AN ASSESSMENT OF THE NATURAL AND ANTHROPOGENIC GEOCHEMISTRY OF THE RED MOUNTAIN CREEK WATERSHED: IRONTON MINING DISTRICT, COLORADO

A Thesis

by

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ABSTRACT

Red Mountain Creek is located in the rich mineralized San Juan Mountains of Southwestern Colorado, where mining from the mid 1800s through the late 1970s occurred. Sampling of the Uncompahgre River in the late 1970s, which is downstream of the five tailings ponds, showed high levels of heavy metals. It was assumed the remaining mine tailings were responsible for the high concentrations of heavy metals in the waters down-valley from the deposits. Thus, in 1983, remediation began with the use of direct re-vegetation of the deposits. This remediation was required as a result of National laws, which mandated the state of Colorado and the Idarado Mining Company develop a Remedial Action Plan (RAP). Interestingly, the tailings were assumed to be the sole source.

Studies over the past twenty years, have suggested for site-specific locations, the highly mineralized zones may be additional sources of inputting heavy metals into streams. We assumed that heavy metal concentrations found in the streams come from the weathering of highly complex mineral assemblages, as well as from mining activities. It was our objective to establish the geochemistry in streams in the areas above and below mining activity and remediated areas and to evaluate the impact of remediation. Water quality data were collected for Aluminum (Al), Cadmium (Cd), Copper (Cu), Iron (Fe), Lead (Pb), Magnesium (Mg), Manganese (Mn), Zinc (Zn), and temperature, specific conductance, pH and dissolved oxygen.

Twenty-seven samples were filtered with a 0.45μm membrane filter and twenty-seven were left unfiltered. Samples were collected in-stream after determining discharge for each stream. The samples of RMC were evaluated by using a Shapiro-Wilks test. There is a definitive difference between pH and dissolved metal concentrations when comparing streams on the east side to west side. In addition, there were five distinct confluences with Red Mountain Creek that provided significant changes in water quality. This was due to hydrothermally altered bedrock, which had and had not been mined.

DEDICATION

To my family and friends who have been there for me and helped me struggle through the graduate experience.

ACKNOWLEDGEMENTS

First and foremost, I thank my parents, for giving me that drive for success, for without them, achieving such high goals would have been difficult. A big thanks to my girlfriend, Keya, for being there for me constantly and for pushing me in times of despair and in times of joy. Thanks to my friends, who helped provide comic relief and for pushing me through.

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I must thank Larry Fiske of Newmont Mining for setting me up with the right people to conduct my research, as well as giving me access to their property. Thanks to Alfred Berry, who runs and manages the Idarado Mining Company, for also giving us access to their property, but for also setting up a tour of the Idarado property. Thanks to Joe Smart, who provided a very useful and insightful tour for my colleagues and myself and for recommending a visit to the old one hundred mine in Silverton. Thanks to Sherm Worthington, for helping me set realistic sights for sample locations and for providing an environmental engineer to sample with us. A big thanks goes to Devon Horntvedt, who taught me so much about field sampling and about the mining in the area. Without your tour and driving, I would still be grounded. Thanks for catching a discharge error, that no doubt saved most of my research. Without your equipment, my legs may still be stained orange.

NOMENCLATURE

RMC	Red Mountain Creek
AMD	Acid Mine Drainage
NARD	Natural Acid Rock Drainage
CWQCC	Colorado Water Quality Control Commission
FA	Filtered Acidified
RA	Raw Acidified

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1. INTRODUCTION AND PROBLEM STATEMENT

Acid mine drainage (AMD) is a major environmental concern and has impacted areas around the world (Hudson-Edwards et al., 2011; Kimball et al., 2002). In the United States, which leads remedial efforts, AMD can be found in every state (BLM). In the western United States, more than 40% of all watersheds have their headwater streams affected by inactive hard-rock mining and AMD produced (von Guerard et al., 2007). Western states include: Nevada (Price, 1995), California (Nordstrom, 2011), Arizona (Brown et al., 1993), Montana (Church et al., 2004), and Colorado (Church et al., 2007). In Colorado's San Juan Mountains, the landscape is littered by the remnants of historical mining and AMD still being produced (Church et al., 2007). Anthropogenic impacts can be felt in streams, rivers and watersheds (Kimball et al., 2002; Runkel et al., 2005). Areas affected by AMD are often located in complex systems in which geochemical and hydrologic processes interact to determine the transport and fate of dissolved metals (Runkel et al., 2005). In addition to anthropogenic effects, hydrothermally altered rock assemblages in these mineralized areas, can have greater impacts on water quality (Neubert et al., 2011; Runkel et al., 2005). Red Mountain Creek (RMC-Figure1) is located in such an area, where both mining and hydrothermal alteration has impacted the water quality. Determining whether dissolved metal concentrations are due to the leaching of surrounding geology or whether it is the product from mining is a difficult task. Are the remediated tailings the sole source of dissolved metal concentrations in Red Mountain Creek, or are there additional sources?

It is the goal of this research to provide an understanding of the relationship between natural and anthropogenic contamination of surface waters.

1.1 Objectives and Questions to be Answered

To accomplish the goal for this thesis, the following objectives were established: 1) Establish the geochemistry in streams above all mining activity, as well as, above remediated areas; 2) Establish the aqueous geochemistry below the mining activity; 3) Evaluate the impact of remediation on the geochemistry of the water.

The following are questions need to be answered in order to determine if the objectives were completed.

1) When dealing with Natural Acid Rock Drainage (NARD) vs. Acid Mine Drainage (AMD), is it possible to proportion them? 2) What is the difference between the mined areas and non-mined areas of both the east and west side of the watershed? 3) Does geology control the geochemistry of the stream?

Red Mountain Creek: Sample Locations

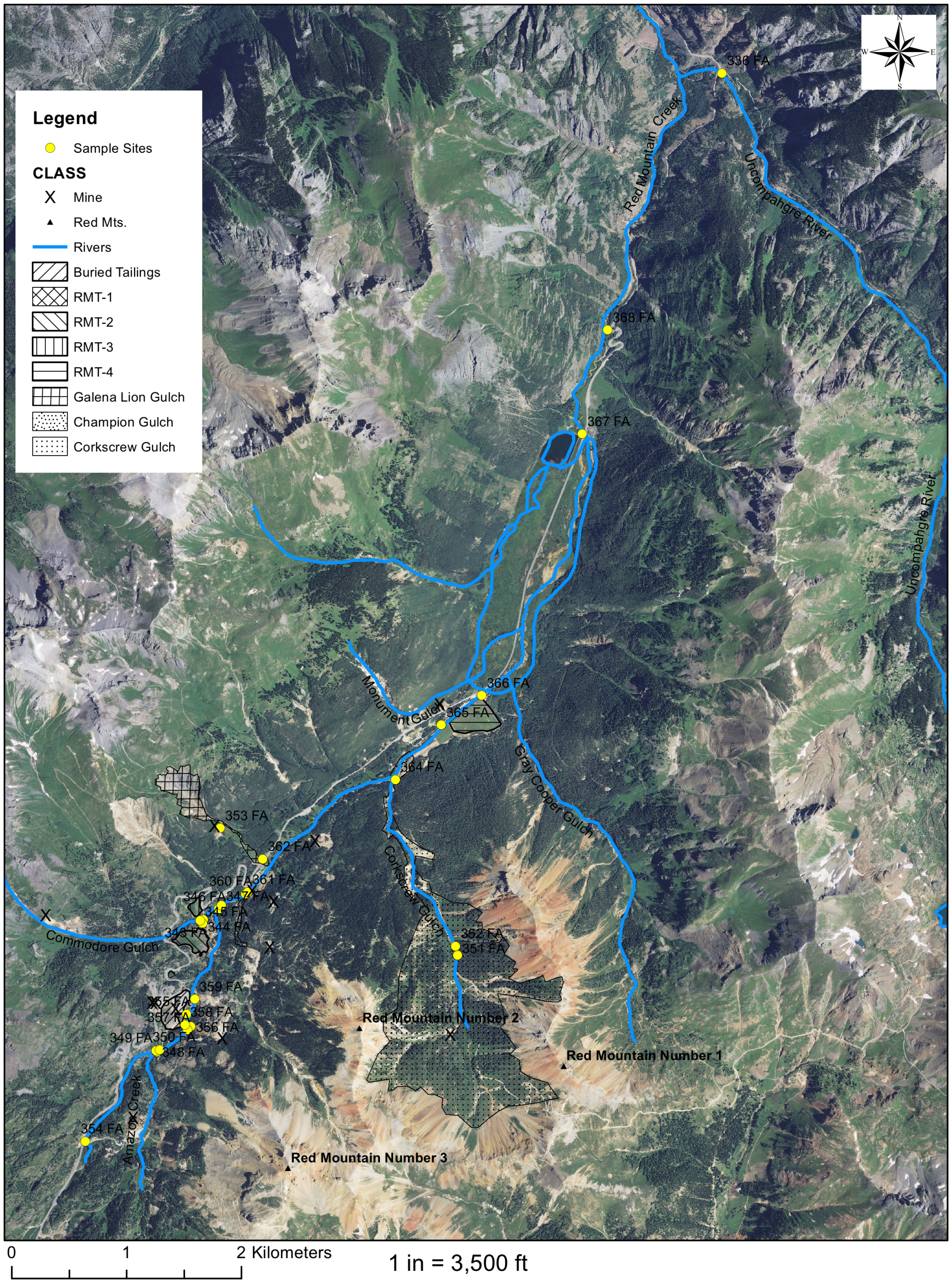


Figure 1. Location of Red Mountain Creek, including 27 Sample Sites, Tailings, Gulches, and Mines

2. STUDY AREA

Red Mountain Creek (RMC) is located in the Southwestern part of Colorado in the San Juan Mountains, in Ouray County. More specifically, RMC is situated between 37°54’30”N, 107°42’0”W and 37°59’30”N, 107°39’30”W. RMC flows through the Ironton, Colorado NW/4 Silverton 15 Quadrangle at N3752.5—W10737.5/7.5 (USGS, 1955). There are two watersheds of focus here: Red Mountain Creek and the Headwaters of the Uncompahgre River. The RMC watershed covers 55 km^2 and the Uncompahgre 105 km^2 as seen in Figure 2. In the RMC watershed, the lowest elevation is 2516.85 m (8,257.8 ft) and the highest is 4202.9 m (13,789.7 ft) as shown in Figure 3. There are multiple streams that flow into RMC, coming from both sides of the watershed. On the west side, streams come from Galena Lion Gulch and from Commodore Creek. On the eastside, there is Amazon Creek, Champion and Corkscrew Gulch. These five were originally thought to have significant effects on water quality.

2.1 Geologic History

The tectonic setting of the San Juan Mountains is one of complex histories. During the Precambrian, the Southwestern part of Colorado was believed to have been part of volcanic arcs (Blair, 1996). By early to mid Paleozoic time, it had become a continental shelf and by the Pennsylvanian Period, this area had two uplifts and two blocks (Blair, 1996). Then in the late Cretaceous, the Laramide Orogeny creates large scale deformation and volcanism (Blair, 1996). By the Early Cenozoic, the Southwestern part of Colorado, a place which now includes the San Juan Mountains, lies in an explosively volcanic locale. This is due to the subducting plate angle becoming more steep and allowing more magma to rise in response to more open space above (see Fig. 2.9 in Blair, 1996). Tertiary volcanism is dominant until the Pleistocene, where the shift in the San Juan Mountains is to glaciation. From the Pleistocene to Holocene (~ 2 million years), the San Juan Mountains have experienced fifteen or more glacial advances, but only six have been recorded by their deposits (Blair, 1996), due to each glaciation removing the previous ones remains. The date of when glaciation invaded the San Juans remains unknown. In order for glaciers to grow, ice accumulation must exceed ice wastage (ablation) rates, and the boundary between the ablation and accumulation zone is called the Equilibrium Line Altitude (ELA), which determines where the permanent snow line is found in the highest mountain ranges (Blair, 1996). In 1996, the ELA was between 12,200-12,300 feet (Blair,1996). During the last glaciation, ~ 18,000 years ago, the ELA was at 10,200-11,300 (Blair, 1996). This allowed glaciers here to form into full-grown glaciers, able to have an ice field covering ~1,900 mi^2 (Blair, 1996). When de-glaciation commenced, the ELA rose in elevation, and glaciers rapidly disappeared, leaving a few north facing cirques with small glaciers (Blair, 1996). Glacier retreat has left huge scars on the landscape in the San Juan Mountains. Erosion has created the U-shaped valleys and canyons, steep-walled mountains, hanging valleys, horns, cirques, and arêtes (Blair, 1996). In addition, to the U-shaped valleys, both lateral and terminal moraines were left, often creating proglacial lakes (Blair, 1996). These often filled with glacial outwash and sediments and have formed the floors of many valleys in the area (Blair, 1996). Multiple glaciations has affected the area, such that landslides, mudslides and rock slides are all common occurrences here.

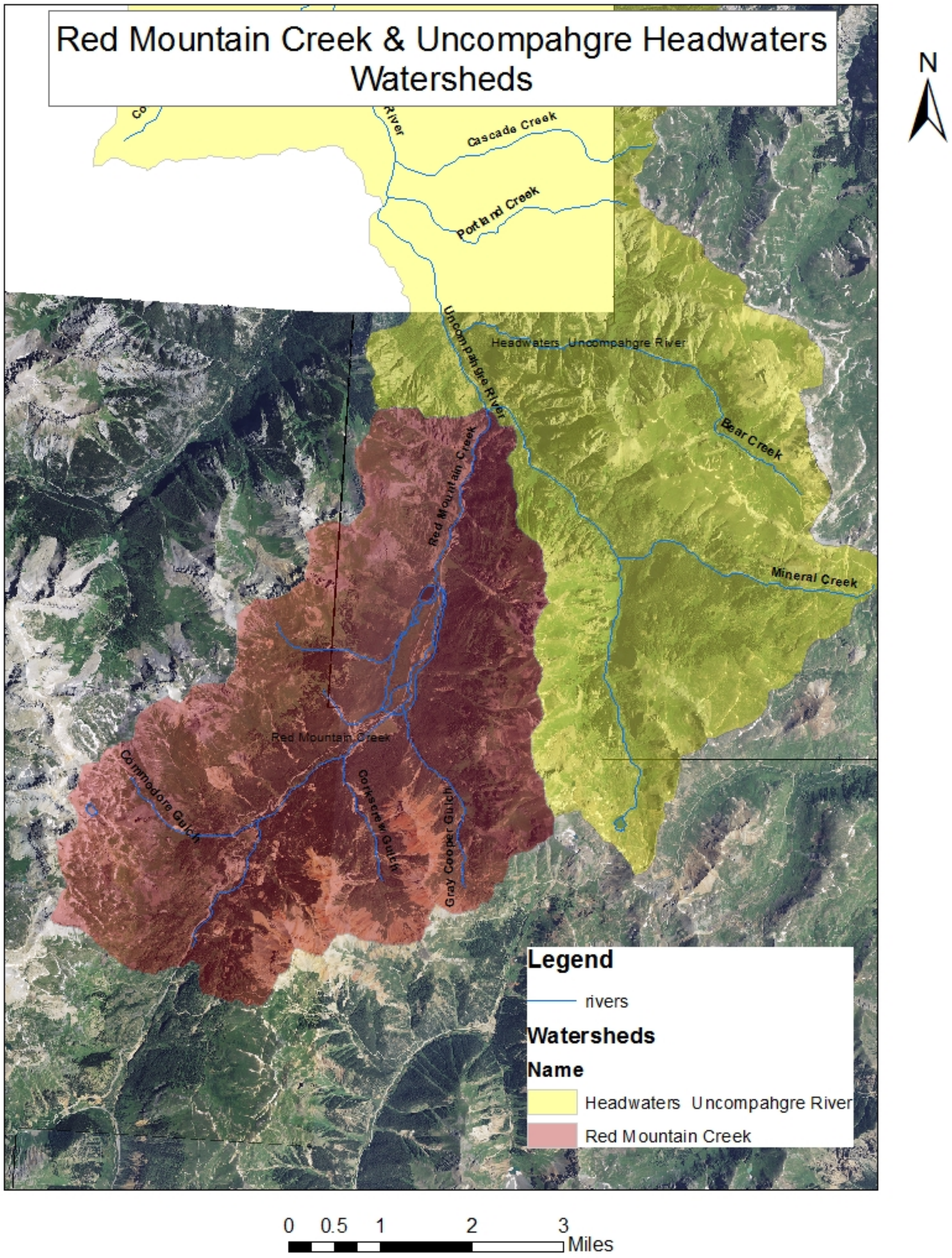


Figure 2. Location of both Red Mountain Creek (55 km^2) and the Uncompahgre River (105 km^2) Watershed

