS.

Smith, S. M., Azain, J. S., Bueghly, Z. C., & Olinger, D. A. (2018). *Reanalysis of Selected Archived NURE-HSSR Sediment and Soil Samples from Arizona, California, Idaho, Montana, Nevada, New Mexico, and Utah*. https://doi.org/10.5066/F7765DHF

Spear, B. (1978a, June 5). Flood forces mine closure. *Durango Herald*.

Spear, B. (1978b, June 6). Witness says mine flood roared. *Durango Herald*.

Spear, B. (1978c, June 7). Mine flood affects city water. *Durango Herald*.

Spear, B. (1978d, June 8). Health officials criticize water notification delay. *Durango Herald.*

Spear, B. (1978e, June 8). Mine may not reopen. *Durango Herald.*

Spear, B. (1978f, June 16). 80 Silverton miners apply for job compensation. *Durango Herald.*

Spear, B. (1978g, June 23). Agencies continue mine probe. *Durango Herald.*

Spear, B. (1978h, June 30). City curtails watering time. *Durango Herald.*

Spear, B. (1978i, July 5). Agency halts mine work. *Durango Herald.*

Spear, B. (1978j, July 30). Standard mine begins long road back. *Durango Herald.*

Spear, B. (1978k, September 28). Mine cleanup progresses. *Durango Herald.*

Spear, B. (1979a, June 10). Mine to open - someday. *Durango Herald.*

Spear, B. (1979b, June 10). Silverton businesses face critical summer. *Durango Herald.*

Standard Metals Corp. announced Tuesday it had filed for... (1984, March 6). *United Press International.*

Standard Metals Corporation. (1978, June 6). *For Immediate Release* [Shareholder Letter].

Standard Metals Corporation. (1978, June 28). *Status Report on the Standard Metals Mine Incident* [Shareholder Letter].

Standard Metals Corporation. (1978, August 11). *Interim Report: First Six Months 1978* [Shareholder Letter].

Standard Metals Corporation. (1978, November 1). *News Release* [Press Release].

Standard Metals Corporation. (1979, January 16). *To bring you up to date on the affairs of Standard Metals* [Shareholder Letter].

Standard Metals Corporation. (1979, November 15). *For Immediate Release* [Shareholder Letter].

Standard Metals Corporation. (1980, January 7). *To Our Shareholders* [Shareholder Letter].

Standard Metals Corporation. (1981, March 26). *News Release* [Press Release].

StreamStats. (n.d.). Retrieved March 23, 2024, from https://streamstats.usgs.gov/ss/

Stumm, W., & Morgan, J. J. (1996). *Aquatic chemistry: chemical equilibria and rates in natural waters* (3rd ed). Wiley.

Thompson, J. P. (2018a). *River of Lost Souls: The Science, Politics, and Greed Behind the Gold King Mine Disaster*. Torrey House Press.

Thompson, J. P. (2018b, March 1). *River of Lost Souls reading aids*. https://riveroflostsouls.com/river-of-lost-souls-reading-aids/

Trout Unlimited Staff. (2022, February 1). *Bringing Back The Upper Animas*. Trout Unlimited. https://www.tu.org/magazine/conservation/from-the-field/bringing-back-the-animas/

US EPA. (2009). *National Primary Drinking Water Regulations*. National Service Center for Environmental Publications. https://nepis.epa.gov/Exe/ZyNET.exe/P1005EJT.txt?ZyActionD=ZyDocument&Client=EPA&Index=2006%20Thru%202010&Docs=&Query=%28zinc%29%20OR%20FNAME%3D%22P1005EJT.txt%22%20AND%20FNAME%3D%22P1005EJT.txt%22&Time=&EndTime=&SearchMethod=1&TocRestrict=n&Toc=&TocEntry=&QField=&QFieldYear=&QFieldMonth=&QFieldDay=&UseQField=&IntQFieldOp=0&ExtQFieldOp=0&XmlQuery=&File=D%3A%5CZYFILES%5CINDEX%20DATA%5C06THRU10%5CTXT%5C00000011%5CP1005EJT.txt&User=ANONYMOUS&Password=anonymous&SortMethod=h%7C-&MaximumDocuments=1&FuzzyDegree=0&ImageQuality=r150g4/r150g4/x150y150g16/i850&Display=hpfr&DefSeekPage=x&SearchBack=ZyActionL&Back=ZyActionS&BackDesc=Results%20page&MaximumPages=1&ZyEntry=3&SeekPage=f

