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POST-RECLAMATION AND PRE-MINING GEOCHEMISTRY OF THE GALENA CREEK WATERSHED IN THE BARKER-HUGHESVILLE MINING DISTRICT, JUDITH BASIN COUNTY, MONTANA

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by

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Abstract

The Barker-Hughesville Mining District in the Little Belt Mountains is home to a heavily mining impacted watershed called Galena Creek which has been the subject of remediation and environmental restoration due to the high levels of metals (including Cd, Cu, Pb, and Zn) which have negatively impacted aquatic life in the drainage. Galena Creek was designated a superfund site in the late 1990's/early 2000's, and since then several constructional efforts have removed mine waste from direct contact with the stream. Despite these efforts, numerous mine water discharges still enter the creek, and the water quality is still impaired. It is possible that the unique geology of the district is contributing a certain amount of background loading of metals and acidity to the stream. However, because the area was mined in the early 1900's, no pre-mining baseline water quality samples were ever collected.

This thesis used several geochemical techniques to assess whether natural weathering of mineralized bedrock influences the water quality of Galena Creek. A detailed synoptic sampling of the stream and all measurable inflows was conducted in mid-summer baseflow conditions. Both filtered and non-filtered samples were taken, along with samples of mineral crusts and in-stream precipitates. Samples were collected for O- and H-isotope analysis of water, O- and S-isotope analysis of dissolved sulfate, and S-isotope analysis of fresh sulfide minerals collected from mine dumps. In addition, representative bulk samples of each of the major rock types in the watershed were collected for laboratory leachate studies. The leachate tests included samples of hydrothermally altered and pyrite-mineralized rock that is thought to comprise up to 20% of the outcrop area of the Hughesville Stock: the main host rock of the area.

Results of the synoptic sampling investigation show that most of the loads of metals and dissolved sulfate in Galena Creek during baseflow conditions can be accounted for from the known mine discharges. The S- and O-isotope composition of sulfate in the stream is similar to that of sulfate in the mine discharges, and the S-isotope composition of sulfate is similar to that of sulfides on the mine dumps. The hydrothermally-altered Hughesville Stock produced leachates with very poor water quality, whereas the unaltered stock and other bedrock units in the watershed produced leachates with much lower concentrations of metals and sulfate. By mixing the leachate water chemistry from each rock type, scaled to the percentage of the total watershed underlain by each rock type, a first pass approximation of the pre-mining water quality of Galena Creek was obtained. Although this type of calculation rests on several assumptions, the results suggest that Galena Creek could have had elevated concentrations of metals and sulfate from natural weathering prior to mining disturbance. Lastly, the concentrations of several metals of interest in Galena Creek were compared to concentrations in Chicago Gulch, a small stream with natural acidity draining an unmined, but hydrothermally altered, stock in the central Judith Mountains. The range in concentrations in the two drainages overlap. Whereas Galena Creek on average has higher concentrations of Mn, Zn and Cd, Chicago Gulch has higher concentrations of Pb and Al. In summary, although the present chemistry of Galena Creek is obviously impacted by the legacy mines, some metals and acidity would have entered the creek due to natural weathering prior to mining.

Keywords: Natural Acid Rock Drainage, Geochemistry, Acid Mine Drainage, Hydrogeology, Leachate, Stable Isotopes, Toxic Metal Contaminants

Dedication

This work is dedicated to my mother, sister, father, and family as well as the friends and mentors who believed in me. Without them and their support I would not have made it this far.

Acknowledgements

Thanks to Wood PLC in Helena, MT and the Doe Run Resources Corporation for funding lab work as well as the USEPA and MTDEQ for their assistance and information. I also want to thank Ashley Huft, Jackie Timmer, and the Montana Bureau of Mines and Geology laboratory for analyzing water samples needed. Lastly, I want to thank my advisor Dr. Chris Gammons and my committee members Dr. Brian St Clair and Dr. Raja Nagisetty for their support and mentorship.

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Glossary of Terms and Acronyms

Term	Definition
BHMD	Barker Hughesville Mining District
USEPA	United States Environmental Protection Agency
MTDEQ	Montana Department of Environmental Quality
MBMG	Montana Bureau of Mines and Geology
USFS	United States Forest Service
FA	Chemical samples that were filtered and preserved with HNO_3
RA	Chemical samples that were not filtered and preserved with HNO_3
FU	Chemical samples that were filtered and unpreserved
SC	Specific Conductivity
pH	Measurement of acidic or basic properties of the water
ORP	Oxidation-Reduction Potential of the water in regards to electron capture ability of the water compared to Ag:AgCl electrode
Eh	Oxidation-Reduction Potential of the water in regards to electron capture ability of the water compared to a standard hydrogen electrode
Alkalinity	A chemical parameter for testing a water samples's ability to buffer acid based on the presence of calcium carbonate
GRC	Gold Run Creek
PW	Pride of the West Creek
BG	Bend Gulch
SV	Silver Creek
GED	Grey Eagle Mine Ditch
BPP	Block P Mine Discharge
GEC	Green Creek (UGEC for upper and LGEC for lower)
DC	Daisy Creek (UDC for upper and LDC for lower)
MM	Moulton Mine Discharge
HS	Galena Creek's Headwater Spring Discharge
CM	Carter Mine
DT	Danny T Mine Discharge
LS	Lucky Strike Mine
HR	Harrison Mine Discharge
MC	Marcelline Mine Discharge
TG	Tiger Mine
COI	Contaminant of Interest

1. Introduction

1.1. Statement of Problem

Knowing the baseline level of background water quality before mining, or other industrial disturbances, would be advantageous in determining remediation strategies for watersheds affected by acid-mine drainage (AMD). AMD is intensified by such industrial operations exposing sulfide surfaces which chemically react with oxygen and water to lower the pH in streams and increase levels of heavy metals which are toxic to aquatic life. However, in many cases, it is predicted that a certain level of poor water quality and abnormally high metal concentrations were present before a significant industrial endeavor. This phenomenon is often called natural acid rock drainage (NARD) and is defined by the United States Environmental Protection Agency (USEPA) as "substances or locations that are not influenced by the releases from a site and are usually described as naturally occurring or anthropogenic" (Nordstrom 2015).

The Galena Creek watershed in the Little Belt Mountains of Montana is a good example of a stream that is impacted by historic mining, but, for which, no pre-mining water chemistry data is available. The main objectives of this thesis are: 1) to conduct a detailed synoptic sampling to quantify sources, concentrations, and loads of contaminants of interest in Galena Creek; and 2) to combine these data with laboratory leachate tests, stable isotopes, and analog site comparison to help constrain what the water quality of Galena Creek might have been like prior to mining.

1.2. Previous Studies of Pre-Mining Water Quality

Prior studies of pre-mining water quality have used different geochemical approaches, including: (1) comparing AMD afflicted watersheds with an analog site that has a similar geological and hydrological setting and no history of industrial disturbance; (2) detailed synoptic water sampling to identify and subtract different sources of AMD and NARD with mass balance calculations; (3) comparing the trace element concentration of pre-mining ferricrete deposits to modern in-stream precipitates; (4) using stable isotopes of water, sulfide minerals, and sulfate to trace and discriminate between NARD vs. AMD; and (5) using laboratory leachate studies to characterize the chemistry of runoff or shallow groundwater interacting with mineralized bedrock.

Finding an undisturbed "analog" watershed for a mining-impacted watershed can be a very difficult task. In his review paper, Nordstrom (2015) explains the differences in using proximal vs. remote analog sites. However, most watersheds that drain mineralized bedrock close to a mining center have also seen mining disturbances which makes finding analog sites increasingly difficult. Not only are analog hard to come by but they also do not provide an exact way to find a baseline level as no sites is going to be precisely the same.

A detailed synoptic sampling investigation, mass balance calculations coupled with geochemical modeling can sometimes be used to separate NARD sources from AMD sources (Nordstrom 2015). However, if the two types of sources are mixed over the same stream reach, separation of what is natural and what is mining-related can be unclear or impossible. Additionally, this method can rely heavily on decisions made by the modeler which adds a degree of inaccuracy and uncertainty (Nordstrom 2015).

Ferricrete trace-element analysis provides another potential way of estimating the pre-modern pH and water quality of streams with NARD (Nimick et al., 2009; Williams et al. 2015;

Edinberg 2016; Gammons et al. 2021). This method requires a continuous outcrop of ferricrete along a stream that experiences a gradual increase in pH: conditions that may not apply to many field sites. It can be hard to tell if a given ferricrete outcrop formed before or after mining, especially for complex legacy sites where reclamation activity has changed the physical and hydrological properties of the stream. Exact dates for the ferrricrete can be obtained if plant matter is preserved that can be dated by radiocarbon methods (Furniss et al. 1999). However, fossilized plant matter in ferricretes cannot be dated if the organic carbon has been replaced by goethite (Edinberg, 2016; Gammons et al., 2021).

Wright and Nordstrom (1999) suggested that the stable isotope composition of dissolved sulfate might be helpful to separate NARD vs. AMD. This method requires that the O-isotopes of sulfate coming from NARD are different (usually enriched in ^{18}O) compared to sulfate coming from AMD. If this can be shown to be the case, then quantifying and separating sources of acid drainage using stable isotopes can be done at a fraction of the cost of conducting a detailed synoptic sampling event (Wright and Nordstrom, 1999).

Leachate methods can be used to approximate the chemistry of water draining various bedrock types. For example, Edinberg (2016) showed that interaction of distilled water with mineralized bedrock in the Judith Mountains, Montana, produced leachate that had similar chemistry to headwater streams in the same area. Problems with leachate tests include the need to collect representative bedrock samples, as well as extrapolation of weathering rates obtained from controlled laboratory conditions to rates that occur in the natural environment.

As stated by Nordstrom (2015), when approaching the question of what background chemistry might have been like in mining affected sites, it is best to employ more than one of the above methods. Each method has its own limitations and using more than one method will typically improve the accuracy of the results, which is important for agencies who need to make reclamation decisions.

1.3. Site Description

1.3.1. History of the Barker Hughesville Mining District and the Galena Creek Watershed

Galena Creek (GC) is located in the Little Belt Mountains of Montana, approximately 10 miles east of the town of Monarch (Figure 1). Galena Creek is a first order stream that joins the Dry Fork of Belt Creek, a tributary to Belt Creek and the Missouri River. Galena Creek runs through the Barker-Hughesville Mining District (BHMD) and has been significantly impacted by acid-mine drainage associated with the historic mining activities (CDM Smith 2016). The 3.5-mile-long span of Galena Creek can be divided into three sections (Figure 2): the upper reach runs from the headwaters to the confluence of Green Creek; the middle reach stretches from the Green Creek confluence to just below the culvert on the main access road near the town of Barker; the lower reach ends at the confluence of Galena Creek and the Dry Fork of Belt Creek. The upper reach of Galena Creek is sometimes marked as Daisy Creek on older topographic maps. However, as shown in Figure 2, Daisy Creek is a smaller tributary that enters Galena Creek near the end of the upper reach.

The elevation of Galena Creek ranges from about 6000′ at its mouth to just under 7000′ at its headwaters (Figure 2). The high point in the watershed is Mixes Baldy Mountain, at 7952′. Annual precipitation for the field area is 21.4 inches and average annual snowfall is 113 inches (CDM Smith 2016). The climate is typical for that of Montana’s mountain areas with most precipitation events happening in the spring season and snowfall in the winter season. The average baseflow near the mouth of Galena Creek is about 2 cubic feet per second (cfs), with a recorded range in flow from 0.4 to 30 cfs (CDM Smith 2016). Tributaries to Galena Creek are shown in Figure 2, and include Daisy Creek, Green Creek, Silver Creek, Bend Gulch, Pride of the West Creek, and Gold Run Creek. Gold Run Creek is by far the largest tributary, nearly doubling the flow of Galena Creek shortly before it runs into the Dry Fork. The flow of Galena Creek is also increased by numerous mine discharges, discussed below.

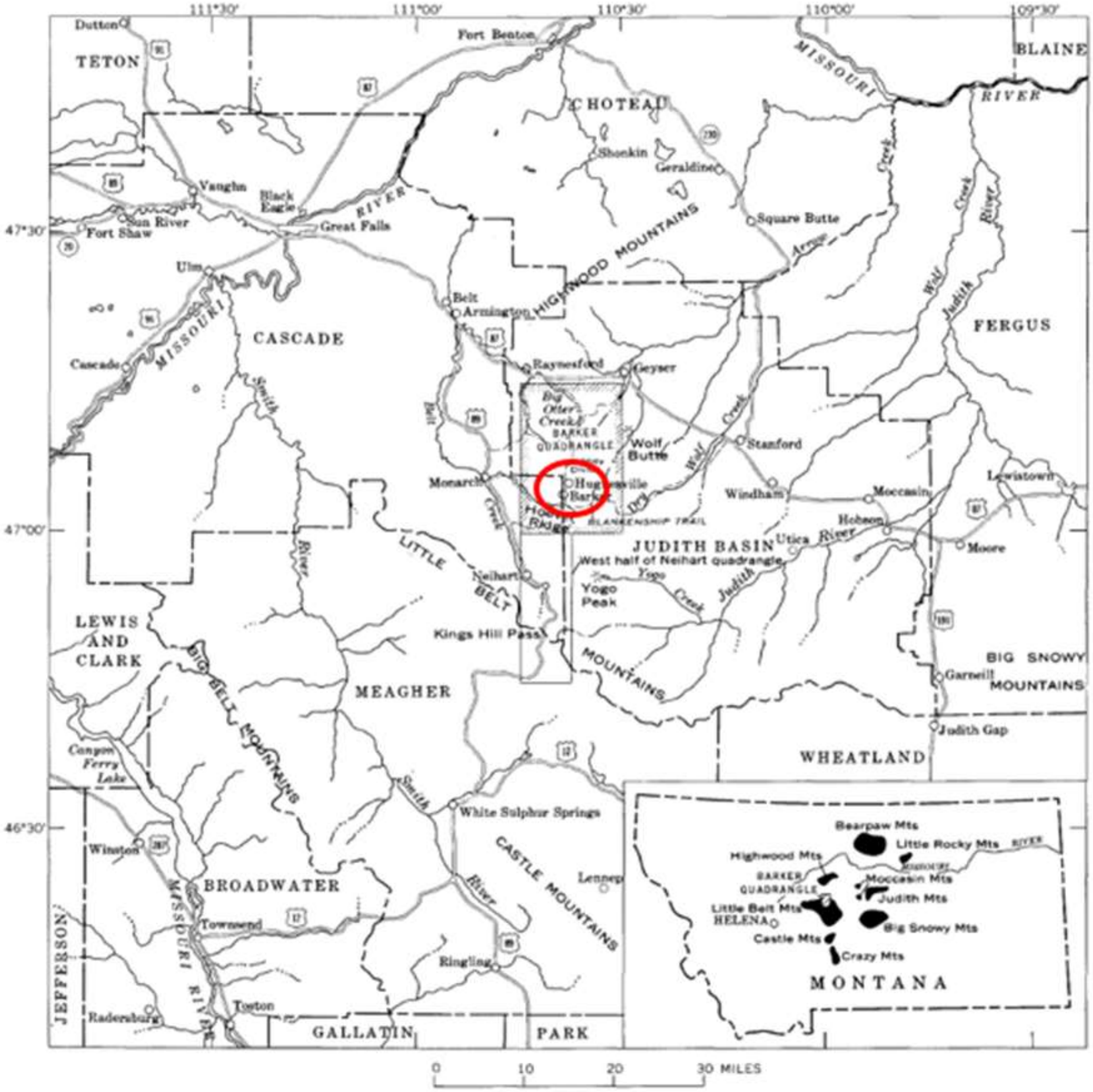

Figure 1. Location of the study area in the Little Belt Mountains, Montana (Witkind 1973)

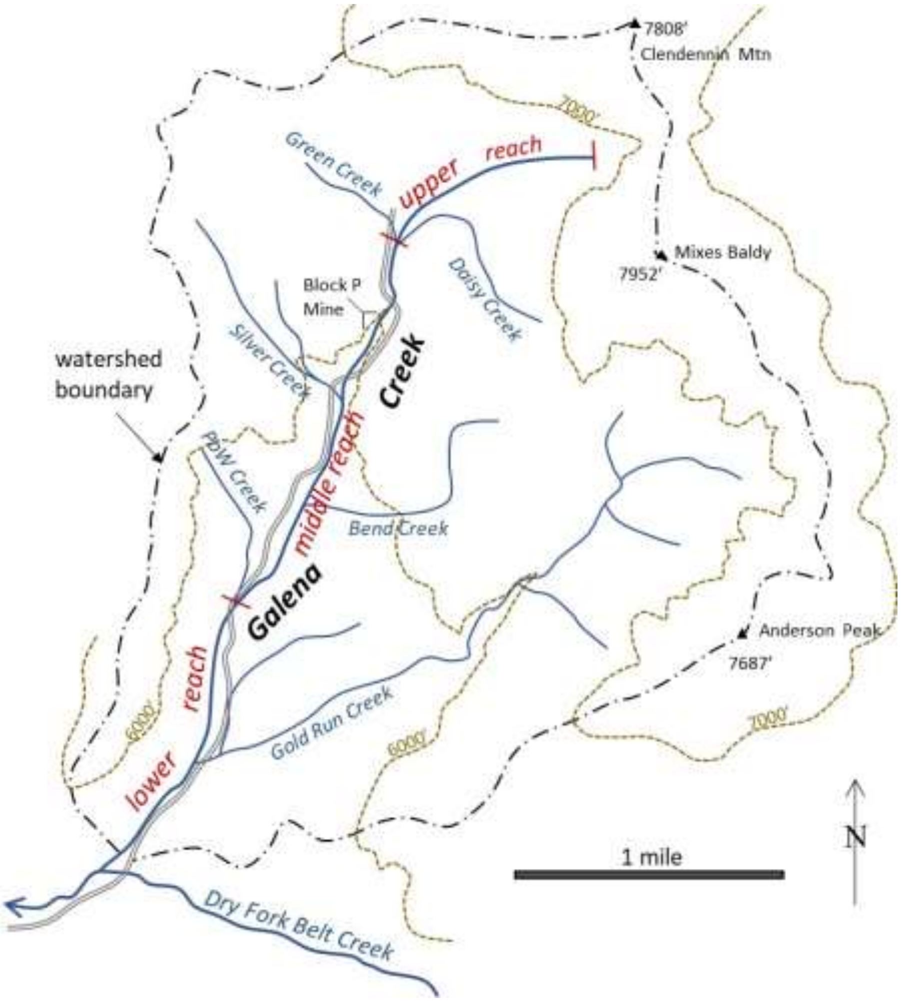

Figure 2. Map of the Galena Creek watershed showing topography, tributary streams, and the location of the Block P mine. Other abandoned mines are shown in Figure 3.

The mines in the BHMD followed mineralized fissure veins in search of Pb, Zn, and Ag sulfide ore deposits (Walker 1991, Witkind 1973, Spiroff 1938, Weed 1900). The total value of the district is estimated at 6 million dollars before mining (Witkind 1973). The largest operation was the Block P mine which followed the Block P vein 1,500 m deep and 1098 m along strike (Walker 1991, Spiroff 1938). Block P reached its peak production in 1929 after being purchased by St. Joseph Lead Co. in 1927 and was the largest producer of lead in Montana at the time (Spiroff 1928). Block P stopped operation near the depression in 1930 and did not re-open until 1941 during World War II when demand for metals was high. The mine then officially closed just after 1943 because the mine shaft designs did not meet new safety requirements the government put into place (Walker 1991). Other mining operations in the district produced over the same time frame, and included the Tiger, Danny T, Carter, Moulton, Pioneer, Grey Eagle, Liberty, Dockter Kalloch, Edwards, Wright Lode, Barker, Harrison, Lucky Strike, and several other low tier operations that were noted in site assessment accounts (CDM Smith 2016). This thesis makes reference to mine sites that are actively discharging water or are in close contact with the Galena Creek itself. These are the Block P, Danny T, Marcelline, Carter, Moulton, Grey Eagle, Tiger, Pioneer, and Harrison mine sites (Fig. 3).

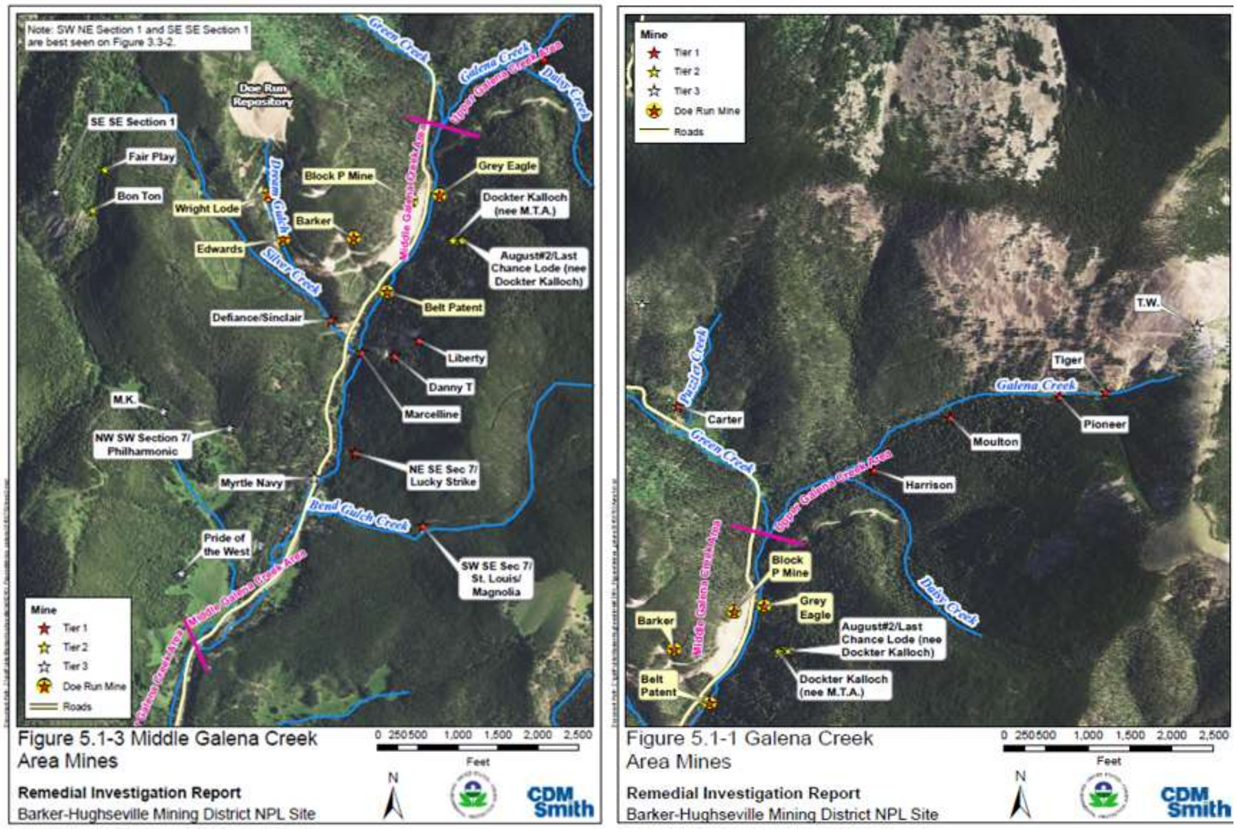

Figure 3 Location of mine sites within the middle and upper reaches of the Galena Creek watershed (CDM Smith 2016)

After closure, the district was not revisited commercially until it was environmentally investigated and designated as a superfund site by the State of Montana, the United States

Environmental Protection Agency (USEPA), the United States Forest Service (USFS), and the Montana Department of Environmental Quality (MTDEQ) between 1991 and 2001 (CDM Smith 2016). Beginning in 2004, efforts have been made by responsible parties and government agencies to improve the quality of the watershed and reduce acid-mine drainage, including relocating mine waste in contact with Galena Creek, minor stream diversion, reconstruction of Galena Creek near the Block P mine, and attempts to block acidic seeps with bentonite at the Block-P mine. Additionally, there have been ongoing efforts to plant non-invasive plant species near impacted sites to return barren areas to pre-disturbed conditions and to plug open holes left by mine workings which caused safety hazards. While important, these reclamation activities changed the physical state of the middle section of Galena Creek, making it difficult to determine the origin of small outcrops of ferricrete and host rocks that occur, for example, in the floodplain of the stream below the Block P mine (CDM Smith 2016, Wood, Environment & Infrastructure, Inc. 2020).

Table I. General Timeline of Activity within the BHMD

Date	**Activity**
1879-1943	Prospecting and active mining
2001	Superfund site designation on National Priorities List
1991- Present	Environmental preliminary and annual studies
2004 - Present	Reclamation efforts and mine waste excavations

1.3.2. Geology

The geology of the Galena Creek area was summarized in detail by Weed (1900), Spiroff (1938), and Witkind (1973), and more recently by Walker (1991). A geologic map, redrawn from Walker (1991), is given in Figure 4, and Table II gives more detailed descriptions of the igneous rock types. The oldest rocks in the study area are Paleozoic sedimentary rocks, including the Mississippian Madison Group limestone. These rocks were intruded in Tertiary time by two large rhyolite laccoliths (dome shaped intrusions) termed the Clendennin Porphyry (55.0 Ma) and the Wolf Porphyry (47.0 Ma), as well as the Hughesville Quartz Monzonite stock (45.0 Ma). As discussed by Witkind (1973), the area now occupied by the Hughesville Stock may have been the magma conduit that fed into the laccoliths. Unlike the laccoliths, which are mostly unmineralized, the Hughesville Stock is hydrothermally altered and mineralized, and contains most of the major Ag-Pb-Zn veins of the district, as well as several mineralized skarn zones at contacts with meta-sedimentary rocks (Figure 4). A set of rhyolite-porphyry dikes, termed the Galena Creek Porphyry (44.0 Ma), cuts the Hughesville stock and to a lesser extent the older laccoliths. These dikes contain minor sulfide minerals. The youngest rock in the field area, termed the Gold Run Tuff by Walker (1991), is a volcanic diatreme filled with brecciated fragments of all older rock types, also containing sparse sulfides. This unit, mapped as “indurated alluvium” by Witkind (1973), was reinterpreted as a diatreme based on the results of exploration drilling in the 1980s (Walker, 1991).

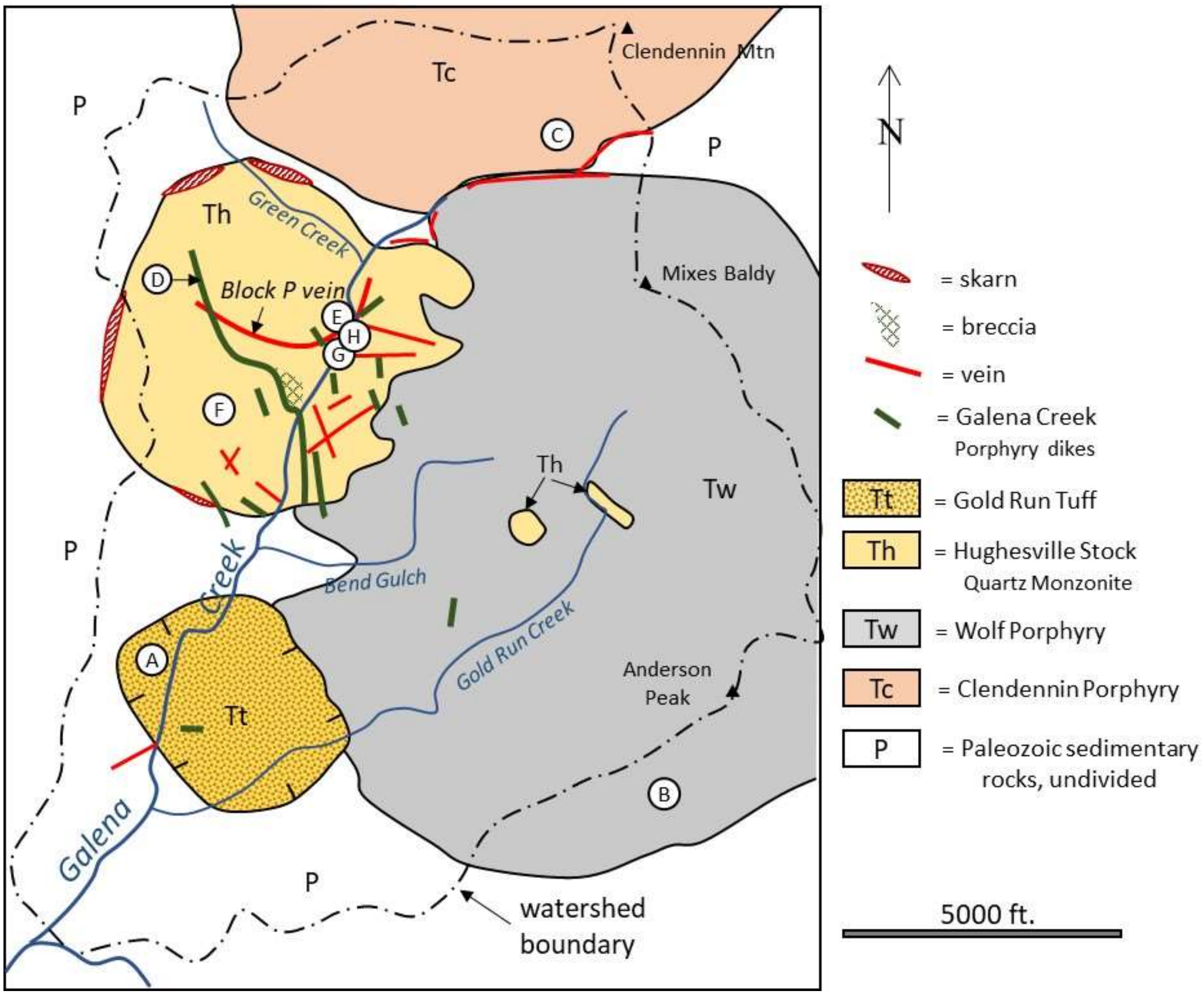

Figure 4. Geologic map of the study area (after Walker, 1991). Letters (A through H) show locations of bulk sample collection for leaching tests.

Table II. Igneous rocks in the project area (after Witkind, 1973, and Walker, 1991)

		Map unit	Rock name	Rock Type and Mineralogy
Youngest	Tt	Tertiary volcanic diatreme	Gold Run Tuff	Weakly lithified volcanic breccia with clasts of all other rock types in the area. Locally contains sparse sulfides.
	Tgc	Rhyolite dikes	Porphyry of Galena Creek	Rhyolite porphyry, with abundant round phenocrysts of clear-smoky quartz, with some sanidine, albite, biotite. Locally hydrothermally altered with pyrite.
	Th	Hughesville Stock	Quartz Monzonite of Hughesville	Quartz monzonite with feldspar phenocrysts. Locally highly altered and mineralized. Altered rock consists of quartz-sericite-pyrite and makes up to 20% of Hughesville stock unit.
Oldest	Tw	Mixes Baldy-Anderson Peak laccolith	Wolf Porphyry	Granite porphyry with large phenocrysts of smoky quartz, sanidine, oligoclase, hornblende, biotite. Non-mineralized.
	Tc	Clendennin-Peterson laccolith	Porphyry of Clendennin Mountain	Rhyolite porphyry with phenocrysts of sanidine, oligoclase, hornblende, biotite. Non-mineralized.