Terrain & Topographic Map of the Ironton Mining District

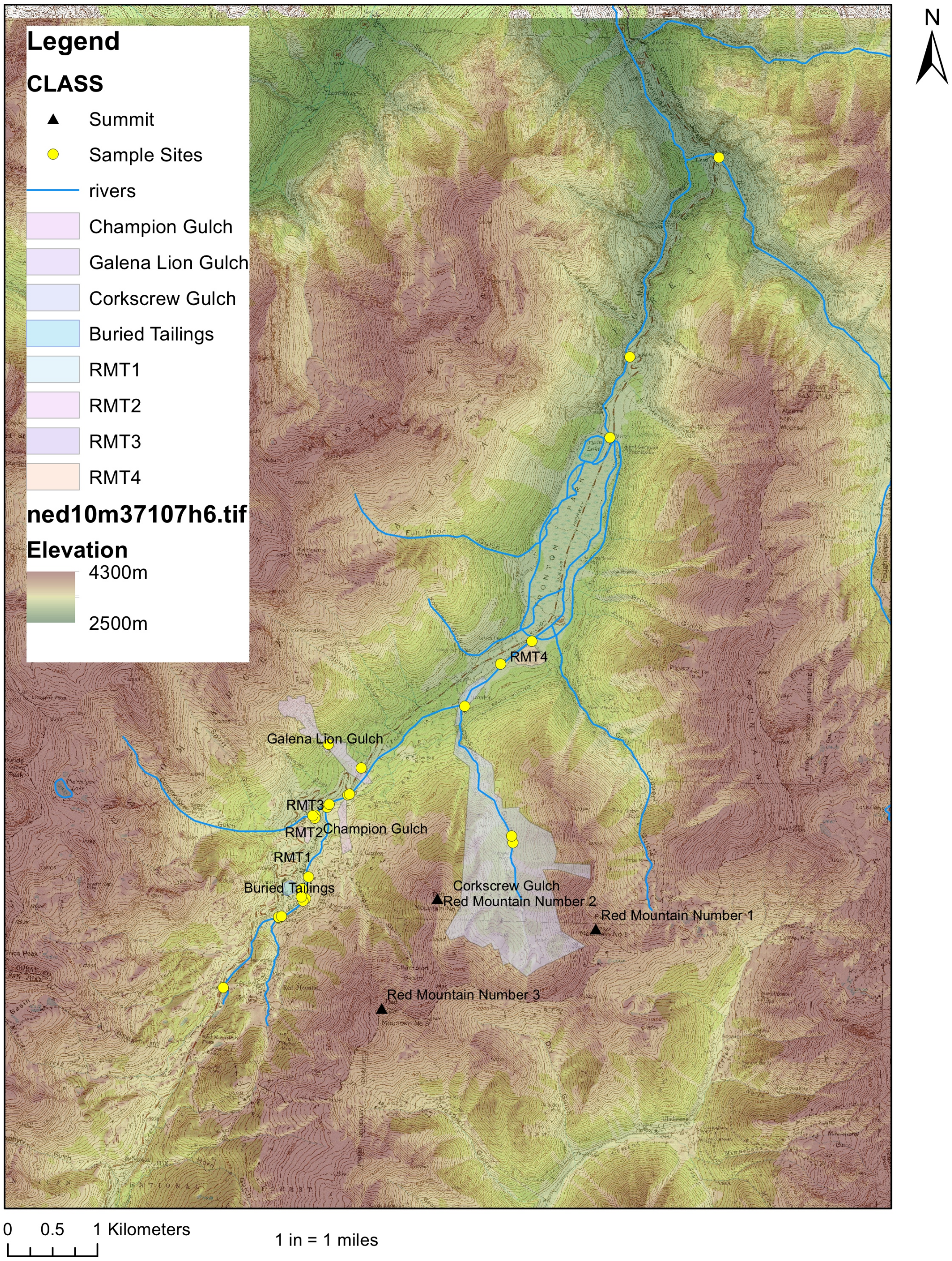


Figure 3. Elevation map of sample sites, gulches, tailings, and mountains

2.2 Units

In this study area the units are explained oldest to youngest. The oldest rocks are Precambrian, undifferentiated, (pCu) quartzite, argillite, and gneiss (Yager and Bove, 2002). Next is MDu, undifferentiated Leadville and Ouray limestones of Lower Mississippian to Upper Devonian in age. Phm is undifferentiated Hermosa and Molas formations of the Pennsylvanian Period, and contain shale, conglomerate, and sandstone (Yager and Bove, 2002). The Telluride conglomerate (Tt) and is Eocene in age (Yager and Bove, 2002). The Cenozoic is most important to this study area and will be dealt with more detail below.

There are two units that are extremely important when looking at this study area. Tsj and Tsv split the area in two and are split by RMC as seen in Figure 4. Unit Tsj, represents the San Juan Formation (Lower Oligocene) and it is an intermediate composition lava flow with volcaniclastic deposits, which consist of mudflow breccia with volcanic clasts, containing sandstone and conglomerate, and often has hornblende in it (Yager and Bove, 2002). The Silverton Volcanic Group (Tsv) (Oligocene), are lava flows of intermediate to silicic composition, and related volcaniclastic sediments that accumulated within and adjacent to San Juan and Uncompahgre calderas post-collapse, and pre-subsidence of the Silverton caldera (Yager and Bove, 2002). The Silverton Volcanic Group is broken into three different members. The first is called the Henson Member, and is composed of volcaniclastic sedimentary rocks such as tuffaceous sandstone and mud-flow breccias (Yager and Bove, 2002; Moore, 2004). The second is the Burns Member, and this is a porphyritic andesite to rhyolite flow (silicic composition

(Moore, 2004)) (Yager and Bove, 2002). The third and final member is called the pyroxene andesite member (Moore, 2004). In the regions of Tsv, the propylitic alteration type is found. The next unit is found from Oligocene to Miocene, and is called Tid or dacite intrustions, as the dacite is porphyritic and can be seen at the National Belle mine (Yager and Bove, 2002). The following three units are Quaternary deposits. Qtg, is talus, glacial deposits, and rock glaciers from the Pleistocene to Holocene, as is Qcl, which is colluvium and landslide deposits. Qal is alluvium from only the Holocene.

2.3 Alteration History

The San Juan Mountains are primarily Tertiary volcanic rocks with hydrothermal alterations (Neubert, 2011). Initial volcanic activity was andesitic and began about 35-40Ma (Neubert et al., 2011). Around 30Ma, volcanic activity became silicic and the San Juan caldera (28.2Ma) and Silverton caldera (27.6Ma) formed (Neubert et al., 2011 & Bove, 2000, 523-533). Multiple events of intrusive activity, resurgent doming, and subsidence caused numerous faults and fractures to form, both adjacent and within these two calderas, creating weak zones and providing channels for hydrothermal fluids (Neubert et al., 2011). Post-Silverton caldera (6-10Ma), silicic magmas associated with metal-rich hydrothermal fluids intruded these weak zones. Along the NW rim of the Silverton caldera, lie the Red Mountains (see Figure 5) (see Fig. 2 in Neubert et al., 2011), where hydrothermal fluids deposited economic grade metallic minerals and altered surrounding bedrock (Neubert et al., 2011). The Red Mountains are hydrothermally altered and consist of acid-sulfate (AS) and quartz-sericite-pyrite (QSP) assemblages (Runkel et al., 2005).

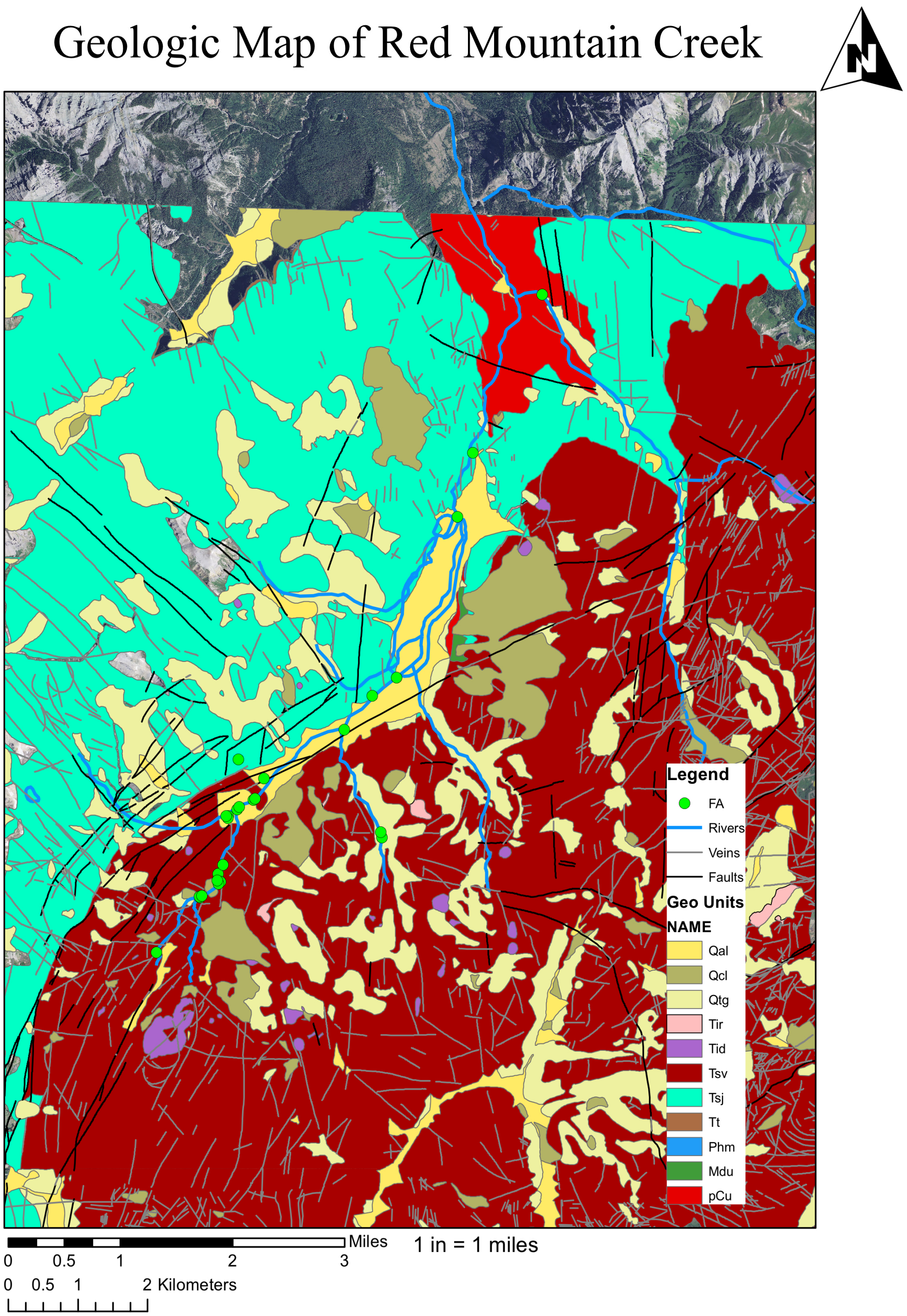


Figure 4. Geologic map showing the clearly marked split between the west side of RMC and the east side. Along RMC, is the Silverton caldera rim

Figure 5. View looking at Red Mountain #2 (left), and Red Mountain #3 (right) and Champion Gulch in between

These assemblages are associated with having up to 15% finely disseminated pyrite, and weather to red, maroon, orange, and yellow (Neubert et al., 2011; Runkel et al., 2005). Waters here have very high metal concentrations and are very acidic (Bove et al., 2007). When sulfide minerals like pyrite (FeS_2) react with atmospheric oxygen and water they begin a chemical reaction process, which leads to the production of natural acid rock drainage (Neubert et al., 2011). There are four reactions that take place to create natural acid rock drainage. Pyrite reacts with air and water to produce ferrous iron, sulfate, and acid ($FeS_2 + 7/2O_2 + H_2O \rightarrow Fe^{2+} + 2SO_4 + 2H^+$) (Neubert et al., 2011). Next, ferrous iron is oxidized to ferric iron ($Fe^{2+} + 1/40 + H^+ \rightarrow Fe^{3+} + 1/2H_2O$)

(Neubert et al., 2011). The ferric iron reacts with pyrite and water to produce a large amount of acid ($FeS_2 + 8H_2O + 14Fe^{3+} \rightarrow 15Fe^{2+} + 2SO_4 + 16H^+$ (Neubert et al., 2011). Last, the ferric iron meets water to become precipitated out of solution (hydrolyzed), and produce more acid ($Fe^{3+} + 3H_2O \rightarrow Fe(OH)_3 + 3H^+$ (Neubert et al., 2011). The west side of RMC is propylitically altered, which consists of calcite, epidote, chlorite, and magnetite (Neubert et al., 2011; Runkel et al., 2005). Because this alteration assemblage is associated with circumneutral waters and low metal concentrations, a very sharp contrast between the west and east side of the watershed can be seen in Figure 6 (Neubert et al., 2011; Nordstrom, 2011; Runkel et al., 2005).

2.4 Climate

Precipitation for Ouray shows summer months with rain and in winter months snows (WRCC). There is a correlation of warmer temperatures in the summer and colder in the winter, shown in Figure 7. In addition, summer months have lower precipitation compared to the high amount of precipitation in the winter months (WRCC). The warmer summer months often experience thunderstorms in the afternoons.

2.5 Colorado Mining Belt and Anthropogenic Impacts

The Colorado Mineral Belt (as seen in Fig. 13 in Moore, 2004) is a Northeast-Southwest trending, Laramide age, mining rich stretch of land. The San Juan Mountains, 10-26 Ma became mineralized and hydrothermally altered (Bove et al., 2000). The Red Mountains lie along the northwestern rim of the Silverton caldera (as seen in Fig. 2 in Neubert et al., 2011), where brecciated pipes and faults have produced metallic minerals of economic grade (Neubert et al., 2011).