US EPA. (2016, February 2). *Basic Information about Lead in Drinking Water* [Overviews and Factsheets]. https://www.epa.gov/ground-water-and-drinking-water/basic-information-about-lead-drinking-water

U.S. Geological Survey. (n.d.). *USGS 09358550 CEMENT CREEK AT SILVERTON, CO Water Quality Data*. Retrieved May 3, 2024, from https://nwis.waterdata.usgs.gov/usa/nwis/qwdata/?site_no=09358550&agency_cd=USGS&inventory_output=0&rdb_inventory_output=file&TZoutput=0&pm_cd_compare=Greater%20than&radio_parm_cds=parm_cd_list&radio_multiple_parm_cds=00400%2C01040%2C01042%2C01045%2C01046&format=html_table&qw_attributes=0&qw_sample_wide=separated_wide&rdb_qw_attributes=0&date_format=YYYY-MM-DD&rdb_compression=file&submitted_form=brief_list

U.S. Geological Survey. (2007). Summary and Conclusions from Investigation of the Effects of Historical Mining in the Animas River Watershed, San Juan County, Colorado. In S. E. Church, P. von Guerard, & S. E. Finger (Eds.), *Integrated Investigations of Environmental Effects of Historical Mining in the Animas River Watershed, San Juan County, Colorado*. U.S. Geological Survey. [Professional Paper 1651].

Vandeberg, D. (1978). *Silverton Colorado Assessor's Parcel Map* [Parcel Assessment].

Vincent, K. R., Church, S. E., & Wirt, L. (2007a). Geomorphology of Cement Creek and its Relation to Ferricrete Deposits. In S. E. Church, P. von Guerard, & S. E. Finger (Eds.), *Integrated Investigations of Environmental Effects of Historical Mining in the Animas*

River Watershed, San Juan County, Colorado. U.S. Geological Survey. [Professional Paper 1651].

Vincent, K. R., Church, S. E., & Wirt, L. (2007b). *Surficial Geologic Deposits Along Cement Creek, Upstream of Silverton, Colorado* [Professional Paper 1651 Plate 5]. U.S. Geological Survey.

Weiser-Alexander, K. (2021). *Eureka, Colorado and the Sunnyside Mine*. Legends of America. https://www.legendsofamerica.com/eureka-colorado/

Widdowson, M. (2003). *Ferricrete* (A. S. Goudie, Ed.; Vol. 1, pp. 365–367). Routledge. http://www.routledge.com/books/Encyclopedia-of-Geomorphology-isbn9780415272988

Yager, D. B., & Bove, D. J. (2007). Geologic Framework. In S. E. Church, P. von Guerard, & S. E. Finger (Eds.), *Integrated Investigations of Environmental Effects of Historical Mining in the Animas River Watershed, San Juan County, Colorado*. U.S. Geological Survey. [Professional Paper 1651].