1.3.3. Mineralization

Spiroff (1938) gave a detailed account of mineralization at the Block P mine. The main Block P vein was mined for over 4000 feet along strike, and to a depth of 1400 feet. The vein had an arcuate (concave to the north) strike (Fig. 4), with steep dips inclined toward the center of the semicircle. Principal ore minerals included galena, sphalerite, pyrite, chalcopyrite, and Ag-bearing tetrahedrite in a gangue of quartz, barite, calcite, rhodochrosite, and minor siderite. As discussed by Spiroff (1938), and later by Witkind (1973), the Hughesville Quartz Monzonite is hydrothermally altered to quartz + sericite + pyrite adjacent to the Block P vein, as well as the other smaller veins that cut the stock. Referring to the Hughesville stock, Witkind (1973) stated that "a conservative estimate is that between 20 and 30 percent of the rock shows significant effects of hydrothermal alteration". Weathering of this volume of hydrothermally altered and pyrite-rich rock could have been a source of natural acid rock drainage prior to mining.

2. Methods

2.1. Synoptic Sampling of Galena Creek

2.1.1. Field Methods

Fieldwork for this project took place in July 2020 from the 20th to the 22nd. The weather was warm and sunny, and no significant precipitation had occurred for at least a week prior to the investigation. During this time of year Galena Creek reaches low streamflow and data collected will reflect solute concentrations and loads under baseflow conditions. The entire length of Galena Creek, as well as all tributaries, was sampled on July 20-21 (Figure 5). On July 22, igneous host rocks and ferricrete rock samples were collected for laboratory characterization.

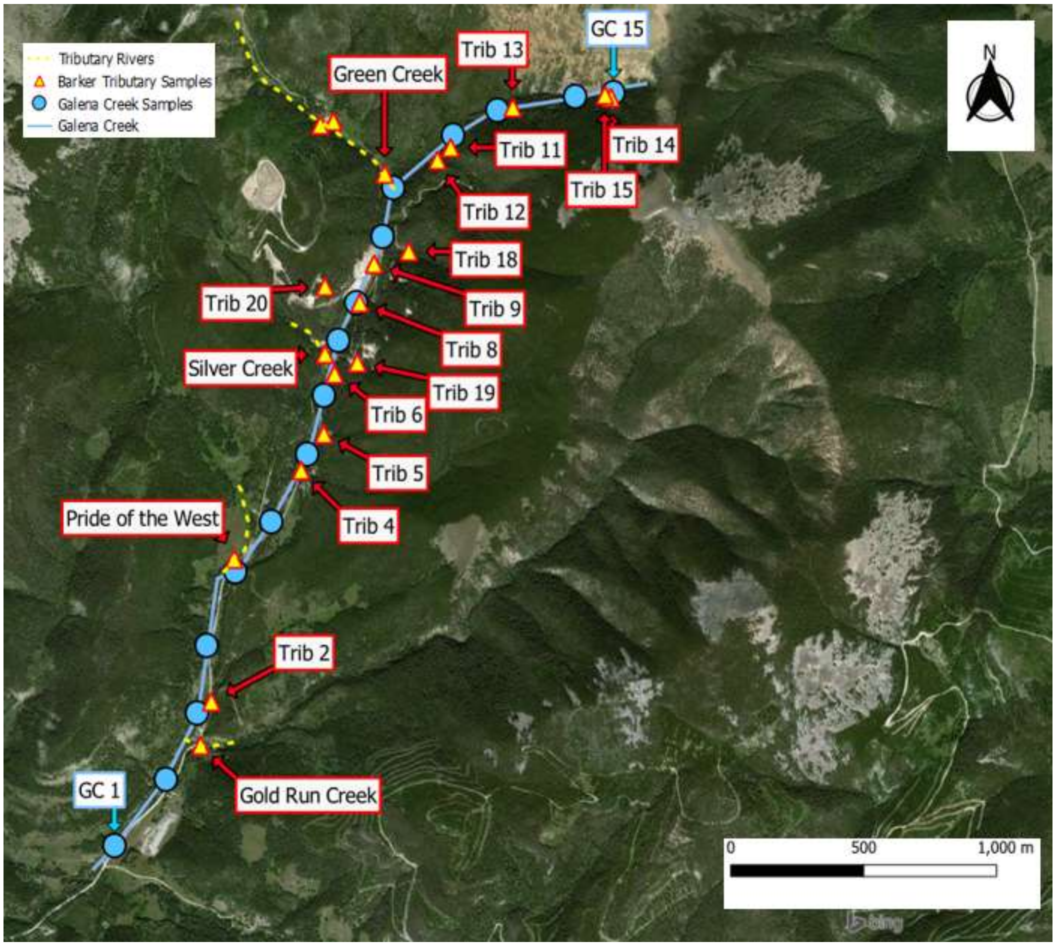

Figure 5. Sampling Locations for Synoptic Field Event at Galena Creek Watershed in BHMD conducted in July 2020.

As seen in Figure 5, 16 surface water locations were sampled along Galena Creek starting at the mouth (GC-1) and working upstream to the headwaters (GC-15). Tributary samples were taken as they were encountered during the same time as the Galena Creek samples. A total of 20 tributary samples were collected, including mine discharges. At each sampling location, field parameters were collected using a YSI 556 multiparameter meter, which included pH, electrical conductivity (EC), temperature (°C), dissolved oxygen (DO), and oxidation-reduction potential (ORP). The pH meter was calibrated with pH 4 and 7 standard solutions at the beginning of the day, and readings were back-corrected to account for minor drift during the sampling event. ORP readings were adjusted to true Eh with a Zobell's solution standard. Since the YSI was recording electric conductivity (EC), not specific conductivity (SC) referenced to 25°C, a separate WTW meter was used to collect the SC values reported in this thesis. Streamflow was determined using a salt dilution method where a known mass of NaCl solution is added to the stream and then the integrated spike in SC is measured with an SC meter at site roughly 20-30m downstream (Moore 2004). This method is believed to have an accuracy of ±5% for small flows (< 1 cfs), decreasing to an accuracy of ±10% for larger flows (> 1 cfs). Where possible, a few tributary flows were measured with a bucket-and-stopwatch method, using a 5-gallon container.

At each main stem location, three sets of water samples were collected: "RU" (raw, unfiltered and unacidified); "FU" (filtered and un-acidified); and "FA" (filtered and acidified to 1% v/v HNO3). All bottles were 60 mL high density polyethylene (HDPE). The FA bottles were acid-washed with 10% HNO_3 and then rinsed 3 times with deionized water prior to field use. All filtrations were done during sample collection by drawing water up into a 60 mL plastic syringe (rinsed 3x with stream water) and then pushing through a disposable 0.2 µm polyethersulfone (PES) filter into the appropriate container, which was rinsed once with filtered water. The FA samples were acidified within 10 hours of collection by addition of 0.6 mL of trace-metal-HNO_3. For tributary streams and mine discharges, only FA and FU samples were collected. Occasionally, a duplicate sample was taken for some tributaries and some Galena Creek sampling stations to check for quality assurance. These samples matched the other samples match closely with the sample they are meant to duplicate confirming good quality measurements from the laboratory. The data for these duplicates can be found in the Appendix as part of the supplementary data and will have a letter “D” as part of the sample name.

Alkalinity measurements were taken for any water samples that had a pH > 4.5. These samples were collected in 120 mL HDPE bottles and were tested using a digital titrator in the laboratory within 48 h of sample collection.

At most of the main stem Galena Creek stations, a sample of in-stream precipitates (ISPs) was collected by skimming off the fluffy coatings of hydrous ferric oxide (HFO) that had settled on cobbles and boulders into a polyethylene bag. In addition, at sites in the middle and lower reaches of Galena Creek, thin black coatings rich in hydrous manganese oxide (HMO) were collected from the undersides of boulders in the stream bed. The ISP and HMO samples were air-dried in the sun at the campsite, and then analyzed for elemental composition with a Niton Gold portable X-ray Fluorescence (XRF) meter (the XRF data is available in Appendix E). Representative subsamples were archived for later use.

Representative bulk samples (> 3 kg) of the major bedrock map units were collected in 5-gallon buckets for later use in the laboratory leachate experiments (see Table III), sample locations are given in Figure 4). Effort was made to break the outcrops with a sledge to get the freshest rock possible, and to avoid any lichen. Each bulk sample consisted of 20 or more smaller fragments up to 6” in diameter. In the case of the hydrothermally-altered Hughesville Stock, samples containing strong “quartz-sericite-pyrite” (QSP) alteration were collected from float in the reconstructed floodplain and on the hillside below the Block P portal.

2.1.2. Analytical Methods

Alkalinity values were assessed in the laboratory using a digital titrator for all samples that had a pH of 4.5 or higher. 0.16N sulfuric acid cartridges were used in the titrator to release into an Erlenmeyer flask that contained the water from the sample being tested and bromcresol green-methyl red pH indicator dye on a magnetic stirrer. Alkalinity on the titrator was recorded once water turned bright pink. Alkalinity concentrations in mg/L $CaCO_{3,eq}$ were also converted to mg/L of HCO_3^- by adjusting for the gram formula weights. This calculation assumes that bicarbonate ion was the only source of alkalinity in the water samples. This is a good assumption because all the samples had $pH < 7.5$, were well-oxidized, and had low concentrations of nutrients (e.g., PO_4^{3-}).

All FA, RA, and FU samples were sent to the Montana Bureau of Mines and Geology (MBMG) geochemical laboratory for analysis. An Inductively Coupled Plasma Mass Spectrometer (ICP-MS) and an Inductively Coupled Plasma-Optical Emission Spectrometer (ICP-OES) were used to analyze FA and RA samples for trace and major solute concentrations data based on EPA methods 200.8 and 200.7, respectively. FU samples were submitted for analysis by Ion Chromatography (IC) according to EPA method 300.0. Laboratory QC checks were performed on the main contaminants of interest, including arsenic, cadmium, copper, lead, and zinc. Results of the QC checks are included in the appendices of this thesis.

A set of filtered but unpreserved water samples was collected for isotopic analysis of H and O in water. The isotope analyses were conducted at MBMG using a Picarro L1102-I cavity ring-down spectrometer (CRDS). Isotopic values are reported in the usual δ notation in units of

‰ (per mil, or parts per thousand), versus Vienna Standard Mean Ocean Water (VSMOW). The analyses were calibrated using isotopic standards USGS 47, USGS 48, and Vienna Standard Mean Ocean Water (VSMOW). Analytical uncertainties are estimated at ±0.2‰ for $\delta^{18}O_{water}$ and ±1‰ for δD_{water}.

Several filtered but unacidified water samples were collected for S- and O-isotope analysis of dissolved sulfate. Dissolved sulfate was precipitated in the lab as barite, following the procedures of Carmody et al. (1998). The white $BaSO_4$ precipitates were filtered, rinsed several times with deionized water, dried overnight at 50˚C, and shipped to the University of Nevada-Reno for S- and O-isotope analysis using a Eurovector elemental analyzer interfaced to a Micromass IsoPrime stable isotope ratio mass spectrometer (IRMS). Analysis followed the methods of Giesemann et al. (1994) for $\delta^{34}S$ and Kornexl et al. (1999) for $\delta^{18}O$. Based on replicate laboratory analyses, analytical uncertainties are ±0.2‰ for $\delta^{34}S_{sulfate}$ and ±0.4‰ for $\delta^{18}O_{sulfate}$. The results are reported in δ notation in units of ‰ vs. Vienna Canon Diablo Troilite (VCDT) for $\delta^{34}S_{sulfate}$ and VSMOW for $\delta^{18}O_{sulfate}$.

Several hand samples containing fresh sulfide minerals were collected from mine dumps in the study area. These samples were carefully picked by hand under a binocular microscope to get pure mineral separates of pyrite, sphalerite, and/or galena that were sent to the University of Nevada-Reno for S-isotope analysis, following the methods described above.

2.2. Leachate Experiments

2.2.1. Design

Leachate experiments used humidity cells in Dr. Gammons' laboratory that were constructed according to the American Society for Testing and Materials, Method D5744-96. The sample chambers were made of clear acrylic with a 4.5" OD x 8" height, and ¼" -thick walls. All the sample chambers were soaked for 2 days with 2% HNO_3 and then rinsed thoroughly with de-ionized water to clean them before use. A cloth filter was placed on top of a perforated acrylic disk at the bottom of each cell. The purpose of the cloth filter was to minimize entrainment of fine sediment out of the cells during leachate collection. Approximately 1.0 kg of crushed rock collected from each of the bedrock units in the study area was added to each cell. Rock descriptions are given in Table III and the location where each of these samples was collected is shown in Figure 4. Photographs of each rock type are included in the Appendix F, and XRF data on the -100 sieve fraction of each rock type are given in Appendix E.

Table III. Sample letter and corresponding rock type for each leachate cell

Sample	Rock type	Sampling frequency
A	Gold Run Tuff collected from an outcrop along lower Galena Creek. The rock is variably weathered, and shows evidence of weak hydrothermal alteration, including sparse pyrite.	Week 1, Week 6
B	Fresh Wolf Porphyry (unweathered and with no obvious hydrothermal alteration)	Week 1, Week 6
C	Fresh Clendennin Porphyry (unweathered and with no obvious hydrothermal alteration)	Week 1, Week 6
D	Porphyry of Galena Creek. Collected from rip-rap at the waste rock repository on top of the hill west of the Block P mine. This rip-rap appears to have been imported from a road switchback that cut through an outcrop of the Galena Creek porphyry dike material. The rock shows weak hydrothermal alteration and sparse pyrite.	Week 1, Week 6
E	Variably weathered and hydrothermally altered Hughesville Stock collected in a 100m transect along the outcrop immediately behind the main Block P portal, along strike of the Block P vein.	Week 1, Week 6
F	Fresh Hughesville Stock (unweathered and with no obvious hydrothermal alteration) collected from outcrops along roadcuts on the hill, several hundred meters west of the Block P mine.	Week 1, Week 6
G	Variably weathered samples of Hughesville Stock with strong quartz-sericite-pyrite alteration and sparse galena, sphalerite collected from dumps and scattered along the toe of the reclaimed hillside near the Block P mine.	Weeks 1, 2, 3, 4, and 6
H	Variably weathered, banded vein material gathered from float near the Block P mine, rich in pyrite, sphalerite, galena, quartz, and some carbonate gangue minerals (calcite, rhodochrosite).	Weeks 2, 4, and 6
Control	Humidity cell set up and leached the same way as the other samples, but with no solid media.	Week 1

The leachate added to the humidity cells was prepared following the USEPA's synthetic precipitation leaching procedure (SPLP). As required for sites west of the Mississippi River, the SPLP extraction solution consisted of de-ionized water with a 60:40 mix of sulfuric acid and nitric acid, adjusted to a pH of 5.0 ± 0.1. Fresh SPLP solution was made each week by dilution of a stock solution of 60:40 sulfuric acid/nitric acid that had a pH close to 4. On Day 1 of each weekly cycle, enough SPLP solution was added to each humidity cell to completely saturate the rock media. The cells were left in a saturated state overnight. Then, on Day 2, a valve at the bottom of the cell was opened to drain the leachate into a 1-L Erlenmeyer flask. The pH and SC of the leachate samples were measured with a Hydrolab MS-5 datasonde, and the mass of leachate was determined by weighing the flasks. Once the samples were collected, the humidity cells were left with their bottom drains open for the remainder of the week, letting them slowly drain. This weekly cycle was repeated for a total of six weeks.

After the first and the last leach cycle, FA and FU samples were collected from each of the humidity cells for ICP-OES, ICP-MS, and IC analysis of major, minor, and trace solutes. These analyses were done at the MBMG lab following the procedures outlined above for the stream samples. Also, any sample that had a pH > 4.5 was analyzed for alkalinity, following the methods outlined above. Because it was considered of highest importance, Sample G, the highly altered and pyrite-rich Hughesville Stock, was sampled for ICP-MS metals every week except week 5. As a control, one humidity cell was set up and leached during the first weekly cycle, but with no solid rock media. This leachate, listed as “Sample Blank” in the datasets of Appendix D, showed somewhat elevated levels of some metals, including Cu, Pb, and Zn.

3. Results

3.1. Synoptic Sampling: Galena Creek

3.1.1. Field Parameters

The streamflow of Galena Creek increased significantly from a small flow of < 1 L/sec in its upper reaches to roughly 100 L/sec at its mouth (Figure 6). Flow increased downstream fed by a mix of tributary streams, mine discharges, and perhaps some very minor groundwater inflow. Gold Run Creek, which enters Galena Creek about 1 km from its mouth, is the biggest tributary stream. The largest measured mine discharge was from the Moulton Mine (4.74 L/sec), followed by the Block P (1.98 L/sec) and the Danny T (0.49 L/sec). The sum of all measured inflows from tributaries and mine discharges taken during the 2-day study was 99.7 L/sec, which is very close to the total flow at the mouth of Galena Creek. This suggests that direct groundwater discharge was a relatively minor contributor to flow in the main stem of the creek during the time of the field sampling. Streamflow data for sampling location GC-7 was anomalously low and removed from Figure 6 due to suspected in-field error when gathering this data.

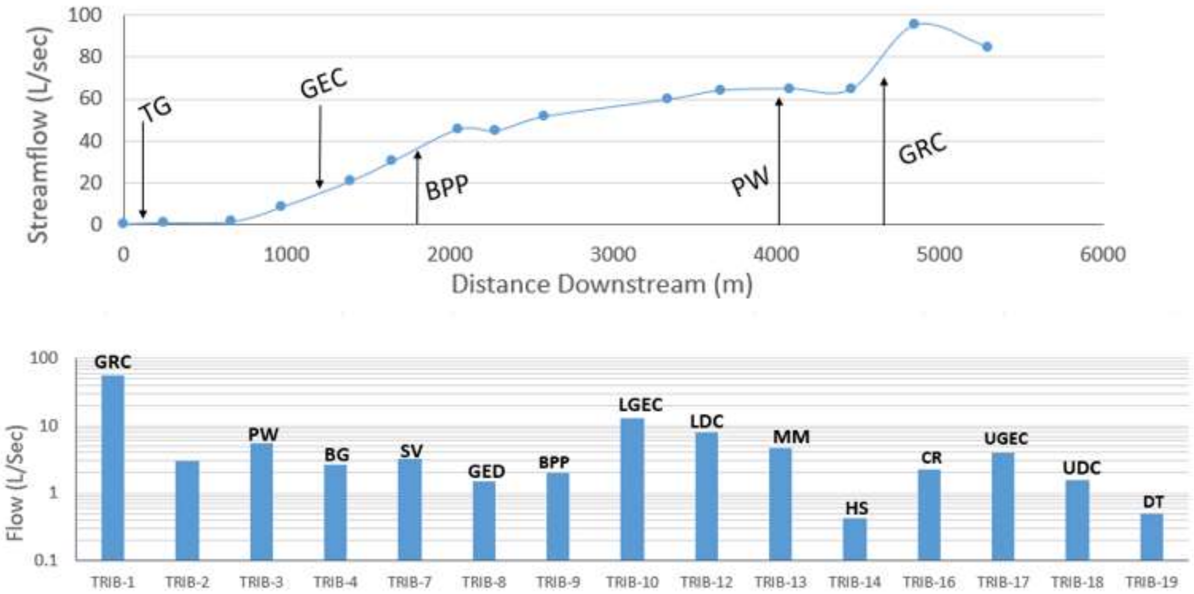

Figure 6. Flows of Galena Creek (top) and tributaries (bottom) measured during the synoptic sampling event. Units are L/sec.

Changes in the pH and SC of Galena Creek with distance downstream are shown in Figure 7. The only sampling locations with strongly acidic pH were upstream of the confluence of the Moulton discharge. The Moulton discharge itself had near-neutral pH, so it had the effect of raising the pH of the main stem of the creek. A slight dip in pH and increase in SC were noted below the Block P discharge, but pH remained near-neutral to the bottom of the stream. Galena Creek was well-oxygenated over its entire length, with daytime temperatures of 8 to 13°C. Raw data for these parameters can be found in Appendix A.

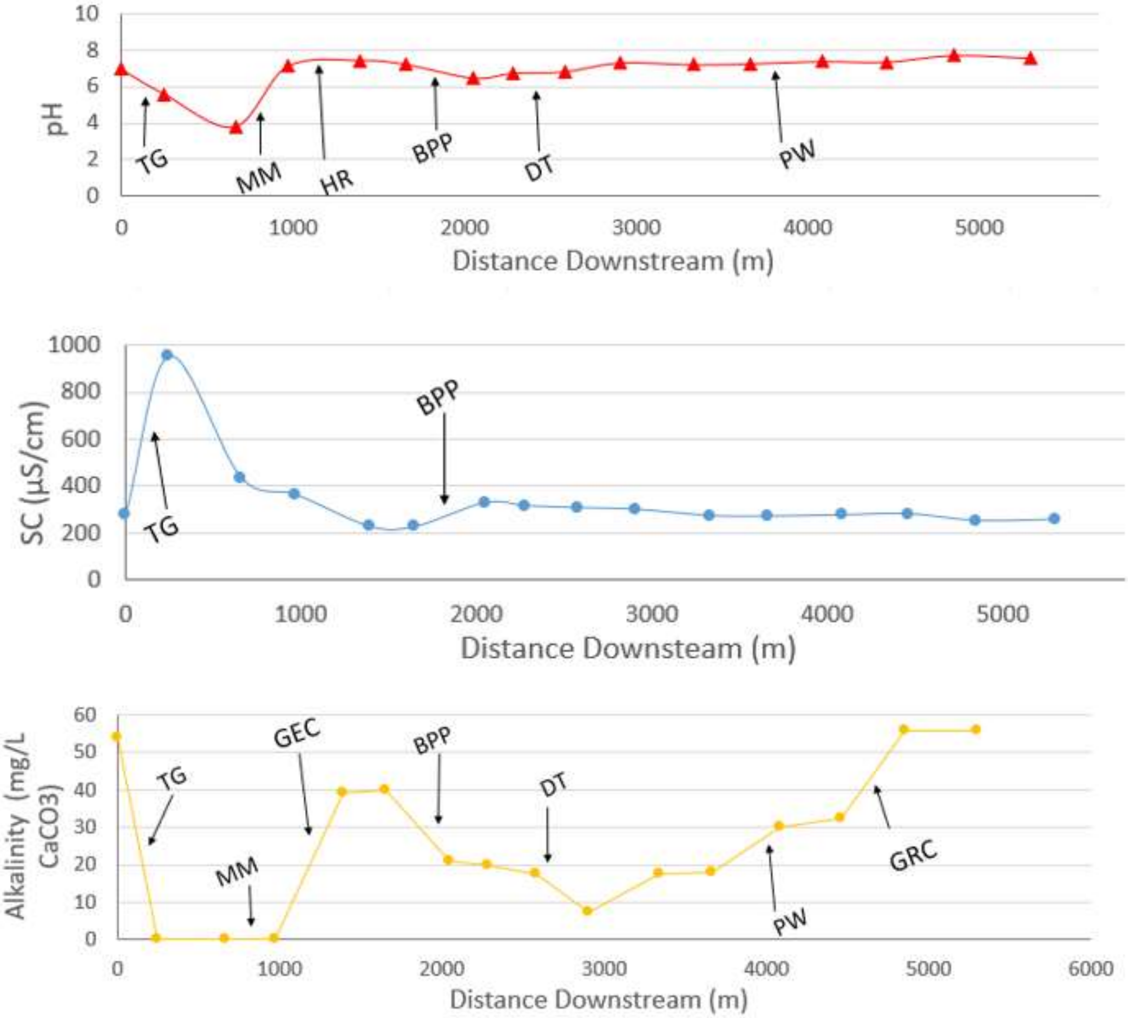

Figure 7. pH, SC, and alkalinity trends in Galena Creek. Tributary inflows are shown with arrows.

3.1.2. Galena Creek Metal Concentrations

Dissolved (filtered to 0.2 μm) and total (unfiltered) metal concentrations for the synoptic analysis of Galena Creek are in Figures 8 & 9, which follow, for each of the contaminants of interest (COI). The COI's for this project include manganese (Mn), iron (Fe), copper (Cu), zinc (Zn), lead (Pb), thallium (Tl), aluminum (Al), arsenic (As), and cadmium (Cd).

Concentrations of dissolved Fe, Mn, Zn, Cd and As followed a pattern with high values in the uppermost reach near the Tiger Mine, a decrease to the mouth of Green Creek, and then an increase below the Block P discharge (Figures 8 and 9). In contrast, concentrations of Cu, Al, and Pb were highest near the Tiger Mine, and decreased to the mouth of Galena Creek without a noticeable spike below the Block P 75' adit discharge. Concentrations of dissolved thallium (Tl) showed the opposite trend, being low in the upper reaches of Galena Creek and increasing below the Block P discharge.

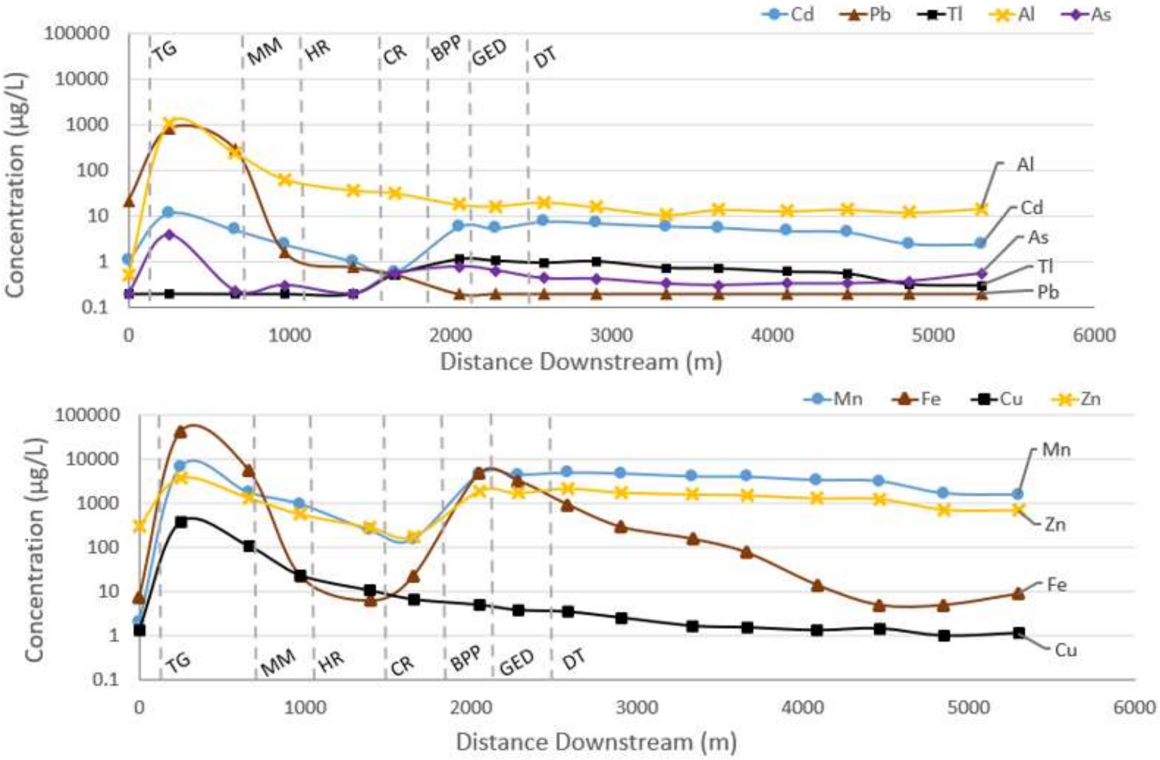

Figure 8. Dissolved concentrations (µg/L) for contaminants of interest in Galena Creek. Dashed lines show the location of significant mine discharges.

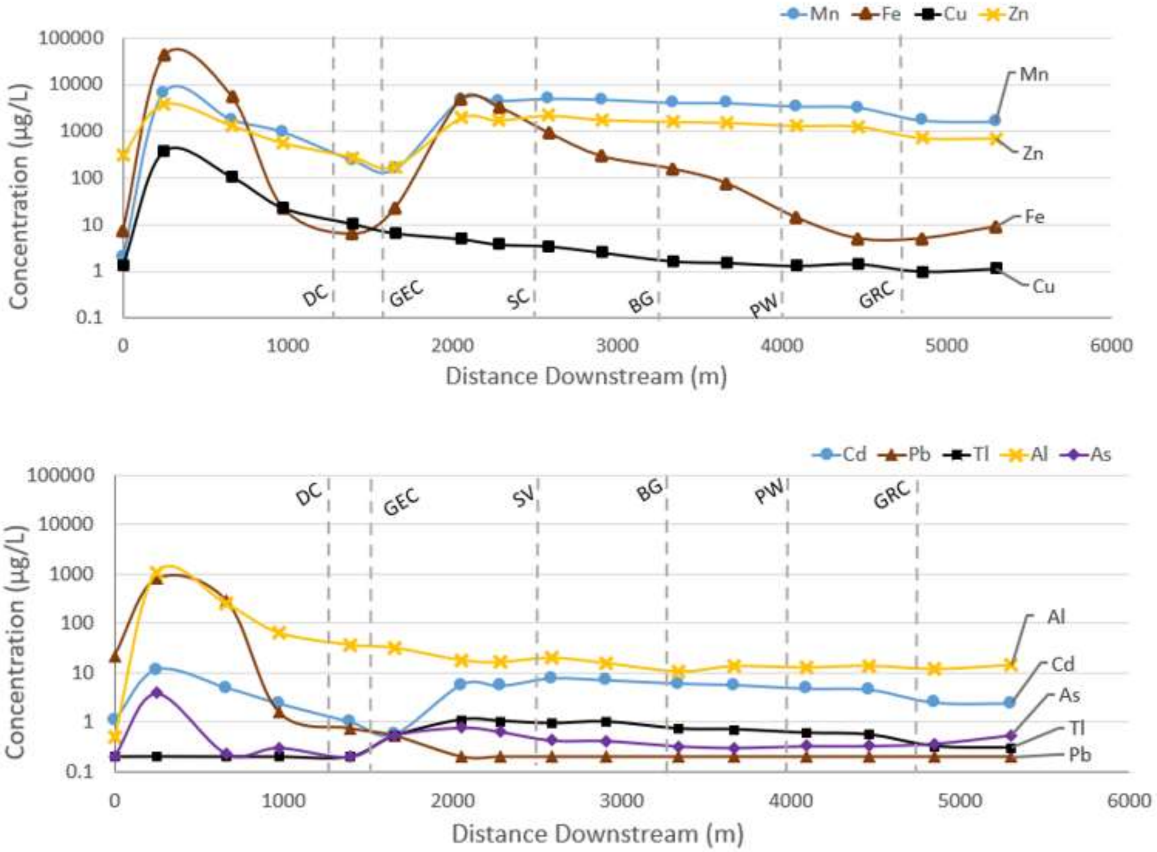

Figure 9. Dissolved concentrations (µg/L) for contaminants of interest in Galena Creek. Dashed lines show the location of significant tributary streams.

Figure 10 shows a comparison of filtered vs. total (unfiltered) concentrations in Galena Creek for each COI. Some solutes, including Mn, Zn, Cd, and Tl, were primarily in the dissolved state, so there is very little difference between their total and filtered concentrations. In contrast, Fe, Al, As, Cu, and Pb all showed a strong tendency to partition into suspended particles. The graph for Fe shows an influx of soluble Fe near the headwaters and again at the Block P discharge (BPP). Each influx was followed by a tail in which soluble Fe decreased rapidly but total Fe remained elevated. This is explained by oxidation of soluble Fe^{2+} to hydrous ferric oxide (HFO), which remained in suspension due to the steep gradient of the stream.