Hydrothermal Alteration Map of Red Mountain Creek

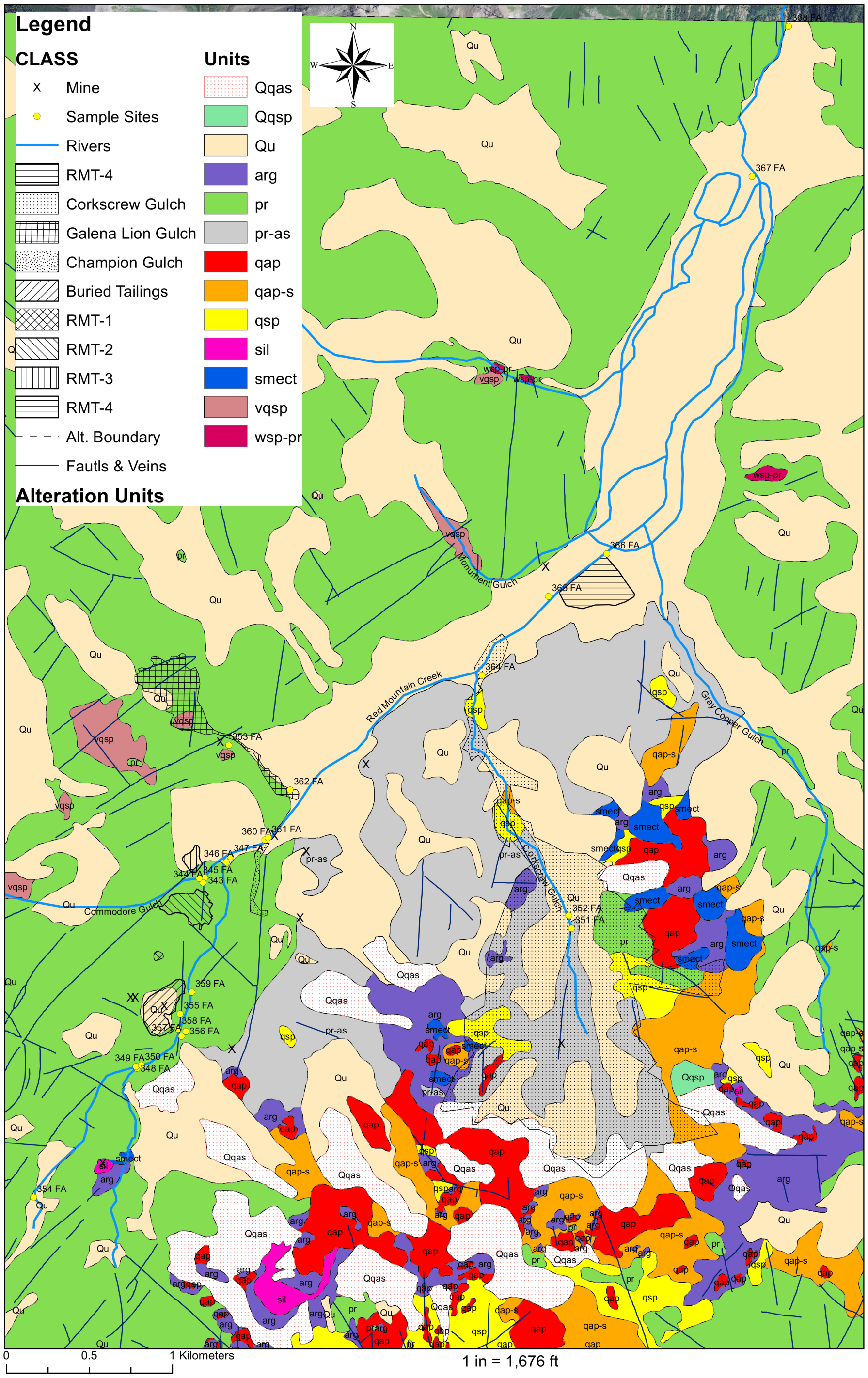


Figure 6. Hydrothermal alteration map. Notice how west of RMC is dominantly propylitic compared to the east, which is a mixture of acid-sulfate assemblages that contain pyrite

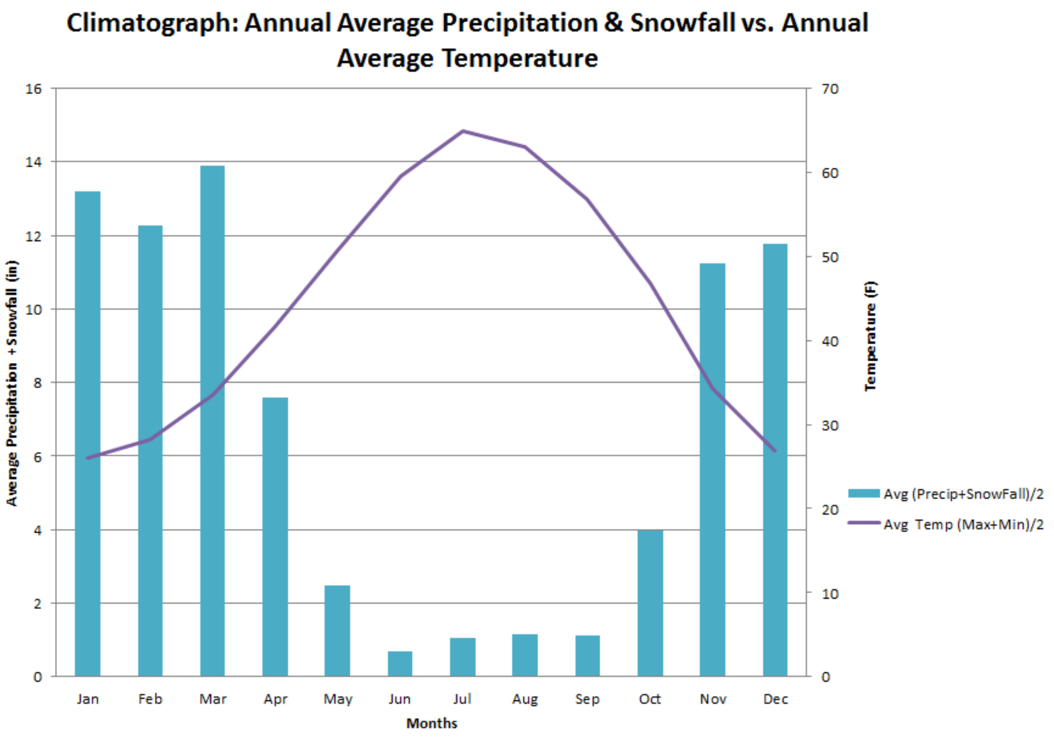


Figure 7. The climate for Ouray (WRCC)

At Idarado, the vein named the Montana-Argentine was ~16,000 feet long and 6 feet wide, and contained large amounts of gold, silver, lead, iron, and zinc (Blair, 1996; Hillebrand, 1957).

In Ouray County, there are 168 mines, with approximately forty-five mines in the RMC watershed. Mining in this area began in the mid 1800s, and continued until 1978. The Idarado Mining Company mined gold and silver and eventually lead, zinc and iron (Hardy, 1999). In 1983, the state of Colorado filed CERCLA against the mining company for natural resource damage to the environment. A Remedial Action Plan (RAP) was developed by the state of Colorado and the Idarado Mining Company. It required the five tailings piles be remediated, as they believed to be the sole source for the high metal concentrations downstream. All of the tailings piles lie along RMC, and acid mine drainage here has had huge environmental impacts. Direct re-vegetation of all five piles commenced and initial remediation has been completed (Hardy, 1999).

3. LITERATURE REVIEW

The geology and geochemistry of RMC has had limited studies over the past fifty years. The USGS did a synoptic sampling study and the Colorado Geological Survey did a section of a book on the Red Mountains. Though the published papers here are limited, if the Animas River watershed is looked at, one can see there is an abundance of studies. These studies and their research can be applied to the RMC watershed. Both watersheds deal with water quality problems due to historical mining, acid mine drainage, and natural acid rock drainage (Church et al., 2007; Kimball et al., 2002; Mast et al., 2007; Nordstrom and Alpers, 1999; Runkel et al., 2005; Wright et al., 2007). Mining activity in this region often led to exposure of sulfide deposits, when brought to the surface, which in turn weathered and produced acid mine drainage (Plumlee et al., 1999; Yager et al., 2000). Acid mine drainage (AMD) refers to when waters drain tailings, underground mines, waste rock and open pits into surface streams (Nordstrom and Alpers, 1999). AMD waters generally have low pH values ranging from five and below with high dissolved metal concentrations such as Al, Cd, Cr, Cu, Fe, Ni, Pb, and Zn (Nordstrom and Alpers, 1999; Nordstrom, 2011).

Water quality not only depends on mining, but the geology of a watershed often is most important as it can dictate pH and dissolved metal concentrations, from weathering and alterations (Wright et al., 2007). The geology of the Red Mountain Creek/Ironton Quadrangle shows that on the west side of the watershed, there is the San Juan Formation compared to the eastside Silverton Volcanics Group (Yager and Bove, 2002). In addition, this quadrangle has been hydrothermally altered to have mineral assemblages rich in sulfides, such that when weathered, it produces natural acid rock drainage (Neubert et al., 2011). Quartz-sericite-pyrite (QSP) altered rock, typically has low pH and high dissolved metal concentrations, compared to propylitic altered rock, which has more neutral pH, and low metal concentrations (Mast et al., 2007; Runkel et al., 2005). Pyrite oxidation often leads to lowered pH, which adversely affects water quality of streams by leaching major and trace metals into it (Verplanck et al., 2009). The distribution of dissolved trace metal concentrations and pH in streams vary greatly in the Animas River (Wright et al., 2007). The presence of mines or mining activity near streams does not necessarily mean, low pH and high dissolved metal concentrations, but does not mean the opposite could be expected (Wright et al., 2007). The presence of mining and associated activities along with the background geology and alteration assemblages present create a unique environment, where the mixing of neutral and acidic waters may be based solely on mining (Wright et al., 2007). However, it may be a result of the geology or of the alteration types that have occurred. When examining the results, one must look at the un-mined areas of altered rock in addition to the areas of mining activities in order to have a more complete understanding of what is significantly affecting the water quality (Mast et al., 2007).

4. METHODS

A total of twenty-seven samples were collected in the field area for analysis (seen in Figure 1). Overall, there were fifty-four samples as each sample can be considered as two samples. Each sample was split into the following two categories; Filtered Acidified (FA) and Raw Acidified (RA). This was a way to easily identify and mark each sample (Runkel, pers. comm., 2013). The majority of the study focuses on RMC, and the gulches that flow into it. The study also focuses on the FA samples. Upon arrival to the Ironton Mining District, it was discovered Governors Gulch was dry which led to sampling at Champion Gulch and Commodore Gulch, in order to maintain consistent sample sites, and to keep sample size at twenty-seven.

4.1 Establishing Both the Aqueous Geochemistry in Streams Above and Below Remediated Areas

4.1.1 Determine Parameters

There are five parameters that must be measured and calculated. In addition to these five, identifying, which metals are of interest, can make a difference. The first order of measurement is calculating discharge. To determine whether or not a stream or seep has an affect on its' confluence, discharge is required. When dealing with streams, there are a couple of things that are required to do, in order for calculations to be made. The equipment used in order to do this was a tape measure and a Sontek/YSI FlowTracker Handheld Acoustic Doppler Velocimeter (ADV) with a measuring rod

(Figure 8 A and B). At a given stream with two people, one person measures the width, with the tape measure.

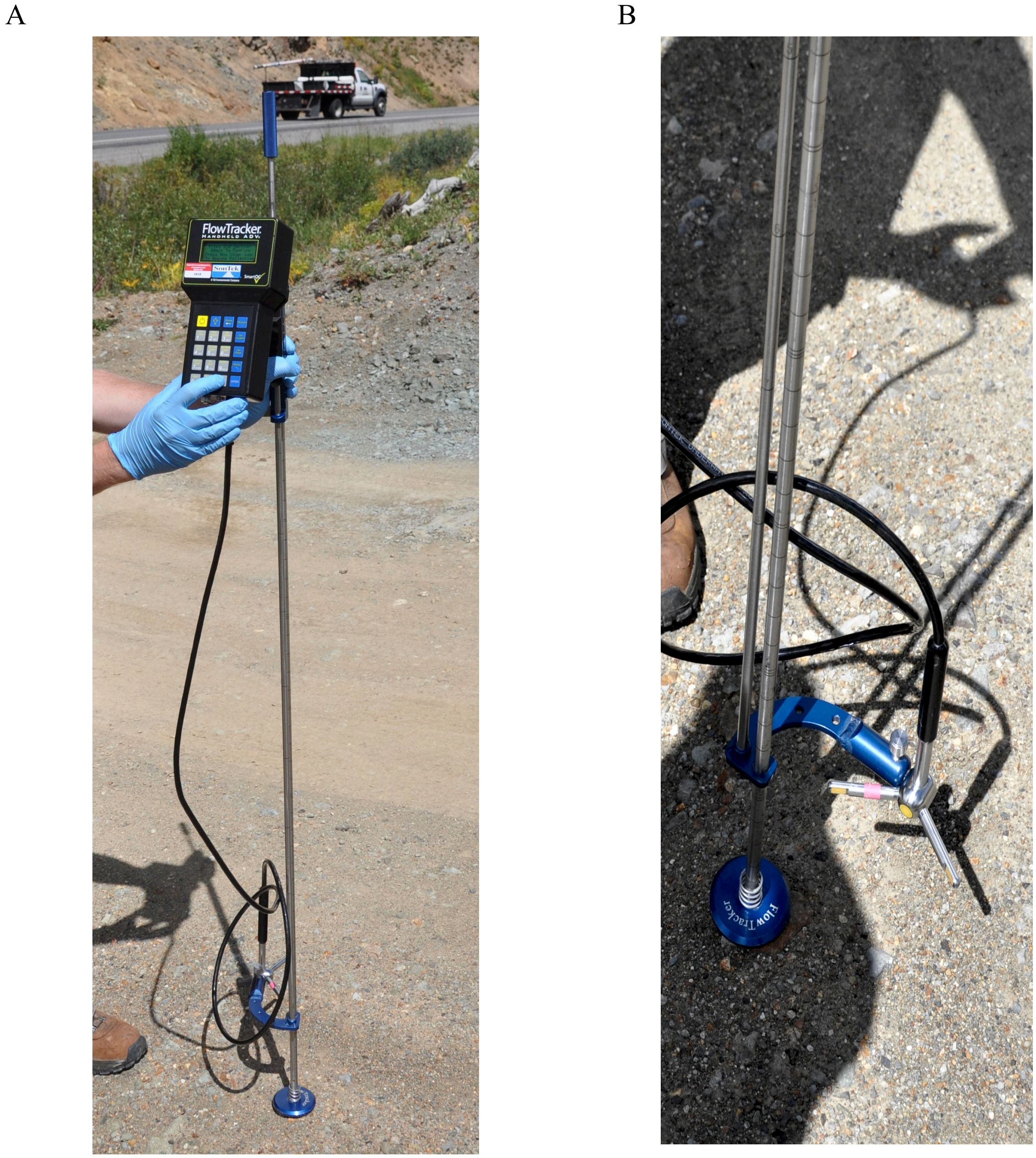


Figure 8. Photos of the Sontek/YSI FlowTracker Handheld Acoustic Velocimeter (ADV) with measuring rod. A) Equipment as a whole. B) Close-up of the 2 prong ADV

Taking note of where bank 1 and bank 2 is will provide the width and indicate the interval at which measurements should be taken. Large widths would be marked with stations at every foot, while smaller widths would have stations every half-foot. This would provide enough stream measurements that a complete cross-sectional area could be determined. At each foot or half-foot station, place the ADV, such that the base is on the stream bottom. Attached to the measuring rod, is the ADV, raise or lower it until it is at just below the water level. Mark the depth down in the field notebook for that sample number. Making sure the rod is straight by checking to see if the bubble is within the circle as well as having the ADV facing upstream (Figure 9). The FlowTracker measures the average velocity over ten seconds. With velocity at each station, and having station width and depth, calculation of discharge can occur. Q = va and a being area (width x depth) and v being velocity discharge for each area is determined. Summing them will provide the total discharge for that stream. In the case of seep where there are small discharges, using a quantified container over a specific amount of time will provide sufficient data to calculate discharge (Ficklin and Mosier, 1999). The next four parameters (temperature, dissolved oxygen, specific conductance and pH) were all determined by using a YSI Pro Plus with a quatro cable.

Temperature is an important first parameter of the four. It can affect the ability of water to hold oxygen. Because it can affect dissolved oxygen it is a parameter that is required. Dissolved oxygen (DO) is the second parameter was measured as it provides information on the water quality and on the health of the water. Slow stagnant waters tend to have low DO compared to fast moving waters with higher DO, however for this studies data, this general rule does not apply. Nor does it apply to cold-water holds more DO than warm.