Appendix A: Historical Photographs

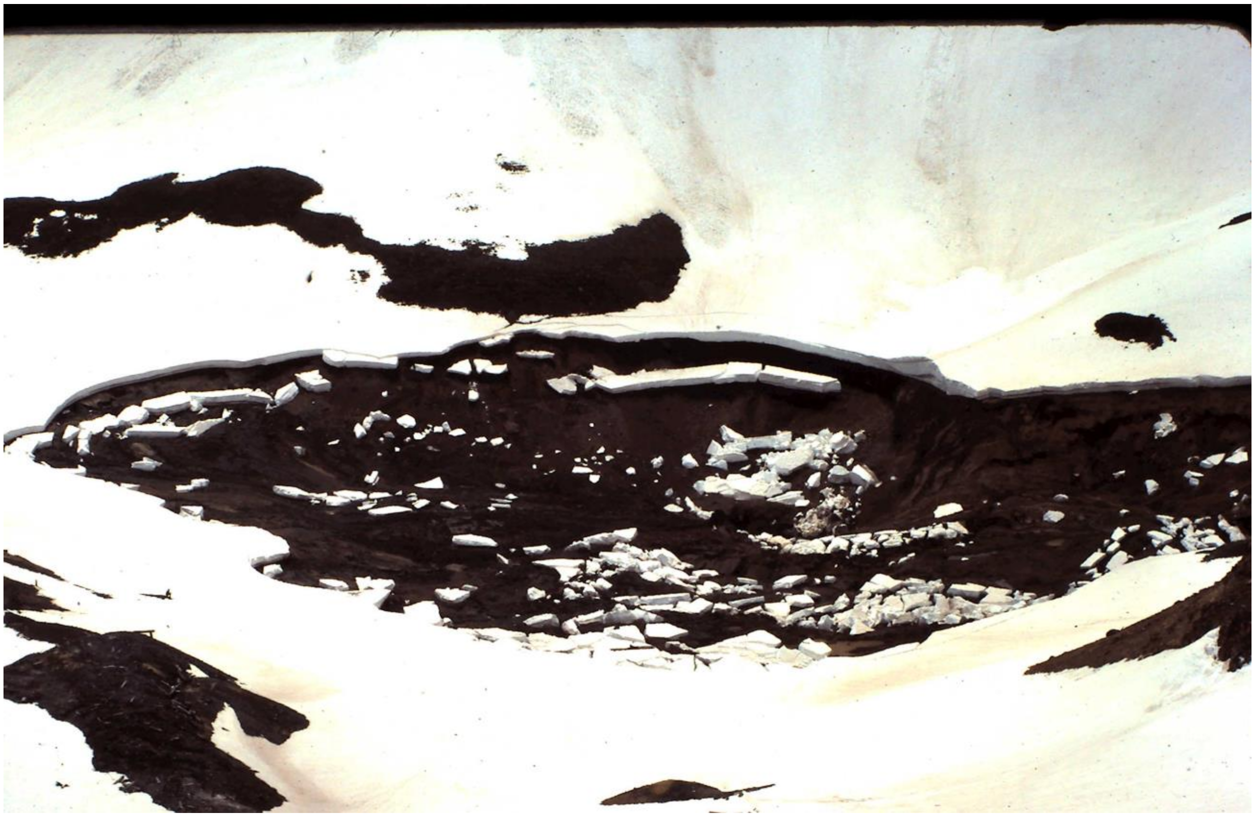
Facing downstream to the south from the entrance of the American Tunnel. William R. Jones, June 5, 1978.

Facing downstream northwest from the entrance to the American Tunnel. William R. Jones, June 5, 1978.

American Tunnel discharge point. William R. Jones, June 5, 1978.

Drained Lake Emma and Hanson Peak. William R. Jones, June 11, 1978.

Lake Emma center at stope. William R. Jones, June 11, 1978.



Drained Lake Emma. William R. Jones, June 11, 1978.

Lake Emma mudflow. William R. Jones, June 11, 1978.

Terry Tunnel entrance. William R. Jones, June 11, 1978.

W. R. Jones at Lake Emma. William R. Jones, June 11, 1978.

Appendix B: Sample Localities and Field Notes

Date collected	Sample Name	Depth	Layered	Method	Height a.w.l.	Flood sed?	Description	Special Notes
Sample Locality: Silverton Mountain								
8/7/2023	SM1	0-1.5"	no	auger	20"	1911 flood maybe	homogenous red brown sand	sand patch surrounded by large cobbles on terrace, hit rock 1.5" down, young pines & older willows
8/7/2023	SM2	0-2"	no	auger	21"	unlikely	red brown clay/mud some pine needles, organics	mud / sand patch behind log jam, very wet, hit roots 2" down
8/7/2023	SM3	0-2"	yes	trowel		no	brown sand/ silt, pine needles	encountered modern tree roots
		2-5"	yes	trowel		probably	red brown silt/ sand	2" down- red then older organic material
Sample Locality: Jane Legge's Creek								1 A. Rang pace = ~25 in
8/5/2023	JL1	0-1"	yes	trowel		probably not	brown sand and silt, moss	no distinct layering between 0-3, but used trowel for top inch
		1-3"	yes	auger		probably not	clay to cobble size, gray/brown	
		3-4"	yes	auger		maybe	gray brown mostly clay/ silt, some cobbles	sand wasn't sticky enough to auger- added water, hit rock at 4"