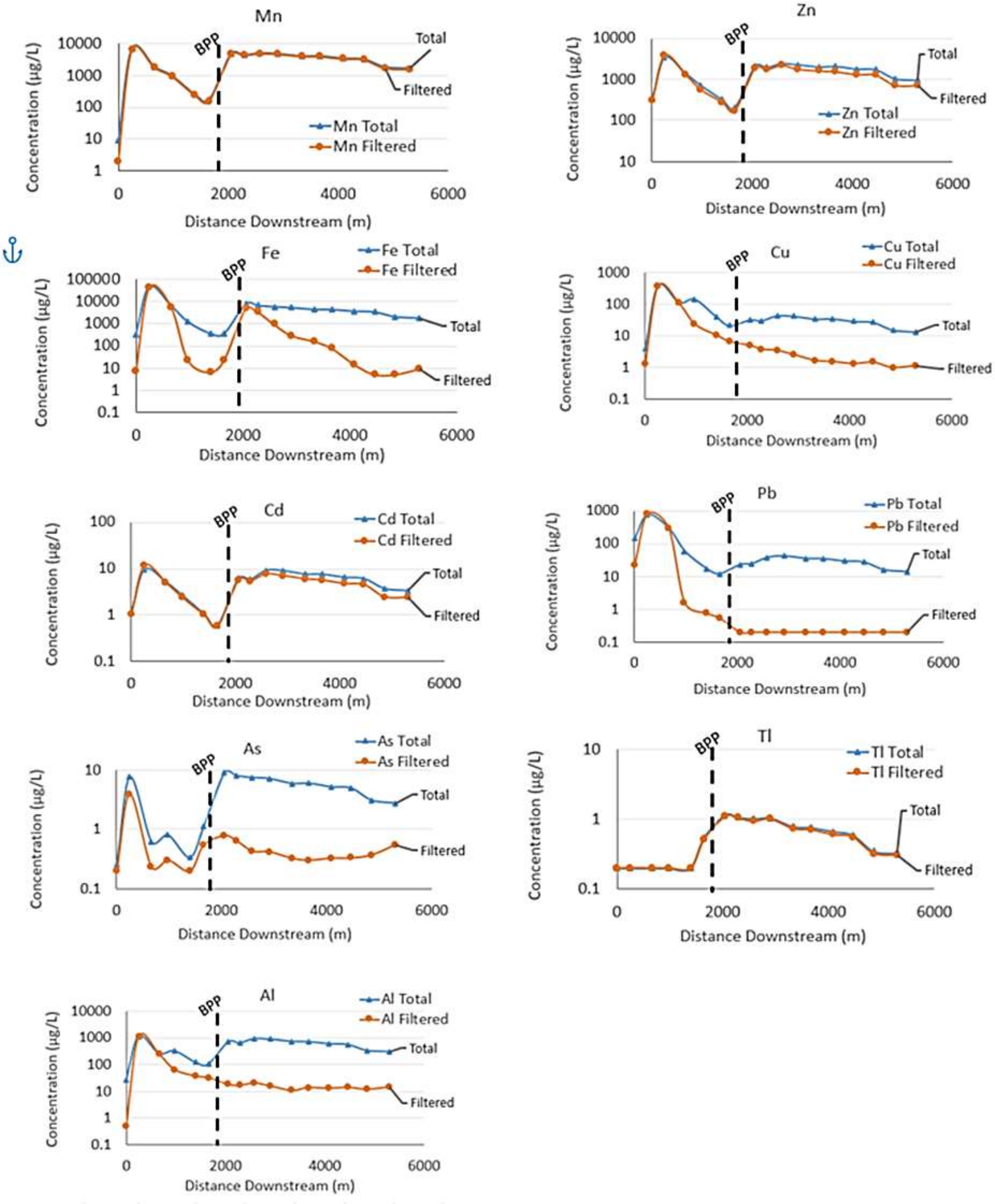

Figure 10. Total (unfiltered) vs. dissolved (filtered) metal concentrations for contaminants of interest in Galena Creek.

3.1.3. Galena Creek Anion Concentrations

The Galena Creek sample results for the four anions Cl^-, F^-, SO_4^{-2}, and HCO_3^- are shown in Figure 11 below. Sulfate is the dominant anion in Galena Creek. Sulfate concentrations are highest at the headwaters (526 mg/L), decrease due to dilution below the Moulton discharge, slightly increase at Block P, then reach a steady level of approximately 100 mg/L in the middle reach of Galena Creek until concentrations decrease again below the confluence of Gold Run Creek. Bicarbonate is the second most abundant anion, with concentrations exceeding 68 mg/L near the mouth of Galena Creek. Bicarbonate concentration was also high at the headwater spring (GC-15). The decrease in bicarbonate through much of the upper and middle reaches of the stream is due to the influx of acidic mine discharges. The sharp drop in bicarbonate concentration at station GC-7 is unexpected and could be a result of a bad alkalinity measurement. Chloride values peak at a range of concentrations between 0.2 and 0.3 mg/L at the headwaters and at the Danny T mine, after which, concentrations decrease at the Moulton and steadily decrease downstream after the middle reach area of Galena Creek. Fluoride follows a similar trend except it does not peak at the Danny T and instead starts at a peak in concentration of 0.528 mg/L and stays at a consistent level in the middle reach of Galena Creek after the Block P mine and Gold Run Creek.

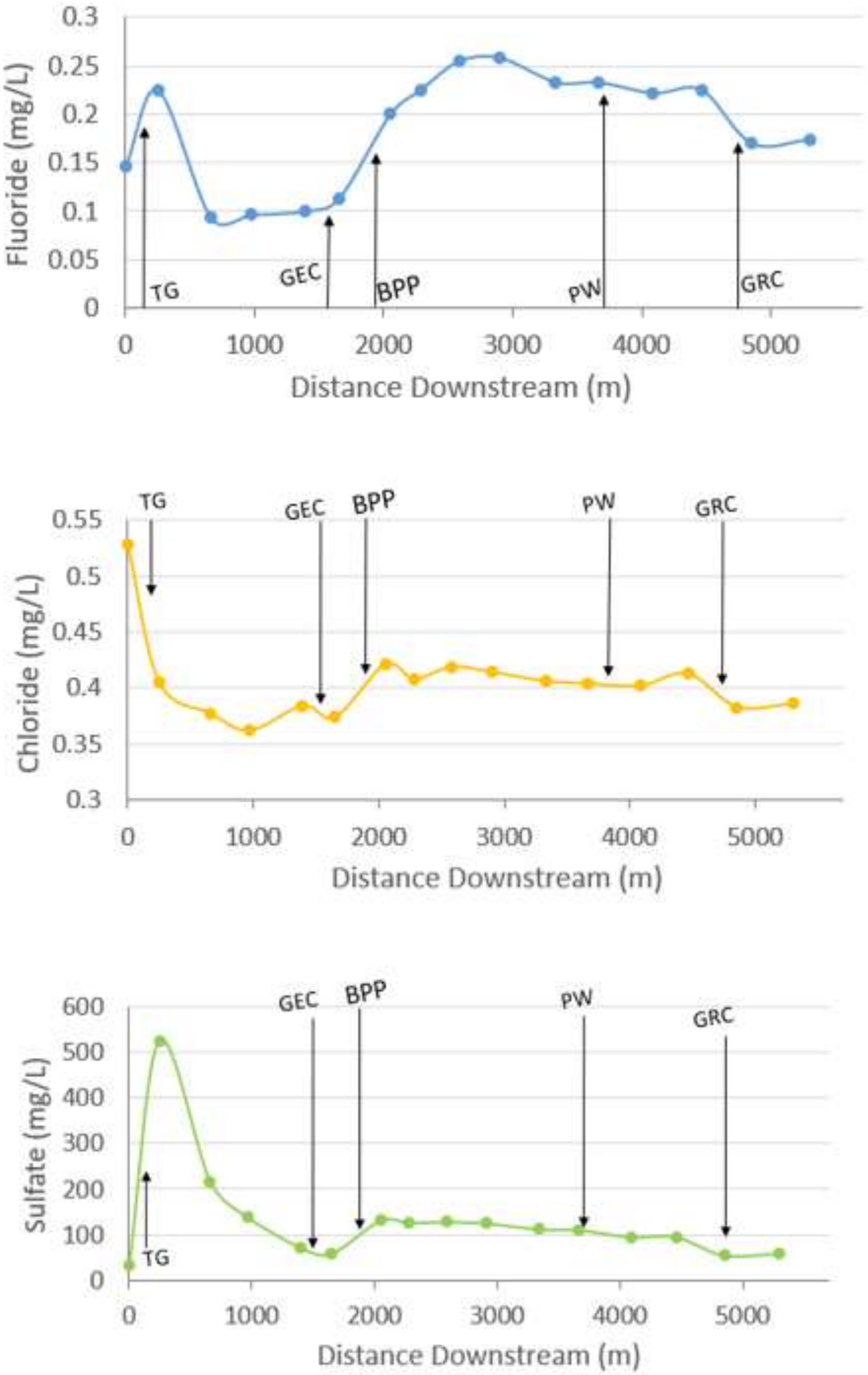

Figure 11. Fluoride (top), chloride (middle), and sulfate (bottom) data in mg/L vs. distance downstream (m) with reference to significant mine and creek tributary locations and Galena Creek sampling stations.

3.1.4. Galena Creek Metal Loads

Dissolved load trends ranged between groups of metals. Iron showed a small peak below the Tiger Mine which quickly dropped back to baseline, and then a much larger peak after the confluence with the Block P discharge, followed by another rapid drop to baseline. Dissolved loads of Zn, Tl, and Cd peaked between the Block P and Danny T mine workings, then gradually decreased to the mouth of the stream. Arsenic (As) load peaked below Block P, then dropped to an intermediate level, and then increased unexpectedly in the last kilometer of the stream. Loads of aluminum show erratic behavior with an overall increase down the entire length of Galena Creek. Unlike the other COIs, loads of Pb and Cu showed their highest values immediately below the Tiger Mine. Copper loads remained high through the middle reach of Galena Creek and then decreased slightly to the mouth. In difference, Pb loads dropped abruptly back to baseline values below the Moulton Mine.

Figure 13 shows the same load data discussed in the previous paragraph, but with the locations of tributary streams marked by vertical dashed lines. Viewing the graphs this way, it appears that there is a stepped increase in load of several metals, including Mn, Zn, and Tl, below the confluence of Silver Creek. The mouth of Silver Creek contains elevated Mn and Zn concentrations (next section), possibly due to mine waste sources in that drainage. Other tributaries, such as Bend Gulch, Pride of the West Creek, and Gold Run Creek, contributed no increases in metal loads to the profiles.

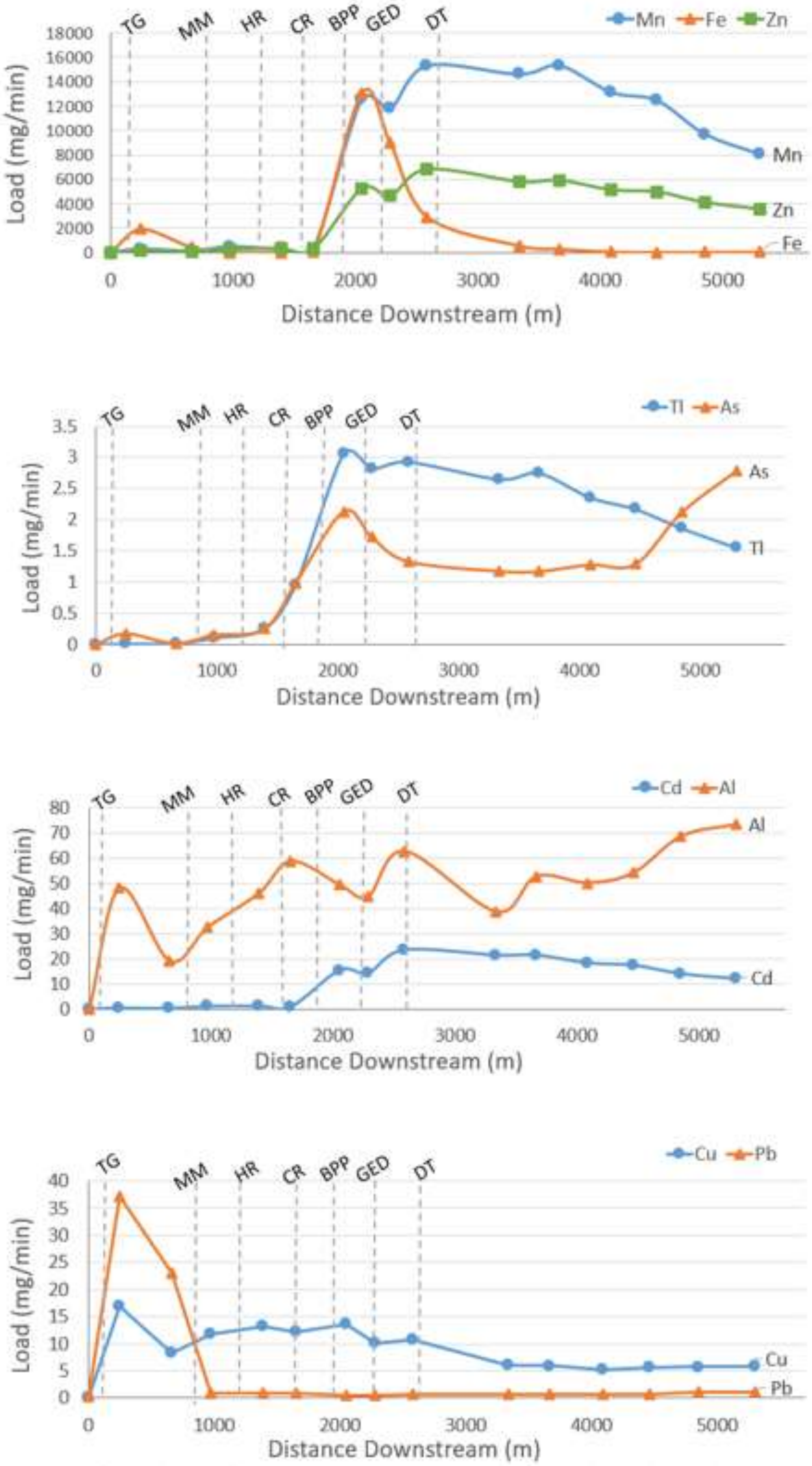

Figure 12. Dissolved load results for Galena Creek samples (mg/min) for each contaminant metals of interest with reference to significant mine remnant locations and distance downstream (m).

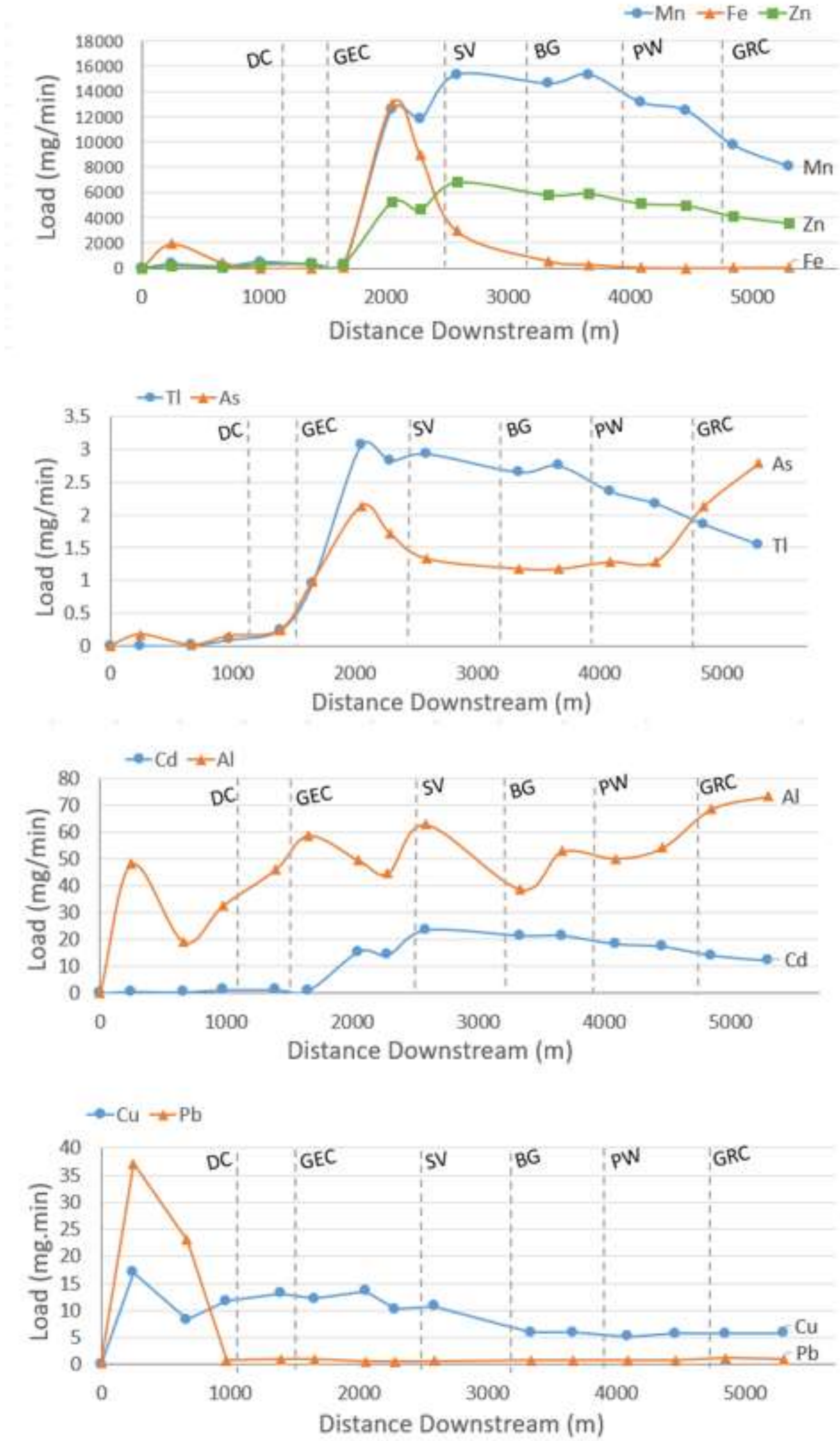

Figure 13. Dissolved load results for Galena Creek samples (mg/min) for each contaminant metals of interest with reference to significant creek tributary locations and distance downstream (m).

3.2. Synoptic Sampling: Tributaries

3.2.1. Tributary Parameter Results

Tributary parameters varied based on source of the water. Mining seeps showed pH’s as low as 3 and SC’s as high as 2000 µS/cm while stream and natural spring inflows had pH > 6 and variable SC. Some of the higher SC tributaries, such as Pride of the West Creek and upper Green Creek, also had high bicarbonate alkalinity, which is a product of natural weathering of bedrock. Raw parameter data for the tributaries can be found in Appendix A.

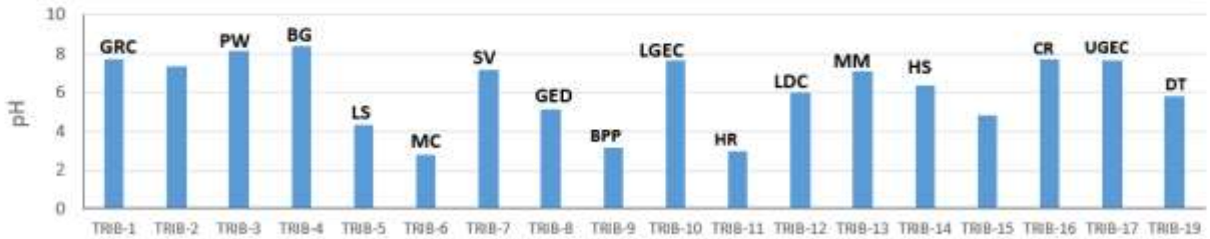

Figure 14. pH values for tributaries and mine seeps.

3.2.2. Tributary Metal Concentrations

Metal concentrations in tributary streams were considerably lower than that in tributary mine seeps for most metal contaminants of interest. Mn, Fe, and Zn, were found in the highest concentrations in tributary seeps compared to other metals and reached higher than 100,000 µg/L in some seep locations while Cu, Cd, Pb, Tl, and As were found in concentrations less than 1000 µg/L or less than 1 µg/L. The Block P (trib 9) and Danny T (trib 19) mine seeps, had the highest concentrations of metal contaminants out of the tributaries, followed by, the Marcelline Mine (trib 6), and trib 15 (Figure 15).

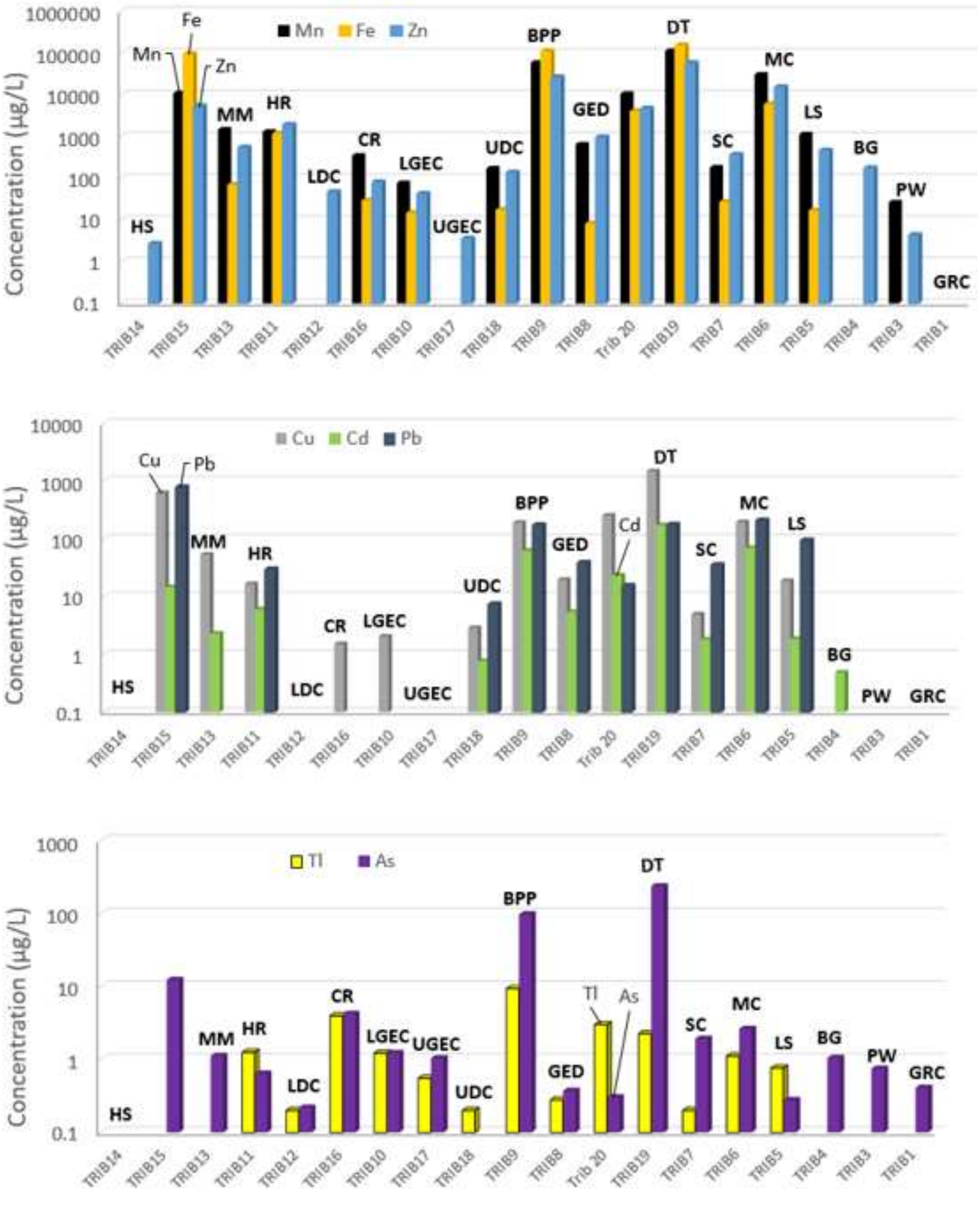

Figure 15. Dissolved concentrations of contaminants of interest in tributary samples.

3.2.3. Tributary Anion Concentrations

Sulfate concentrations were highest in samples taken from mine seeps, particularly at the Block P mine and at the Danny T mine. Here, sulfate reached concentrations as high as 1305 mg/L and 1802 mg/L respectively. Chloride and fluoride concentrations stayed consistent across tributary samples and ranged between 2 mg/L and 0.1 mg/L. Concentrations of the bicarbonate ion were highest in Gold Run Creek (trib 1), the Moulton Mine discharge (trib 13), upper Green Creek (trib 17) and the Carter Mine discharge (trib 16).

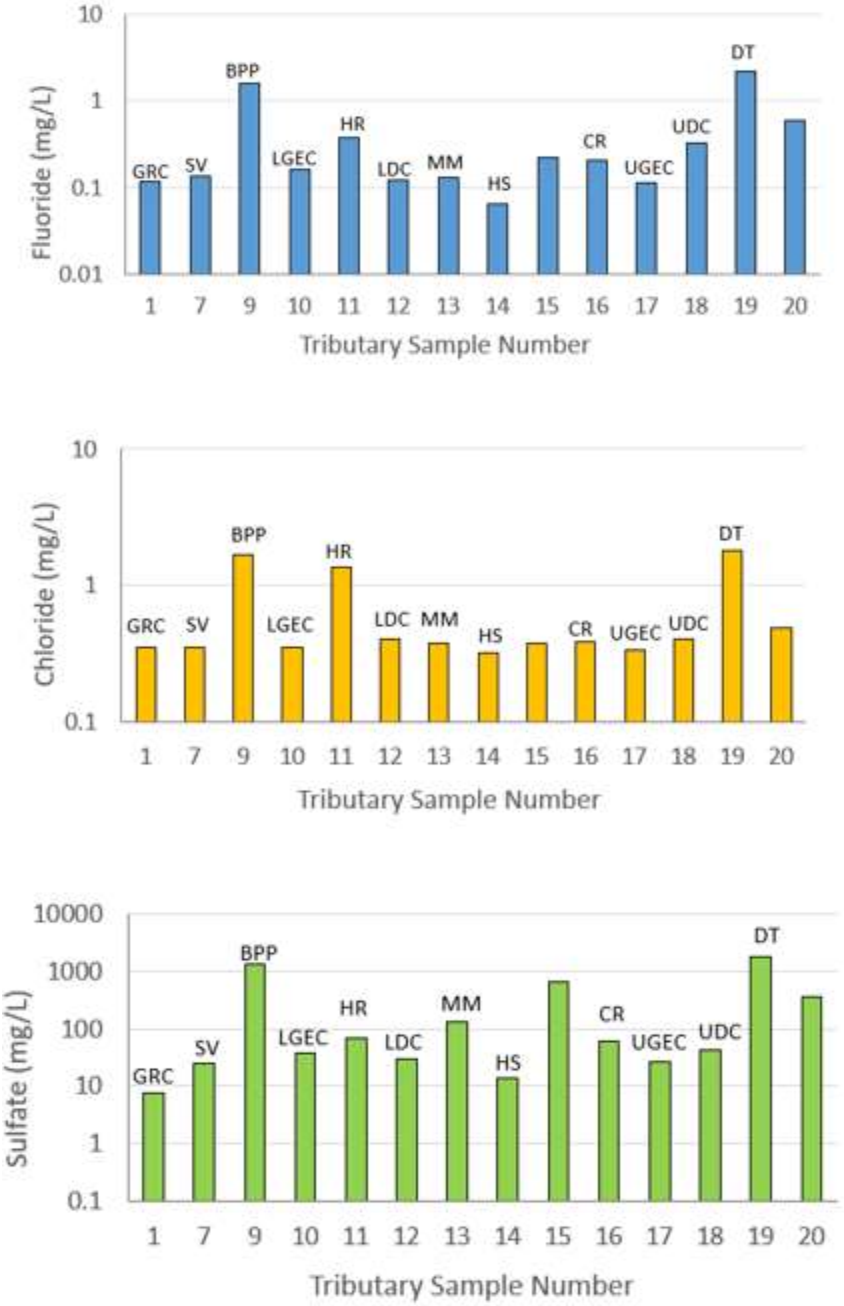

Figure 16. Anion concentrations (mg/L) for tributary samples.

3.2.4. Tributary Metal Loads

Tributary loads were highest for most contaminants of interest at the Block P discharge and the Danny T adit seep for all metals shown in Figure 17. The Moulton Mine discharge also showed high loads of dissolved Mn, Cu, Fe, and Zn near 800 mg/min, 27 mg/min, 35mg/min, and 300 mg/min, respectively. The Moulton seep showed non-detectable amounts of dissolved Pb, however, Galena Creek near the Moulton and Pioneer mine sites has a relatively high dissolved Pb load. This is likely due to Pb's non-conservative nature causing data differences in total and dissolved Pb concentrations. The tributary streams had lower metal loads relative to the mine seeps except for loads of Al which, on average, exhibited higher loads in some of tributary streams when compared to some mine seeps.

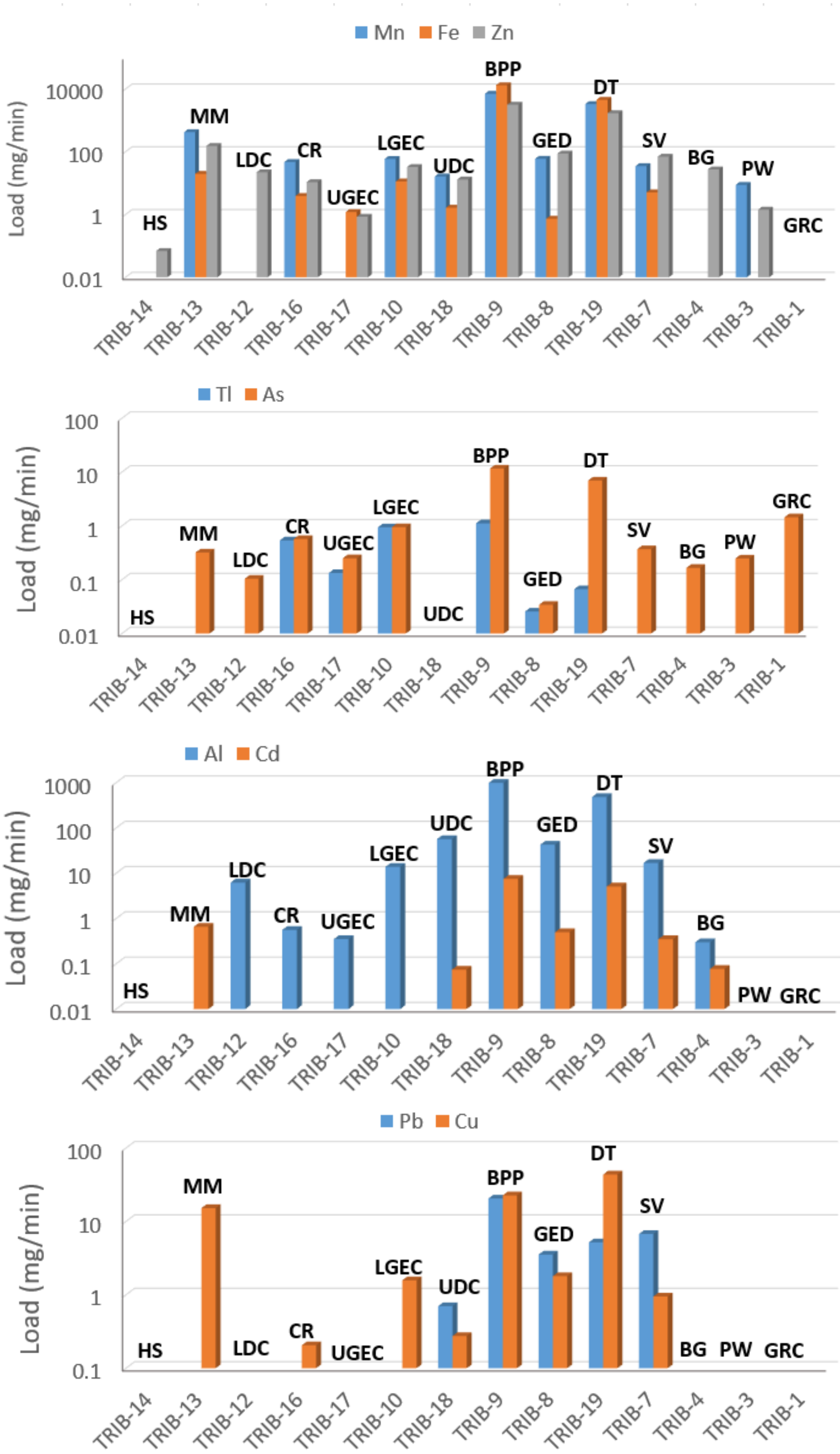

Figure 17. Loads (mg/min) of contaminants of interest in tributary samples.