Figure 9. Using the FlowTracker and measuring tape at Sample 368

The third parameter is specific conductivity and is measured in micro-siemens/cm (μS/cm). Specific conductance provides the concentration of total dissolved solids (TDS) (Ficklin and Mosier, 1999). In addition, when stream discharge is high, specific conductivity is low and when discharge is low, conductivity is high as seen on the USGS Water Science School. The fourth parameter is very important and it is pH. When pH is approximately 7, it usually is considered neutral, but for this study, values around 7 to 8 are considered circumneutral (Runkel et al., 2005; Nordstrom, 2011). A pH less than 7 is considered acidic while pH above 8 is considered basic. The lower a pH, the higher the dissolved metal concentrations are and when pH is high, dissolved metal concentrations decrease (Wright et al., 2007). Dissolved metal concentrations are very dependent on pH as it determines whether a metal will precipitate or dissolve in a given stream. Given that certain metals precipitate and adsorb at certain pH values and that certain metals are associated with mining related activities, the following eight have been chosen: Aluminum (Al), Cadmium (Cd), Copper (Cu), Iron (Fe), Lead (Pb), Magnesium (Mg), Manganese (Mn), and Zinc (Zn).

4.2. Sampling Protocols

4.2.1. Sample Equipment

Samples were taken in new 250 ml polypropylene bottles, provided by Dr. Franco Marcantonio. Each field sample had approximately 250 mL and later would be filtered and acidified (filtering and acidifying post-field sampling will be discussed in section 4.2.3. In order to determine what the concentrations were for dissolved metals only, this study used a 0.45 micrometer (µm), 33 millimeter diameter, PolyEtherSulfone (PES) membrane filter, from Millipore, in order to allow the maximum volume of water to be filtered, while allowing for less time consumption. The use of a 0.45 µm filter is a set standard used by USGS, and is required for the EPA (Ficklin and Mosier, 1999; Neubert et al., 2011, 5; Runkel et al., 2005, 5; Wright et al., 2007, 524). In order to have excellent time management, use of 60 ml reusable syringes with Luer-lock tips were used. The 60 ml syringes provided the maximum volume of water that could be at one given time. Luer-lock tips provide a much more secure attachment to the filters which nicely screw into the syringe. Two gallons of deionized (DI) water were purchased at Walmart in Durango, Colorado. Deionized water is an extremely important piece of equipment that is required for any sampling and it will be discussed more in section 4.2.3. When a stream is narrow, or to collect samples from a broad stretch of stream, water was collected using a half-gallon plastic milk jug, that had the bottom and two sides partially removed. This acted as a water grabber (Runkel, pers. comm., 2013). Also, using powder free nitrile examination gloves to do the many tasks required is essential.

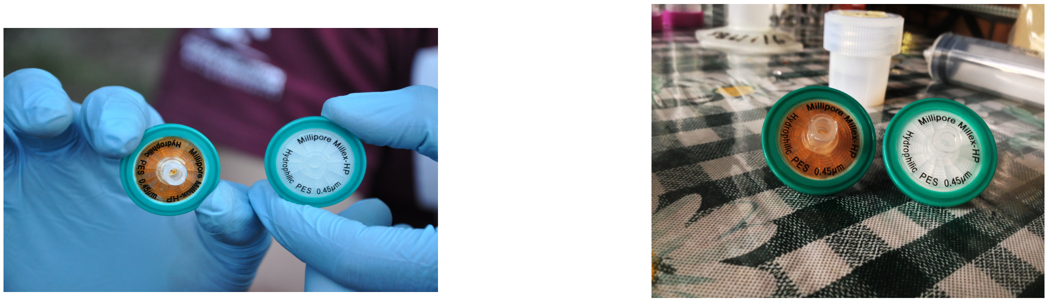
4.2.2 Field Sampling

Field sampling required a variety of different tasks be done prior, during and post sampling. Post sampling will be discussed in section 4.2.3. This section deals with calibration of the YSI Pro Plus and how to take all four of the parameters wanted, how to collect of water samples, necessary equipment and how to deal with shallow streams where the YSI will not fit. Prior to fieldwork it is necessary to make sure all necessary equipment is ready to go as well as knowing where sample locations might be. Calibration of the YSI Pro Plus consisted of three different parts. The first was to use a three point pH calibration at four, seven and ten. The second was to calibrate dissolved oxygen and this was done by using a water saturated air method. Last, specific conductivity was calibrated using a 250 μS conductivity standard. Every morning, before field sampling commenced, these calibrations were done. At each sample field site, GPS was used first to mark sample number, latitude and longitude, and elevation. This information was transferred to a field data form in a map case. At the stream site, the YSI probe must be entirely submerged; it is recommended that gloves are worn during any sample taking. Then allow sufficient time for each of the four parameters to stabilize (Ficklin and Mosier, 1999). This allows for a more accurate reading. After this was done, one 250 mL bottle was opened, filled with stream water, rinsed and emptied a total of three times. Every bottle must have the sample stream water used to rinse that bottle and it must be done three times, as was the water grabber (Ficklin and Mosier, 1999). Also, after all three rinses, once the bottle was full, it was closed and marked with tape the sample number. From there, using the FlowTracker and the measuring tape, the steps as stated in the previous section were completed. In the situation where the YSI could not be placed below the water surface (such as Sample 344), the use of a clean and quantified container was used. This bottle like the others was rinsed three times with the sample water. Placing the probe into the container and allowing for it to make adjustments, the four parameters could be measured.

4.2.3 Post-Field Sampling

This is the procedure for filtering and acidifying all samples. As part of safety protocol requires, gloves and safety goggles were worn during this part, as it involves concentrated 14 M (Molar) nitric acid. Prior to filtering, 10 mL of the 100 mL bottle nitric acid was carefully poured into a smaller, sealable beaker. This was to lessen the likelihood of contamination. For filtered samples, a clean 250 mL bottle was filled with

DI water and shook to coat the inside of the bottle. Then the 100 mL cylinder was rinsed with DI water. The 60 mL syringes came in individual cases, such that the cases were filled with DI water and syringes were soaked in it. When this was completed, the sample that was to be filtered was opened. The syringe that was soaking was removed and approximately three mL of the sample was pulled into the syringe. The plunger was then pulled back to just beyond the 60 mL marker; this was to make sure the entire syringe was touched by the sample. Then the sample water was ejected out. This was repeated three times. With this complete, the syringe was placed back into the sample and 60 mL of sample water was pulled in. From here, the 0.45 µm filter was screwed into the syringe, and then the sample water was pushed through it into the 100 mL cylinder. After it had expelled all 60 mL of the sample, the filter was removed, and the syringe pulled another 40 mL of sample into it. The filter was re-attached and the sample pushed through into the 100 mL cylinder (Figure 10 A&B). When there was 100 mL of sample water, the filter was removed and disposed of, while the syringe was put back into the case full of DI water. Now the acidification process begins.


10A

10B

Figure 10. Comparison of a clean and used filter. A) Filtered versus clean B) There is a substantial amount of dissolved solids (orange) after a sample is filtered

In order to acidify, an automatic pipette was used with disposable tips. The tips were left in the bag they came in and instead of risk contaminating any of these tips by touching them with gloves on, the pipette was inserted into the bag to connect the tip. Once connected, the tip connected was tightened using gloves. The pipette used required pushing the plunger down until it stops. Place the tip in the small beaker without touching the bottom or sides and slowly release the plunger, letting the acid slowly fill up the tip. Once filled, place the pipette tip into the 100 mL cylinder and again without touching the sides, slowly push down on the plunger and release the acid into the sample. Push down until the first stop is reached. Then push again, until the second stop is felt; this expels any acid droplets at the opening of the tip. When this has occurred, remove the pipette out of the cylinder and dispose of the tip by pushing down to the third stop. Only 100 µL (0.1 mL) of nitric acid are required for acidification of the 100 mL samples being taken. Once the sample in the cylinder has been acidified, a new 250 mL bottle that has been rinsed with DI water three times, has the Filtered Acidified (FA) sample poured into it. Placing scotch tape onto the bottle and marking it with a sharpie the sample number and letters FA, it is placed into a gallon-sized bag and again the sample number is marked on it. The syringe is now taken out of its' case and again approximately three mL of the sample are pulled into the syringe all the way to the back, just past 60 mL. The water is then pushed back out. The syringe is then placed back into the sample and pulls 60 mL of water into it (always making sure the syringe never touches the sides of the bottle). That 60 mL and an additional 40 mL are plunged into the cylinder. When 100 mL is reached, the sample is acidified. The remainder of the sample that is un-acidified is poured out, leaving an empty container. The cylinder empties into this container, which is now marked as the sample number and Raw Acidified (RA). It is placed next to the same sample but filtered, and they are rubber banded together and sealed in a gallon bag for storage.

4.2.4 Running Tests

All 54 samples were taken back to the radiogenic isotope lab run by Dr. Franco Marcantonio at Texas A&M University, where they would be run in the Inductively Coupled Plasma-Mass Spectrometer (ICP-MS). In order for these samples to be run, they must have an internal standard created. Indium, the element used most by this lab had numbers too high and it would not make for a suitable standard. With other elements like yttrium and scandium also being too high, Dr. Robert Runkel was contacted again, this time inquiring about the internal standard used in his paper. It was recommended that rhodium (Rh) be used (Runkel, pers. comm., 2013). Rhodium was tested and with little amounts in the samples, it became fit to be the internal standard. Using external calibration quantification such that a stock was prepared that contained all the elements of interest, it was then an external standard was prepared. This external standard had concentrations ranging from 2 ppb to 1000 ppb for all elements of interest, and became the number of times diluted. The 100 mL samples, carefully had 2 mL removed and put into a 50 mL centrifuge tube. The 2 mL sample then had 10 mL of 2% nitric acid added to it. The 2% nitric acid was prepared in the lab by using the 14 M nitric acid and Milli Q water. The sample then had 10 ppb of Rh added to it. Blanks of the 2% nitric acid were analyzed every ten samples.

5. RESULTS

Table 1. Samples and their five measured parameters.

Sample #	pH	Water Temp (C°)	Spec. Cond.(µS/cm)	D.O %, mg/l	Discharge m^3/s
336	8.23	10.9	109.1	73.3, 8.1	1.40E-01
343	7.925	8.9	107.3	88.2, 10.19	
344	2.75	17.3	3015	74, 7.04	6.17E-05
345	6.52	9.7	113.2	88.3, 10.03	4.65E-02
346	3.12	10.2	602	85.2, 9.55	7.55E-02
347	3.31	10.4	431.9	89.5, 9.90	9.89E-02
348	2.95	11	881	87.6, 9.64	1.29E-02
349	7.3	10.9	93.2	85, 9.42	2.62E-02
350	3.66	10.9	320.3	84.1, 9.3	5.11E-02
351	3.27	7.77	657	86.4, 10.26	
352	3.35	7.9	659	83.6, 9.90	
353	6.71	6.7	613	45.7, 5.58	
354	8.02	12.3	76	59, 6.39	1.21E-02
355	6.32	15.8	717	57.1, 5.52	3.03E-04
356	2.67	9	1665	65, 7.46	6.31E-03

Table 1 Continued

Sample #	pH	Water Temp (C°)	Spec. Cond.(µS/cm)	D.O %, mg/l	Discharge m^3/s
357	3.27	11.7	320.4	57.6, 6.37	6.03E-02
358	3.1	12.7	480.5	61.3, 6.56	7.01E-02
359	3.06	15.1	528	57.5, 5.76	4.56E-03
360	2.77	12.9	1345	59.5, 6.30	1.27E-01
361	3.1	12.2	480.1	62.1, 6.65	4.89E-03
362	7.93	10.8	7.93	59.9, 6.62	5.10E-04
364	2.96	6.8	529	66.5, 8.08	2.10E-01
365	3.2	7.2	577	66.4, 7.82	8.65E-02
366	3.07	8.6	603	69.1, 8.0	5.33E-02
367	6.35	10.5	394.1	68.3, 7.62	1.69E-01
368	3.47	9.3	513	69.4, 7.97	
KOA	8.7	18.6	299.3	68.1, 5.75	

Note: The samples above were combined, as each parameter was the same for both FA and RA.

Table 2. The water geochemistry results of dissolved Magnesium, Zinc, Cadmium, Lead and Aluminum concentrations.

Sample #	Mg (ppm)	Zn (ppm)	Cd (ppm)	Pb (ppm)	Al (ppm)
336 FA	5.483	0.452	0.010	0.002	0.089
336 RA	5.354	0.273	0.755	0.005	0.116
343 FA	3.563	0.395	0.269	0.000	0.103
343 RA	3.488	0.720	0.424	0.018	0.689
344 FA	24.340	4.205	0.146	0.003	6.753

Table 2 Continued

Sample #	Mg (ppm)	Zn (ppm)	Cd (ppm)	Pb (ppm)	Al (ppm)
344 RA	23.485	4.050	0.078	0.002	6.342
345 FA	3.214	0.336	0.029	0.000	0.110
345 RA	0.941	0.187	0.027	0.005	0.132
346 FA	8.452	4.009	0.227	0.165	59.323
346 RA	8.563	4.011	0.230	0.171	58.413
347 FA	6.864	2.889	0.193	0.113	39.205
347 RA	6.794	2.878	0.195	0.115	39.270
348 FA	9.807	3.276	0.131	0.390	91.993
348 RA	11.130	3.765	0.145	0.445	116.258
349 FA	2.376	0.048	0.009	-0.001	0.026
349 RA	2.343	0.035	0.029	0.000	0.031
350 FA	4.445	1.046	0.041	0.111	26.531
350 RA	4.589	1.052	0.040	0.123	27.714
351 FA	17.448	2.826	0.014	0.116	17.402
351 RA	18.055	2.821	0.015	0.115	16.322
352 FA	19.691	2.631	0.131	0.088	14.598
352 RA	18.715	2.457	0.174	0.086	13.604
353 FA	12.913	0.193	0.003	0.000	0.031
353 RA	12.499	0.196	0.002	0.005	0.057
354 FA	2.507	0.047	0.032	0.001	0.037
354 RA	2.670	0.061	0.004	0.001	0.184
355 FA	44.534	22.107	0.598	0.210	2.421
355 RA	45.292	21.779	0.782	0.214	2.652
356 FA	12.388	1.800	0.047	0.010	38.004
356 RA	15.996	2.271	0.058	0.013	47.846
357 FA	5.423	1.617	0.052	0.162	32.600
357 RA	5.448	1.513	0.046	0.166	32.790
358 FA	7.203	3.115	0.090	0.154	60.328
358 RA	6.826	2.983	0.082	0.154	62.869
359 FA	7.443	3.161	0.093	0.170	58.294
359 RA	7.614	3.353	0.096	0.183	59.876
360 FA	8.458	0.783	0.026	0.020	36.634
360 RA	8.513	0.897	0.027	0.021	37.379
361 FA	7.452	3.204	0.079	0.134	61.398
361 RA	7.479	3.224	0.079	0.136	59.376

Table 2 Continued

Sample #	Mg (ppm)	Zn (ppm)	Cd (ppm)	Pb (ppm)	Al (ppm)
362 FA	12.063	0.132	0.001	0.000	0.022
362 RA	11.770	0.177	0.002	0.004	0.129
364 FA	13.543	1.465	0.014	0.031	18.014
364 RA	13.418	1.428	0.014	0.031	17.405
365 FA	12.193	2.867	0.061	0.095	51.333
365 RA	12.100	2.862	0.062	0.101	52.917
366 FA	12.262	2.870	0.062	0.097	52.197
366 RA	12.272	2.841	0.061	0.101	52.711
367 FA	8.001	0.013	0.001	0.001	0.185
367 RA	8.100	0.035	0.001	0.002	0.396
368 FA	12.108	1.800	0.038	0.048	29.142
368 RA	12.312	1.804	0.038	0.053	29.309
KOA FA	6.253	0.020	0.000	0.000	0.045
KOA RA	6.279	0.019	0.000	0.000	0.020

Table 3. The water geochemistry results of dissolved Manganese, Iron, and Copper concentrations and notes about the sample sites.