8/5/2023	JL2	0-4"	no	auger	1.21 paces	maybe	red brown silt sand	next to spring, could get annual water, water in auger hole 4" down
8/5/2023	JL3	0-3"	no	auger	3.5 paces	maybe but unlikely	red clay/ mud with little sand, some moss and grass	very wet, hole filled w water, likely a channel that sometimes floods
8/5/2023	JL4	0-1.5"	yes	auger	3.5 paces	no	red silt sand	1mm thick black layer separating two red layers at 1.5" down
		1.5-3.5"	yes	auger		maybe	red brown silt sand	grass on bank, young trees just east
8/5/2023	JL5	0-1"	no	trowel	7.2 paces	possible, unlikely	light brown sand w some silt	on top of bank, between young trees and older bushes
Sample Locality: Railroad								
8/5/2023	RR1	0-1"	no	trowel	20"	maybe	light orange sand w some silt	sandy patches on point bar, becomes iron hydroxide clay and pebbles 1" down, little vegetation

8/5/2023	RR2	0-3.5"	no	trowel	18"	probably not	red brown sand, some wood chips	sand in middle of point bar w cobbles around it, could be from more recent flood
8/5/2023	RR3	0-2"	no	trowel	48"	1911 more likely	light brown clay to sand	very dry, clear line of sand deposits on tall bar, little vegetation, on top of bigger clasts, some young trees, next to half buried rr tie
8/5/2023	RR4	0-2"	no	trowel	48"	1911	light brown sand, little silt, few pebbles	possible 1911 flood deposit
8/5/2023	RR5	0-1"	no	trowel	24"	probably	orange to dark brown mud	terrace below RR3/RR4, collected moss for sed on bottom
8/5/2023	RR6	0-1"	no	trowel	20"	unlikely	red brown sand	sand surrounded by moss on lower terrace, on top of aluminum-crete and ferricrete that make creek bank
Sample Locality: Grassy Gulch spring flood level about 9" above current water level								
8/5/2023	GG1	0-9"	yes	trowel	24"	no	light brown to light orange silt to cobbles	more modern deposit, not obviously from flood of interest

		9-11"	yes	trowel		yes	bright orange silt/clay	top layer of flood deposit-gradational contact with above and below
		11-12"	yes	trowel		yes	orange silt to cobble	lower layer of flood deposit, looked darker in field
		12-16"	yes	trowel		no	gray brown fine sand to cobble	below what we believe are the flood deposits
8/5/2023	GG2	0-1"	yes	trowel	16"	no	dark brown silt w organic material	gleysol, vegetation above sampled mud fhA
		1-2"	yes	trowel		yes	top: dark brown silt w wood, bottom: bright orange clay	flood horizon-horizontally next to GG1 9-12, underlain by rock fhB
8/5/2023	GG3	0-2"	yes	trowel		probably not	light brown silt	sediment pulled from bottom of moss growing
		2-4"	yes	trowel		maybe	light brown silt	
8/6/2023	GG4	0-8"	yes	auger	17"	possible	light brown to light orange clay	grass growing on top, hit roots 8" down, slight dark horizon 3" down but not enough to justify splitting sample

8/6/2023	GG5	0-3"	yes	auger	16"	no	light brown silt	muddy dip with pine trees between this channel and main channel, right above organic dark layer
		3-7"	yes	auger		yes?	light brown silt with darker organic layer at top	
8/6/2023	GG6	0-3"	yes	auger	16"	no	red brown sand	slightly higher, dry sand instead of mud, same veg/organic layer 3" down
		3-6.5"	yes	auger		probably	medium brown silt to pebbles, organic	split at 3" horizon
8/6/2023	GG7	0-8"	no	auger	24"	no	light brown silt to sand	further from creek in dense pines w grass on top, no clear stratigraphy
8/7/2023	GG8	0-4.5"	yes	trowel	15"	probably	dark brown silt w organic material, red silt on bottom	gleysol just south of GG2
		4.5-6"	yes	trowel		yes	nearly black clay	just below red layer
		6-8"	yes	trowel		maybe	grey brown clay with some brown	organic material in gley
8/7/2023	GG9	0-6"	yes	trowel	22"	no	orange brown silt to (mostly) cobbles	right next to old fence
		6-8"	yes	trowel		yes	red silt	