3.3. Leachate Experiment Results

3.3.1. Leachate Parameter Results

Data for pH, SC, and other parameters from the leachate tests are summarized in Figure 18 and Table IV. The different rock samples showed a large range in leachate pH. Cell G, the “quartz-sericite-pyrite” altered Hughesville Stock, had the lowest pH, consistently below 3 for the entire experiment. Cells D (Block P outcrop transect), F (porphyry of Galena Creek), and H (Block P sulfide-rich vein material) also had acidic pH, between 3 and 4.5. Cell E, the unaltered Hughesville Stock, began with a pH near 5 which rose to 6.5 by the end of the experiment. Cells A, B, and C (Gold Run Tuff, Wolf Porphyry, Clendennin Porphyry, respectively) had near-neutral pH that rose slightly over the duration of the test.

Rock samples G, H, and A recorded the highest SC values out of all the samples reaching as high as 5000 µS/cm in rock H (sulfide-rich vein sample from Block P) at week 2 of the experiment. The unaltered Hughesville Stock (Cell E) had the lowest SC. Most cells showed a decrease in SC over the 5-week test, consistent with flushing of solutes out of the partly weathered samples. However, some cells, including Cells G (hydrothermally altered Hughesville Stock), and H (Block P mineralized vein) appeared to reach a steady state SC in the last 2-3 weeks of the experiment. Alkalinity values decreased from near 75 mg/L CaCO3 to near 30 mg/L CaCO3 in samples with pH’s consistently above 5.

The dissolved oxygen content of the leachates remained > 3 mg/L over the entire test, indicating that oxic conditions prevailed in the humidity cells (Table IV). Samples A, B, and C had significant bicarbonate alkalinity (> 60 mg/L $CaCO_3$), which decreased by about half by the end of the experiment. This could indicate leaching of secondary carbonate minerals in the partly weathered samples.

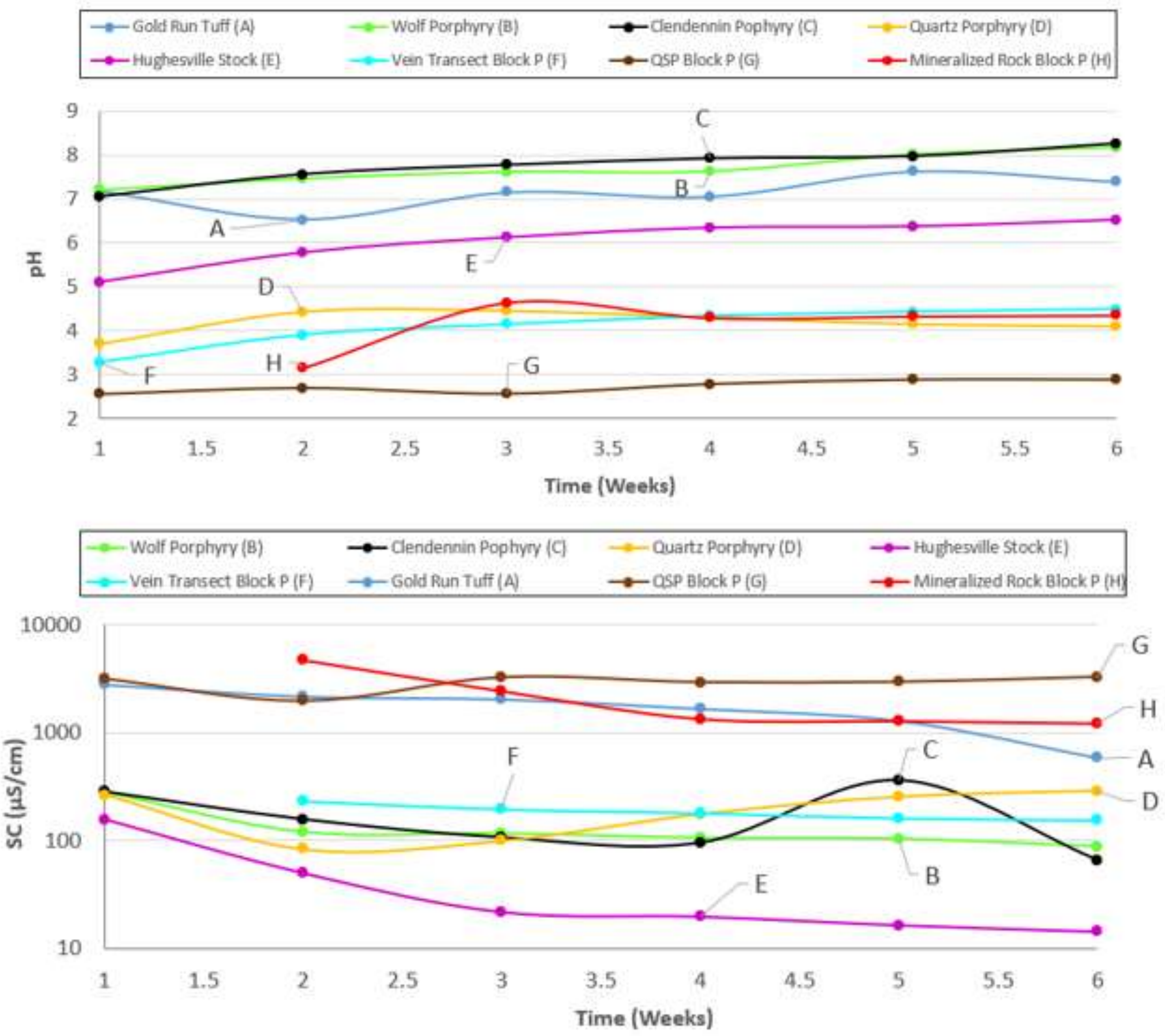

Figure 18. pH and SC over time for leachate rock sample experiments.

Table IV. Water drained, pH, SC, Dissolved Oxygen, and alkalinity over time for each sample in the leachate experiment

DATE	Week	Sample	H2O drained (g)	pH	SC (µS/cm)	DO (ppm)	Alkalinity (mg/L CaCO3)
11/6/2020	1	A	246.3	7.18	2762	5.3	75
		B	212.7	7.21	278	3.9	74
		C	384.6	7.05	284	3.1	68
		D	424.9	3.70	263	5.5	0
		E	335.8	5.11	156	4.9	3
		F	326.8	3.27	N/A		0
		G	255.1	2.55	3133	4.4	0
		Blank	500.0	7.74			
11/13/2020	2	A	267.0	6.53	2140	5.9	
		B	244.1	7.47	119	5.7	
		C	360.0	7.56	157	4.4	
		D	502.5	4.43	83	6.6	
		E	302.9	5.78	50	6.7	
		F	260.6	3.90	232	6.7	
		G	259.4	2.69	1960	4.4	
		H	195.9	3.14	4686	5.0	
11/20/2020	3	A	222.9	7.15	2019	6.6	
		B	217.7	7.62	116	5.9	
		C	375.9	7.77	107	5.6	
		D	404.6	4.45	100	6.1	
		E	312.6	6.12	22	6.9	
		F	288.5	4.14	195	6.9	
		G	265.1	2.56	3232	4.1	
		H	201.9	4.64	2411	4.6	
11/27/2020	4	A	209.3	7.05	1647	6.7	
		B	207.9	7.63	105	6.3	
		C	340.1	7.92	95	6.1	
		D	386.5	4.30	175	5.9	
		E	282.7	6.34	20	6.8	
		F	261.1	4.33	180	6.9	
		G	259.6	2.78	2914	3.8	
		H	144.0	4.29	1328	5.9	
12/4/2020	5	A	221.8	7.63	1276	6.7	
		B	221.0	8.02	103	6.3	
		C	347.5	7.97	363	6.3	
		D	382.8	4.15	252	5.5	
		E	286.1	6.37	16	6.9	
		F	286.2	4.43	160	7.0	
		G	255.8	2.88	2938	3.3	
		H	212.0	4.33	1271	4.8	
12/11/2020	6	A	203.7	7.39	579	7.5	48
		B	232.3	8.18	88	6.8	38
		C	334.8	8.26	66	6.7	31
		D	425.8	4.10	285	6.0	0
		E	308.5	6.52	14	7.0	4
		F	266.2	4.49	153	7.0	0
		G	254.9	2.88	3260	3.8	0
		H	212.3	4.35	1207	6.0	0

3.3.2. Leachate Anion Results

The dominant anion for the most leachate samples was sulfate (Table V), although Cells A, B and C also had significant bicarbonate ion (see above). Most rock samples decreased in sulfate over time except for rock D which increased from week 1 to week 5. Rock samples A (Gold Run Tuff), G (Hydrothermally altered Hughesville Stock) and H (mineralized Block P vein) had the highest sulfate concentrations (> 1000 mg/L). This is consistent with the fact that samples G and H had the highest concentration of pyrite and other sulfides, while sample A (Gold Run Tuff) also had some pyrite.

Table V. Concentrations of anions (mg/L) in leachate experiments over time

Sample Name	Date	Fluoride	Chloride	Nitrite	Bromide	Nitrate	Phosphate	Sulfate
A-1	11/6/2020	0.35	2.78	0.11	<0.01	2.92	<0.02	2121
B-1	11/6/2020	0.81	4.97	0.09	0.21	2.94	<0.02	9
C-1	11/6/2020	0.80	7.38	0.06	<0.01	0.93	<0.02	28
D-1	11/6/2020	0.18	1.58	<0.01	<0.01	3.96	<0.02	124
E-1	11/6/2020	0.62	38.3	<0.01	0.14	1.76	<0.02	35
F-1	11/6/2020	0.48	4.18	<0.01	<0.01	1.47	0.02	186
G-1	11/6/2020	8.24	2.05	0.09	<0.01	2.57	0.20	1977
Blank	11/6/2020	0.08	0.36	<0.01	<0.01	0.36	<0.02	43
G-2	11/13/2020	4.87	0.92	0.07	0.15	0.32	0.08	1106
H-1	11/13/2020	1.34	6.94	<0.01	<0.01	0.05	<0.02	4019
G-3	11/20/2020	4.52	0.54	0.09	0.13	0.10	0.11	1517
G-4	11/27/2020	1.86	0.44	0.09	0.14	0.09	0.16	1356
H-2	11/27/2020	0.24	2.64	0.09	<0.01	0.11	<0.02	1477
G-5	12/11/2020	1.31	0.40	0.10	<0.01	0.08	0.41	1562
H-3	12/11/2020	0.19	1.08	0.08	<0.01	0.07	<0.02	949
A-2	12/11/2020	0.49	0.36	<0.01	<0.01	0.10	<0.02	580
B-2	12/11/2020	0.73	0.37	<0.01	0.09	0.11	<0.02	2
C-2	12/11/2020	0.54	0.36	0.09	<0.01	0.10	0.02	4
D-2	12/11/2020	0.13	0.39	<0.01	<0.01	0.08	0.05	181
E-2	12/11/2020	0.35	0.45	<0.01	<0.01	0.08	<0.02	15
F-2	12/11/2020	0.50	0.93	<0.01	<0.01	0.13	0.02	132

NOTE: Nitrite and Nitrate are reported as N. Phosphate is reported as P.

3.3.3. Concentrations of Contaminants of Interest

Concentrations of contaminants of interest in the leachate tests are summarized in Table VI and Figure 19. By far the highest concentrations of most COIs were produced from cells G (hydrothermally altered Hughesville Stock) and H (mineralized Block P vein), although Cell F (bedrock transect behind the Block P mine) also had high values of several COIs, including Mn, Zn, Cu, Cd, and Pb. Concentrations in weekly samples from Cell G appeared to reach a steady state towards the end of the test for all of the COIs, including Al (~ 9 mg/L) , Mn (~110 mg/L), Fe (~200 mg/L), Cu (~ 4 mg/L), Zn (~18 mg/L), As (500-800 μg/L), Cd (~ 120 μg/L), Tl (~ 5 μg/L), and Pb (~ 2 mg/L). Concentrations of COIs for Cell H (the sulfide-rich vein sample) dropped sharply after the first week but were closer in the last two leachate samples, indicating flushing of soluble metal salts (e.g., sulfates, hydroxides, or carbonate minerals) out of the partly weathered samples in the first flush. Cell A, from the Gold Run Tuff, had generally low concentrations of COIs, with the, possible, exception of thallium (up to 9 μg/L). This sample had circum-neutral pH and leached a large amount of Ca out of the rock, possibly, from dissolution of secondary calcite and/or gypsum. Samples B, C, and E (unaltered Wolf, Clendennin, and Hughesville stock) had somewhat elevated COI concentrations after the first leach that decreased dramatically at the end of the test. This suggests flushing of COIs that were weakly adsorbed to the partly weathered outcrop samples. Sample D (porphyry of Galena Creek) leached COIs at generally low concentrations. Note that the sample blank data listed in Table VI shows the presence of a few metals, particularly, Pb at 89 μg/L. The source of this lead could have come from potentially some leftover residue in the cell that made through the nitric cleaning or from the filter cloth, but this level of metals would not have impacted the conclusions made from the dataset in this thesis.

Table VI. Metal concentrations (µg/L) for leachate samples over time

Sample Name	**Date Sampled**	**Al**	**Ca**	**Mn**	**Fe**	**Cu**	**Zn**	**As**	**Cd**	**Tl**	**Pb**
G-1	11/6/2020	22900	220000*	94300*	281000*	8090*	37000*	478	102	21	2150*
G-2	11/13/2020	9750	120000*	81000*	113000*	3790	20100	250	196	16	2220
G-3	11/20/2020	11800	112000*	124000*	168000*	4480	31600	672	201	8	2060
G-4	11/27/2020	8990	35795	114000*	152000*	3830	17900	561	163	6	2080
G-5	12/11/2020	9200	22441	112000*	242000*	4310	17500	883	118	5	1710
H-1	11/13/2020	8570	38554	420000*	1222000*	9590	487000*	357	2830	26	3410
H-2	11/27/2020	239	18087	466000*	46600*	491	162000*	115	1210	8	3080
H-3	12/11/2020	136	9132	285000*	36000*	636	87600*	95	696	8	3960
A-1	11/6/2020	3	476000*	282	<5	6	36	2	1	9	0.2
A-2	12/11/2020	1	174000*	12.8	<5	<1	4	1	<0.2	3	<0.2
B-1	11/6/2020	18	36300*	1690	54	88	78	1	<0.2	<0.2	1
B-2	12/11/2020	27	11400*	156	<5	8	5	1	<0.2	0.4	0.4
C-1	11/6/2020	60	38700*	1170	1130	137	181	5	1	<0.2	68
C-2	12/11/2020	34	10900*	89.6	8	43	9	3	<0.2	<0.2	1
D-1	11/6/2020	189	16200*	277	2370	49	166	4	2	2	3
D-2	12/11/2020	295	20000*	300	293	60	238	4	3	2	3
E-1	11/6/2020	53	10100*	465	32	39	190	2	1	0.3	6
E-2	12/11/2020	18	327	3	<5	6	19	1	<0.2	<0.2	0.4
F-1	11/6/2020	945	22500*	2680*	83	156	4100*	1	60	2	309
F-2	12/11/2020	399	12800*	1830	24	66	2770*	1	40	1	130
Blank	11/6/2020	11	103	<2	6	4	27	<0.2	<0.2	<0.2	89

Note: All values with an * are ICP-OES to replace ICP-MS values that were over-range

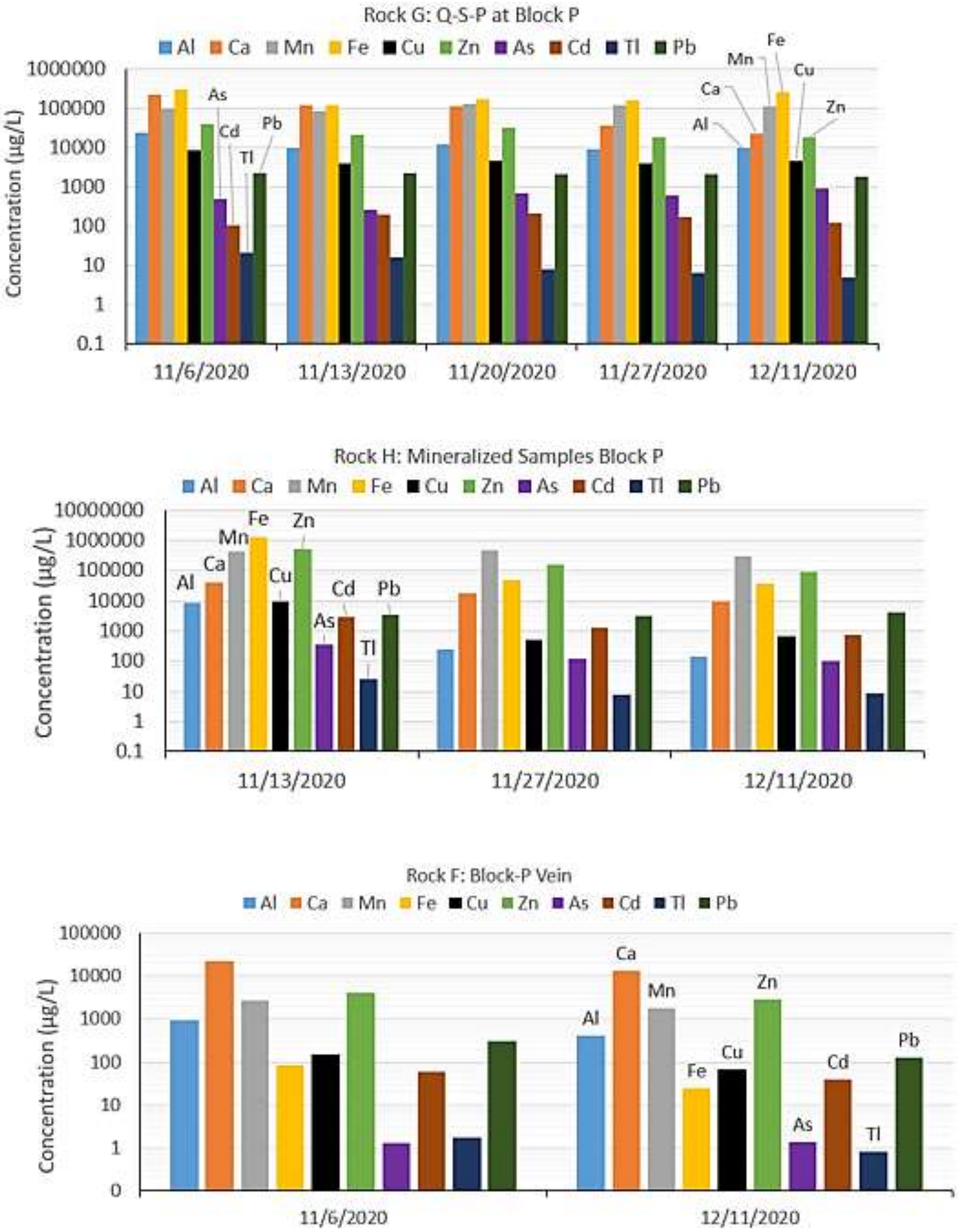

Figure 19. Concentrations of contaminants of interest in leachates from mineralized rock samples G, H, and F over time.

3.4. Stable Isotope Results

3.4.1. Water Isotopes

Results of O- and H-isotope analysis of filtered water samples from Galena Creek and tributaries are summarized in Table VII and Figure 20. All the values are similar to each other and plot between the global meteoric water line (MWL) of Craig (1961) and the Butte meteoric water line of Gammons et al. (2006). It is interesting that the sample from the Block P discharge is the isotopically lightest sample in the data set, although the differences are small compared to the rest of the samples. The fact that the Block P water is lighter may have to do with the extensive mine pool in the underground workings which would have a longer residence time compared to the other mine seeps and streams. None of the samples show any evidence of evaporation, which is indicated by enrichment of δ^{18}O relative to the MWL, off the MWL (Gammons et al., 2006).

Table VII. Water isotope data. Units are ‰ vs. the VSMOW standard.

Sample	**Notes**	**$\delta\ ^{18}$O**	**δ D**
GC-1	Mouth of Galena Creek	-18.5	-141
TRIB-1	Gold Run Creek	-18.7	-142
TRIB-7	Silver Creek	-18.9	-143
TRIB-9	Block P	-19.0	-146
TRIB-10	Green Creek	-18.9	-144
TRIB-11	Harrison seep	-18.6	-141
TRIB-13	Moulton seep	-18.3	-138
TRIB-14	Headwater spring	-18.8	-143
TRIB-16	Carter seep	-18.2	-136
TRIB-19	Danny T seep	-18.8	-143

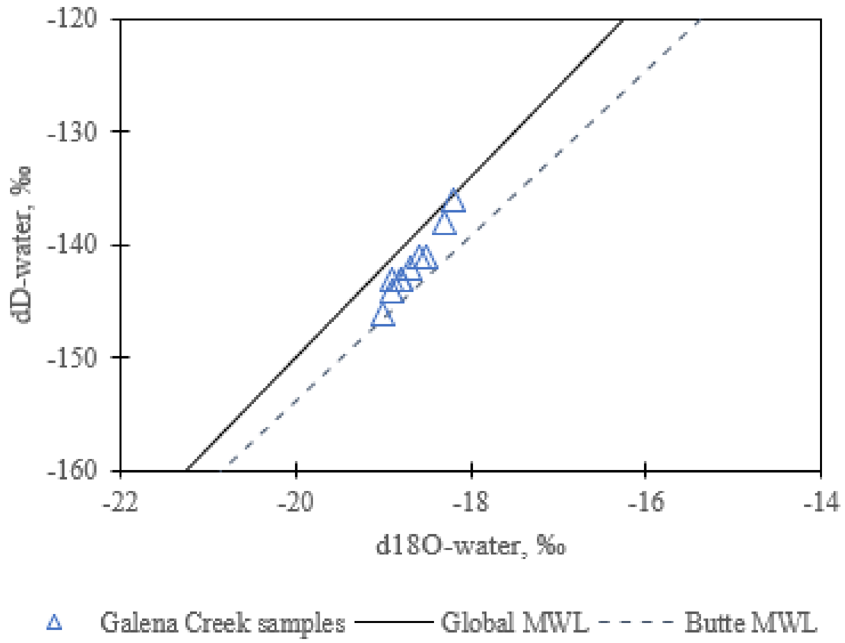

Figure 20. Isotopic composition of water samples from Galena Creek and tributaries. The global meteoric water line (MWL) and Butte MWL are from Craig (1961) and Gammons and others (2006).

3.4.2. Sulfide and Sulfate Isotopes

Sulfur isotope data for 8 sulfide mineral separates from mine dumps in the study area are summarized in Table VIII. The range in δ^{34}S is +3.0 to +6.6 ‰, with an average value of +5.0 ±1.2 ‰. There is no consistent difference in δ^{34}S between mines or between mineral type (galena vs. pyrite vs. sphalerite). The S- and O-isotope composition of 6 samples of dissolved sulfate from Galena Creek and mine adit seeps in the field area are summarized in Table IX. The S-isotope composition of sulfate ranges from +3.1 to +6.1 ‰, with an average of +4.5 ± 1.3 ‰. Values of δ^{18}O-sulfate have a tight range from -12.0 to -13.8 ‰, averaging -13.1 ± 0.6‰. The stable isotope data for sulfides and sulfates are discussed further in the next chapter.

Table VIII. Isotopic data for sulfide minerals. Units are ‰ vs. the VCDT standard.

Mine dump	Mineral	$\delta^{34}S$
Block P	galena	4.1
Block P	pyrite	5.7
Block P	pyrite	4.9
Danny T	pyrite	6.2
Danny T	sphalerite	6.6
Pioneer	pyrite	3.0
Moulton	pyrite	4.5
Harrison	pyrite	5.1
average		5.0
stdev		1.2

Table IX. Isotopic composition of dissolved sulfate. Units are ‰ vs. VCDT for S, and vs. VSMOW for O.

Sample	Notes	$\delta\,^{34}S$	$\delta\,^{18}O$
Trib-9	Block P discharge	6.1	-13.0
Trib-11	Harrison seep	3.2	-13.0
Trib-13	Moulton seep	3.1	-13.3
Trib-19	Danny T seep	5.7	-13.6
GC-1		5.0	-12.1
GC-16		4.1	-13.8
avg		4.5	-13.1
stdev		1.3	0.6

4. Discussion

4.1. Metal Loading Summary and Concentration Comparisons to Regulatory Standards

Data from the synoptic investigation of this thesis can be used to help determine whether there are significant sources of NARD in Galena Creek today. One indirect line of evidence of NARD might be, for example, if all the known mine discharges and tributaries could not account for the total metal load at the mouth of Galena Creek.

The percent of the total load of each contaminant of interest at the mouth of Galena Creek (GC1) that can be accounted for from the five measured mine discharges (Moulton, Carter, Block P, Grey Eagle, and Danny T) is summarized in Table X. During the investigation period, the sum of the loads from the mine seeps accounts for 100% or more of the total load of Mn, Fe, Cu, Zn, Tl, Al, and As at GC1. The mine seeps account for only 81% and 42% of the Cd and Pb loads, respectively. However, when Galena Creek at GC13 (GC upstream of Green Creek) is added as a highly contaminated tributary stream, it is seen that the load from the mine discharges + GC13 accounts for 87% and 83% of the Cd and Pb loads, respectively, at the mouth of Galena Creek. These results demonstrate that the known mine discharges can account for nearly all, or more than all, of the metal load at the mouth of Galena Creek. There is no need to assume that there are additional loads coming from influent groundwater and/or NARD sources of contamination. The relative contributions of each mine discharge to the total metal loads are summarized in the pie graphs of Figures 21 to 22. Note, in Figures 21 and 22, “Upper Galena” represents the incoming metal load from mine discharges and tributaries upstream of the confluence with Green Creek.

Table X. Relative contribution of mine discharges to total metal loads in Galena Creek

Location	Mn	Fe	Cu	Zn	Cd	Pb	Tl	Al	As
Mine discharges (dissolved load, mg/minute)									
Moulton	421	20	15.2	154	0.65	-	-	-	0.32
Carter	47	4	0.2	11	-	-	0.54	0.6	0.57
Block P	7069	13187	22.6	3148	7.46	20.5	1.11	986	11.6
Grey Eagle	60	1	1.8	88	0.50	3.53	0.03	42.6	0.03
Danny T	3322	4498	43.5	1693	5.07	5.17	0.07	479	6.97
Total Mine Seeps	10919	17709	83.3	5094	13.7	29.2	1.74	1508	19.5
Streams (total loads, mg/minute)									
Upper Galena (GC13)	317	432	49.0	400	1.30	21.5	0.25	155	0.42
Galena at GC1	8408	8914	67.2	4795	16.9	69.4	1.65	1575	14.01
Percent of total load at GC1 accounted for by seeps and tribs									
Mine seeps only	130%	199%	124%	106%	81%	42%	105%	100%	139%
Mine seeps + GC13	129%	203%	178%	113%	87%	83%	145%	110%	156%

The minor missing inputs for Pb and Cd shown in Figures 21, 22 and Table X can be explained by Pb's ability to attach and be carried by Fe and Al which would remove a minor part of the suspended load from this dataset. A very small amount of Pb and Cd could also be discharging from a minor leakage not sampleable as part of this study. This does not prove that there was never NARD before mining occurred, just that there is likely not a major source of it in the present day after mining disturbance. Since most of the highly mineralized rock was removed by mining, natural weathering of this material is no longer a major source of metal loading to the stream.

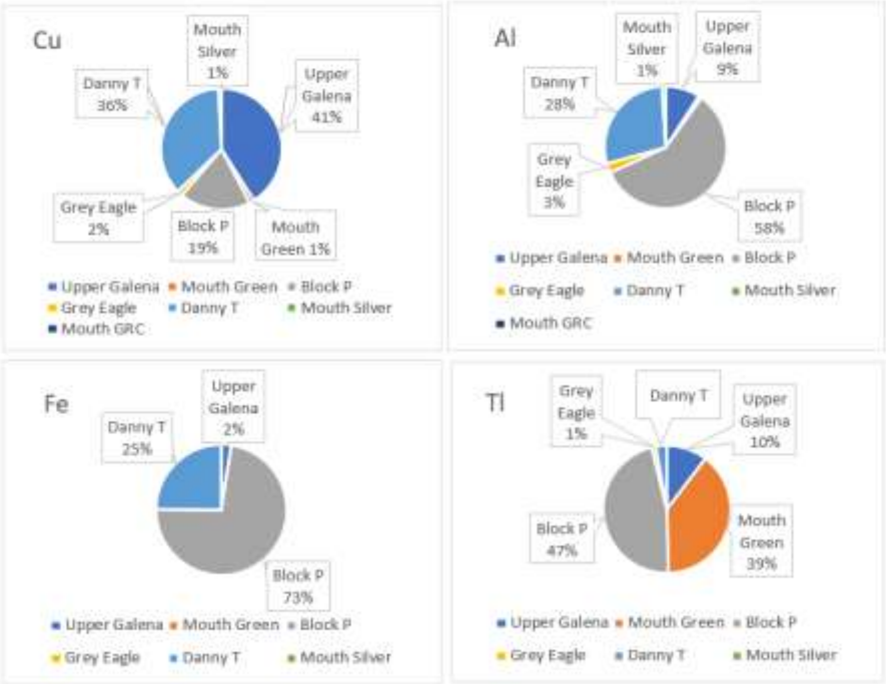

Figure 21. Total metal loads for contaminants of interest compared to the metal load of the mouth of Galena Creek (Cu, Al, Fe, Tl).

Figure 22. Total metal loads for contaminants of interest compared to the metal load of the mouth of Galena Creek (As, Mn, Cd, Pb).