Sample #	Mn (ppm)	Fe (ppm)	Cu (ppm)	Notes
336 FA	0.061	0.152	0.020	Uncompahgre River, above tunnel
336 RA	0.065	0.133	0.063	
343 FA	0.456	0.054	0.015	Commodore below RMT2N
343 RA	0.463	3.368	0.111	
344 FA	13.945	13.554	0.257	RMT2N seep
344 RA	13.575	13.001	0.236	
345 FA	0.278	0.096	0.011	Commodore above RMT2N
345 RA	0.074	0.933	0.030	
346 FA	2.312	41.021	4.067	RMC above Commodore
346 RA	2.342	67.695	4.165	
347 FA	1.761	17.403	2.642	RMC below Commodore
347 RA	1.780	50.189	2.692	
348 FA	2.732	96.797	5.402	Amazon Creek above RMC
348 RA	3.260	133.940	5.807	
349 FA	0.018	0.113	0.012	RMC above Amazon Creek
349 RA	0.024	0.204	0.015	

Table 3 Continued

Sample #	Mn (ppm)	Fe (ppm)	Cu (ppm)	Notes
350 FA	0.809	25.335	1.610	RMC below Amazon Creek
350 RA	0.856	42.652	1.687	
351 FA	3.850	50.829	0.133	Corkscrew Gulch, above non-id adit
351 RA	3.995	55.411	0.137	
352 FA	4.216	53.729	0.097	Corkscrew Gulch, below no named adit
352 RA	3.967	52.914	0.094	
353 FA	2.154	3.324	0.002	Mt. King, below collapsed portal
353 RA	2.174	4.147	0.003	
354 FA	0.069	0.251	0.003	Headwaters RMC
354 RA	0.152	1.173	0.004	
355 FA	11.361	0.016	1.457	Buried Tailings Seep
355 RA	11.611	0.119	1.530	
356 FA	1.080	58.241	2.738	Genessee Mine
356 RA	1.395	76.260	3.482	
357 FA	1.252	25.662	2.284	RMC above Genessee
357 RA	1.274	49.527	2.284	
358 FA	2.151	59.568	4.520	RMC below Genessee
358 RA	2.147	96.438	4.551	
359 FA	2.254	45.501	4.336	RMC above Treasury weepline; by decrepit flume
359 RA	2.342	94.355	4.612	
360 FA	0.810	59.546	0.536	Champion Gulch/Creek
360 RA	0.815	59.036	0.588	
361 FA	2.427	68.502	3.108	RMC below Champion Gulch
361 RA	2.350	87.057	2.990	
362 FA	0.753	0.054	0.002	Mt. King near the highway, in meadow
362 RA	0.821	1.255	0.003	
364 FA	3.133	26.016	0.168	Corkscrew above RMC
364 RA	3.077	27.259	0.164	
365 FA	2.598	18.359	2.229	RMC above RMT4
365 RA	2.646	63.072	2.236	
366 FA	2.663	17.856	2.287	RMC below RMT4, by RMC-1
366 RA	2.615	61.138	2.198	
367 FA	0.945	0.468	0.004	Crystal Lake above RMC
367 RA	0.963	2.564	0.001	
368 FA	2.578	3.562	1.179	RMC below Crystal Lake, Ironton
368 RA	2.687	27.605	1.217	

Table 3 Continued

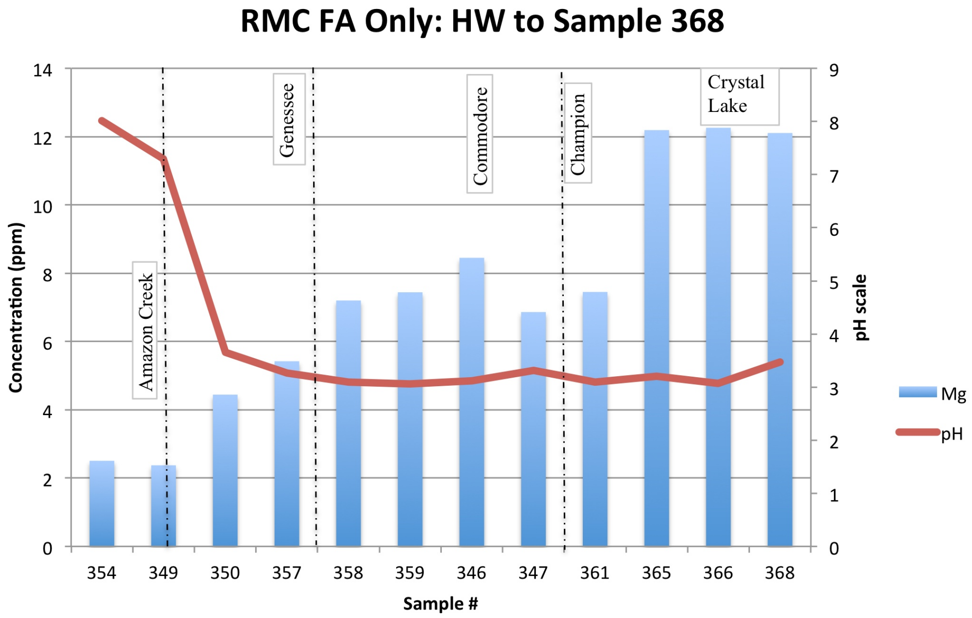
Sample #	Mn (ppm)	Fe (ppm)	Cu (ppm)	Notes
KOA FA	0.009	0.055	0.005	KOA campground, North of Ouray
KOA RA	0.007	0.051	0.004	

6. DISCUSSION

6.1 Red Mountain Creek: Headwaters to Sample 368

RMC at its headwaters, Sample 354 has a pH of 8, and has Mg levels at 2.5 ppm, which is below average river water from North America (4.9 ppm) and the world (3.7 ppm) (Berner (1987). Zinc is at 0.047 ppm and is below the 0.05 ppm stream standard for aquatic life in Colorado (Nash, 2002, 32). Cadmium is 0.032 ppm, is above the 0.001 ppm aquatic life stream standard. Lead is significantly lower than the standard of 0.025 ppm, at 0.0008 ppm. Aluminum is 0.037 ppm, and is lower than the aquatic standards (0.1 ppm). Manganese is at 0.069 ppm and is also significantly lower than the aquatic standard of 1.0 ppm. Iron is at 0.25 ppm and is 0.75 ppm lower than the standard. Copper is 0.003 ppm, and is again lower than the aquatic standard of 0.01 ppm. Sample 349, has a pH of 7, and shows a nominal decrease in all trace metal concentrations, except zinc and copper. This may be due to the vegetation lining the ditch in which RMC flows through until just above the confluence. The pH is still at good habitable levels. Sample 348 was taken at Amazon Creek, just a few feet away from RMC, before the confluence and is shown on Figures 11A-H. All five of the dashed line locations, will be discussed in greater detail after this section.

11A



11B

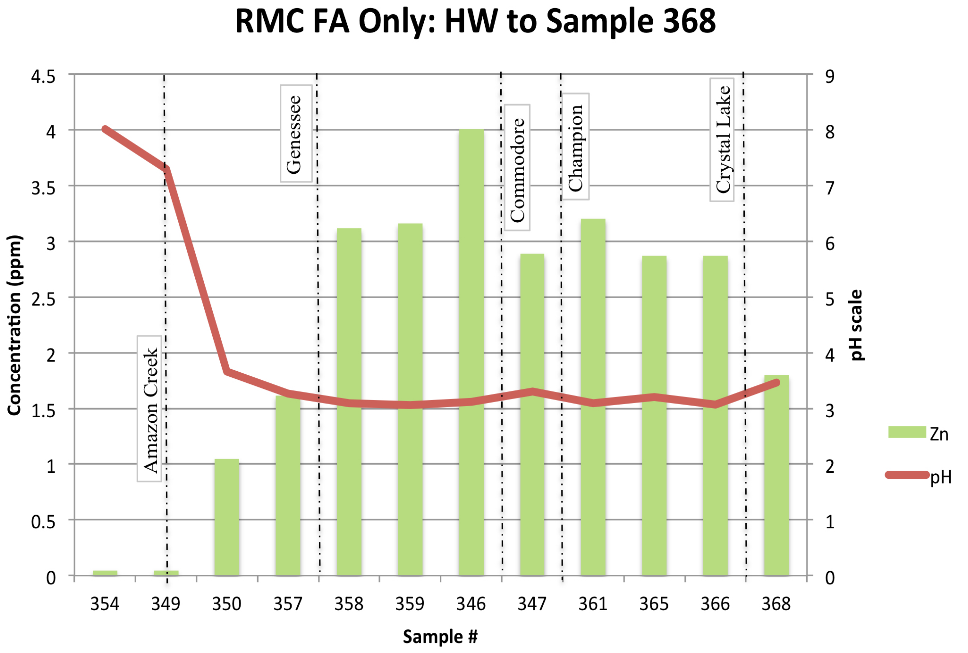
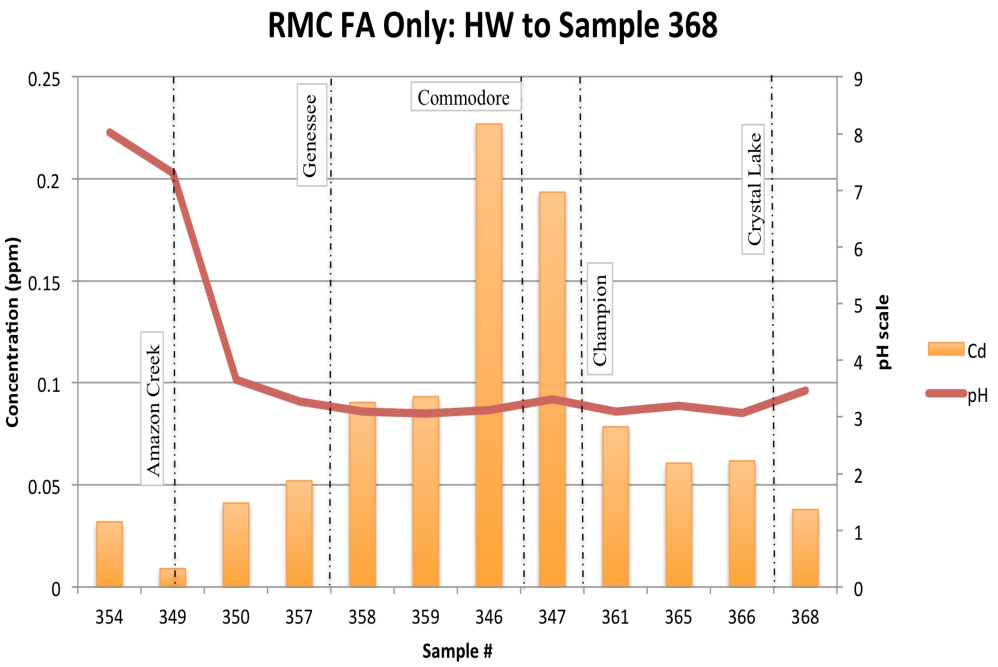


Figure 11. Metal concentrations of all eight parameters for only RMC FA from the Headwaters to Sample 368. A) Magnesium B) Zinc C) Cadmium D) Lead E) Aluminum F) Manganese G) Iron H) Copper

11C



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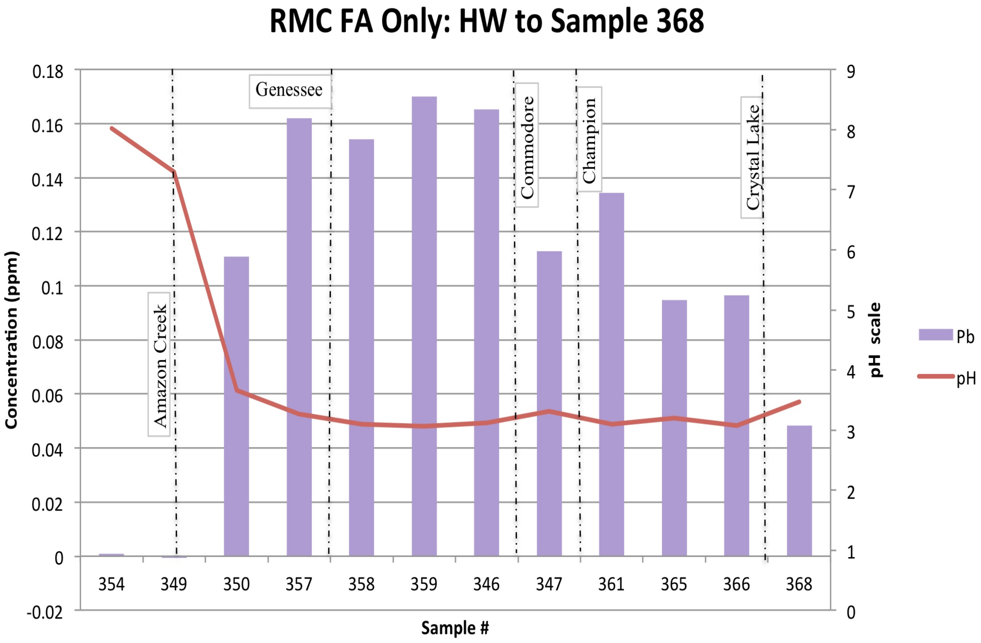
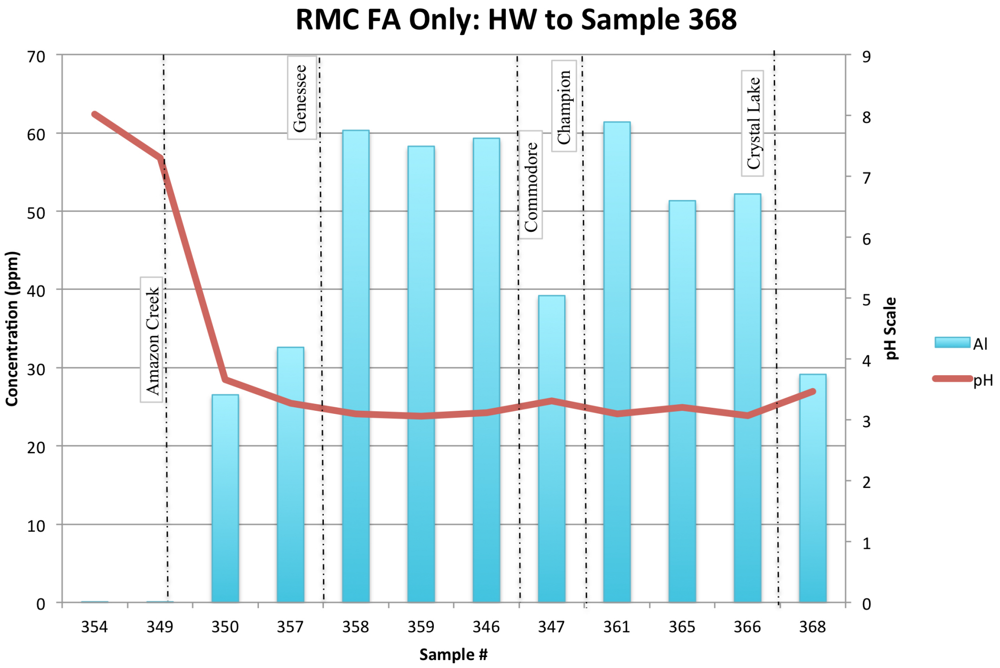