		8-9"	yes	trowel		yes	red brown silt and organic material	
		9-11"	yes	trowel		no	light gray brown sand	poorly sorted
Sample Locality: Downstream Canyon debris around- rusted culvert, post/beam, tree from bog								
8/6/2023	DC1	0-1.5"	yes	auger	18"	no	medium brown fine sand	sandy patch w grass, near creek with old pine trees behind
		1.5-4"	yes	auger		maybe	orange brown sand to silt with organics	split at fine red layer ~2 mm thick on this sample
8/6/2023	DC2	0-6"	no	auger	20"	contains	light brown silt to sand	flood plain meadow between creek and ferricrete, red mud between boulders, organic layer 2" down but can't split along it
Sample Locality: Confluence with Animas River								
8/6/2023	CF1	0-4.5"	yes	trowel	22"	no	medium brown silt to sand	sandy patch in lower ditch/ pothole past big cobbles, no veg, very red layer and organics 2" down
		4.5-6"	yes	trowel		no	light brown silt	

8/6/2023	CF2	0-4"	no	trowel	24"	no	medium brown silt to sand	pothole on other side of cobble hill, less obvious but had red sand layer

Appendix C: Photographs of Sample Sites

SM1

SM2

SM3

JL2

JL3

JL4

JL5

RR1

RR2

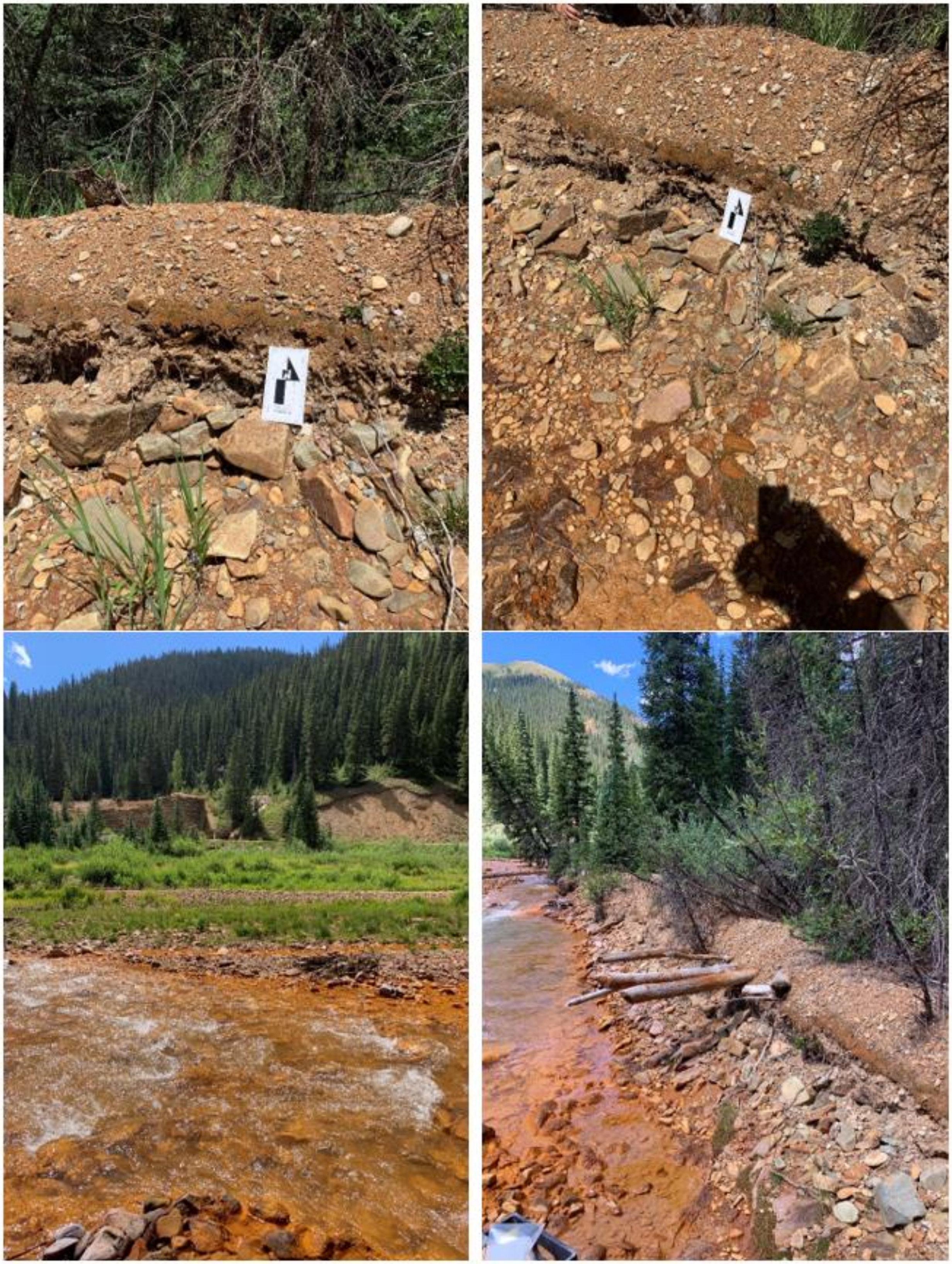
RR3

RR4

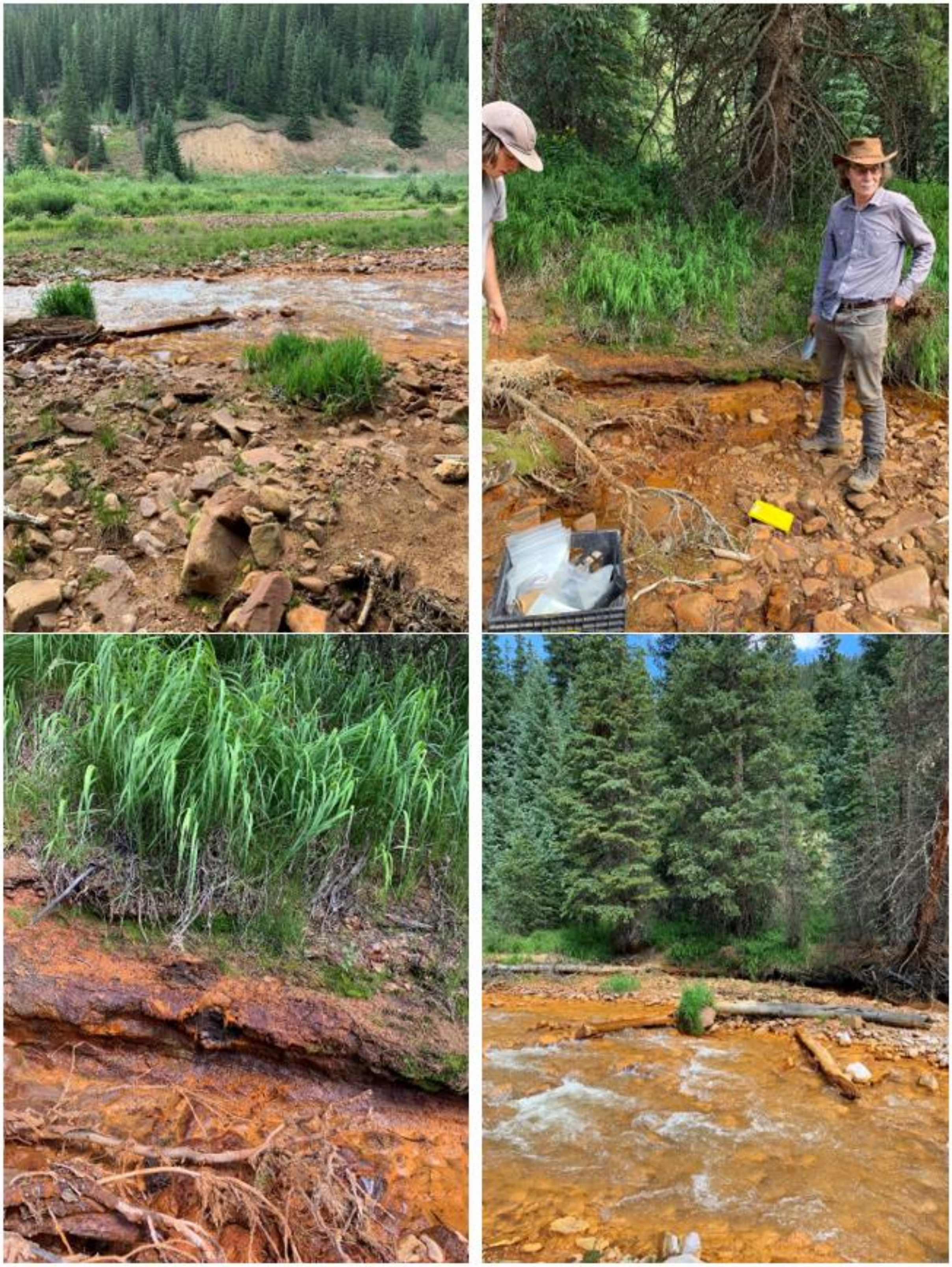
RR5

RR6

GG1



GG2



GG3

GG4

GG5

GG6

GG7

GG8

GG9

DC1

DC2

CF1

CF2

Appendix D: TerraSpec HALO™ Mineralogy of All Samples

Sample	Depth	Sediment Classification	Identified Minerals
Sample Locality: Silverton Mountain			
SM1	0-1.5"	non flood	ferrihydrite, k-illite, vermiculite, clinozoisite
SM2	0-2"	unclassified	ferrihydrite, k-illite, vermiculite
SM3	0-2"	non flood	ferrihydrite, k-illite, vermiculite, goethite
	2-5"	flood	ferrihydrite, k-illite, goethite
Sample Locality: Jane Legge's Creek			
JL1	0-1"	non flood	k-illite, clinozoisite, vnir
	1-3"	non flood	k-illite, clinozoisite, vnir
	3-4"	unclassified	k-illite, clinozoisite, vnir
JL2	0-4"	unclassified	ferrihydrite, k-illite, vermiculite, FeMg chlorite
JL3	0-3"	unclassified	ferrihydrite, smectite/illite
JL4	0-1.5"	non flood	ferrihydrite, k-illite
	1.5-3.5"	unclassified	ferrihydrite, k-illite, vermiculite