Figure 23 plots the total and dissolved (filtered to 0.2 μm) concentrations of Pb, Zn, Cu, and Cd in Galena Creek along with the DEQ-7 hardness-adjusted standards for chronic exposure to aquatic life (MTDEQ 2012). The State of Montana bases their aquatic life standards on total recoverable (TR) concentrations, which involves a microwave/acid digestion of an unfiltered water sample. In this thesis, "total concentrations" were measured on samples that were unfiltered and acidified to 1% v/v with HNO3. Because these samples were never micro-wave digested, the "total" concentrations reported in this thesis are equal to or less than the concentrations that would have been obtained following TR protocols. However, this difference does not change any of the major conclusions of this study.

As shown in Figure 23, concentrations of total Pb, Zn, Cu and Cd exceeded regulatory standards (or were very close to the standards) for all samples in Galena Creek. Maximum exceedances occur in the headwaters below the Tiger Mine, and again in the middle reach below the Block P and Danny T discharges. Unlike Zn and Cd, there is a clear split between total and dissolved concentrations for Cu and Pb. All filtered samples in the middle and lower reaches of Galena Creek met regulatory standards for Cu and Pb, whereas total samples did not (although total Cu at the mouth of Galena Creek below the confluence of Gold Run Creek was close to the standard). This underscores the tendency of copper and lead to partition into suspended (filterable) particles which remain suspended all the way to the mouth of Galena Creek. Although thallium does not have an aquatic standard, concentrations of Tl in the middle reach of Galena Creek are well above the EPA human-health standard of 0.24 mg/L (EPA, 2003), as shown in Figure 10 of the Results. To the best of the author's knowledge, there are no residents in the area that rely on Galena Creek as a source of drinking water.

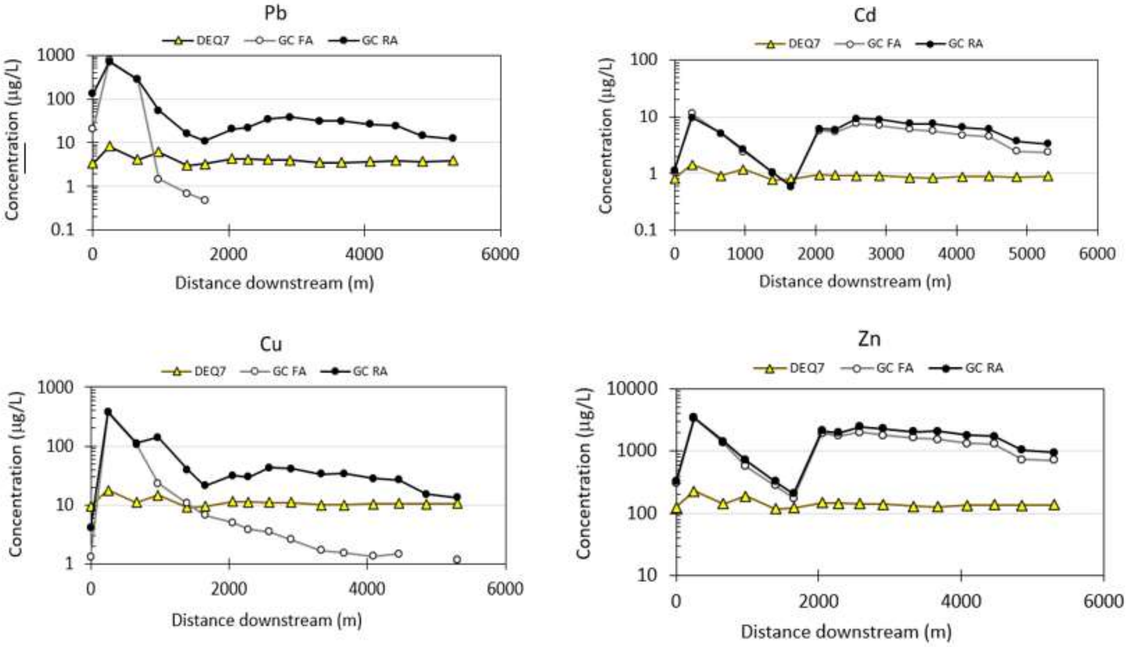

Figure 23. Dissolved and total metal concentration data for major metal contaminants compared to the MTDEQ-7 standards for water quality along the stream adjusted with hardness.

4.2. Leachate Experiment Mass Balance Calculations and Assumptions

4.2.1. Mass Balance Calculation

Results of the bedrock leaching experiments were used to create a “first pass” estimate of what the pre-mining concentration at the mouth of Galena Creek may have been. In the simplest case, the chemistry at the mouth of the creek would be equal to the chemistry of water draining each rock type in the drainage scaled to the fraction of the drainage underlain by each rock type. This idea can be written out as a mass balance equation:

Equation 1. Mass Balance: Leachate

$$C_{GC} = C_1*f_1 + C_2*f_2 + C_3*f_3 + C_4*f_4 + C_5*f_5 \tag{1}$$

where C_{GC} is the concentration of a solute at the mouth of Galena Creek, C1 to C5 are the concentrations draining rock types 1 to 5, and f1 to f5 are the fractions of the total watershed underlain by each rock type 1 to 5. The main rock units selected for leachate studies in this study include: 1) the Wolf Porphyry; 2) the Clendennin porphyry; 3) the Gold Run Tuff; 4) the unaltered Hughesville Stock; and 5) hydrothermally altered Hughesville Stock. Table XI summarizes the concentrations of selected solutes in the last leachate sample collected for each of these rock types, as well as the fraction of the total watershed that is underlain by each rock type. Table XI also shows the estimated solute concentrations at the mouth of Galena Creek, based on equation (1), the measured concentrations at the mouth of Galena Creek (GC-1, filtered), and the ratio of the estimated/measured concentrations. Some solutes (e.g., Al, Fe, Cu, As, Pb) have estimated concentrations that are much greater than their observed concentrations. The most likely reason is that equation (1) assumes conservative behavior for all solutes. Concentrations of dissolved Al and Fe coming from acidic seeps draining the hydrothermally altered stock should drop sharply in Galena Creek because of precipitation of hydrous Al and Fe oxides at pH values > 5. It can be assumed that As, Cu, and Pb would adsorb strongly onto these hydrous metal oxides in a pre-mining scenario, just as they did in the synoptic sampling of this thesis. Concentrations of major ions (Ca^{2+}, Mg^{2+}, K^{+}, Na^{+}, and SO_4^{2-}), as well as the more conservative trace elements (Mn, Zn, Cd, Tl), show reasonably good agreement between the predicted and measured values. The higher predicted concentrations of Ca and Mg compared to their measured values might be because no attempt was made to include Paleozoic sedimentary rock in the mass balance equation. Although Paleozoic rocks do not cover a large area of the drainage, water draining these rocks could have high Ca/Mg content owing to the presence of carbonates (limestone, dolomite) in the section.

Table XI. Concentration calculations in µg/L for the mouth of Galena Creek based on leachate experiment results and surface area of major rock units present in the watershed

Calculated/ measured ratio	Measured Concentration at mouth of Galena Creek	Calculated Concentration at mouth of Galena Creek	Gold-Run-Tuff	Clenndenin	Wolf Porphyry	Stock-unaltered	Stock QSP-ALTERED	Rock Unit	
			A	C	B	E	G	Leachate Sample ID	
			0.096	0.11	0.43	0.15	0.017	Fraction of watershed	
6.5*	27	175*	0.73	34.2	27.1	17.8	9200	Concentrations in µg/L	**Al**
1.2	1590	1980	12.8	89.6	156	2.82	112000		**Mn**
460*	8.9	4100*	<5	7.58	<5	<5	242000		**Fe**
72*	1.15	82.6*	<1	42.9	8.49	5.61	4310		**Cu**
0.43	705	303	3.58	8.82	4.71	18.6	17500		**Zn**
29*	0.55	15.8*	0.6	2.73	0.83	0.79	883		**As**
0.83	2.39	2	<0.2	<0.2	<0.2	<0.2	118		**Cd**
1.7	0.31	0.53	3.09	<0.2	0.35	<0.2	4.71		**Tl**
>100*	<0.2	29.4*	<0.2	1.32	0.37	0.39	1710		**Pb**
0.7	33.6	23.4	174	10.9	11.4	0.3	22.4	Concentrations in mg/L	**Ca**
0.53	8.0	4.3	35.6	1.45	1.44	0.12	1.87		**Mg**
44	0.1	2.7	8.25	1.69	3.54	0.93	2.51		**K**
0.57	2.4	1.4	0.56	1.08	2.38	1.06	0.21		**Na**
1.5	58.9	86.1	580	4.2	2.4	14.6	1562		**SO_4^-**

4.2.2. Limitations to the Mass Balance Model

There are several reasons why the predicted chemistry for the mouth of Galena Creek based on the mass balance approach discussed in the preceding section could be in error. These include:

i) The bedrock samples collected in the field might not be representative of each rock type. For example, the bulk sample of "hydrothermally altered Hughesville stock" was collected from pieces of waste rock located near the Block P portal and may have been biased to a higher pyrite content compared to the altered stock as a whole.

ii) Although the leachate tests were conducted over a 5-week period, it is unlikely that a steady state solute release rate was attained for all the samples. Some of the graphs of solute concentration vs. time for the leachate samples show a general decrease in concentration in many cases not reaching a steady-state value.

iii) The rate of release of solutes from the leaching tests may not match the actual rate of solute release in the natural setting due to chemical weathering. In fact, it is likely that the release of solutes is more rapid in the benchtop experiments since the humidity cells are designed to simulate "accelerated" chemical weathering.

Points (i) and (iii) are probably the biggest sources of uncertainty in the mass balance model. These limitations would have been very difficult if not impossible to get around in a study such as this thesis that had limited funding and time.

4.3. Comparison of Galena Creek to Nearby Sites with Natural Acid Rock Drainage

Another way to estimate the pre-mining geochemistry of a stream like Galena Creek is to find an analog stream with similar geology and hydrothermal alteration that has not been mined. Figure 24 shows the location of several sites in Montana that are known to contain extensive ferricrete deposits formed during the natural weathering of sulfide mineral deposits. Of these, the central Judith Mountains (Williams et al. 2015; Gammons et al. 2021) and the Mt. Evans area of the Anaconda Range west of Butte (Doolittle 2017) are the only such locations that are in unmined drainages. Other sites containing ferricretes, such as Swift Gulch in the Little Rocky Mountains, Fisher and Daisy Creeks in the New World district near Cooke City, and Paymaster Creek near Lincoln, suffer from the same problem as Galena Creek in that it is hard to separate aspects of the chemistry of each drainage that are natural vs. mining-related (Nimick et al. 2009).

Figure 24. Map of Montana (MBMG, 2007) showing the study area of this thesis (1) in relation to known areas of natural acid rock drainage; (2) central Judith Mountains; (3) Little Rocky Mountains; (4) Paymaster Creek; (5) Mount Evans in the Anaconda Range; (6) New World District.

Of the sites shown in Figure 24, the Red Mountain area of the Judith Mountains is probably the closest analog to Galena Creek. As discussed by Williams et al. (2015), three small streams draining different sides of Red Mountain are strongly acidic (pH < 4) in their headwaters, grading to near-neutral pH with increased distance downstream. A recent study (Gammons et al., 2021) looked in detail at one of these streams named Chicago Gulch. Similarities between Galena Creek and Chicago Gulch include: i) they have a similar drainage area and streamflow; ii) they have a similar climate and range in elevations; and iii) they have a similar geology. The geology of the headwaters of Chicago Gulch consists of a Tertiary-aged, hydrothermally altered granitic stock, a similar situation to the Hughesville Stock of Galena Creek. One important difference is that Red Mountain is strongly altered and pyrite-rich over its entire outcrop area, whereas only 10 to 20% of the Hughesville Stock is hydrothermally altered (Witikind, 1973).

Filtered solute concentrations measured in Chicago Gulch by Gammons et al. (2021) are compared to Galena Creek (this study) for aluminum, manganese, iron, and sulfate (Figure 25), and zinc, arsenic, cadmium, thallium, and lead (Figure 26). Both studies involved a detailed synoptic sampling conducted in summer baseflow conditions. The complete set of synoptic samples, collected from the top to the bottom of each watershed, is summarized side-by-side using box-and-whisker plots. The results show higher concentrations of some solutes in Galena Creek compared to Chicago Gulch, including Mn, Zn, and Cd. Other solutes, including sulfate, As and Tl, show a similar range in concentration in the two drainages. Still other solutes, including Al, Fe, and Pb, have higher overall concentrations in the unmined drainage (Chicago Gulch) compared to the mined drainage (Galena Creek).

The comparable levels of dissolved metals combined with the similarities in geology between the two streams support the idea that the Judith Mountains could be used as an analog site for the Galena Creek watershed. The biggest difference between the two sites, besides the lack of mining history in the Judith Mountains, is the larger extent of hydrothermally altered rock rich in pyrite at the summit and flanks of Red Mountain at Chicago Gulch compared to the lesser surface area of hydrothermally altered rock in the Galena Creek watershed.

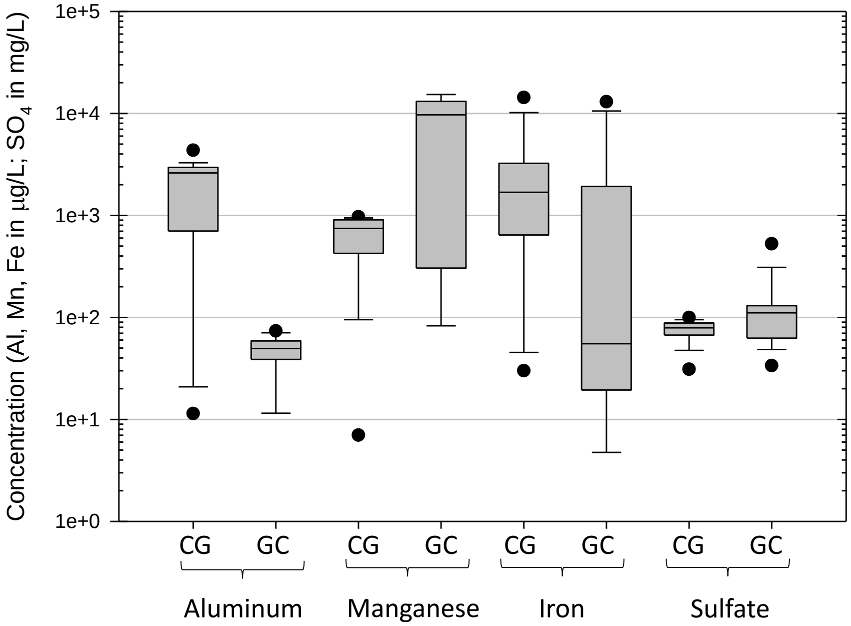

Figure 25. Box and whisker plot showing the range in concentrations of dissolved Al, Mn, Fe, and sulfate in Chicago Gulch (CG) and Galena Creek (GC), measured during baseflow conditions (data for CG from Gammons et al., 2021).

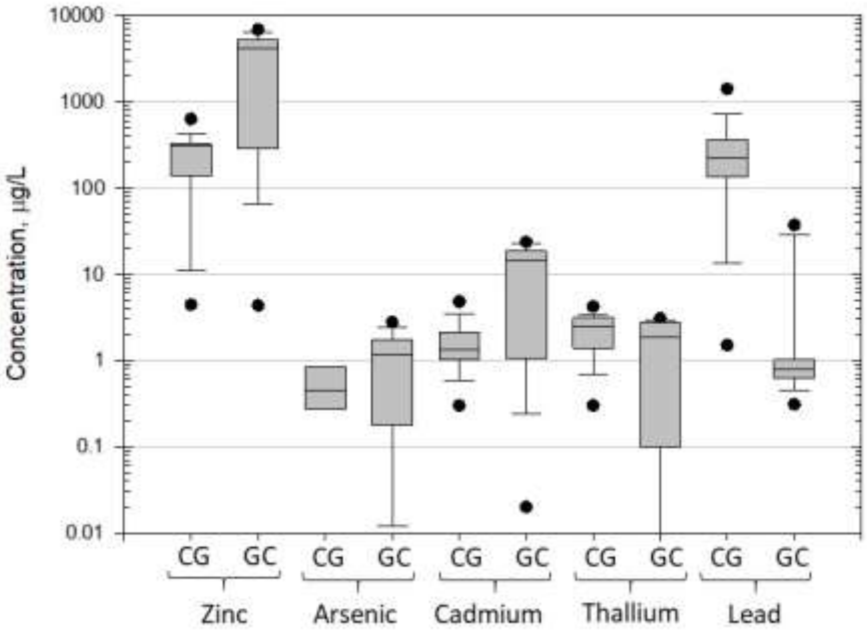

Figure 26. Box and whisker plot showing the range in concentrations of dissolved Zn, As, Cd, Tl, and Pb in Chicago Gulch (CG) and Galena Creek (GC), measured during baseflow conditions (data for CG from Gammons et al., 2021).

4.4. Stable Isotope Analyses

The S-isotope composition of sulfide minerals from mines of the Barker-Hughesville district overlaps closely with the S-isotope composition of dissolved sulfate in Galena Creek and the major mine seeps (Fig. 27). This is good evidence that most if not all the sulfate flowing down Galena Creek was sourced by oxidation of sulfide minerals (pyrite, galena, sphalerite). As reviewed by Seal (2003), there is negligible fractionation of S-isotopes during oxidation of sulfide minerals. Also, because there is no systematic difference between the $\delta^{34}S$ of sulfides or sulfates collected from the different mines, S-isotopes cannot be used to calculate the relative contribution of sulfate to Galena Creek from the different mines, or from background sources.

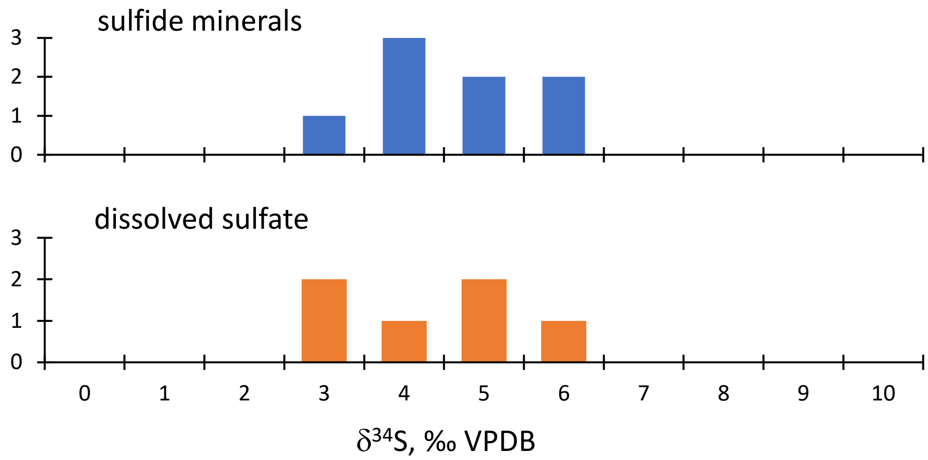

Figure 27. Comparison of the S-isotope composition of sulfide minerals and dissolved sulfate from the study area.

The S-isotope compositions of dissolved sulfate samples collected in this study are plotted vs. their O-isotope compositions in Figure 28. Also shown are the average δ^{18}O of water samples from the field area (this study) and the δ^{18}O of atmospheric oxygen. As discussed by Seal (2003) and Wright and Nordstrom (1999), sulfate that comes from severe acid mine drainage often has δ^{18}O-sulfate values that are close to those of the surrounding water. In contrast, sulfate that comes from oxidation of pyrite at higher pH conditions tends to have a δ^{18}O signal closer to that of atmospheric oxygen. The reasons for these trends are due to the different mechanisms of pyrite oxidation at low pH vs. at high pH. At pH below about 4, pyrite oxidation takes place with dissolved Fe^{3+} as the main oxidant, as follows:

Equation 2. Differing Chemical Reactions for Pyrite Oxidation at high and low pH

$$FeS_2(s) + 14Fe^{3+} + 4H_2O = 15Fe^{2+} + 2SO_4^{2-} + 8H^+ \qquad (a)$$

$$FeS_2(s) + H_2O + 7/2O_2(g) = Fe^{2+} + 2SO_4^{2-} + 2H^+ \qquad (b)$$

In reaction (a), it makes sense that most of the O molecules in sulfate would come from water. As opposed to, when pH > 4, Fe^{3+} is no longer soluble, and pyrite oxidation involves atmospheric oxygen. In reaction (b), there is a greater likelihood that some O in sulfate would be inherited from O_2 (g). If the above assumptions are correct, this would lead to a positive correlation between $\delta^{18}O$-sulfate and pH across a spectrum of acidic environments. Because natural acid rock drainage (NARD) is thought to take place at pH's that are higher than acid mine drainage (AMD), this could mean that sulfate coming from NARD would have a higher (more positive) value of $\delta^{18}O$ than sulfate coming from AMD. In fact, the situation is not this simple, and there are other side-reactions that complicate the O-isotope mass balance during oxidation of pyrite (Seal, 2003).

Probably the most important conclusion from the isotope results of this thesis is that the S- and O-isotope composition of sulfate at the mouth of Galena Creek is essentially the same as that of sulfate coming from the known mine discharges. There is no evidence, isotopically, to suggest that significant sulfate is entering the creek from other sources, such as natural acid rock drainage. However, this does not mean that sulfate did not enter the creek from NARD *prior* to mining in the watershed.

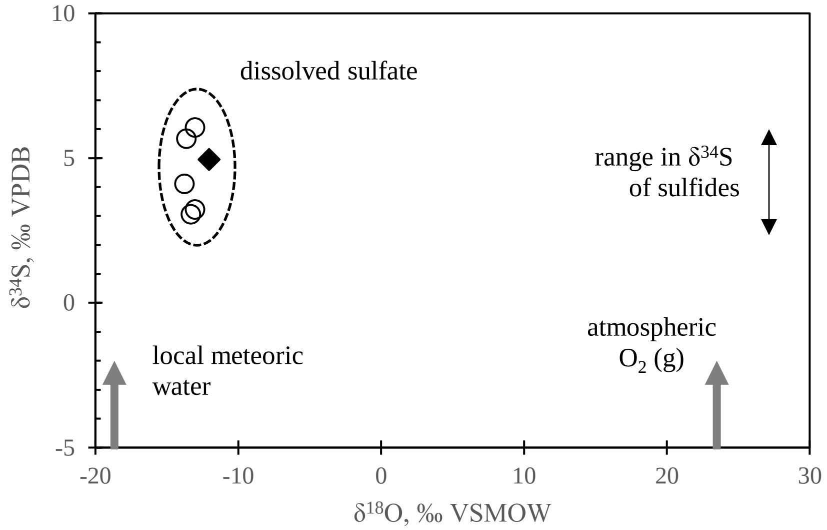

Figure 28. S- vs. O-isotope crossplot for dissolved sulfate at the mouth of Galena Creek (filled diamond) and tributary mine seeps and springs (open circles). Values from Tables VIII & IX.

5. Conclusions

The following are some of the more important findings of this thesis:

- Despite contamination from historic mining, most of Galena Creek under baseflow conditions has a near-neutral pH over its middle and lower reaches and has improved since recent constructional and reclamation efforts were completed.
- During mid-summer, most of the water flowing down Galena Creek can be accounted for by mine discharges and tributary streams. Groundwater inflows are negligible under baseflow conditions.
- Most or all of the loads of each contaminant of interest (Al, As, Cd, Cu, Fe, Mn, Pb, Zn, sulfate) in Galena Creek today can be traced to the known discharges from the historic mines.
- Dissolved Al and Fe from mine discharges precipitates as hydrous Al and Fe oxides after dilution and oxidation with the main stem of Galena Creek. Some metals (e.g., As, Pb, Cu) adsorb strongly onto the hydrous Al-Fe oxides, a fraction of which remains suspended all the way to the mouth of Galena Creek. Other metals (e.g., Zn, Cd, Tl) adsorb weakly onto the hydrous oxides, and therefore behave conservatively.
- The Hughesville Stock, in the center of the district, is mineralized and hydrothermally altered. Leachates produced by interacting synthetic precipitation with pyrite-rich Hughesville Stock had low pH (< 3) and very high concentrations of several contaminants of interest, including As, Cd, Cu, Pb, Tl, Zn, and sulfate. Natural weathering of this altered rock could have contributed metals and acidity to Galena Creek prior to historic mining.

- Concentrations of trace metals and sulfate in Galena Creek are broadly similar to those in Chicago Gulch, a small stream with natural acid rock drainage in the central Judith Mountains of Montana. Because Chicago Gulch has a similar-sized watershed with a similar climate and geology, it could possibly be used as reference or analog site to Galena Creek.
- The stable S-isotope composition of dissolved sulfate in Galena Creek is similar to that of sulfide minerals (pyrite, sphalerite, galena) collected from several mine dumps in the study area. Also, the S- and O-isotope composition of dissolved sulfate in the Galena Creek is similar to that of sulfate coming from the mine discharges. This means that the main source of sulfate in Galena Creek is oxidation of pyrite and other sulfide minerals in the mine workings.
- Although there is little chemical or isotopic evidence for natural acid rock drainage occurring in Galena Creek today, this does not mean that NARD did not occur prior to mining. In fact, the leachate studies conducted in this thesis, coupled with a comparison to Chicago Gulch (a possible analog site), suggests that significant loading of acidity, metals and sulfate would have occurred due to natural weathering of the mineralized Hughesville Stock.

6. References

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7. Appendix A: Supplementary Parameter Data

7.1. Table A-1: Parameter Data for Galena Creek

Sample	**Date**	**Time**	**Distance Downstream meters**	**SC µS/cm**	**pH**	**DO mg/L**	**Eh mV**	**Temp °C**	**Alkalinity mg/L CaCO3**
GC 1	7/20/2020	8:30	5299	256	7.54	10.20	155	8.09	56
GC 2	7/20/2020	9:42	4849	251	7.69	9.95	136	8.64	56
GC 3	7/20/2020	10:30	4461	280	7.33	10.31	94	9.54	32
GC 4	7/20/2020	11:05	4087	275	7.36	9.75	144	9.73	30
GC 5	7/20/2020	11:50	3664	270	7.23	9.81	167	9.55	18
GC 6	7/20/2020	12:10	3335	272	7.18	9.68	174	9.88	18
GC 7	7/20/2020	13:45	2904	299	7.28	8.82	179	12.52	8
GC 8	7/20/2020	14:50	2582	306	6.78	8.65	187	13.27	18
GC 9	7/20/2020	15:40	2282	314	6.70	8.67	192	12.97	20
GC 10	7/20/2020	16:45	2049	328	6.44	8.98	218	11.64	21
GC 11	7/20/2020	17:35	1652	226	7.21	9.60	302	8.71	40
GC 12	7/20/2020	18:35	1392	226	7.42	9.67	236	7.82	39
GC 13	7/21/2020	10:15	972	361	7.10	9.98	184	6.53	N/A
GC 14	7/21/2020	11:22	661	432	3.76	9.26	606	8.26	N/A
GC 16	7/21/2020	13:45	249	950	5.58	9.77	673	10.47	N/A
GC 15	7/21/2020	12:45	0	275	6.93	7.91	274	8.45	54

7.2. Table A-2: Parameter Data for Tributaries

Sample	Date	Time	Distance Downstream (m)	SC µS/cm	pH	DO mg/L	Eh mV	Temp °C	Alkalinity mg/L CaCO3	Bicarbonate mg/L
Trib 1 (Gold Run Ck.)	7/20/2020	10:05	4832	207	7.71	10.0	70	8.84	88	107.4
Trib 2	7/20/2020	10:45	3894	169	7.36	10.0	131	8.94	0	0
Trib 3 (Pride of the West)	7/20/2020	11:25	3936	379	8.11	9.08	137	12.6	161	196.4
Trib 4 (Bend Gulch)	7/20/2020	13:20	3201		8.40	9.24	149	9.24	14	17.1
Trib 5 (Lucky Strike Mine)	7/20/2020	14:20	2963		4.35	2.62	203	8.74	0	0
Trib 6 (Marcelline Mine)	7/20/2020	15:15	2626		2.79	7.61	496	4.57	0	0
Trib 7 (Silver Ck.)	7/20/2020	16:10	2555	183	7.16	9.03	199	11.4	57	69.5
Trib 8 (Grey Eagle Ditch)	7/20/2020	16:30	2218	116	5.11	7.69	257	19.0	0	0
Trib 9 (Block P Discharge)	7/20/2020	17:10	1995		3.15	4.86	626	8.90	0	0
Trib 10 (Lower Green Ck.)	7/20/2020	18:11	1578	239	7.66	9.86	254	7.66	71	86.6
Trib 11 (Harrison Mine)	7/21/2020	9:31	1184		3.00	7.38	235	5.93	0	0
Trib 12 (Lower Daisy Ck.)	7/21/2020	9:50	1290	94	6.00	10.1	167	5.46	10	12.2
Trib 13 (Moulton Mine)	7/21/2020	10:55	758	444	7.07	9.65	213	3.72	90	109.8
Trib 14 (Headwater Spring)	7/21/2020	12:30	216	156	6.34	80.8	307	3.97	43.1	52.6
Trib 15	7/21/2020	13:30	247		4.80	7.94	677	4.03	0	0
Trib 16 (Carter Mine)	7/21/2020	15:00	1576	366	7.70	11.1	125	9.16	115	140.3
Trib 17 (Upper Green Ck.)	7/21/2020	15:45	1576	323	7.66	12.4	110	7.72	130	158.6
Trib 18 (Upper Daisy Ck.)	7/21/2020	16:15	1916		N/A	13.3	127	8.16	6	7.32
Trib 19 (Danny T Mine)	7/21/2020	16:45	2523	2130	5.78	5.60	671	6.00	0	0
Trib 20	7/22/2020	12:00	2226	N/A	N/A	N/A	N/A	N/A	N/A	N/A

8. Appendix B: Supplementary Anion Data

8.1. Table B-1: Anion Data for Galena Creek

Sample	Distance Downstream (m)	Fluoride	Chloride	Sulfate	Bicarbonate
GC-1	5299	0.17	0.39	59	68.3
GC-2	4849	0.17	0.38	55	68.3
GC-3	4461	0.22	0.41	95	39.5
GC-4	4087	0.22	0.40	95	36.8
GC-5	3664	0.23	0.40	110	22.1
GC-6	3335	0.23	0.41	112	21.4
GC-7	2904	0.26	0.41	125	9.15
GC-8	2582	0.25	0.42	128	21.6
GC-9	2282	0.22	0.41	126	24.3
GC-10	2049	0.20	0.42	131	25.6
GC-11	1652	0.11	0.37	59	48.9
GC-12	1392	0.10	0.38	73	47.6
GC-13	972	0.10	0.36	138	0
GC-14	661	0.09	0.38	217	0
GC-16	249	0.23	0.41	526	0
GC-15	0	0.15	0.53	34	65.9

8.2. Table B-2: Anion Data for Tributaries

Tributary	Fluoride	Chloride	Sulfate	Bicarbonate
1	0.12	0.36	7.44	107.4
7	0.13	0.35	24.3	69.5
9	1.61	1.70	1305	0
10	0.16	0.36	37.8	86.6
11	0.38	1.38	69.6	0
12	0.12	0.40	30.3	12.2
13	0.13	0.38	129	109.8
14	0.07	0.33	13.5	52.6
15	0.22	0.38	652	0
16	0.20	0.39	59.4	140.3
17	0.11	0.34	26.4	158.6
18	0.33	0.41	41.4	7.32
19	2.16	1.81	1802	0
20	0.60	0.50	363	N/A