Figure 11 Continued

11E



11F

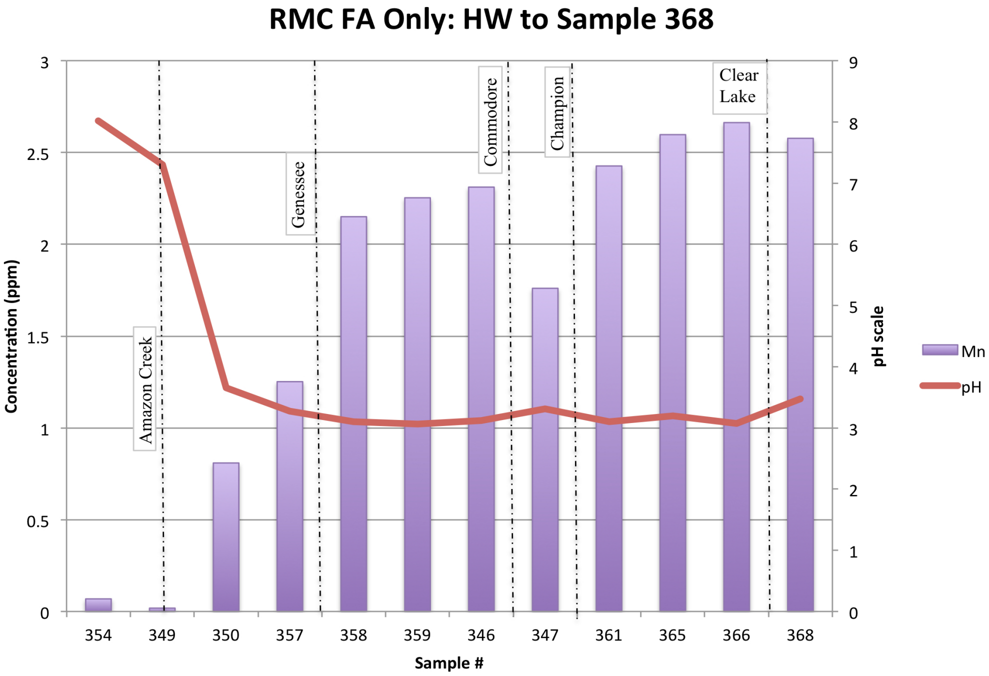
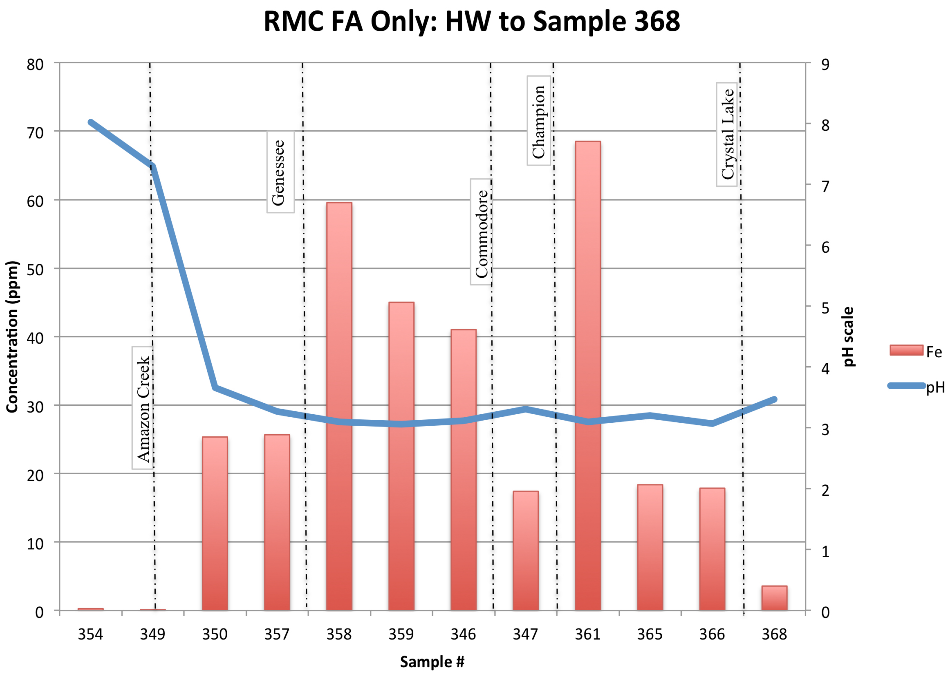


Figure 11 Continued

11G



11H

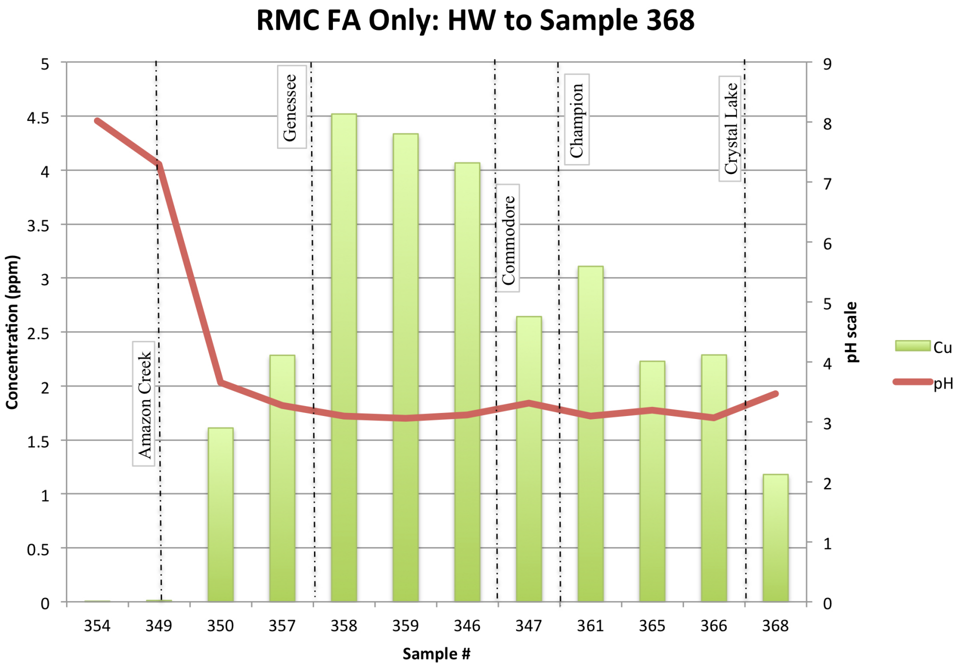


Figure 11 Continued

From these figures, there is a very rapid decrease in pH from Sample 349 to Sample 350, which is RMC below Amazon Creek. Seven of the eight metals (with cadmium being the exception), increase in concentrations. Differences from the headwaters to below the confluence of RMC and Amazon Creek, show increases in magnesium with 1.94 ppm, zinc with 1.0 ppm, lead with 0.1 ppm, manganese with 0.74 ppm, and copper with 1.61 ppm. Aluminum has significantly increased by 26.5 ppm and iron by 25.1 ppm. pH has dropped to 3.66 and from this point on to Sample 368, pH varies, but is consistently within a pH of three. Figure 12 shows the headwaters down to Sample 350. There is a significant difference between RMC and Amazon Creek. On the RMC side, there is no mining activity. On the Amazon Creek side, there is extensive mining activity. The mining activity appears to be the cause for the increased concentrations of dissolved metals. In the next section, this will be examined in greater detail.

Location of the RMC Headwaters and Amazon Creek

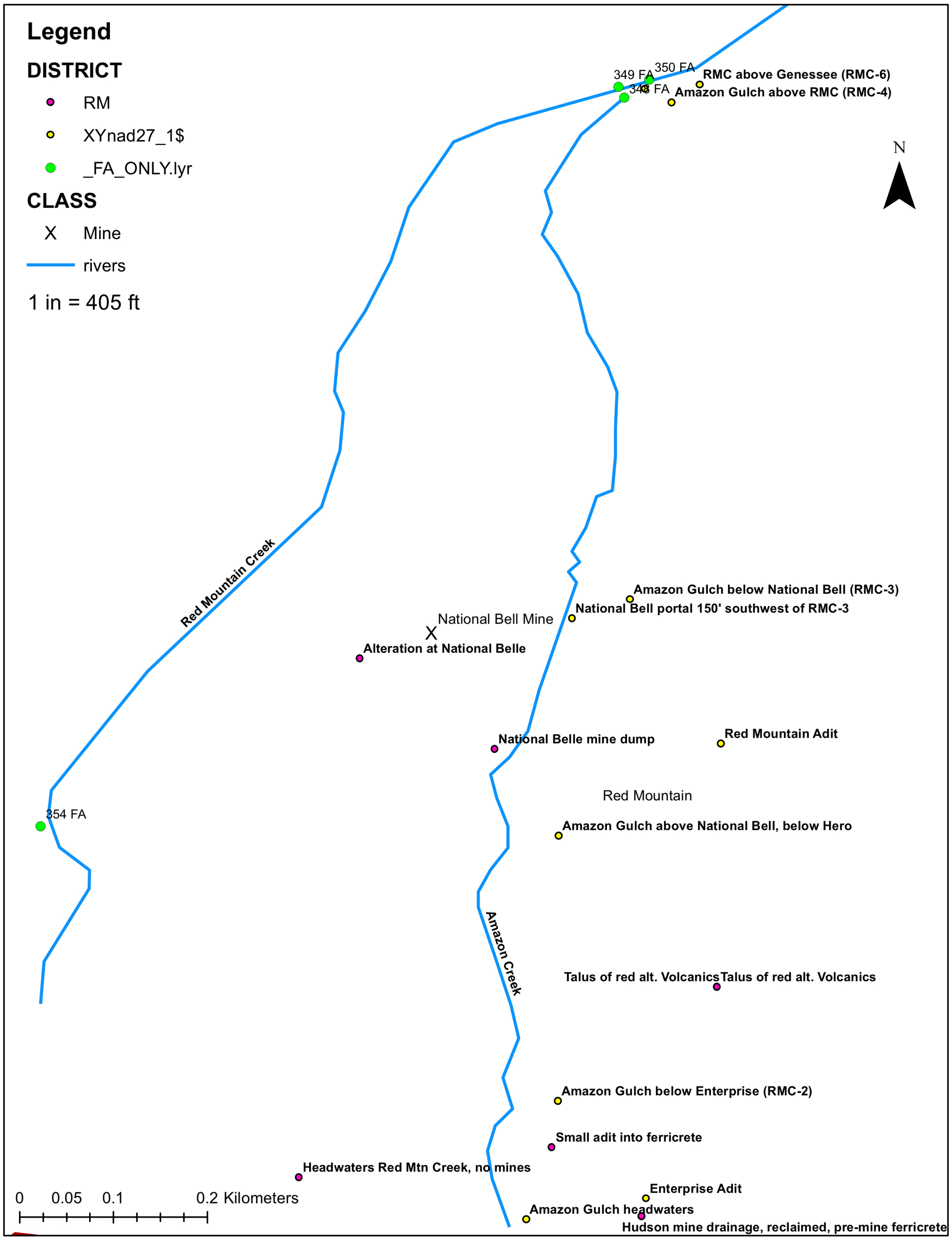


Figure 12. Close-up of the RMC headwaters and Amazon Creek

Sample 357, which is above Genessee, has increased in all trace metal concentrations, with the exception of cadmium and lead, when compared to Sample 350. Magnesium increases by 0.98 ppm, zinc by 0.57 ppm, aluminum by 6.07 ppm, manganese by 44.0 ppm, iron by 0.33 ppm, and copper by 0.67 ppm. This increase in concentrations is due to pH dropping to 3.27. Low pH values coincide with high dissolved trace metal concentrations (Wright et al., 2007). Elevated concentrations also typically are increasingly more soluble and mobile at lower pH ranges (Neubert et al., 2011). Sample 356 was taken at the Genessee Mine, and just below the confluence with RMC, is where Sample 358 was taken (Figure 13). There is still a decline in pH as it drops to 3.1. This low pH, correlates directly to the high dissolved trace metal concentrations, as seen in Figures 11A-H. Both cadmium and lead are not significantly changing here. Sample 358 compared to Sample 357, shows magnesium has increased by 1.78 ppm, zinc by 1.5 ppm, and manganese by 0.9 ppm. Aluminum has increased by 27.7 ppm. Iron has increased by 33.9 ppm and has a total concentration of 59.57 ppm. Copper increases by 2.24 ppm for a total concentration of 4.52 ppm, such that this is the highest concentration it will be at, as this study moves downstream. At Sample 359, pH of RMC is at its lowest, 3.06. Concentrations only increase for magnesium (0.24 ppm), zinc (0.05 ppm), lead (0.02 ppm), and manganese (0.1 ppm) from Sample 358. Cadmium levels are still nominal. Aluminum, iron, and copper all show a decrease in concentrations, respectively by 2.0 ppm, 14.1 ppm, and 0.18 ppm. This decrease in concentration is the result from the mixing of the buried tailings seep with RMC. Sample 355 was taken at the buried tailings seep, above Sample 359.

Location of Genessee Mine Samples

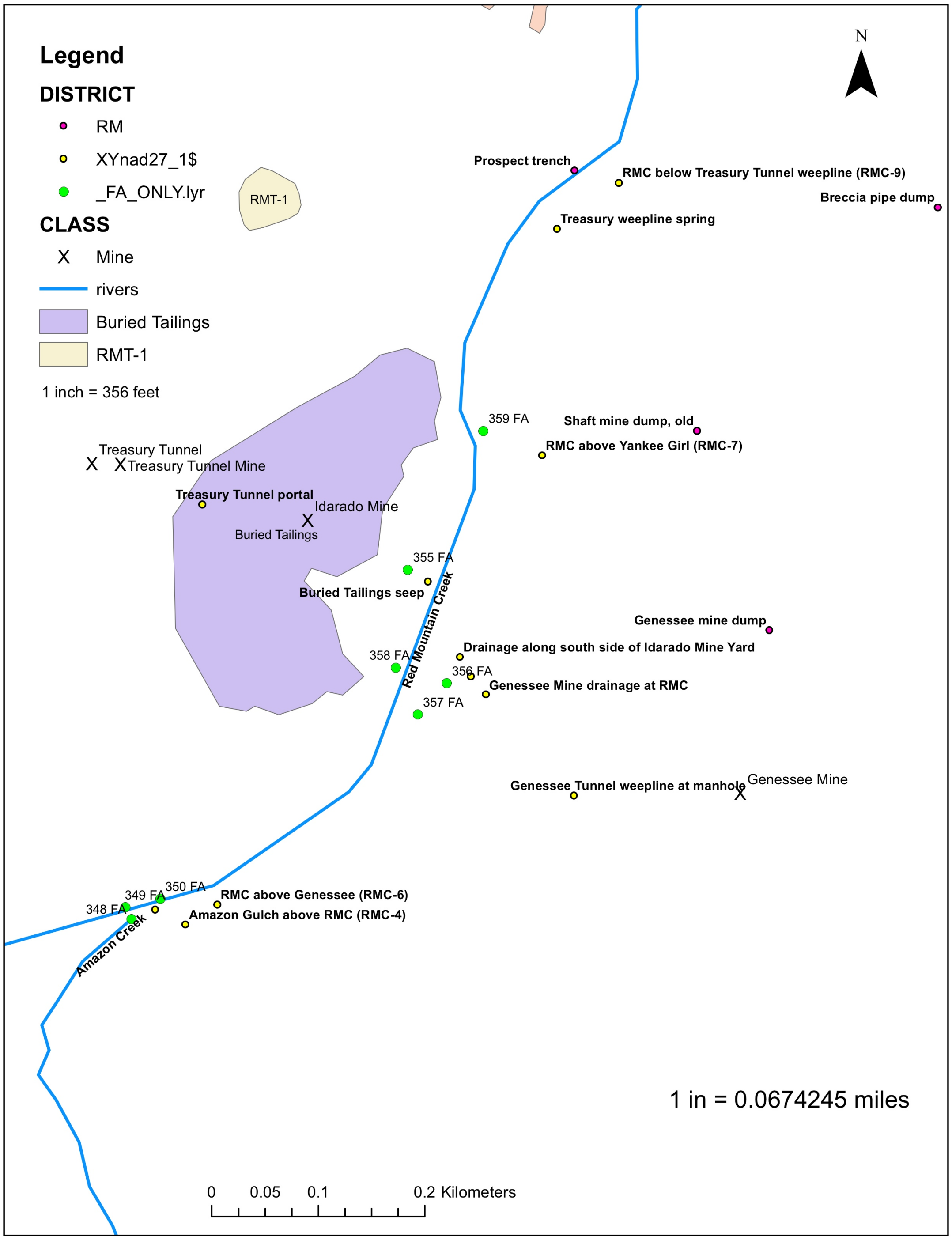


Figure 13. Post-confluence of RMC with Amazon to Genessee Mine

The seep entering RMC, had a pH of 6.32. Mixing this much higher pH with the lower pH of 3.1, can contribute to the precipitation of trace metals such as aluminum and iron from the dissolved phase to solid phase (Wright et al., 2007). These precipitates can have copper adsorption, which leads to decreased copper concentrations (Wright et al., 2007, 519, 527). Sample 358 had a high iron concentration and low pH, and when it mixed with the high pH water of the buried tailings seep, it precipitated yellow iron sulfates or orange iron oxyhydroxides (Wright et al., 2007, 530), as seen in Figure 14. Total concentrations at Sample 359 for dissolved trace metals are as follows: magnesium, 7.44 ppm, zinc, 3.16 ppm, cadmium, .09 ppm, lead, .17 ppm, aluminum, 58.29 ppm, manganese, 2.25 ppm, iron, 45.0 ppm, and copper, 4.3 ppm.