JL5	0-1"	possible, unlikely	ferrihydrite, k-illite, jarosite
Sample Locality: Railroad			
RR1	0-1"	unclassified	ferrihydrite, k-illite
RR2	0-3.5"	non flood	ferrihydrite, k-illite
RR3	0-2"	non flood	ferrihydrite, k-illite, mg-illite, goethite
RR4	0-2"	non flood	ferrihydrite, k-illite, vermiculite, nontronite
RR5	0-1"	flood	ferrihydrite, rectorite
RR6	0-1"	unclassified	ferrihydrite, k-illite, vermiculite
Sample Locality: Grassy Gulch			
GG1	0-9"	non flood	ferrihydrite, rectorite, phengite
	9-11"	flood	ferrihydrite, smectite/illite
	11-12"	flood	ferrihydrite, rectorite
	12-16"	non flood	ferrihydrite, k-illite, vermiculite
GG2	0-1"	non flood	laumontite
a	1-2"	flood	chabazite, gypsum, dioptase
b		flood	thomsonite-ca, vermiculite, iron smectite
GG3	0-2"	non flood	ferrihydrite, k-illite, vermiculite
	2-4"	unclassified	ferrihydrite, k-illite, vermiculite
GG4	0-8"	unclassified	ferrihydrite, k-illite, palygorskite
GG5	0-3"	non flood	ferrihydrite, k-illite, vermiculite, goethite
	3-7"	flood	ferrihydrite, k-illite, vermiculite, goethite