9. Appendix C: Supplemental Data-Galena Creek Synoptic Study

9.1. Table C-1 ICP-MS Results

Sample Name	7Li µg/L	9Be µg/L	11B µg/L	27Al µg/L	31P µg/L	39K µg/L	43Ca µg/L	49Ti µg/L	51V µg/L	52Cr µg/L
Trib 1 FA	< 0.5	< 0.2	3.25	< 0.5	< 5	44.3	19600	< 0.5	< 0.5	< 0.2
Trib 3 FA	< 0.5	< 0.2	2.49	< 0.5	15.0	40.7	46400	< 0.5	< 0.5	< 0.2
Trib 4 FA	< 0.5	< 0.2	1.51	1.89	16.9	67.2	4140	< 0.5	< 0.5	< 0.2
Trib 5 FA	3.29	0.22	1.99	540	<5	112	10800	1.51	< 0.5	< 0.2
Trib 6 FA	15.4	3.58	< 0.2	7800	18.5	68.3	31900	7.14	< 0.5	1.03
Trib 7 FA	< 0.5	< 0.2	2.17	87.9	10.1	64.2	20300	0.57	< 0.5	< 0.2
Trib 8 FA	2.16	0.25	1.35	464	7.72	89.8	6640	0.99	< 0.5	< 0.2
Trib 9 FA	9.44	4.65	2.67	8590	151	227	86600	16.8	5.30	1.75
Trib 9 FA DUP	9.82	4.83	2.23	8780	147	229	86900	17.5	6.53	2.83
Trib 10 FA	< 0.5	< 0.2	0.631	17.9	25.0	50.8	18800	0.71	< 0.5	< 0.2
Trib 11 FA	< 1.25	0.56	< 0.5	1720	< 12.5	86.3	4070	1.58	< 1.25	< 0.5
Trib 12 FA	< 0.5	< 0.2	1.05	13.0	10.3	48.9	6230	0.70	< 0.5	< 0.2
Trib 13 FA	< 0.5	< 0.2	1.29	< 0.5	< 5	62.5	3830	2.53	< 0.5	< 0.2
Trib 14 FA	< 0.5	< 0.2	1.47	< 0.5	12.3	43.3	13300	< 0.5	< 0.5	< 0.2
Trib 15 FA	< 0.5	0.22	1.40	869	83.2	97.1	35900	9.49	< 0.5	0.63
Trib 16 FA	2.32	< 0.2	0.96	4.1	< 5	69.0	25800	1.22	< 0.5	< 0.2
Trib 17 FA	< 0.5	< 0.2	0.53	1.46	47.6	24.8	30600	0.53	< 0.5	< 0.2
Trib 18 FA	< 0.5	< 0.2	< 0.2	593	< 5	72.7	2930	0.56	< 0.5	< 0.2
Trib 19 FA	14.8	6.81	< 0.5	17000	495	57.9	62500	20.0	7.05	5.31
Trib 20 FA	4.83	3.38	< 0.2	6365	< 5	104	15800	3.72	< 0.5	0.82
GC 0(FA Blank)	< 0.5	< 0.2	4.02	0.625	< 5	< 5	< 5	< 0.5	< 0.5	< 0.2
GC 1 FA	2.26	< 0.2	2.10	14.5	< 5	61.9	22400	1.13	< 0.5	< 0.2
GC 1 FA DUP	2.37	< 0.2	2.41	12.1	< 5	61.4	22000	1.15	< 0.5	< 0.2
GC 2 FA	2.23	< 0.2	2.31	12.1	< 5	60.0	21900	1.05	< 0.5	< 0.2
GC 3 FA	2.19	< 0.2	1.98	14.0	< 5	69.4	22600	1.83	< 0.5	< 0.2
GC 4 FA	2.15	< 0.2	1.94	12.9	< 5	71.9	22400	1.74	< 0.5	< 0.2
GC 5 FA	2.40	< 0.2	1.94	13.8	< 5	70.8	20000	1.92	< 0.5	< 0.2
GC 6 FA	2.49	< 0.2	1.95	10.8	< 5	72.8	20800	1.94	< 0.5	< 0.2
GC 7 FA	3.10	< 0.2	2.29	15.8	< 5	72.8	22900	2.27	< 0.5	< 0.2
GC 8 FA	2.63	< 0.2	1.84	20.3	< 5	72.9	23400	2.22	< 0.5	< 0.2
GC 9 FA	2.13	< 0.2	1.74	16.7	< 5	74.4	23400	2.24	< 0.5	< 0.2
GC 10 FA	2.25	< 0.2	2.05	18.2	< 5	74.8	24900	2.30	< 0.5	< 0.2
GC 11 FA	< 0.5	< 0.2	1.77	32.3	9.19	58.9	18000	1.07	< 0.5	< 0.2
GC 12 FA	< 0.5	< 0.2	1.51	37.2	< 5	62.4	18100	1.33	< 0.5	< 0.2
GC 13 FA	< 0.5	< 0.2	2.13	64.6	< 5	62.1	28400	2.38	< 0.5	< 0.2
GC 14 FA	< 0.5	< 0.2	1.87	247	7.32	62.7	21800	2.72	< 0.5	< 0.2
GC 15 FA	< 0.5	< 0.2	2.14	< 0.5	5.31	72.2	21300	0.64	< 0.5	< 0.2
GC 16 FA	< 0.5	0.39	0.73	1060	29.2	87.1	36800	6.32	< 0.5	0.48
GC0 (RA Blank)	< 0.5	< 0.2	4.20	0.937	< 5	< 5	< 5	< 0.5	< 0.5	< 0.2
GC1 RA	2.21	< 0.2	2.36	311	12.2	65.6	23200	1.30	< 0.5	< 0.2
GC1 RA DUP	2.51	< 0.2	2.87	306	9.6	64.8	23100	1.44	< 0.5	< 0.2
GC2 RA	2.44	< 0.2	2.78	338	10.4	67.2	24200	1.54	< 0.5	< 0.2
GC3 RA	2.21	0.28	2.03	563	15.4	71.9	23400	2.24	< 0.5	< 0.2
GC4 RA	2.27	0.29	2.03	606	17.3	72.5	23000	2.20	< 0.5	< 0.2
GC5 RA	2.27	0.35	1.68	715	20.6	74.8	21200	2.55	< 0.5	< 0.2
GC6 RA	2.26	0.36	1.76	736	18.1	73.5	20900	2.54	< 0.5	< 0.2
GC7 RA	2.44	0.42	1.65	880	21.0	75.6	23400	2.53	< 0.5	< 0.2
GC8 RA	2.41	0.43	1.58	924	19.2	76.7	24200	2.69	< 0.5	< 0.2
GC9 RA	< 0.5	0.38	1.19	647	22.1	72.4	23200	2.82	< 0.5	< 0.2
GC10 RA	< 0.5	0.38	1.45	698	23.8	76.6	24800	3.06	< 0.5	< 0.2
GC11 RA	< 0.5	< 0.2	1.39	107	12.2	60.8	18300	2.26	< 0.5	< 0.2
GC12 RA	< 0.5	< 0.2	2.45	125	7.6	77.3	18000	1.49	< 0.5	< 0.2
GC13 RA	< 0.5	< 0.2	2.90	329	14.5	102	30100	2.56	< 0.5	< 0.2
GC14 RA	< 0.5	< 0.2	2.34	264	8.8	64.7	22300	3.19	< 0.5	< 0.2
GC15 RA	< 0.5	< 0.2	2.55	27.5	7.9	72.1	20800	1.12	< 0.5	< 0.2
GC16 RA	< 0.5	0.40	1.72	1130	48.0	90.6	38600	6.86	< 0.5	0.60

ICP-MS Results Continued

Sample Name	55Mn µg/L	56Fe µg/L	59Co µg/L	60Ni µg/L	63Cu µg/L	66Zn µg/L	71Ga µg/L	75As µg/L	82Se µg/L
Trib 1 FA	< 2	< 5	<0.5	<0.5	< 1	< 1	6.14	0.41	< 0.2
Trib 3 FA	26.6	< 5	<0.5	<0.5	< 1	4.3	2.35	0.75	< 0.2
Trib 4 FA	< 2	< 5	<0.5	0.58	< 1	174	2.27	1.05	< 0.2
Trib 5 FA	1130	16.7	1.52	3.02	18.8	460	1.85	0.28	< 0.2
Trib 6 FA	31100	5800	23.4	18.2	195	14200	< 0.5	2.63	0.73
Trib 7 FA	182	26.7	<0.5	<0.5	4.95	363	1.58	1.93	< 0.2
Trib 8 FA	652	8.06	1.21	2.70	19.6	955	2.56	0.37	< 0.2
Trib 9 FA	61400	110000	46.6	55.3	190	24600	1.09	97.9	< 0.5
Trib 9 FA DUP	61300	111000	46.7	55.7	190	24400	1.14	98.1	1.99
Trib 10 FA	76.9	14.7	<0.5	0.80	2.05	42.3	1.37	1.23	< 0.2
Trib 11 FA	1310	1160	4.58	6.87	16.6	1900	1.02	0.64	< 0.5
Trib 12 FA	< 2	< 5	<0.5	0.59	< 1	46.7	2.04	0.22	< 0.2
Trib 13 FA	1480	69.5	0.55	1.45	53.3	540	1.19	1.13	< 0.2
Trib 14 FA	< 2	< 5	<0.5	<0.5	< 1	2.68	3.60	< 0.2	< 0.2
Trib 15 FA	11300	96200	2.74	6.20	627	4960	0.93	12.3	0.65
Trib 16 FA	350	29.1	0.69	2.18	1.52	80.0	< 0.5	4.22	< 0.2
Trib 17 FA	< 2	< 5	<0.5	<0.5	< 1	3.56	1.99	1.04	< 0.2
Trib 18 FA	172	17.3	1.12	2.18	2.88	137	2.63	< 0.2	< 0.2
Trib 19 FA	113000	151000	47.3	31.6	1480	52900	2.94	237	1.65
Trib 20 FA	10300	3810	20.0	19.2	253	4190	0.65	0.30	< 0.2
GC 0(FA Blank)	< 2	< 5	<0.5	<0.5	< 1	< 1	< 0.5	< 0.2	< 0.2
GC 1 FA	1590	9.0	1.26	1.69	1.15	705	3.04	0.55	< 0.2
GC 1 FA DUP	1600	< 5	1.29	1.68	1.06	718	3.12	0.51	< 0.2
GC 2 FA	1700	< 5	1.37	1.77	< 1	721	3.19	0.37	< 0.2
GC 3 FA	3160	< 5	2.55	3.33	1.5	1280	1.56	0.33	< 0.2
GC 4 FA	3310	14.2	2.64	3.37	1.3	1320	1.56	0.33	< 0.2
GC 5 FA	3870	76.8	3.08	3.99	1.5	1540	1.39	0.30	< 0.2
GC 6 FA	4030	158	3.18	4.16	1.7	1620	1.40	0.33	< 0.2
GC 7 FA	4660	296	3.85	4.73	2.6	1780	1.32	0.42	< 0.2
GC 8 FA	4890	950	3.91	4.69	3.5	2000	1.34	0.43	< 0.2
GC 9 FA	4340	3310	3.62	4.71	3.8	1730	1.39	0.64	< 0.2
GC 10 FA	4710	4920	3.95	5.01	5.0	1920	1.39	0.78	< 0.2
GC 11 FA	156	22.4	<0.5	1.10	6.7	173	1.45	0.54	< 0.2
GC 12 FA	245	6.31	<0.5	1.60	10.6	280	1.78	< 0.2	< 0.2
GC 13 FA	967	22.8	0.55	2.36	23.2	564	1.30	0.31	< 0.2
GC 14 FA	1770	5670	0.77	3.34	107	1340	1.25	0.23	< 0.2
GC 15 FA	< 2	7.1	<0.5	<0.5	1.3	303	3.09	< 0.2	< 0.2
GC 16 FA	6690	42200	2.82	6.02	373	3380	0.97	3.87	0.43
GC0 (RA Blank)	< 2	28.2	<0.5	<0.5	< 1	< 1	< 0.5	< 0.2	< 0.2
GC1 RA	1660	1760	1.33	1.77	13.3	947	3.19	2.77	< 0.2
GC1 RA DUP	1650	1740	1.30	1.74	13.4	959	3.19	2.81	< 0.2
GC2 RA	1850	2010	1.52	1.93	15.2	1030	3.51	3.10	< 0.2
GC3 RA	3220	3350	2.55	3.47	26.5	1720	1.67	4.95	< 0.2
GC4 RA	3430	3600	2.78	3.57	28.3	1780	1.66	5.18	< 0.2
GC5 RA	4030	4290	3.29	4.27	34.0	2070	1.56	5.94	< 0.2
GC6 RA	4000	4360	3.23	4.13	33.6	2010	1.52	5.92	< 0.2
GC7 RA	4750	5270	3.99	5.03	41.0	2270	1.64	7.13	< 0.2
GC8 RA	5020	5760	4.09	5.07	42.5	2420	1.49	7.43	< 0.2
GC9 RA	4350	6600	3.65	4.75	29.9	1950	1.46	7.94	< 0.2
GC10 RA	4770	7570	4.01	5.09	31.5	2120	1.46	8.87	< 0.2
GC11 RA	170	344	<0.5	1.21	21.0	205	1.56	1.11	< 0.2
GC12 RA	256	348	<0.5	1.55	39.4	322	1.66	0.34	< 0.2
GC13 RA	991	1190	0.62	2.75	140	707	1.40	0.82	< 0.2
GC14 RA	1850	6450	0.84	3.36	112	1430	1.30	0.62	< 0.2
GC15 RA	9.2	317	<0.5	<0.5	4.0	325	3.36	0.26	< 0.2
GC16 RA	6880	47600	2.88	6.23	378	3430	0.95	7.59	0.433

ICP-MS Results Continued

Sample Name	85Rb µg/L	88Sr µg/L	90Zr µg/L	93Nb µg/L	98Mo µg/L	105Pd µg/L	107Ag µg/L	111Cd µg/L	118Sn µg/L
Trib 1 FA	1.41	189	< 0.5	< 0.5	1.09	< 0.5	< 0.2	< 0.2	< 0.5
Trib 3 FA	1.09	126	< 0.5	< 0.5	0.82	< 0.5	< 0.2	< 0.2	< 0.5
Trib 4 FA	2.30	48.1	< 0.5	< 0.5	< 0.5	< 0.5	< 0.2	0.49	< 0.5
Trib 5 FA	8.53	118	< 0.5	< 0.5	< 0.5	< 0.5	< 0.2	1.85	< 0.5
Trib 6 FA	27.5	402	0.64	< 0.5	0.51	0.8	0.5	70.1	< 0.5
Trib 7 FA	4.14	72.5	< 0.5	< 0.5	0.78	< 0.5	< 0.2	1.82	< 0.5
Trib 8 FA	7.08	271	< 0.5	< 0.5	< 0.5	< 0.5	< 0.2	5.42	< 0.5
Trib 9 FA	33.7	744	2.58	< 1.25	1.38	1.3	< 0.5	62.8	< 1.25
Trib 9 FA DUP	33.2	738	1.19	< 1.25	2.27	< 1.25	< 0.5	62.8	< 1.25
Trib 10 FA	3.62	65.7	< 0.5	< 0.5	0.63	< 0.5	< 0.2	< 0.2	< 0.5
Trib 11 FA	7.53	61.4	< 1.25	< 1.25	< 1.25	< 1.25	< 0.5	6.01	< 1.25
Trib 12 FA	1.75	147	< 0.5	< 0.5	< 0.5	< 0.5	< 0.2	< 0.2	< 0.5
Trib 13 FA	1.61	158	< 0.5	< 0.5	1.15	< 0.5	< 0.2	2.30	< 0.5
Trib 14 FA	1.24	111	< 0.5	< 0.5	1.15	< 0.5	< 0.2	< 0.2	< 0.5
Trib 15 FA	2.95	64.0	0.60	< 0.5	< 0.5	< 0.5	< 0.2	14.7	< 0.5
Trib 16 FA	5.98	99.8	< 0.5	< 0.5	1.05	< 0.5	< 0.2	< 0.2	< 0.5
Trib 17 FA	1.14	65.4	< 0.5	< 0.5	0.88	< 0.5	< 0.2	< 0.2	< 0.5
Trib 18 FA	5.09	123	< 0.5	< 0.5	< 0.5	< 0.5	< 0.2	0.773	< 0.5
Trib 19 FA	15.3	610	1.59	< 1.25	1.47	< 1.25	< 0.5	173	< 1.25
Trib 20 FA	17.2	121	< 0.5	< 0.5	< 0.5	< 0.5	< 0.2	23.4	< 0.5
GC 0(FA Blank)	< 0.5	< 1	< 0.5	< 0.5	< 0.5	< 0.5	< 0.2	< 0.2	< 0.5
GC 1 FA	3.05	166	< 0.5	< 0.5	< 0.5	< 0.5	< 0.2	2.39	< 0.5
GC 1 FA DUP	3.04	167	< 0.5	< 0.5	0.64	< 0.5	< 0.2	2.43	< 0.5
GC 2 FA	3.12	168	< 0.5	< 0.5	0.71	< 0.5	< 0.2	2.47	< 0.5
GC 3 FA	4.49	145	< 0.5	< 0.5	< 0.5	< 0.5	< 0.2	4.50	< 0.5
GC 4 FA	4.47	143	< 0.5	< 0.5	< 0.5	< 0.5	< 0.2	4.74	< 0.5
GC 5 FA	4.89	149	< 0.5	< 0.5	< 0.5	< 0.5	< 0.2	5.60	< 0.5
GC 6 FA	4.93	152	< 0.5	< 0.5	< 0.5	< 0.5	< 0.2	6.01	< 0.5
GC 7 FA	5.47	169	< 0.5	< 0.5	< 0.5	< 0.5	< 0.2	6.98	< 0.5
GC 8 FA	5.58	174	< 0.5	< 0.5	< 0.5	< 0.5	< 0.2	7.62	< 0.5
GC 9 FA	5.19	170	0.55	< 0.5	0.84	< 0.5	0.3	5.37	< 0.5
GC 10 FA	5.27	168	< 0.5	< 0.5	< 0.5	< 0.5	< 0.2	5.70	< 0.5
GC 11 FA	2.82	95.8	< 0.5	< 0.5	< 0.5	< 0.5	< 0.2	0.58	< 0.5
GC 12 FA	1.91	121	< 0.5	< 0.5	< 0.5	< 0.5	< 0.2	1.03	< 0.5
GC 13 FA	1.43	119	< 0.5	< 0.5	0.89	< 0.5	0.3	2.39	< 0.5
GC 14 FA	1.36	58.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.2	4.96	< 0.5
GC 15 FA	1.23	106	< 0.5	< 0.5	< 0.5	< 0.5	< 0.2	1.06	< 0.5
GC 16 FA	2.41	78.1	< 0.5	< 0.5	< 0.5	< 0.5	< 0.2	11.5	< 0.5
GC0 (RA Blank)	< 0.5	< 1	< 0.5	< 0.5	< 0.5	< 0.5	< 0.2	< 0.2	< 0.5
GC1 RA	3.03	166	< 0.5	< 0.5	1.17	< 0.5	0.3	3.33	< 0.5
GC1 RA DUP	3.08	166	< 0.5	< 0.5	0.67	< 0.5	< 0.2	3.31	< 0.5
GC2 RA	3.25	176	< 0.5	< 0.5	0.65	< 0.5	< 0.2	3.69	< 0.5
GC3 RA	4.53	148	< 0.5	< 0.5	< 0.5	< 0.5	< 0.2	6.06	< 0.5
GC4 RA	4.58	146	< 0.5	< 0.5	< 0.5	< 0.5	< 0.2	6.46	< 0.5
GC5 RA	5.05	155	< 0.5	< 0.5	< 0.5	< 0.5	< 0.2	7.52	< 0.5
GC6 RA	4.90	152	< 0.5	< 0.5	< 0.5	< 0.5	< 0.2	7.57	< 0.5
GC7 RA	5.49	169	< 0.5	< 0.5	< 0.5	< 0.5	< 0.2	8.97	< 0.5
GC8 RA	5.61	173	< 0.5	< 0.5	0.70	< 0.5	0.4	9.18	< 0.5
GC9 RA	5.27	169	< 0.5	< 0.5	< 0.5	< 0.5	< 0.2	5.89	< 0.5
GC10 RA	5.34	168	< 0.5	< 0.5	< 0.5	< 0.5	< 0.2	6.13	< 0.5
GC11 RA	3.00	99.8	< 0.5	< 0.5	< 0.5	< 0.5	< 0.2	0.60	< 0.5
GC12 RA	2.14	125	< 0.5	< 0.5	< 0.5	< 0.5	< 0.2	1.05	< 0.5
GC13 RA	1.86	123	< 0.5	< 0.5	< 0.5	< 0.5	< 0.2	2.67	< 0.5
GC14 RA	1.48	61.6	< 0.5	< 0.5	< 0.5	< 0.5	< 0.2	5.13	< 0.5
GC15 RA	1.36	106	< 0.5	< 0.5	< 0.5	< 0.5	< 0.2	1.14	< 0.5
GC16 RA	2.38	79.4	< 0.5	< 0.5	< 0.5	< 0.5	< 0.2	9.53	< 0.5

ICP-MS Results Continued

Sample Name	121Sb µg/L	133Cs µg/L	137Ba µg/L	139La µg/L	140Ce µg/L	141Pr µg/L	146Nd µg/L	182W µg/L	205Tl µg/L
Trib 1 FA	< 0.2	< 0.5	95.9	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2
Trib 3 FA	< 0.2	< 0.5	42.3	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2
Trib 4 FA	< 0.2	< 0.5	42.0	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2
Trib 5 FA	< 0.2	1.8	33.4	3.8	6.1	0.8	2.6	< 0.2	0.8
Trib 6 FA	< 0.2	7.1	5.3	55.2	115	14.5	53.5	< 0.2	1.1
Trib 7 FA	0.3	1.4	30.1	0.5	0.8	< 0.2	0.3	< 0.2	< 0.2
Trib 8 FA	< 0.2	< 0.5	46.8	3.4	5.9	0.9	3.3	< 0.2	0.3
Trib 9 FA	0.7	29.4	4.3	46.5	108	13.4	49.2	< 0.2	9.4
Trib 9 FA DUP	1.3	29.3	4.6	46.0	107	13.4	49.2	< 0.2	9.8
Trib 10 FA	< 0.2	1.7	26.1	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	1.2
Trib 11 FA	< 0.5	1.5	18.7	5.2	10.0	1.1	4.1	< 0.2	1.2
Trib 12 FA	< 0.2	< 0.5	37.7	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2
Trib 13 FA	< 0.2	< 0.5	21.9	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2
Trib 14 FA	< 0.2	< 0.5	67.5	0.2	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2
Trib 15 FA	< 0.2	< 0.5	10.5	1.7	3.6	0.4	1.9	< 0.2	< 0.2
Trib 16 FA	< 0.2	2.6	7.5	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	4.0
Trib 17 FA	< 0.2	0.6	37.7	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	0.6
Trib 18 FA	< 0.2	< 0.5	48.6	1.2	1.9	0.3	1.1	< 0.2	< 0.2
Trib 19 FA	< 0.5	6.2	2.42	116	244	28.1	106	< 0.2	2.3
Trib 20 FA	< 0.2	13.8	10.4	30.7	62.7	7.2	25.6	< 0.2	3.0
GC 0(FA Blank)	< 0.2	< 0.5	< 1	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2
GC 1 FA	< 0.2	1.1	59.2	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	0.3
GC 1 FA DUP	< 0.2	1.1	58.1	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	0.3
GC 2 FA	< 0.2	1.2	60.4	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	0.3
GC 3 FA	< 0.2	1.9	29.2	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	0.6
GC 4 FA	< 0.2	1.9	29.9	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	0.6
GC 5 FA	< 0.2	2.2	26.7	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	0.7
GC 6 FA	< 0.2	2.3	27.2	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	0.7
GC 7 FA	< 0.2	2.6	25.6	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	1.0
GC 8 FA	< 0.2	2.7	26.2	0.2	0.2	< 0.2	< 0.2	< 0.2	0.9
GC 9 FA	< 0.2	2.8	26.8	< 0.2	< 0.2	< 0.2	< 0.2	0.2	1.1
GC 10 FA	< 0.2	2.9	27.1	0.4	0.4	< 0.2	< 0.2	< 0.2	1.1
GC 11 FA	< 0.2	0.9	28.3	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	0.5
GC 12 FA	< 0.2	< 0.5	31.6	0.2	0.2	< 0.2	< 0.2	< 0.2	< 0.2
GC 13 FA	< 0.2	< 0.5	25.4	0.4	0.4	< 0.2	< 0.2	0.3	< 0.2
GC 14 FA	< 0.2	< 0.5	23.9	1.9	2.9	0.3	1.2	< 0.2	< 0.2
GC 15 FA	< 0.2	< 0.5	61.1	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2
GC 16 FA	< 0.2	< 0.5	14.9	7.1	12.0	1.5	5.3	< 0.2	0.2
GC0 (RA Blank)	< 0.2	< 0.5	< 1	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2
GC1 RA	< 0.2	1.2	62.2	2.0	4.1	0.5	1.9	< 0.2	0.3
GC1 RA DUP	< 0.2	1.2	61.0	1.9	3.9	0.5	1.8	< 0.2	0.3
GC2 RA	< 0.2	1.3	68.1	2.3	4.6	0.6	2.1	< 0.2	0.4
GC3 RA	< 0.2	1.9	31.9	3.7	7.8	1.0	3.6	< 0.2	0.6
GC4 RA	< 0.2	2.0	32.7	4.1	8.4	1.1	3.9	< 0.2	0.7
GC5 RA	< 0.2	2.3	29.8	4.8	9.9	1.3	4.6	< 0.2	0.8
GC6 RA	< 0.2	2.3	28.8	4.9	10.2	1.3	4.6	< 0.2	0.8
GC7 RA	< 0.2	2.7	27.9	6.1	12.5	1.5	5.8	< 0.2	1.0
GC8 RA	< 0.2	2.8	27.8	6.1	12.8	1.6	5.9	< 0.2	1.0
GC9 RA	< 0.2	2.8	27.6	4.1	8.8	1.1	4.0	< 0.2	1.1
GC10 RA	< 0.2	3.0	27.7	4.3	9.4	1.2	4.2	< 0.2	1.2
GC11 RA	< 0.2	0.9	30.0	0.7	1.0	< 0.2	0.5	< 0.2	0.6
GC12 RA	< 0.2	< 0.5	31.9	0.9	1.3	< 0.2	0.6	< 0.2	< 0.2
GC13 RA	< 0.2	< 0.5	27.4	2.8	4.1	0.5	1.7	< 0.2	< 0.2
GC14 RA	< 0.2	< 0.5	24.4	2.0	3.1	0.4	1.3	< 0.2	< 0.2
GC15 RA	< 0.2	< 0.5	66.3	0.3	0.2	< 0.2	< 0.2	< 0.2	< 0.2
GC16 RA	< 0.2	< 0.5	13.6	6.35	10.8	1.3	5.3	< 0.2	< 0.2

ICP-MS Results Continued

Sample Name	206Pb µg/L	207Pb µg/L	208Pb µg/L	232Th µg/L	238U µg/L
Trib 1 FA	< 0.2	< 0.2	< 0.2	< 0.2	5.0
Trib 3 FA	< 0.2	< 0.2	< 0.2	< 0.2	0.6
Trib 4 FA	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2
Trib 5 FA	86.5	95.1	94.0	< 0.2	0.3
Trib 6 FA	192	214	208	1.9	21.3
Trib 7 FA	32.2	35.7	35.2	< 0.2	0.5
Trib 8 FA	35.9	39.4	38.4	< 0.2	0.8
Trib 9 FA	158	175	172	2.6	6.2
Trib 9 FA DUP	158	173	170	1.9	6.2
Trib 10 FA	< 0.2	< 0.2	< 0.2	< 0.2	1.1
Trib 11 FA	27.0	30.0	29.6	< 0.5	5.0
Trib 12 FA	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2
Trib 13 FA	< 0.2	< 0.2	< 0.2	< 0.2	5.9
Trib 14 FA	< 0.2	< 0.2	< 0.2	< 0.2	9.9
Trib 15 FA	727	796	783	0.3	1.1
Trib 16 FA	< 0.2	< 0.2	< 0.2	< 0.2	4.4
Trib 17 FA	< 0.2	< 0.2	< 0.2	0.2	0.7
Trib 18 FA	6.6	7.4	7.34	< 0.2	0.4
Trib 19 FA	161	178	176	13.5	28.9
Trib 20 FA	13.9	15.5	15.3	1.3	11.8
GC 0(FA Blank)	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2
GC 1 FA	< 0.2	< 0.2	< 0.2	0.2	2.6
GC 1 FA DUP	< 0.2	< 0.2	< 0.2	< 0.2	2.6
GC 2 FA	< 0.2	< 0.2	< 0.2	< 0.2	2.7
GC 3 FA	< 0.2	< 0.2	< 0.2	< 0.2	0.8
GC 4 FA	< 0.2	< 0.2	< 0.2	0.3	0.8
GC 5 FA	< 0.2	< 0.2	< 0.2	< 0.2	0.7
GC 6 FA	< 0.2	< 0.2	< 0.2	< 0.2	0.7
GC 7 FA	< 0.2	< 0.2	< 0.2	< 0.2	0.8
GC 8 FA	< 0.2	< 0.2	< 0.2	< 0.2	0.9
GC 9 FA	< 0.2	< 0.2	< 0.2	0.9	0.8
GC 10 FA	< 0.2	< 0.2	< 0.2	< 0.2	0.9
GC 11 FA	0.5	0.5	0.5	< 0.2	1.1
GC 12 FA	0.7	0.7	0.7	< 0.2	1.4
GC 13 FA	1.5	1.5	1.6	0.8	3.1
GC 14 FA	277	304	296	0.3	0.8
GC 15 FA	20.3	22.5	22.1	< 0.2	3.6
GC 16 FA	753	826	817	0.5	2.1
GC0 (RA Blank)	0.3	0.3	0.3	< 0.2	< 0.2
GC1 RA	12.5	13.9	13.7	0.7	3.0
GC1 RA DUP	12.3	13.5	13.3	< 0.2	2.9
GC2 RA	14.2	15.7	15.5	< 0.2	3.2
GC3 RA	24.4	26.9	26.7	< 0.2	1.3
GC4 RA	26.3	29.0	28.6	< 0.2	1.4
GC5 RA	31.1	34.6	34.0	< 0.2	1.5
GC6 RA	31.6	34.9	34.6	< 0.2	1.5
GC7 RA	38.1	42.0	41.2	0.2	1.8
GC8 RA	34.1	37.6	37.4	0.6	1.9
GC9 RA	22.0	24.3	24.0	0.2	1.5
GC10 RA	20.4	22.6	22.5	< 0.2	1.6
GC11 RA	10.8	12.0	11.8	< 0.2	1.1
GC12 RA	15.8	17.5	17.3	< 0.2	1.4
GC13 RA	54.9	60.7	58.7	< 0.2	3.6
GC14 RA	278	306	297	< 0.2	0.9
GC15 RA	131	145	141	< 0.2	3.8
GC16 RA	704	770	754	0.5	1.7