Figure 14. Orange iron oxyhydroxide precipitate from the mixing of RMC with the, Buried Tailings Seep. The low pH mixing with high pH causes iron to precipitate out

Sample 346 is located on RMC above the confluence with Commodore Gulch (Figure 15). When compared to Sample 359, the pH has increased to 3.12, as well as, magnesium, zinc, cadmium, aluminum, and manganese by 1.0 ppm, 0.85 ppm, 0.13 ppm, 1.03 ppm, and 0.06 ppm, respectively. Lead has stayed the same, but both iron (4.48 ppm) and copper (0.27 ppm) have decreased. Sample 347 was taken below the confluence of Commodore Gulch (Samples 343, 344, 345) and RMC. From Figures 11A-H, pH values show an increasing slope. All dissolved trace metal concentrations have decreased at Sample 347. Compared to Sample 346, magnesium has decreased by 1.59 ppm and is 4.36 ppm greater than the headwaters. Zinc is 1.12 ppm less, but 2.84 ppm greater than the headwaters. Cadmium and lead are not significantly lowered, but both are greater than the headwaters; Cd is 0.16 ppm, Pb is 0.11 ppm. Manganese is 0.55 ppm less and 1.69 ppm greater than the headwaters. Aluminum, iron, and copper show very significant drops in concentrations. Respectively, concentrations decrease by 27.11 ppm, 23.62 ppm, and 1.42 ppm. This can be attributed to Commodore Gulch and will be explained in detail in the next section. Aluminum is 29.17 ppm greater than the headwaters as is iron by 17.15 ppm and copper by 2.64 ppm.

Sample 361 is located downstream of the confluence of RMC with Champion Gulch. Champion Gulch (Figure 15), is located between Red Mountain # 2 and #3, and has visible hydrothermal alteration. Figure 16 shows RMC and both Champion and Commodore Gulch. Looking at Figures 11A-H, pH has been lowered to 3.1, and dissolved trace metal concentrations have all increased, with the exception of cadmium. These changes are the result of Sample 360, which was taken at Champion Gulch.

Explanations for the concentration increases will be explained in the next section. Sample 361 has magnesium levels, which have increased by 0.59 ppm, zinc by 0.32 ppm, lead by 0.02 ppm, aluminum by 22.19 ppm, manganese by 0.67 ppm, iron by 51.1 ppm, and copper by 0.47 ppm.

Figure 15. Champion Gulch is situated in the bottom left corner below Red Mountain #2

Sample Locations of Commodore Gulch and Champion Gulch

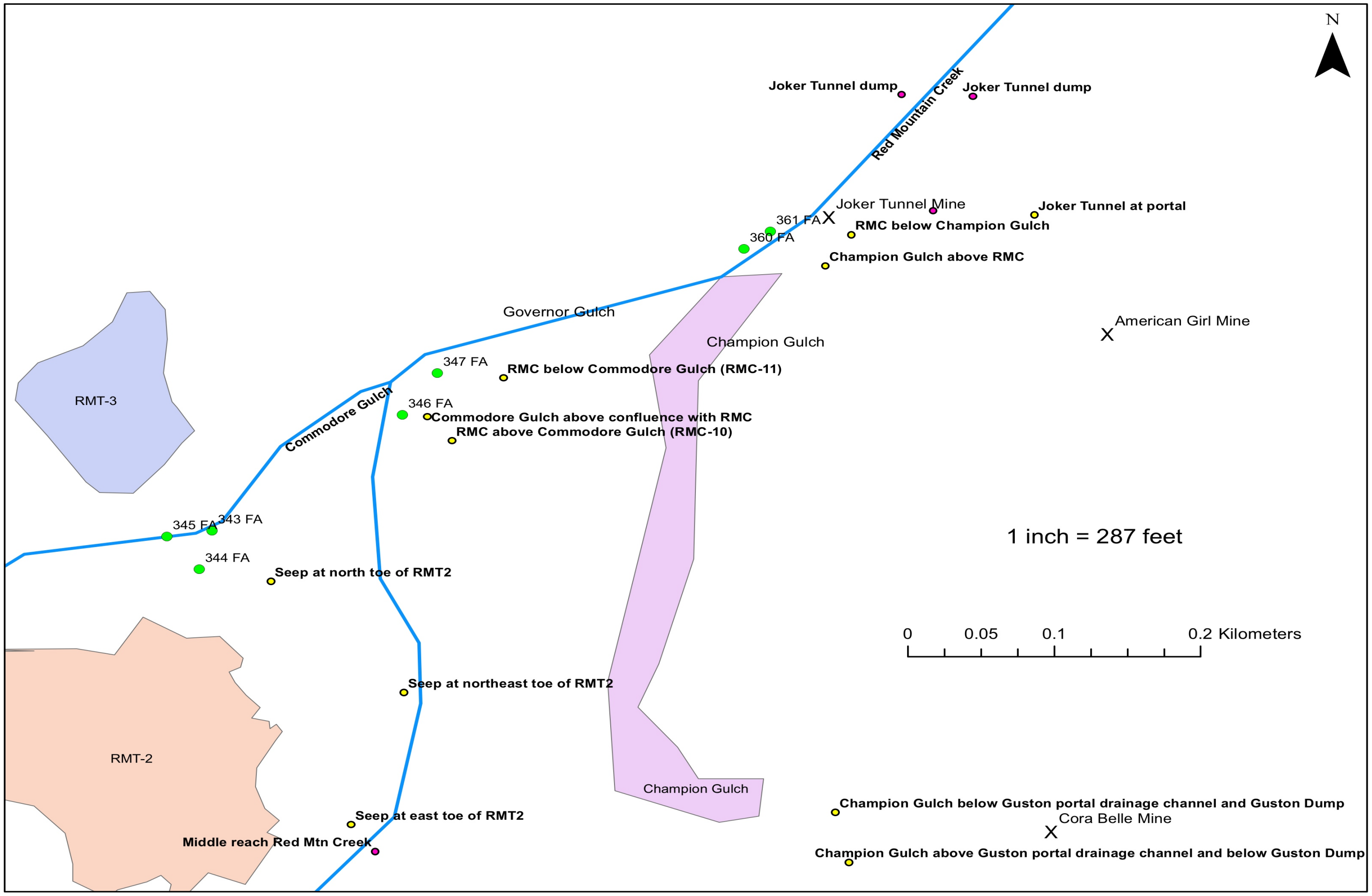


Figure 16. Map of sample sites and mining related activity

Sample 365 is located on RMC above Red Mountain Tailing #4 (RMT4) (Figure 16). When compared to Sample 361 upstream, only magnesium and manganese increase in concentration. Magnesium increases by 4.74 ppm and manganese by 0.17 ppm. Zinc decreases in concentration by 0.34 ppm, cadmium by 0.02 ppm, lead by 0.04 ppm, and copper by 0.88 ppm. Aluminum loses 10.07 ppm, but iron decreases by 50.14 ppm. There is an anomaly here because the loss of 50 ppm of iron is not explained by a 0.1 increase in pH. The pH at Sample 365 is 3.2, in which anything higher than that would cause iron to become more insoluble (Wright et al., 2007). This would be an area of interest for future sampling and research. Sample 366 was taken below RMT4 and above the stream gauging station RMC-1. The pH has dropped to 3.07 here, and all trace metals increase in concentrations, except for iron. Magnesium, zinc, lead, manganese, and copper increase by a non-significant amount. Aluminum increases by 0.86 ppm, the largest of the increases. Iron loses 0.50 ppm more and this can be attributed to amount of iron particulates (43.28 ppm) at this location. The last sample taken on RMC is Sample 368. All of the trace metals decrease in concentration. This is due to Crystal Lake, which is where Sample 367 was taken. Sample 368 magnesium, zinc, cadmium, lead, aluminum, manganese, iron and copper concentrations decrease by 0.15 ppm, 1.07 ppm, 0.02 ppm, 0.05 ppm, 23.06 ppm, 0.09 ppm, 14.29 ppm, and 1.11 ppm respectively.

Map of RMT4 to Sample 368

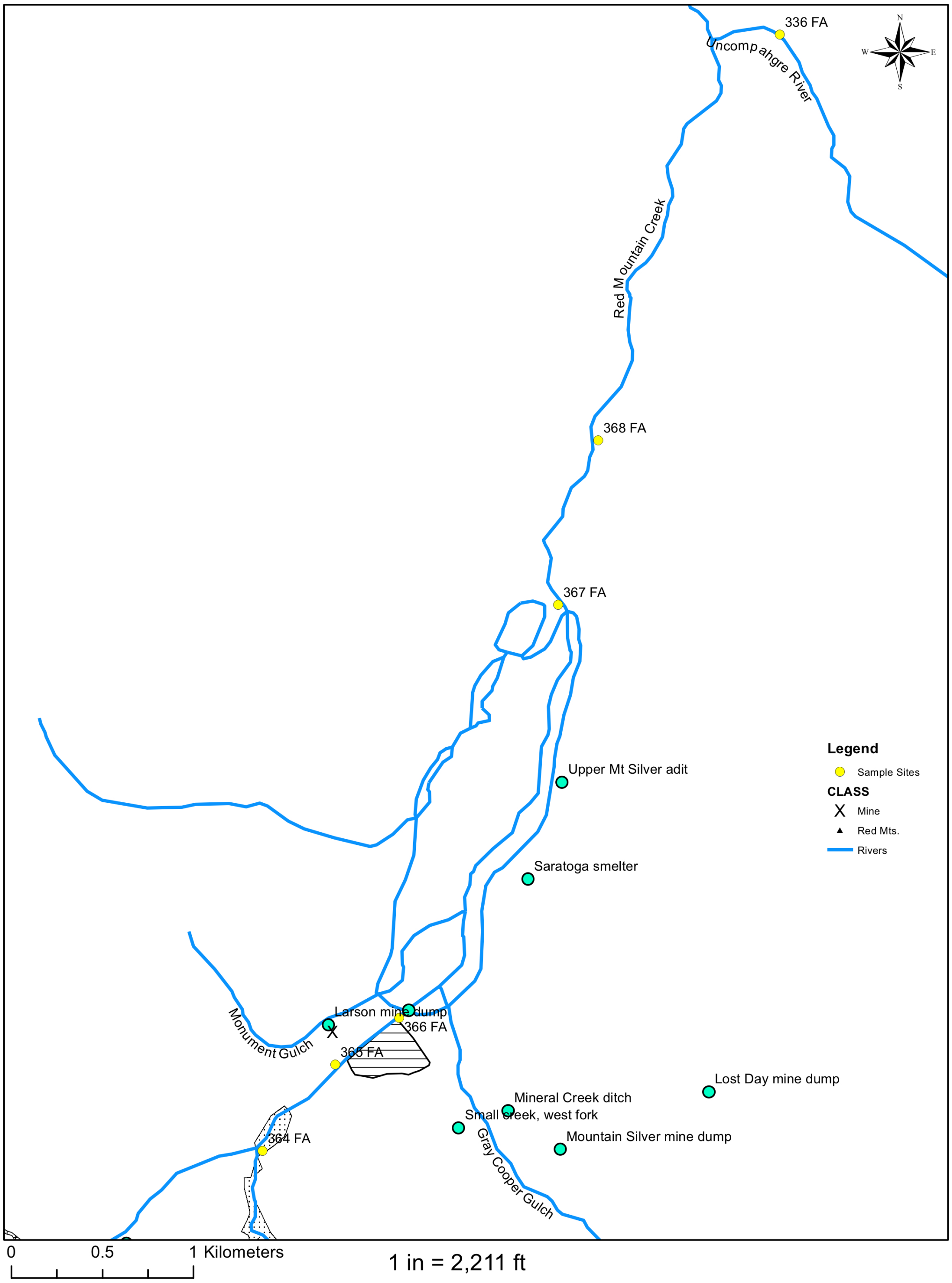


Figure 17. Sample locations from above RMT4 to Sample 368

6.2 Confluences with Significant Influences

In Figures 11A-H, there were five dashed lines, all of which represent a location and sample that significantly affected RMC. The first of five, begins with Amazon Gulch, or Sample 348, where pH is 2.95. When looking downstream, Amazon Gulch is on the right side (Figure 18) and RMC the left (Figure 19). After the confluence of Amazon Gulch with RMC, pH significantly drops to 3.66 (Sample 350; Figure 20 A-C), from Sample 349's 7.3. This low pH allows Amazon to have high concentrations of dissolved trace metals.

Figure 18. Amazon Creek looking upstream (Sample 348)

Figure 19. RMC above the confluence with Amazon (Sample 349)

20A

Figure 20. Confluence of Amazon Creek with RMC. A) Confluence of Amazon and RMC B) Close-up of the barrier (due to precipitation occurring) C) Site of Sample 350, where mixing occurs and orange iron precipitates

20B

20C

Figure 20 Continued

Table 4, shows the significant loading for all eight elements.

Table 4. Amazon Creek dissolved metal concentrations for Filtered Acidified.

Sample #	Mg (ppm)	Zn (ppm)	Cd (ppm)	Pb (ppm)	Al (ppm)	Mn (ppm)	Fe (ppm)	Cu (ppm)
348 FA	9.81	3.28	0.13	0.39	91.99	2.73	96.8	5.4

These high concentrations can be attributed to previous mining activity along Amazon Gulch, as well as, hydrothermal alteration. Amazon flows by the National Belle mine, and drains the Red Mountain and Enterprise adit, and Hudson mine (Figure 12). National Belle was primarily mined for silver, lead, copper and gold (Moore, 2004). The mine itself sits on an area that has been hydrothermally altered. There has been argillic, smectitic, and silicified alteration types as shown in Figure 21. The alteration type changes outward, going from silicified to argillic, then smectitic, and finally to propylitic rock, all of which makes this an acid sulfate assemblage (Bove et al., 2007). It is a volcanic pipe with a knob that extends 200 feet above the ground surface, and the knob itself, is silicified breccia (Moore, 2007; see fig. 6 in Bove et al., 2007). Within this pipe, were natural caves with oxide lead ores followed by sulfide ores (Moore, 2007). The uppermost oxide lead ores were mined for production (Moore, 2007; see fig. 6 in Bove el al., 2007). These oxide ores contain abundant clay minerals (kaolinite ($Al_2Si_2O_5(OH)_4$) and dickite ($Al_2Si_2O_5(OH)_4$), both are aluminosilicates), alunite ($KAl_3(SO_4)_2(OH)_6$), diaspore (aluminum hydroxide), pyrophyllite ($AlSi_2O_5(OH)_2$) and quartz (see fig. 6 in Bove et al., 2007; Moore, 2007; Neubert et al., 2011, xiii-xiv). Here the walls of the caves and ore itself are encased in limonite (hydrous ferric oxide) (Moore, 2007; Neubert et al., 2011, xiv). Underneath the oxide ore, was the sulfide ore, and it included pyrite (FeS_2), galena (PbS), chalcopyrite ($CuFeS_2$), and enargite (Cu_3AsS_4) (see fig. 6 in Bove et al., 2007; Moore, 2007; Neubert et al., 2011, xii-xiv). Lead, copper, iron, and aluminum are abundant in the minerals just mentioned, and from leaching and weathering from dump sites have contributed concentrations that exceed CWQCCs stream standards for metals for aquatic life (Nash, 2011). In addition, both iron and aluminum are typical weathering products associated with argillic assemblages adjacent to ore bearing zones (Neubert et al., 2011). High manganese concentrations can be attributed to the propylitic area surrounding National Belle, all the way up to Sample 350, seen in Figure 21. Generally, propylitic altered rocks are associated with elevated manganese concentrations (Neubert et al., 2011). It is speculated the increased zinc and cadmium concentrations come from sulfides from the second layer of ore in National Belles volcanic pipe.