GG6	0-3"	non flood	ferrihydrite, k-illite
	3-6.5"	flood	ferrihydrite, k-illite, vermiculite, goethite
GG7	0-8"	non flood	ferrihydrite, illite/smectite, muscovite
GG8	0-4.5"	flood	hematite, chabazite
	4.5-6"	flood	laumontite, vnir
	6-8"	unclassified	ferrihydrite, laumontite
GG9	0-6"	non flood	ferrihydrite, k-illite, vermiculite
	6-8"	flood	ferrihydrite, illite/smectite, muscovite
	8-9"	flood	ferrihydrite, illite/smectite, muscovite
	9-11"	non flood	ferrihydrite, k-illite, clinozoisite, goethite
Sample Locality: Downstream Canyon			
DC1	0-1.5"	non flood	ferrihydrite, k-illite, vermiculite
	1.5-4"	unclassified	ferrihydrite, rectorite, phengite
DC2	0-6"	unclassified	ferrihydrite, rectorite, phengite
Sample Locality: Confluence with Animas River			
CF1	0-4.5"	non flood	ferrihydrite, k-illite, vermiculite
	4.5-6"	non flood	ferrihydrite, k-illite, vermiculite
CF2	0-4"	non flood	ferrihydrite, k-illite, vermiculite

Full spectra reading available in supplemental material.

Appendix E: ActLabs Bulk Elemental Geochemistry Data

See attached supplemental materials.

Appendix F: Element Geochemistry Normalization Values

Element	Concentration	Units	Source	Notes
Ag	0.0142	ppm	GERM	
Al	6.7	%	GERM	
Au	3200	ppb	GERM	
Ba	636	ppm	GERM	
Bi	0.0066	ppm	GERM	
Ca	2.59545	%	GERM	Converted from weight percent oxide
Cd	0.03	ppm	GERM	
Ce	67	ppm	GERM	
Co	14.3	ppm	GERM	
Cr	2100	ppm	GERM	
Cs	0.0085	ppm	GERM	
Dy	5.8	ppm	Rollinson	
Er	3.4	ppm	Rollinson	
Eu	0.7	ppm	GERM	
Fe	14.1	%	GERM	
Gd	5.2	ppm	GERM	
Ge	0.0035	ppm	GERM	
Hf	6.3	ppm	GERM	
Ho	1.04	ppm	Rollinson	
K	3.2951	%	GERM	Converted from weight percent oxide
La	31	ppm	GERM	
Lu	0.42	ppm	GERM	
Mg	1.72458	%	GERM	Converted from weight percent oxide
Na	0.14	%	GERM	
Nb	13	ppm	GERM	
Nd	27.4	ppm	GERM	
Ni	58	ppm	GERM	
P	0.05668	%	GERM	Converted from weight percent oxide
Pb	20	ppm	GERM	
Pr	7.9	ppm	Rollinson	
Rb	125	ppm	GERM	
Re	0.000002	ppm	GERM	
Sb	0.0073	ppm	GERM	
Sc	30	ppm	GERM	
Se	0.08	ppm	GERM	
Sm	2.3	ppm	GERM	
Sr	142	ppm	GERM	
Ta	1.1	ppm	GERM	

Tb	0.85	ppm	GERM	
Te	0.0005	ppm	GERM	
Th	12.3	ppm	GERM	
Ti	0.4197	%	GERM	Converted from weight percent oxide
Tl	0.00041	ppm	GERM	
Tm	0.5	ppm	Rollinson	
U	0.104	ppm	GERM	
V	130	ppm	GERM	
Y	35	ppm	GERM	
Yb	1.9	ppm	GERM	
Zn	2.7	ppm	GERM	
Zr	200	ppm	GERM	
As	8	ppm	NURE	
B	20	ppm	NURE	
Be	2	ppm	NURE	
Cu	26	ppm	NURE	
Li	24.5	ppm	NURE	
Mn	673	ppm	NURE	
Mo	0.92	ppm	NURE	
Sn	1.67	ppm	NURE	
W	1.25	ppm	NURE	
Ga			None found	
Hg	90	ppm	NURE	Discarded due to reported analytical inaccuracy in dataset
In			None found	
S			None found	