9.2. Table C-2 ICP-MS Quality Assurance

Lab ID		Dilution	65Cu µg/L	66Zn µg/L	75As µg/L	111Cd µg/L	206Pb µg/L	207Pb µg/L	208Pb µg/L	232Th µg/L
MDL			0.564	0.976	0.449	0.460	0.472	0.463	0.467	0.211
CRQL			2.00	2.00	1.00	1.00	1.00	1.00	1.00	1.00
INSTRUMENT										
ICV		1	109.1	111.9	112.8	112.4	111.6	113.5	113.0	NA
RECOVERY	(85-115)		109%	112%	113%	112%	112%	113%	113%	
ICV TEST		1	PASS	PASS	PASS	PASS	PASS	PASS	PASS	
ICB		1	-0.0145	-0.1177	0.0205	0.0220	0.0211	0.0175	0.0191	0.0191
ICB TEST			PASS	PASS	PASS	PASS	PASS	PASS	PASS	PASS
DISSOLVED - NO PREP										
DISS BLANK		1	-0.0265	-2.6090	0.0139	-0.0051	-0.0276	-0.0350	-0.0319	0.0484
ICB TEST			PASS	PASS	PASS	PASS	PASS	PASS	PASS	PASS
DISS BLANK		1	0.0930	-2.5380	######	-0.0074	-0.0308	-0.0360	-0.0324	-0.0227
ICB TEST			PASS	PASS	PASS	PASS	PASS	PASS	PASS	PASS
LCS-S-241		1	450.1	990.4	46.6	28.9	39.9	39.7	39.1	NA
RECOVERY	(85-115)		1	1	100%	99%	99%	99%	98%	
LCS-WS-253		1	1414.6	317.5	12.1	49.0	78.9	80.9	78.5	NA
RECOVERY	(85-115)		101%	102%	114%	97%	99%	98%	97%	
FORTIFICATION AND DUPLICATION										
2021W0052		1	0.149	0.524	0.409	0.0546	0.0214	0.0199	0.0269	0.0402
2021W0052-MD		1	0.117	0.475	0.415	0.0581	0.0266	0.0174	0.0230	0.0209
RPD	< 20%		24%	10%	1%	6%	22%	13%	16%	63%
			OK <5X MDL				**OK <5X MDL**			**OK <5X MDL**
2021W0053		1	0.102	4.33	0.751	######	-0.0255	-0.0309	-0.0260	0.0239
2021W0053-LFM		1	54.6	55.8	54.0	54.8	58.8	59.0	57.4	27.1
RECOVERY	(75-125)		109%	103%	106%	110%	118%	118%	115%	108%
2021W0063		1	0.140	50.7	0.219	0.0621	0.0437	0.0409	0.0406	0.0233
2021W0063MD		1	0.131	50.8	0.207	0.0591	0.0407	0.0344	0.0430	0.0096
RPD	< 20%		6%	0%	6%	5%	7%	17%	6%	83%
										OK <5X MDL
2021W0064		1	51.8	511	1.10	2.30	0.0510	0.0523	0.0474	0.121
2021W0064LFM		1	101	533	54.2	55.2	57.5	57.0	56.0	26.9
RECOVERY	(75-125)		99%	45%	106%	106%	115%	114%	112%	107%

				>4X SA OK						
2021W0073		1	1.15	667	0.549	2.38	0.0554	0.0642	0.0615	0.2325
2021W0073MD		1	1.14	670	0.557	2.38	0.0567	0.0618	0.0640	0.0643
RPD	< 20%		1%	0%	1%	0%	2%	4%	4%	113%
										OK <5X MDL
2021W0074		1	1.1	687	0.506	2.43	0.0285	0.0210	0.0265	0.0155
2021W0074LFM		1	55.0	715	54.3	56.5	57.0	57.5	55.4	26.4
RECOVERY	(75-125)		108%	54%	108%	108%	114%	115%	111%	106%
				>4X SA OK						
2021W0084		1	6.63	175	0.542	0.580	0.485	0.535	0.534	0.022
2021W0084MD		1	6.44	172	0.550	0.538	0.501	0.527	0.534	0.014
RPD	< 20%		3%	2%	2%	7%	3%	1%	0%	48%
										OK <5X MDL
2021W0085		1	10.2	267	0.168	0.930	0.7	0.8	0.8	0.0
2021W0085LFM		1	66.0	303	55.53	58.18	61.8	61.4	59.6	28.1
RECOVERY	(75-125)		112%	73%	111%	115%	122%	121%	118%	112%
				>4X SA OK						
2021W0097		1	33.4	1987	5.97	7.48	31.8	35.4	34.8	0.179
2021W0097MD		1	34.8	2074	6.06	7.67	33.5	36.7	36.7	0.192
RPD	< 20%		4%	4%	1%	3%	5%	4%	5%	7%
2021W0098		1	39.5	2214	6.93	8.50	38.2	42.1	40.5	0.2
2021W0098LFM		1	97.5	2297	64.4	67.4	98.2	102	101	29.8
RECOVERY	(75-125)		116%	167%	115%	118%	120%	119%	121%	118%
				>4X SA OK						

TOTAL RECOVERY PREP

CALIBRATION VERIFICATION

CCV-1		1	104.65	98.37	99.42	100.12	100.40	99.55	99.47	49.28
CCV TEST	(90-110)		101%	102%	99%	97%	96%	97%	96%	96%
CCB-1		1	-0.0380	-2.5740	0.0244	-0.0010	-0.0269	-0.0311	-0.0283	0.1338
CCB TEST			PASS	PASS	PASS	PASS	PASS	PASS	PASS	PASS
CCV-2		1	104.35	98.88	99.39	99.79	100.98	99.49	100.92	49.61
CCV TEST	(90-110)		104%	99%	99%	100%	101%	99%	101%	99%
CCB-2		1	-0.0383	-2.5611	0.0139	-0.0005	-0.0284	-0.0361	-0.0340	0.1332
CCB TEST			PASS	PASS	PASS	PASS	PASS	PASS	PASS	PASS

CCV-3		1	104.40	98.14	99.93	99.92	99.47	99.80	99.78	49.66
CCV TEST	(90-110)		103%	109%	102%	100%	97%	97%	97%	97%
CCB-3		1	-0.0376	-2.6257	0.0246	0.0017	-0.0225	-0.0297	-0.0268	0.1409
CCB TEST			PASS	PASS	PASS	PASS	PASS	PASS	PASS	PASS
CCV-4		1	105.19	97.54	99.50	100.48	100.99	99.56	99.85	49.00
CCV TEST	(90-110)		103%	108%	102%	100%	99%	99%	99%	99%
CCB-4		1	-0.0241	-2.632	0.008	-0.0027	-0.0325	-0.0332	-0.0327	0.1396
CCB TEST			PASS	PASS	PASS	PASS	PASS	PASS	PASS	PASS
CCV-5		1	104.71	99.18	100.18	99.85	100.99	101.64	100.27	49.17
CCV TEST	(90-110)		102%	109%	102%	98%	96%	96%	96%	96%
CCB-5		1	-0.0336	-2.5143	0.025	-0.002	-0.0309	-0.0358	-0.0310	0.1380
CCB TEST			PASS	PASS	PASS	PASS	PASS	PASS	PASS	PASS
CCV-6		1	103.84	97.45	99.69	99.65	100.74	99.98	100.73	49.12
CCV TEST	(90-110)		102%	107%	101%	97%	93%	94%	94%	94%
CCB-6		1	-0.024	-2.529	0.009	-0.001	-0.032	-0.038	-0.034	0.141
CCB TEST			PASS	PASS	PASS	PASS	PASS	PASS	PASS	PASS
CCV-7		1	108.46	101.10	101.91	104.44	104.18	104.20	102.78	51.11
CCV TEST	(90-110)		103%	106%	100%	102%	100%	99%	99%	99%
CCB-7		1	-0.023	-2.58	0.022	-0.001	-0.02	-0.03	-0.02	0.14
CCB TEST			PASS	PASS	PASS	PASS	PASS	PASS	PASS	PASS
CCV-8		1	106.06	99.31	99.86	103.41	102.72	102.54	102.84	50.64
CCV TEST	(90-110)		102%	106%	101%	99%	97%	96%	99%	99%
CCB-8		1	-0.044	-2.484	0.009	-0.004	-0.032	-0.035	-0.034	0.139
CCB TEST			PASS	PASS	PASS	PASS	PASS	PASS	PASS	PASS
CCV-9		1	103.01	97.91	98.08	100.37	101.02	100.42	101.59	49.44
CCV TEST	(90-110)		96%	101%	96%	96%	96%	95%	95%	95%
CCB-9		1	-0.035	-2.585	0.017	-0.001	-0.034	-0.039	-0.033	0.146
CCB TEST			PASS	PASS	PASS	PASS	PASS	PASS	PASS	PASS
CCV-10		1	104.76	102.40	99.19	104.56	103.90	104.00	104.86	51.38
CCV TEST	(90-110)		95%	99%	93%	95%	94%	94%	93%	93%
CCB-10		1	0.0845	-1.5548	0.0739	0.1101	0.0491	0.0414	0.0472	0.4568
CCB TEST			PASS	PASS	PASS	PASS	PASS	PASS	PASS	PASS
CCV-11		1	105.86	101.97	99.25	104.91	104.00	104.34	104.72	52.39
CCV TEST	(90-110)		95%	99%	93%	95%	94%	94%	93%	93%
CCB-11		1	0.1500	-2.1779	0.1398	0.1641	0.0910	0.0907	0.0943	0.4995
CCB TEST			PASS	PASS	PASS	PASS	PASS	PASS	PASS	PASS
CCV-12		1	101.05	97.37	95.33	102.07	101.85	103.73	102.56	49.91
CCV TEST	(90-110)		95%	99%	93%	95%	94%	94%	93%	93%
CCB-12		1	0.1467	-2.1548	0.1254	0.1825	0.1308	0.1356	0.1366	0.4691
CCB TEST			PASS	PASS	PASS	PASS	PASS	PASS	PASS	PASS

9.3. Table C-3 ICP-OES Results

Sample Name	Al mg/L	As mg/L	B mg/L	Ba mg/L	Be mg/L	Ca mg/L	Cd mg/L	Co mg/L	Cr mg/L
Trib1	<0.0228	<0.1	<0.0135	0.101	<0.0063	29.6	<0.0061	<0.006	<0.0151
Trib3	<0.0228	<0.1	<0.0135	0.0407	<0.0063	72.7	<0.0061	<0.006	<0.0151
Trib4	<0.0228	<0.1	<0.0135	0.0414	<0.0063	6.22	<0.0061	<0.006	<0.0151
Trib5	0.526	<0.1	<0.0135	0.0328	<0.0063	16.1	<0.0061	<0.006	<0.0151
Trib6	7.57	<0.1	<0.0135	<0.0108	<0.0063	50.2	0.0746	0.0210	<0.0151
Trib7	0.0764	<0.1	<0.0135	0.0288	<0.0063	29.5	<0.0061	<0.006	<0.0151
Trib8	0.445	<0.1	<0.0135	0.0462	<0.0063	9.80	<0.0061	<0.006	<0.0151
Trib9	8.30	<0.1	0.0371	<0.0108	<0.0063	132	0.0702	0.0414	0.0249
Trib9-D	8.24	<0.1	0.0361	<0.0108	<0.0063	131	0.0711	0.0396	0.0243
Trib10	<0.0228	<0.1	<0.0135	0.0251	<0.0063	28.1	<0.0061	<0.006	<0.0151
Trib11	1.71	<0.1	<0.0135	0.0200	<0.0063	6.67	0.00667	<0.006	<0.0151
Trib 12	<0.0228	<0.1	<0.0135	0.0375	<0.0063	9.23	<0.0061	<0.006	<0.0151
Trib13	<0.0228	<0.1	<0.0135	0.0219	<0.0063	57.9	<0.0061	<0.006	<0.0151
Trib 14	<0.0228	<0.1	<0.0135	0.0657	<0.0063	20.0	<0.0061	<0.006	<0.0151
Trib15	0.785	<0.1	0.0317	0.0133	<0.0063	52.9	0.0212	<0.006	<0.0151
Trib16	<0.0228	<0.1	<0.0135	<0.0108	<0.0063	38.7	<0.0061	<0.006	<0.0151
Trib17	<0.0228	<0.1	<0.0135	0.0365	<0.0063	45.4	<0.0061	<0.006	<0.0151
Trib18	0.575	<0.1	<0.0135	0.0470	<0.0063	4.42	<0.0061	<0.006	<0.0151
Trib19	16.3	0.251	0.0501	<0.0108	0.00802	95.1	0.305	0.0410	0.0475
Trib20	6.14	<0.1	<0.0135	0.0110	<0.0063	24.8	0.0240	0.0176	<0.0151
GC0	<0.0228	<0.1	<0.0135	<0.0108	<0.0063	<0.0128	<0.0061	<0.006	<0.0151
GC1	0.0274	<0.1	<0.0135	0.0577	<0.0063	33.6	<0.0061	<0.006	<0.0151
GC1-D	<0.0228	<0.1	<0.0135	0.0582	<0.0063	33.2	<0.0061	<0.006	<0.0151
GC2	<0.0228	<0.1	<0.0135	0.0600	<0.0063	32.5	<0.0061	<0.006	<0.0151
GC3	0.0229	<0.1	<0.0135	0.0294	<0.0063	33.7	<0.0061	<0.006	<0.0151
GC4	0.0252	<0.1	<0.0135	0.0301	<0.0063	33.0	<0.0061	<0.006	<0.0151
GC5	0.0236	<0.1	<0.0135	0.0270	<0.0063	30.5	<0.0061	<0.006	<0.0151
GC6	<0.0228	<0.1	<0.0135	0.0273	<0.0063	30.7	0.00667	<0.006	<0.0151
GC7	<0.0228	<0.1	<0.0135	0.0259	<0.0063	34.0	0.00694	<0.006	<0.0151
GC8	0.0276	<0.1	<0.0135	0.0260	<0.0063	34.4	0.00835	<0.006	<0.0151
GC9	<0.0228	<0.1	<0.0135	0.0267	<0.0063	34.8	<0.0061	<0.006	<0.0151
GC10	0.0249	<0.1	<0.0135	0.0265	<0.0063	35.2	0.00666	<0.006	<0.0151
GC11	0.0404	<0.1	<0.0135	0.0292	<0.0063	26.8	<0.0061	<0.006	<0.0151
GC12	0.0424	<0.1	<0.0135	0.0312	<0.0063	26.4	<0.0061	<0.006	<0.0151
GC13	0.0699	<0.1	<0.0135	0.0253	<0.0063	43.8	<0.0061	<0.006	<0.0151
GC14	0.241	<0.1	<0.0135	0.0249	<0.0063	32.1	<0.0061	<0.006	<0.0151
GC15	<0.0228	<0.1	<0.0135	0.0581	<0.0063	29.6	<0.0061	<0.006	<0.0151
GC16	1.03	<0.1	0.0159	0.0174	<0.0063	54.9	0.0154	<0.006	<0.0151

ICP-OES Results Continued

Sample Name	Cu mg/L	Fe mg/L	K mg/L	Li mg/L	Mg mg/L	Mn mg/L	Mo mg/L	Na mg/L	Ni mg/L
Trib1	<0.0073	<0.0157	0.349	<0.0188	7.21	<0.009	<0.013	1.77	<0.0097
Trib3	<0.0073	<0.0157	0.435	<0.0188	5.66	0.0305	<0.013	1.47	<0.0097
Trib4	<0.0073	<0.0157	0.633	<0.0188	2.06	<0.009	<0.013	2.46	<0.0097
Trib5	0.0194	0.0204	1.11	<0.0188	3.66	1.12	<0.013	2.52	<0.0097
Trib6	0.195	5.94	0.674	<0.0188	12.3	30.7	<0.013	3.71	0.0204
Trib7	<0.0073	0.0281	0.615	<0.0188	2.41	0.183	<0.013	1.65	<0.0097
Trib8	0.0192	<0.0157	0.874	<0.0188	2.17	0.666	<0.013	3.59	<0.0097
Trib9	0.193	111	2.36	<0.0188	22.9	59.5	<0.013	6.58	0.0567
Trib9-D	0.200	110	2.30	<0.0188	22.6	58.8	<0.013	6.64	0.0552
Trib10	<0.0073	0.0233	0.443	<0.0188	10.6	0.0902	<0.013	2.45	<0.0097
Trib11	0.0175	1.23	0.876	<0.0188	1.93	1.40	<0.013	4.25	<0.0097
Trib 12	<0.0073	<0.0157	0.450	<0.0188	2.22	<0.009	<0.013	3.01	<0.0097
Trib13	0.0563	0.0693	0.615	<0.0188	18.4	1.49	<0.013	2.45	<0.0097
Trib 14	<0.0073	<0.0157	0.397	<0.0188	6.45	<0.009	<0.013	1.75	<0.0097
Trib15	0.636	94.4	0.974	<0.0188	17.0	10.9	<0.013	0.720	<0.0097
Trib16	<0.0073	0.0358	0.687	<0.0188	21.5	0.360	<0.013	3.01	<0.0097
Trib17	<0.0073	<0.0157	0.120	<0.0188	13.0	<0.009	<0.013	1.53	<0.0097
Trib18	<0.0073	0.0259	0.786	<0.0188	1.36	0.187	<0.013	3.66	<0.0097
Trib19	1.54	153	0.617	<0.0188	21.4	110	<0.013	4.55	0.0334
Trib20	0.264	4.02	1.09	<0.0188	5.95	10.6	<0.013	4.75	0.0224
GC0	<0.0073	<0.0157	<0.06	<0.0188	<0.0078	<0.009	<0.013	0.0258	<0.0097
GC1	<0.0073	<0.0157	0.597	<0.0188	7.99	1.62	<0.013	2.41	<0.0097
GC1-D	<0.0073	<0.0157	0.594	<0.0188	7.97	1.64	<0.013	2.35	<0.0097
GC2	<0.0073	<0.0157	0.608	<0.0188	7.73	1.72	<0.013	2.30	<0.0097
GC3	<0.0073	<0.0157	0.692	<0.0188	7.89	3.21	<0.013	2.66	<0.0097
GC4	<0.0073	0.0204	0.681	<0.0188	7.55	3.38	<0.013	2.60	<0.0097
GC5	<0.0073	0.0800	0.742	<0.0188	7.74	3.99	<0.013	2.82	<0.0097
GC6	<0.0073	0.177	0.692	<0.0188	7.80	4.08	<0.013	2.85	<0.0097
GC7	<0.0073	0.300	0.753	<0.0188	8.56	4.75	<0.013	3.01	<0.0097
GC8	<0.0073	0.961	0.768	<0.0188	8.66	4.95	<0.013	2.93	<0.0097
GC9	0.00872	3.34	0.748	<0.0188	9.12	4.41	<0.013	3.02	<0.0097
GC10	<0.0073	4.79	0.722	<0.0188	9.31	4.62	<0.013	2.94	<0.0097
GC11	0.0103	0.0224	0.619	<0.0188	8.50	0.174	<0.013	2.76	<0.0097
GC12	0.0126	<0.0157	0.618	<0.0188	7.55	0.256	<0.013	2.57	<0.0097
GC13	0.0230	0.0256	0.653	<0.0188	14.4	0.991	<0.013	2.24	<0.0097
GC14	0.114	5.79	0.667	<0.0188	10.0	1.83	<0.013	1.65	<0.0097
GC15	<0.0073	<0.0157	0.676	<0.0188	7.28	<0.009	<0.013	2.02	<0.0097
GC16	0.399	43.2	0.883	<0.0188	18.1	6.90	<0.013	1.32	<0.0097

ICP-OES Results Continued

Sample Name	P mg/L	Pb mg/L	Sb mg/L	Se mg/L	Si mg/L	Sr mg/L	Ti mg/L	Tl mg/L	V mg/L	Zn mg/L
Trib1	<0.0546	<0.0336	<0.0411	<0.0737	5.70	0.196	<0.0062	<0.0444	<0.0088	<0.0055
Trib3	<0.0546	<0.0336	<0.0411	<0.0737	7.02	0.130	<0.0062	<0.0444	<0.0088	0.00796
Trib4	<0.0546	<0.0336	<0.0411	<0.0737	9.80	0.0485	<0.0062	<0.0444	<0.0088	0.181
Trib5	<0.0546	0.0798	<0.0411	<0.0737	11.4	0.115	<0.0062	<0.0444	<0.0088	0.468
Trib6	<0.0546	0.180	<0.0411	<0.0737	23.2	0.407	<0.0062	<0.0444	<0.0088	15.2
Trib7	<0.0546	<0.0336	<0.0411	<0.0737	7.81	0.0707	<0.0062	<0.0444	<0.0088	0.372
Trib8	<0.0546	<0.0336	<0.0411	<0.0737	15.8	0.278	<0.0062	<0.0444	<0.0088	0.974
Trib9	0.217	0.164	<0.0411	<0.0737	25.1	0.783	0.00670	<0.0444	<0.0088	26.5
Trib9-D	0.165	0.161	<0.0411	<0.0737	24.8	0.784	0.00663	<0.0444	<0.0088	26.5
Trib10	<0.0546	<0.0336	<0.0411	<0.0737	10.9	0.0653	<0.0062	<0.0444	<0.0088	0.0520
Trib11	<0.0546	<0.0336	<0.0411	<0.0737	19.0	0.0636	<0.0062	<0.0444	<0.0088	2.06
Trib 12	<0.0546	<0.0336	<0.0411	<0.0737	10.4	0.150	<0.0062	<0.0444	<0.0088	0.0557
Trib13	<0.0546	<0.0336	<0.0411	<0.0737	6.72	0.164	<0.0062	<0.0444	<0.0088	0.587
Trib 14	<0.0546	<0.0336	<0.0411	<0.0737	5.03	0.113	<0.0062	<0.0444	<0.0088	0.00593
Trib15	0.107	0.907	<0.0411	<0.0737	4.36	0.0742	<0.0062	<0.0444	<0.0088	5.34
Trib16	<0.0546	<0.0336	<0.0411	<0.0737	12.7	0.100	<0.0062	<0.0444	<0.0088	0.0938
Trib17	<0.0546	<0.0336	<0.0411	<0.0737	7.59	0.0667	<0.0062	<0.0444	<0.0088	0.00752
Trib18	<0.0546	<0.0336	<0.0411	<0.0737	16.1	0.127	<0.0062	<0.0444	<0.0088	0.148
Trib19	0.563	0.177	<0.0411	<0.0737	24.0	0.726	0.00682	<0.0444	<0.0088	57.6
Trib20	<0.0546	<0.0336	<0.0411	<0.0737	23.2	0.131	<0.0062	<0.0444	<0.0088	4.65
GC0	<0.0546	<0.0336	<0.0411	<0.0737	0.298	<0.0111	<0.0062	<0.0444	<0.0088	<0.0055
GC1	<0.0546	<0.0336	<0.0411	<0.0737	8.16	0.175	<0.0062	<0.0444	<0.0088	0.762
GC1-D	<0.0546	<0.0336	<0.0411	<0.0737	8.30	0.176	<0.0062	<0.0444	<0.0088	0.769
GC2	<0.0546	<0.0336	<0.0411	<0.0737	8.32	0.176	<0.0062	<0.0444	<0.0088	0.772
GC3	<0.0546	<0.0336	<0.0411	<0.0737	10.1	0.153	<0.0062	<0.0444	<0.0088	1.40
GC4	<0.0546	<0.0336	<0.0411	<0.0737	10.2	0.154	<0.0062	<0.0444	<0.0088	1.47
GC5	<0.0546	<0.0336	<0.0411	<0.0737	10.7	0.160	<0.0062	<0.0444	<0.0088	1.72
GC6	<0.0546	<0.0336	<0.0411	<0.0737	10.8	0.161	<0.0062	<0.0444	<0.0088	1.78
GC7	<0.0546	<0.0336	<0.0411	<0.0737	11.0	0.178	<0.0062	<0.0444	<0.0088	1.98
GC8	<0.0546	<0.0336	<0.0411	<0.0737	11.1	0.181	<0.0062	<0.0444	<0.0088	2.20
GC9	<0.0546	<0.0336	<0.0411	<0.0737	11.4	0.182	<0.0062	<0.0444	<0.0088	1.94
GC10	<0.0546	<0.0336	<0.0411	<0.0737	11.2	0.173	<0.0062	<0.0444	<0.0088	2.08
GC11	<0.0546	<0.0336	<0.0411	<0.0737	10.8	0.101	<0.0062	<0.0444	<0.0088	0.192
GC12	<0.0546	<0.0336	<0.0411	<0.0737	10.0	0.123	<0.0062	<0.0444	<0.0088	0.305
GC13	<0.0546	<0.0336	<0.0411	<0.0737	7.56	0.123	<0.0062	<0.0444	<0.0088	0.626
GC14	<0.0546	0.237	<0.0411	<0.0737	6.04	0.0634	<0.0062	<0.0444	<0.0088	1.53
GC15	<0.0546	<0.0336	<0.0411	<0.0737	5.05	0.108	<0.0062	<0.0444	<0.0088	0.329
GC16	<0.0546	0.821	<0.0411	<0.0737	5.83	0.0900	<0.0062	<0.0444	<0.0088	3.90

10. Appendix D: Supplemental Data-Leachate Experiment

10.1. Table D-1 Leachate ICP-MS Results

Sample Name	**7Li µg/L**	**9Be µg/L**	**11B µg/L**	**27Al µg/L**	**31P µg/L**	**31P mg/L**	**39K µg/L**	**39K mg/L**	**43Ca µg/L**
A1	28.2	< 0.2	181	2.86	10.9	0.0109	2210	2.21	252000
B1	2.63	< 0.2	696	18.0	59.0	0.0590	818	0.818	20000
C1	5.96	0.427	497	60.2	105	0.105	519	0.519	19700
D1	5.88	0.294	44.4	189	29.5	0.0295	806	0.806	8640
E1	< 0.5	< 0.2	408	53.1	35.0	0.0350	509	0.509	5530
F1	6.18	1.38	155	945	26.2	0.0262	533	0.533	12100
G1	4.62	9.36	81.3	22900	815	0.815	1600	1.60	107000
Sample Blank	< 0.5	< 0.2	3.38	10.7	< 5	< 0.005	6.48	0.00648	103
G-2	< 5	8.11	< 2	9750	250	0.250	785	0.785	55807
H-1	20.7	10.8	< 2	8570	22.0	0.0220	56.7	0.0567	38554
G-3	< 5	7.89	< 2	11800	1880	1.88	571	0.571	50436
G-4	< 5	5.69	< 2	8990	1590	1.59	422	0.422	35795
H-2	< 5	< 2	< 2	239	< 50	< 0.05	< 5	< 0.05	18087
G-5	< 5	3.88	< 2	9200	2970	2.97	252	0.252	22441
H-3	< 5	< 2	< 2	136	< 50	< 0.05	< 5	< 0.05	9132
A-2	13.0	< 0.2	17.6	0.727	< 5	< 0.005	837	0.837	78038
B-2	< 0.5	0.241	23.1	27.1	12.3	0.0123	364	0.364	5255
C-2	< 0.5	< 0.2	9.55	34.2	23.0	0.0230	179	0.179	4940
D-2	2.24	0.602	< 0.2	295	< 5	< 0.005	501	0.501	8900
E-2	< 0.5	< 0.2	27.6	17.8	24.5	0.0245	108	0.108	327
F-2	4.00	0.771	15.0	399	< 5	< 0.005	264	0.264	5744

ICP-MS Results Continued

Sample Name	43Ca	49Ti	51V	52Cr	55Mn	55Mn	56Fe	56Fe	59Co
	mg/L	µg/L	µg/L	µg/L	µg/L	mg/L	µg/L	mg/L	µg/L
A1	252	26.3	< 0.5	0.506	282	0.282	< 5	< 0.005	1.55
B1	20.0	0.547	< 0.5	0.801	1690	1.69	54.3	0.0543	0.704
C1	19.7	1.88	1.15	3.31	1170	1.17	1130	1.13	2.58
D1	8.64	1.40	< 0.5	< 0.2	277	0.277	2550	2.55	4.12
E1	5.53	0.537	< 0.5	< 0.2	465	0.465	31.7	0.0317	0.884
F1	12.1	1.49	< 0.5	0.346	2930	2.93	82.7	0.0827	3.04
G1	107	12.68	38.5	15.9	96600	96.6	285000	285	65.0
Sample Blank	0.103	< 0.5	< 0.5	< 0.2	< 2	< 0.002	6.25	0.00625	< 0.5
G-2	55.8	10.3	13.9	6.50	75700	75.7	104000	104	35.5
H-1	38.6	56.2	2.76	3.10	354000	354	1010000	1010	212
G-3	50.4	14.9	32.8	9.92	112000	112	152000	152	34.8
G-4	35.8	11.4	24.1	8.23	104000	104	137000	137	28.6
H-2	18.1	15.9	< 5	0.001	438000	438	41400	41.4	44.2
G-5	22.4	13.6	19.3	8.94	96100	96.1	207000	207	31.9
H-3	9.13	7.10	< 5	< 2	254000	254	36000	36.0	11.2
A-2	78.0	6.77	< 0.5	< 0.2	12.8	0.0128	< 5	< 0.005	< 0.5
B-2	5.25	< 0.5	1.04	0.424	156	0.156	< 5	< 0.005	< 0.5
C-2	4.94	< 0.5	0.822	0.274	89.6	0.0896	7.58	0.00758	< 0.5
D-2	8.90	1.33	< 0.5	< 0.2	300	0.300	293	0.293	6.53
E-2	0.327	< 0.5	< 0.5	< 0.2	2.82	0.00282	< 5	< 0.005	< 0.5
F-2	5.74	< 0.5	< 0.5	< 0.2	1830	1.83	24.1	0.0241	1.68

ICP-MS Results Continued

Sample Name	60Ni µg/L	63Cu µg/L	66Zn µg/L	71Ga µg/L	75As µg/L	82Se µg/L	85Rb µg/L	88Sr µg/L	90Zr µg/L
A1	< 0.5	5.95	36.2	1.04	1.92	10.4	92.7	1600	4.07
B1	11.2	88.4	77.6	18.0	1.17	0.828	7.72	254	1.56
C1	18.2	137	181	6.56	5.23	1.09	7.17	202	116
D1	3.32	48.6	166	6.12	3.55	< 0.2	30.9	159	0.750
E1	3.70	38.9	190	15.9	1.88	0.951	7.86	113	< 0.5
F1	7.54	156	4060	2.33	1.27	< 0.2	21.7	58.7	< 0.5
G1	89.5	6520	33200	1.20	478	1.32	102	165	1.26
Sample Blank	< 0.5	4.39	26.5	< 0.5	< 0.2	< 0.2	< 0.5	< 1	< 0.5
G-2	56.7	3790	20100	< 5	250	< 2	67.4	175	< 5
H-1	26.7	9590	397000	10.9	357	4.54	6.01	14.7	< 5
G-3	48.2	4480	31600	< 5	672	< 2	48.1	168	< 5
G-4	38.0	3830	17900	< 5	561	< 2	37.1	125	< 5
H-2	8.35	491	150000	< 5	115	< 2	< 5	17.7	< 5
G-5	29.9	4310	17500	6.33	883	< 2	26.0	112	< 5
H-3	2.1	636	78700	< 5	95.3	< 2	< 5	12.6	< 5
A-2	< 0.5	< 1	3.58	3.29	0.597	0.919	36.9	389	0.638
B-2	< 0.5	8.49	4.71	4.76	0.830	0.662	3.43	67.4	< 0.5
C-2	1.03	42.9	8.82	5.45	2.73	0.546	2.72	51.5	4.62
D-2	4.40	59.7	238	53.0	3.56	< 0.2	24.6	179	< 0.5
E-2	< 0.5	5.61	18.6	1.38	0.786	0.762	1.87	7.06	< 0.5
F-2	4.49	66.4	2520	53.8	1.37	< 0.2	10.4	34.6	< 0.5

ICP-MS Results Continued

Sample Name	93Nb µg/L	98Mo µg/L	105Pd µg/L	107Ag µg/L	111Cd µg/L	118Sn µg/L	121Sb µg/L	133Cs µg/L	137Ba µg/L
A1	1.14	33.1	1.04	0.471	0.791	< 0.5	0.658	37.7	29.9
B1	0.512	12.2	< 0.5	< 0.2	< 0.2	< 0.5	10.2	< 0.5	400
C1	0.858	27.7	0.964	0.330	1.13	2.86	11.9	< 0.5	134
D1	< 0.5	< 0.5	< 0.5	0.774	1.55	< 0.5	0.366	2.68	132
E1	< 0.5	2.85	< 0.5	< 0.2	0.985	< 0.5	5.53	< 0.5	355
F1	< 0.5	< 0.5	< 0.5	< 0.2	60.4	0.637	0.248	3.79	49.9
G1	0.654	1.41	0.929	0.261	102	< 0.5	1.42	30.5	3.86
Sample Blank	< 0.5	< 0.5	< 0.5	0.440	< 0.2	< 0.5	< 0.2	< 0.5	1.23
G-2	5.84	< 5	< 5	13.1	196	< 5	3.86	45.0	11.7
H-1	< 5	< 5	< 5	< 2	2830	< 5	77.9	11.6	< 10
G-3	< 5	< 5	< 5	3.02	201	< 5	3.35	40.1	< 10
G-4	< 5	< 5	< 5	4.22	163	< 5	3.07	35.9	< 10
H-2	< 5	< 5	< 5	< 2	1210	< 5	59.0	5.15	< 10
G-5	< 5	< 5	< 5	12.3	118	< 5	3.18	30.8	89.1
H-3	< 5	< 5	< 5	< 2	696	< 5	50.6	< 5	33.4
A-2	< 0.5	46.0	< 0.5	< 0.2	< 0.2	< 0.5	< 0.5	14.4	74.4
B-2	< 0.5	8.33	< 0.5	< 0.2	< 0.2	< 0.5	9.52	< 0.5	100
C-2	< 0.5	7.93	< 0.5	0.349	< 0.2	< 0.5	4.91	< 0.5	110
D-2	< 0.5	< 0.5	< 0.5	< 0.2	2.50	< 0.5	< 0.5	1.63	900
E-2	< 0.5	1.22	< 0.5	< 0.2	< 0.2	< 0.5	3.67	< 0.5	30.0
F-2	< 0.5	< 0.5	< 0.5	0.465	40.2	< 0.5	< 0.5	1.50	954

ICP-MS Results Continued

Sample Name	139La µg/L	140Ce µg/L	141Pr µg/L	146Nd µg/L	182W µg/L	205Tl µg/L	206Pb µg/L	207Pb µg/L	208Pb µg/L	232Th µg/L	238U µg/L
A1	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	9.08	0.214	0.263	0.242	< 0.2	195
B1	2.85	1.19	0.331	1.08	0.469	< 0.2	0.873	0.913	0.902	< 0.2	2.71
C1	20.7	47.4	6.94	30.6	1.18	< 0.2	64.2	67.3	68.0	12.87	2.43
D1	1.27	2.52	0.362	1.44	< 0.2	2.10	2.77	2.97	2.92	0.588	3.53
E1	1.33	2.64	0.442	1.75	< 0.2	0.297	6.27	6.41	6.42	0.209	1.23
F1	5.77	9.04	1.38	5.06	< 0.2	1.79	278	306	309	< 0.2	4.11
G1	75.6	186	25.3	110	< 0.2	20.9	2300	2570	2590	153	200
Sample Blank	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	81.0	88.7	88.5	< 0.2	< 0.2
G-2	69.3	166	21.7	88.2	< 2	15.8	2010	2240	2220	27.1	84.5
H-1	8.86	27.4	4.79	24.8	< 2	25.8	3060	3390	3410	5.79	32.8
G-3	100	241	31.8	130	< 2	7.93	1900	2140	2060	65.5	91.0
G-4	78.3	187	24.8	100	< 2	6.39	1860	2140	2080	60.4	68.1
H-2	2.47	5.38	< 2	3.66	< 2	7.61	2840	3160	3080	2.39	< 2
G-5	80.9	195	25.2	104	< 2	4.71	1560	1770	1710	61.4	51.7
H-3	< 2	3.24	< 2	< 2	< 2	8.22	3520	3920	3960	< 2	< 2
A-2	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	3.09	< 0.2	< 0.2	< 0.2	0.413	26.7
B-2	0.209	< 0.2	< 0.2	< 0.2	0.480	0.349	0.351	0.377	0.371	< 0.2	1.55
C-2	1.10	2.39	0.354	1.54	0.496	< 0.2	1.22	1.31	1.32	0.861	0.966
D-2	2.31	4.46	0.636	2.44	< 0.2	1.50	3.03	3.32	3.27	0.403	11.3
E-2	0.363	0.670	< 0.2	0.487	< 0.2	< 0.2	0.382	0.396	0.394	0.240	0.412
F-2	2.05	3.17	0.466	1.71	< 0.2	0.798	120	134	130	< 0.2	0.488

10.2. Table D-2 Leachate ICP-MS Quality Assurance

Lab ID		Dilution	65Cu µg/L	66Zn µg/L	75As µg/L	111Cd µg/L	206Pb µg/L	207Pb µg/L	208Pb µg/L	232Th µg/L
MDL			0.564	0.976	0.449	0.460	0.472	0.463	0.467	0.211
CRQL			2.00	2.00	1.00	1.00	1.00	1.00	1.00	1.00
INSTRUMENT										
ICV		1	101.0	102.0	98.8	99.5	98.2	103.6	100.6	NA
RECOVERY	(85-115)		101%	102%	99%	100%	98%	104%	101%	
ICV TEST		1	PASS	PASS	PASS	PASS	PASS	PASS	PASS	
ICB		1	0.0167	-0.0359	0.0145	0.0108	0.7652	0.7678	0.7614	0.0025
ICB TEST			PASS	PASS	PASS	PASS	PASS	PASS	PASS	PASS
DISSOLVED - NO PREP										
DISS BLANK		1	0.0132	21.9862	0.0369	0.0008	0.0140	0.0161	0.0151	0.0321
ICB TEST			PASS	FAIL 0.000	PASS	PASS	PASS	PASS	PASS	PASS
DISS BLANK		1	0.1132	0.4499	0.0188	0.0012	0.0238	0.0227	0.0256	0.0183
ICB TEST			PASS	PASS	PASS	PASS	PASS	PASS	PASS	PASS
LCS-S-241		1	453.8	1046.5	47.2	28.3	36.6	36.5	38.3	NA
RECOVERY	(85-115)		109%	108%	111%	108%	104%	104%	109%	
LCS-WS-253		1	1478.1	346.6	12.4	48.2	79.7	75.9	77.7	NA
RECOVERY	(85-115)		109%	110%	122%	102%	107%	102%	105%	
FORTIFICATION AND DUPLICATION										
2021W415		1	86.396	75.904	1.169	0.1878	0.8730	0.9131	0.9022	0.0380
2021W0415-MD		1	91.396	78.925	1.246	0.1780	0.8703	0.9085	0.8890	0.0393
RPD	< 20%		6%	4%	6%	5%	0%	1%	1%	3%
			OK <5X MDL				**OK <5X MDL**			**OK <5X MDL**
2021W0416		1	133.653	175.38	5.056	1.12825	63.8050	67.2047	69.3881	12.6873
2021W0416-LFM		1	174.4	211.7	50.6	59.2	121.0	124.5	124.8	43.3
RECOVERY	(75-125)		82%	73%	91%	116%	114%	115%	111%	123%
TOTAL RECOVERY PREP										
CALIBRATION VERIFICATION										
CCV-1		1	96.65	98.63	96.55	97.54	98.54	96.81	98.46	48.57
CCV TEST	(90-110)		97%	99%	97%	98%	99%	97%	98%	97%
CCB-1		1	0.0727	0.0758	0.0217	0.0070	0.0147	0.0227	0.0168	0.0799
CCB TEST			PASS	PASS	PASS	PASS	PASS	PASS	PASS	PASS
CCV-2		1	96.22	98.28	98.14	99.83	102.84	100.36	100.94	50.45
CCV TEST	(90-110)		96%	98%	98%	100%	103%	100%	101%	101%
CCB-2		1	0.0500	0.0365	0.0518	0.0042	0.0164	0.0186	0.0166	0.0773
CCB TEST			PASS	PASS	PASS	PASS	PASS	PASS	PASS	PASS

CCV-3		1	96.30	98.41	95.97	102.20	106.15	105.35	105.72	53.38
CCV TEST	(90-110)		96%	98%	96%	102%	106%	105%	106%	107%
CCB-3		1	0.0466	0.0241	0.0399	0.0053	0.0218	0.0273	0.0232	0.0788
CCB TEST			PASS	PASS	PASS	PASS	PASS	PASS	PASS	PASS
CCV-4		1	96.51	98.61	93.86	108.76	109.68	108.34	108.02	55.73
CCV TEST	(90-110)		97%	99%	94%	109%	110%	108%	108%	111%
CCB-4		1	0.0702	0.115	0.047	0.0061	0.0188	0.0208	0.0191	0.0808
CCB TEST			PASS	PASS	PASS	PASS	PASS	PASS	PASS	PASS
CCV-5		1	94.78	96.96	92.69	100.02	102.05	101.63	102.72	51.02
CCV TEST	(90-110)		95%	97%	93%	100%	102%	102%	103%	102%
CCB-5		1	0.0663	0.0878	0.037	0.005	0.0154	0.0185	0.0155	0.0925
CCB TEST			PASS	PASS	PASS	PASS	PASS	PASS	PASS	PASS
CCV-6		1	95.43	100.19	94.32	100.47	104.02	103.38	101.78	51.84
CCV TEST	(90-110)		95%	100%	94%	100%	104%	103%	102%	104%
CCB-6		1	0.068	0.062	0.011	0.006	0.018	0.019	0.018	0.110
CCB TEST			PASS	PASS	PASS	PASS	PASS	PASS	PASS	PASS
CCV-7		1	105.39	108.60	106.87	102.58	101.80	101.14	100.92	50.85
CCV TEST	(90-110)		105%	109%	107%	103%	102%	101%	101%	102%
CCB-7		1	0.090	0.13	0.019	0.006	0.01	0.02	0.01	0.09
CCB TEST			PASS	PASS	PASS	PASS	PASS	PASS	PASS	PASS
CCV-8		1	103.03	107.35	103.80	103.73	105.72	105.52	105.50	52.82
CCV TEST	(90-110)		103%	107%	104%	104%	106%	106%	105%	106%
CCB-8		1	0.075	0.007	0.028	0.007	0.018	0.023	0.016	0.095
CCB TEST			PASS	PASS	PASS	PASS	PASS	PASS	PASS	PASS
CCV-9		1	99.89	104.00	98.36	106.78	110.98	108.89	110.44	54.66
CCV TEST	(90-110)		100%	104%	98%	107%	111%	109%	110%	109%
CCB-9		1	0.069	0.054	0.019	0.005	0.014	0.018	0.016	0.096
CCB TEST			PASS	PASS	PASS	PASS	PASS	PASS	PASS	PASS
CCV-10		1	91.12	97.18	90.04	102.85	105.06	104.51	107.27	53.58
CCV TEST	(90-110)		91%	97%	90%	103%	105%	105%	107%	107%
CCB-10		1	0.0854	0.9369	0.0602	0.0072	0.0208	0.0247	0.0238	0.0818
CCB TEST			PASS	PASS	PASS	PASS	PASS	PASS	PASS	PASS
CCV-11		1	94.76	98.37	95.92	101.81	104.72	105.62	103.63	52.03
CCV TEST	(90-110)		95%	98%	96%	102%	105%	106%	104%	104%
CCB-11		1	0.0726	0.3481	0.0842	0.0054	0.0207	0.0265	0.0198	0.0972
CCB TEST			PASS	PASS	PASS	PASS	PASS	PASS	PASS	PASS
CCV-12		1	97.86	99.55	99.04	100.59	104.84	101.74	103.00	51.70
CCV TEST	(90-110)		98%	100%	99%	101%	105%	102%	103%	103%
CCB-12		1	0.0685	0.1388	0.0815	0.0090	0.0167	0.0206	0.0186	0.0939

CCB TEST			PASS	PASS	PASS	PASS	PASS	PASS	PASS	PASS
CCV-13			97.48	100.80	93.20	114.57	117.70	116.82	116.56	61.56
CCV TEST	(90-110)		98%	100%	99%	101%	105%	102%	103%	103%
CCB-13		1	0.0664	0.0265	0.0702	0.0062	0.0218	0.0268	0.0231	0.1190
CCB TEST			PASS	PASS	PASS	PASS	PASS	PASS	PASS	PASS
CCV-14			94.22	99.37	90.55	112.53	115.00	116.10	115.02	59.67
CCV TEST	(90-110)		98%	100%	99%	101%	105%	102%	103%	103%
CCB-14		1	0.0357	0.1013	0.0905	0.0046	0.0368	0.0424	0.0364	0.1123
CCB TEST			PASS	PASS	PASS	PASS	PASS	PASS	PASS	PASS
CCV-15			86.9242	90.5793	81.07162	111.5617	118.1601	109.5083	114.6005	58.33
CCV TEST	(90-110)		98%	100%	99%	101%	105%	102%	103%	103%
CCB-15		1	0.040103	0.417438	0.100132	0.022619	0.054715	0.059714	0.054061	0.11773
CCB TEST			PASS	PASS	PASS	PASS	PASS	PASS	PASS	PASS

10.3. Table D-3 ICP-OES Results

Sample Name	mg/L Al	mg/L As	mg/L B	mg/L Ba	mg/L Be	mg/L Ca	mg/L Cd	mg/L Co	mg/L Cr
A1	0.131	<0.1	0.200	0.0264	<0.0131	476	<0.0037	<0.0042	<0.0146
B1	0.0381	<0.1	0.693	0.330	<0.0131	36.3	<0.0037	<0.0042	<0.0146
C1	0.0805	<0.1	0.508	0.120	<0.0131	38.7	<0.0037	<0.0042	<0.0146
D1	0.204	<0.1	0.0516	0.114	<0.0131	16.2	<0.0037	<0.0042	<0.0146
E1	0.0571	<0.1	0.397	0.293	<0.0131	10.1	<0.0037	<0.0042	<0.0146
F1	0.904	<0.1	0.151	0.0421	<0.0131	22.5	0.0473	<0.0042	<0.0146
G1	24.6	0.552	0.521	0.00946	0.0159	220	0.298	0.0742	0.0431
Blank	<0.0373	<0.1	<0.0138	<0.0072	<0.0131	0.197	<0.0037	<0.0042	<0.0146
G-2	10.8	0.295	0.192	0.0130	<0.012	120	0.205	0.0439	0.0304
H-1	9.90	0.419	1.73	<0.0092	0.0124	83.0	3.16	0.261	0.113
G-3	13.6	0.816	0.256	<0.0092	<0.012	112	0.231	0.0421	0.0461
G-4	10.6	0.686	0.232	0.00969	<0.012	77.3	0.185	0.0339	0.0450
H-2	0.278	0.126	0.116	<0.0092	<0.012	40.0	1.24	0.0550	0.139
G-5	10.4	1.10	0.339	0.103	<0.012	48.8	0.168	0.0397	0.0428
H-3	0.162	0.106	0.0838	0.0323	<0.012	19.4	0.707	0.0141	0.0813
A-2	<0.0307	<0.1	0.0365	0.0689	<0.012	174	<0.0041	<0.0022	<0.0168
B-2	<0.0307	<0.1	0.0413	0.104	<0.012	11.4	<0.0041	<0.0022	<0.0168
C-2	0.0371	<0.1	0.0201	0.113	<0.012	10.9	<0.0041	<0.0022	<0.0168
D-2	0.321	<0.1	<0.011	0.743	<0.012	20.0	<0.0041	0.00760	<0.0168
E-2	<0.0307	<0.1	0.0446	0.0298	<0.012	0.718	<0.0041	<0.0022	<0.0168
F-2	0.467	<0.1	0.0291	0.899	<0.012	12.8	0.0393	<0.0022	<0.0168

ICP-OES Results Continued

Sample Name	mg/L Cu	mg/L Fe	mg/L K	mg/L Li	mg/L Mg	mg/L Mn	mg/L Mo	mg/L Na	mg/L Ni
A1	0.0140	<0.0128	22.4	0.0374	180	0.269	0.0331	4.54	0.00783
B1	0.0888	0.0722	7.91	<0.0261	5.12	1.55	0.0120	10.3	0.0118
C1	0.145	1.10	5.13	<0.0261	6.12	1.11	0.0279	8.96	0.0201
D1	0.0518	2.37	7.74	<0.0261	4.69	0.259	<0.005	0.817	<0.0054
E1	0.0400	0.0389	4.79	<0.0261	1.96	0.425	<0.005	11.7	<0.0054
F1	0.162	0.0867	5.19	<0.0261	1.32	2.68	<0.005	3.16	0.00808
G1	8.09	281	17.8	<0.0261	6.67	94.3	<0.005	1.77	0.130
Blank	0.00796	0.0162	<0.118	<0.0261	0.0148	<0.0164	<0.005	0.0573	<0.0054
G-2	4.59	113	7.62	<0.036	3.65	81.0	<0.009	0.734	0.0746
H-1	12.0	1222	0.240	<0.036	14.3	420	<0.009	2.09	0.0150
G-3	5.50	168	5.75	<0.036	3.62	124	<0.009	0.401	0.0698
G-4	4.73	152	4.26	<0.036	2.66	114	<0.009	0.261	0.0557
H-2	0.640	46.6	0.133	<0.036	9.86	466	<0.009	0.592	0.0282
G-5	5.38	242	2.51	<0.036	1.87	112	<0.009	0.207	0.0458
H-3	0.820	40.2	<0.131	<0.036	4.74	285	<0.009	0.340	0.0123
A-2	<0.006	<0.0176	8.25	<0.036	35.6	0.0274	0.0556	0.567	<0.0065
B-2	0.0113	<0.0176	3.54	<0.036	1.44	0.178	0.0104	2.38	<0.0065
C-2	0.0533	<0.0176	1.69	<0.036	1.45	0.100	<0.009	1.08	<0.0065
D-2	0.0736	0.340	5.11	<0.036	5.55	0.334	<0.009	0.221	0.00686
E-2	0.00932	<0.0176	0.931	<0.036	0.124	<0.157	<0.009	1.06	<0.0065
F-2	0.0812	0.0343	2.69	<0.036	0.745	2.04	<0.009	0.556	0.00808

ICP-OES Results Continued

Sample Name	**mg/L**	**mg/L**	**mg/L**	**mg/L**	**mg/L**	**mg/L**	**mg/L**	**mg/L**	**mg/L**	**mg/L**
	P	**Pb**	**Sb**	**Se**	**Si**	**Sr**	**Ti**	**Tl**	**V**	**Zn**
A1	<0.0195	<0.0204	<0.0198	<0.0167	3.11	1.69	<0.0105	0.0226	<0.0139	0.0535
B1	0.0487	<0.0204	<0.0198	<0.0167	4.21	0.251	<0.0105	<0.0183	<0.0139	0.0783
C1	0.0925	0.0593	<0.0198	<0.0167	6.83	0.203	<0.0105	<0.0183	<0.0139	0.187
D1	0.0331	<0.0204	<0.0198	<0.0167	8.35	0.160	<0.0105	<0.0183	<0.0139	0.170
E1	0.0258	<0.0204	<0.0198	<0.0167	6.22	0.111	<0.0105	<0.0183	<0.0139	0.190
F1	<0.0195	0.243	<0.0198	<0.0167	17.4	0.0568	<0.0105	<0.0183	<0.0139	4.10
G1	0.602	2.15	<0.0198	<0.0167	15.3	0.266	<0.0105	0.111	<0.0139	37.0
Blank	<0.0195	0.0731	<0.0198	<0.0167	0.222	<0.0069	<0.0105	<0.0183	<0.0139	0.0278
G-2	0.222	2.20	<0.0161	<0.0193	11.6	0.201	<0.0104	0.0834	<0.0127	21.4
H-1	<0.0168	3.45	0.100	<0.0193	5.68	0.0235	<0.0104	0.379	<0.0127	487
G-3	1.91	2.12	<0.0161	<0.0193	9.91	0.195	<0.0104	0.115	<0.0127	22.9
G-4	1.69	2.10	<0.0161	0.0250	7.76	0.151	<0.0104	0.109	<0.0127	19.3
H-2	0.0576	3.18	0.0174	0.192	4.41	0.0218	<0.0104	0.425	<0.0127	162
G-5	3.34	1.78	<0.0161	<0.0193	6.41	0.137	<0.0104	0.0935	<0.0127	18.9
H-3	0.0347	4.03	0.0329	0.121	3.32	0.0154	<0.0104	0.262	<0.0127	87.6
A-2	<0.0168	<0.0233	<0.0161	<0.0193	2.03	0.470	<0.0104	<0.032	<0.0127	0.00990
B-2	<0.0168	<0.0233	<0.0161	<0.0193	2.95	0.0812	<0.0104	<0.032	<0.0127	0.00603
C-2	0.0284	<0.0233	<0.0161	<0.0193	3.30	0.0583	<0.0104	<0.032	<0.0127	0.00966
D-2	<0.0168	<0.0233	<0.0161	<0.0193	6.34	0.197	<0.0104	<0.032	<0.0127	0.255
E-2	<0.0168	<0.0233	<0.0161	<0.0193	2.86	0.00787	<0.0104	<0.032	<0.0127	0.0213
F-2	<0.0168	0.133	<0.0161	<0.0193	13.3	0.0394	<0.0104	<0.032	<0.0127	2.77

11. Appendix E: In-Stream Precipitate Data (XRF)

11.1. Table E-1 XRF data for in stream precipitate samples for notable metals

Sample Name	Fe	Si	Al	S	K	Mn	Zn	Cu	Pb	As
	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm
GC-1	68840	138781	32907	2593	13372	17534	9431	334	395	118
GC-2	78146	52874	6944	1964	2209	25176	11922	372	531	88
GC-3	78035	74057	12662	2394	2974	8037	7512	379	399	121
GC-4	141665	121184	26537	2014	3756	17264	13516	626	764	137
GC-5	129491	59768	12061	2192	3980	40955	10486	478	979	167
GC-6	201349	26276	5417	654	807	6929	8751	809	782	165
GC-7	311607	84302	29448	2707	2243	40737	14395	926	1198	137
GC-8	146294	54259	11642	2015	3066	30332	5820	347	824	135
GC-9	175191	28033	6277	749	799	33646	6767	483	345	72
GC-10	223299	29352	5872	650	746	25456	4994	601	345	100
GC-11	158893	123186	34445	9849	4665	8089	12747	5598	5132	< LOD
GC-12	400948	7840	4414	16688	692	< LOD	416	584	2496	< LOD
GC-13	491922	7274	< LOD	96607	1308	< LOD	387	< LOD	664	91
avg	200437	62091	15719	10852	3124	23105	8242	961	1143	121
stdev	128805	44118	11631	26165	3364	12578	4549	1472	1327	31
rsd	64.3%	71.1%	74.0%	241.1%	107.7%	54.4%	55.2%	153.1%	116.2%	25.7%

11.2. Table E-2 XRF data (mg/kg) for Mn-oxide and Fe-oxide crusts on boulders in the streambed

SAMPLE	Crust type	Pb	As	Zn	Cu	Ni	Fe	Mn	Ca	K
Mean Error		48	43	425	79	85	1600	1499	566	399
GC1-A	MnOx	< LOD	< LOD	44778	203	< LOD	25301	202935	11688	2065
GC1-B	MnOx	< LOD	46	38059	342	< LOD	32660	184066	17533	3018
GC-2A	MnOx	214	< LOD	31933	131	< LOD	60313	151948	12498	2510
GC-2B	MnOx	< LOD	< LOD	52429	272	265	54857	256773	10716	1327
GC-3A	MnOx	107	46	18380	219	293	29443	140636	7514	3924
GC-3B	MnOx	< LOD	< LOD	59242	449	160	43023	296870	4604	2343
GC-4A	MnOx	281	84	12543	197	184	34703	81620	11568	7849
GC-4B	MnOx	458	112	3232	235	146	45960	23523	6905	26155
GC-5A	MnOx	229	46	10566	268	240	30984	93391	4872	8329
GC-5B	MnOx	533	111	22357	541	410	49691	157716	5776	5292
GC-6A	MnOx	926	176	7331	748	366	147290	49342	52	80
GC-6B	MnOx	660	129	12278	352	282	65981	100785	5388	4529
GC-6B	FeOx	513	304	3720	482	< LOD	154946	762	3742	1725
GC-7A	MnOx	329	91	13453	182	262	36460	140447	2319	6700
GC-7B	Mn/FeOx	376	81	6276	267	206	49074	63783	5286	15779
GC-7B	FeOx	566	249	4463	900	134	206007	1130	2440	628
GC-8A	MnOx	5074	762	3509	321	103	44193	64781	8076	5833
GC-8B	MnOx	416	161	23265	547	354	156186	156113	1084	1592
GC-8B	FeOx	509	314	8007	1822	< LOD	291524	1513	5711	619
GC-9A	MnOx	763	1006	28731	425	< LOD	84645	182461	5282	2995
GC-9A	FeOx	630	612	9146	1136	499	256127	57066	300	81
GC-9B	FeOx	592	131	5900	947	643	179223	41974	47	8
GC-10A	FeOx	56	< LOD	3234	481	332	114132	3156	13931	60
GC-10B	FeOx	154	373	4279	901	226	260197	7078	3316	1115
GC-11A	MnOx	700	166	12641	2996	235	25520	95808	15029	9182
GC-11B	MnOx	305	81	15640	1430	294	39553	88141	6198	1066
GC-12a	MnOx	797	181	9816	3599	267	45308	76277	9310	5105
GC-12B	MnOx	469	105	8225	1686	239	39255	68131	9922	11412

Note: Mn-oxide crusts were collected from the underside of boulders in the streambed.
Fe-oxide crusts were collected from the tops of boulders in the streambed.

XRF data (mg/kg) for Mn-oxide and Fe-oxide crusts on boulders in the streambed continued

SAMPLE	Crust	S	Te	Sb	Sn	Cd	Te	Ag	Ce	Al	Si
Mean Error		254	73	33	25	20	73	13	237	2229	1578
GC1-A	MnOx	1350	467	144	86	129	467	33	590	10986	25611
GC1-B	MnOx	1951	517	231	122	81	517	48	< LOD	14883	24280
GC-2A	MnOx	2266	680	270	149	129	680	61	< LOD	13611	34476
GC-2B	MnOx	1256	1106	< LOD	< LOD	73	1106	< LOD	1191	15550	27519
GC-3A	MnOx	1343	643	241	142	108	643	53	< LOD	15660	38396
GC-3B	MnOx	1942	894	< LOD	< LOD	90	894	< LOD	991	33303	46295
GC-4A	MnOx	1863	239	88	37	37	239	< LOD	451	11362	37093
GC-4B	MnOx	142	225	112	60	29	225	< LOD	14	1173	7040
GC-5A	MnOx	42	298	89	50	67	298	20	14	343	1623
GC-5B	MnOx	1602	489	194	102	104	489	53	< LOD	19324	36884
GC-6A	MnOx	101	817	< LOD	< LOD	< LOD	817	< LOD	12	366	1295
GC-6B	MnOx	2877	409	129	63	76	409	28	516	30512	73225
GC-6B	FeOx	1820	442	< LOD	< LOD	< LOD	442	< LOD	502	8769	50080
GC-7A	MnOx	1582	483	176	82	78	483	37	505	9109	37387
GC-7B	Mn/FeOx	3558	298	111	62	55	298	25	484	25723	114077
GC-7B	FeOx	889	614	< LOD	< LOD	< LOD	614	< LOD	529	9025	43333
GC-8A	MnOx	13361	272	97	44	46	272	19	744	22866	57169
GC-8B	MnOx	1763	1064	< LOD	< LOD	< LOD	1064	< LOD	798	13705	32621
GC-8B	FeOx	2115	612	< LOD	< LOD	< LOD	612	< LOD	2277	47447	109344
GC-9A	MnOx	9855	464	< LOD	< LOD	< LOD	464	< LOD	985	15842	48912
GC-9A	FeOx	198	714	< LOD	< LOD	< LOD	714	< LOD	80	1236	4308
GC-9B	FeOx	< LOD	752	< LOD	< LOD	< LOD	752	< LOD	11	< LOD	
GC-10A	FeOx	97	288	< LOD	< LOD	< LOD	288	< LOD	33	904	5206
GC-10B	FeOx	2472	879	< LOD	< LOD	< LOD	879	< LOD	1221	16892	67064
GC-11A	MnOx	< LOD	345	149	68	58	345	< LOD	491	< LOD	
GC-11B	MnOx	2175	411	154	102	55	411	28	295	3251	13759
GC-12a	MnOx	4560	351	132	79	67	351	23	533	21699	53941
GC-12B	MnOx	3889	323	117	46	43	323	23	390	21195	67021

11.3. Table E-3 XRF analyses of samples used in leachate studies (mg/kg)

SAMPLE	Cell #	Pb	As	Zn	Cu	Ni	Co	Fe	Mn	S	Al	Si
Blank (crucible)		24	< LOD	< LOD	< LOD	< LOD	< LOD	964	< LOD	429	n.a.	n.a.
Clendennin ppy	C	259	< LOD	679	315	< LOD	< LOD	23948	442	998	33413	264566
Galena Creek ppy	D	223	65	79	65	45	< LOD	10009	138	3198	76608	290211
Wolf ppy	B	119	< LOD	107	124	< LOD	< LOD	18816	685	1062	8658	91605
Hughesville Stock (fresh)	E	92	20	224	89	< LOD	291	32233	536	1099	43628	253531
Gold Run Tuff	A	95	32	315	148	152	< LOD	19918	572	361	3770	26884
Outcrop transect behind Block P	F	7116	461	351	408	131	< LOD	122071	2751	2976	6864	35949
QSP-altered Hughesville Stock	G	2267	347	1896	973	< LOD	370	55359	502	75267	48349	195659
Clendennin rerun	C	254	< LOD	508	331	187	< LOD	20779	523	85	2438	25407

12. Appendix F: Photographs

12.1. Figure F1 Representative Hand Samples for Leachate Experiments

Sample B: Wolf Porphyry

Sample G: QSP Altered-Hughesville Stock

Sample A: Gold Run Tuff

Sample C: Clendennin Porphyry

Sample E: Unaltered-Hughesville Stock

Sample H: Mineralized Rock-Block P

Sample D: Galena (Quartz) Porphyry

Sample F: Vein Transect-Block P

SIGNATURE PAGE

This is to certify that the thesis prepared by Austin C. Neaville entitled "Post-Reclamation and Pre-Mining Geochemistry of the Galena Creek Watershed in the Barker-Hughesville Mining District, Judith Basin County, Montana" has been examined and approved for acceptance by the Department of Geological Engineering, Montana Technological University, on this 12 day of May, 2021.

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