Hydrothermal Alteration Map of Red Mountain Creek: HW to Sample 359

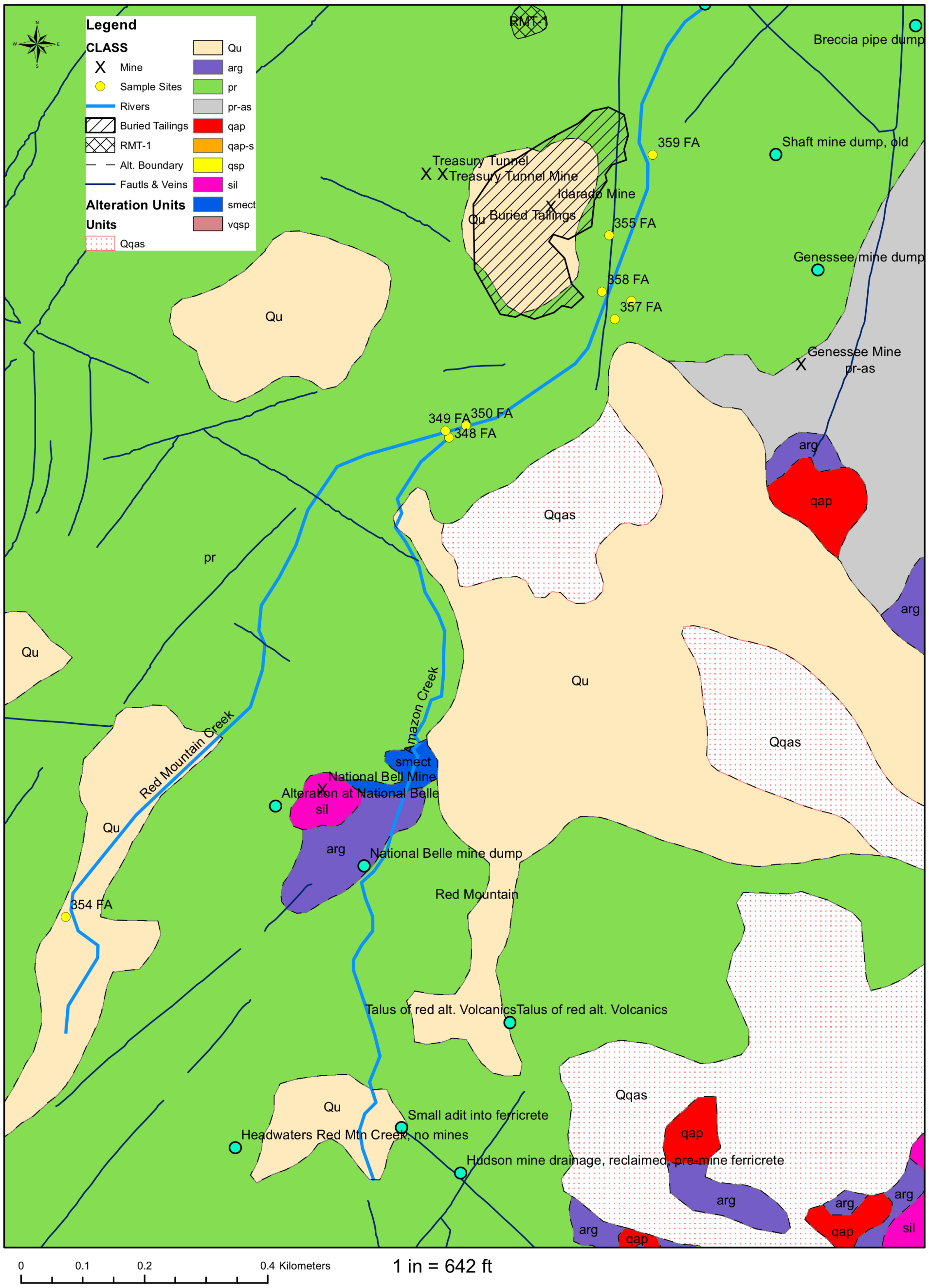


Figure 21. Alteration assemblages for the area including the headwaters of RMC and Amazon Creek to Genessee. Note: there are four alteration assemblages around the National Belle Mine

These sulfides could have been altered hydrothermally, or undergone oxidation when brought to the surface and placed in dumps. Increased magnesium levels could be the result of chlorite or biotite, dissolution, both of which is found in propylitic assemblages (Neubert et al., 2011). It is also speculated that magnesium concentrations could also be high due to the unit Tsv, which often contains pyroxene and hornblende, both of which have magnesium in it (from phlogopite, the Mg member of biotite, which is found in unit Tsv, and can be seen in Figures 4 and 22).

Since this area was hydrothermally altered predominantly by propylitic assemblages as seen in Figure 21, there should be substantial acid neutralization. However, because the area was extensively mined, it appears the mining significantly enhanced the metal concentration in Amazon, such that when Sample 350 is taken, pH drops to 3 and shows increases in all metal concentrations with the exception being cadmium.

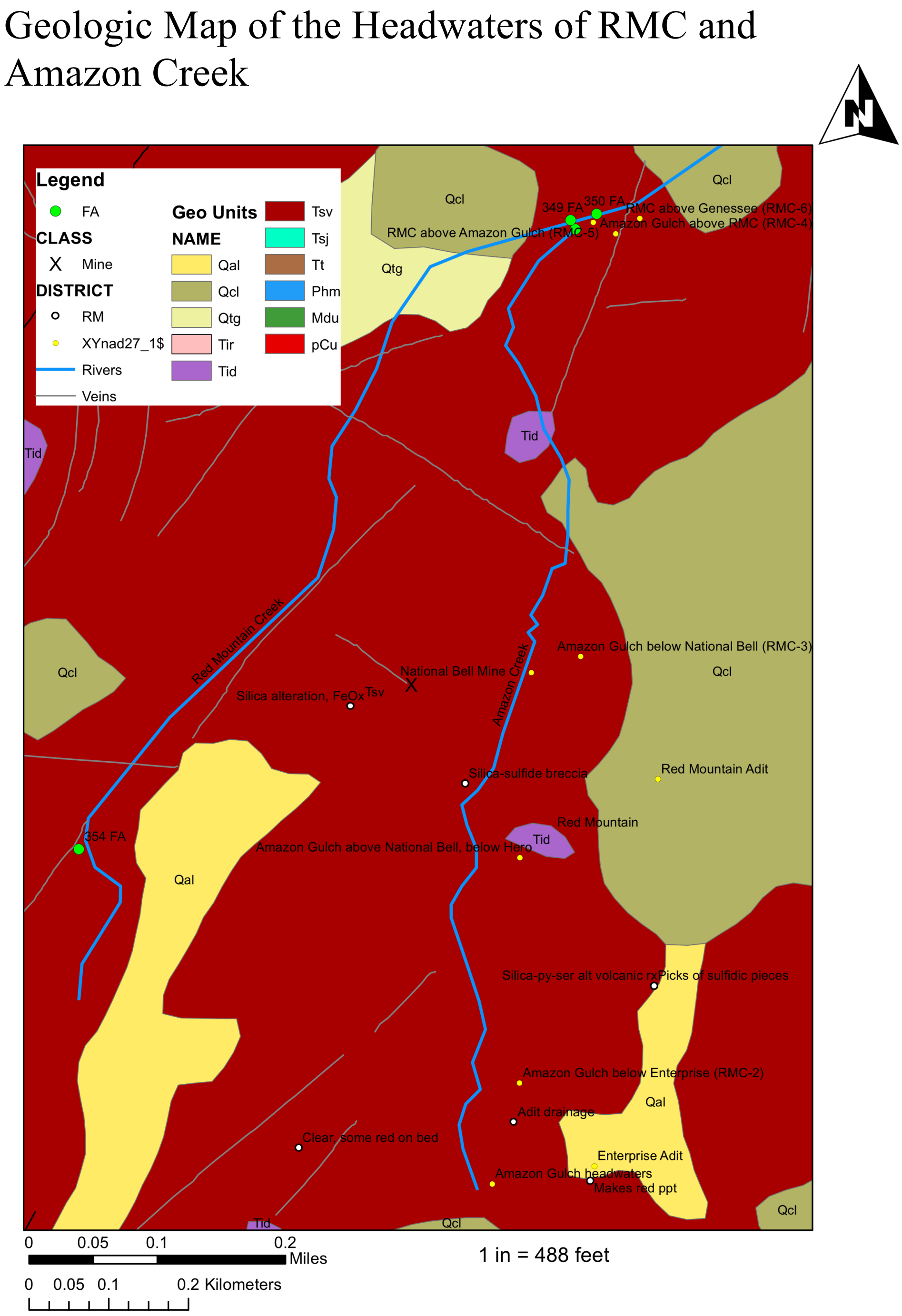


Figure 22. Geology of the area around National Belle Mine and Amazon Creek

The second dashed line represents Sample 356, which is the Genessee Mine, shown in Figure 23. Here, the pH is 2.67 and after the confluence with RMC, pH is at 3.1 (above Genessee, RMC had a pH of 3.27). Dissolved trace metal concentrations for Sample 356 are shown in Table 5.

Table 5. Genessee Mine dissolved metal concentrations for Filtered Acidified.

Sample #	Mg (ppm)	Zn (ppm)	Cd (ppm)	Pb (ppm)	Al (ppm)	Mn (ppm)	Fe (ppm)	Cu (ppm)
356 FA	12.39	1.8	0.05	0.01	38	1.08	58.24	2.74

Despite having a lower pH than Amazon Creek, only magnesium is higher in concentration at Genessee. The Genessee Mine itself sits at the top of a hill, where acidic waters from the mine and waste have drained downhill and have killed all the vegetation as seen in Figure 24 A&B. There is a weepline that travels downhill to a point where drainage spills out and that is where Sample 356 was taken. Genessee Mine itself lies on the perimeter of pr-as (mixed propylitic and alteration units of acid sulfate suite (Bove et al., 2007)) and pr (propylitic (Bove et al., 2007)) as seen in Figure 23. Propylitic assemblages are considered to provide excellent acid neutralizing abilities, due to the chlorite, epidote, sericite, illite, and most importantly calcite (Bove et al., 2007; Neubert et al., 2011). Sample 356 is located in a propylitic area, but pH is still very acidic. When propylitic altered rocks overlie and are adjacent to other intensified alterations (such as acid sulfate) these metal rich, acidic waters can occur in propylitic terrane (Neubert et al., 2011). Speculation of high magnesium levels are due to the geology of the area as seen in Figure 25.

Alteration Map of Red Mountain Creek: Sample 350 to Sample 361

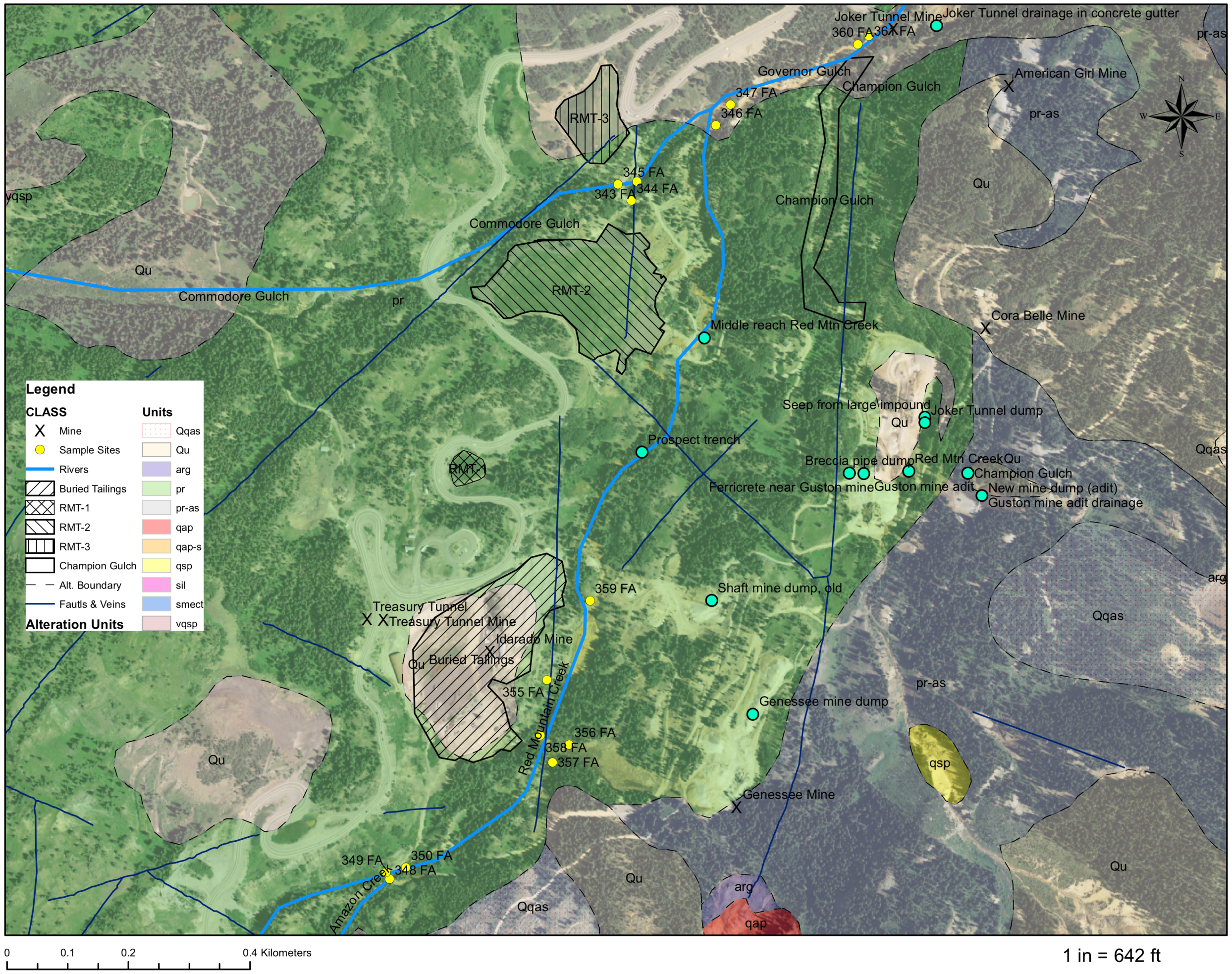


Figure 23. Alteration assemblages of Genessee, with Commodore and Champion in view

24A

24B

Figure 24. Views of Genessee Mine from both sides of RMC. A) At the Idarado Mine/Buried Tailings looking across RMC to the Genessee Drainage and able to see the yellow arrow pointing at where B is at B) Looking downhill from the Genessee Drainage; Across the valley in red, is where Figure 24A was taken

Geologic Map of the Genessee Mine Area

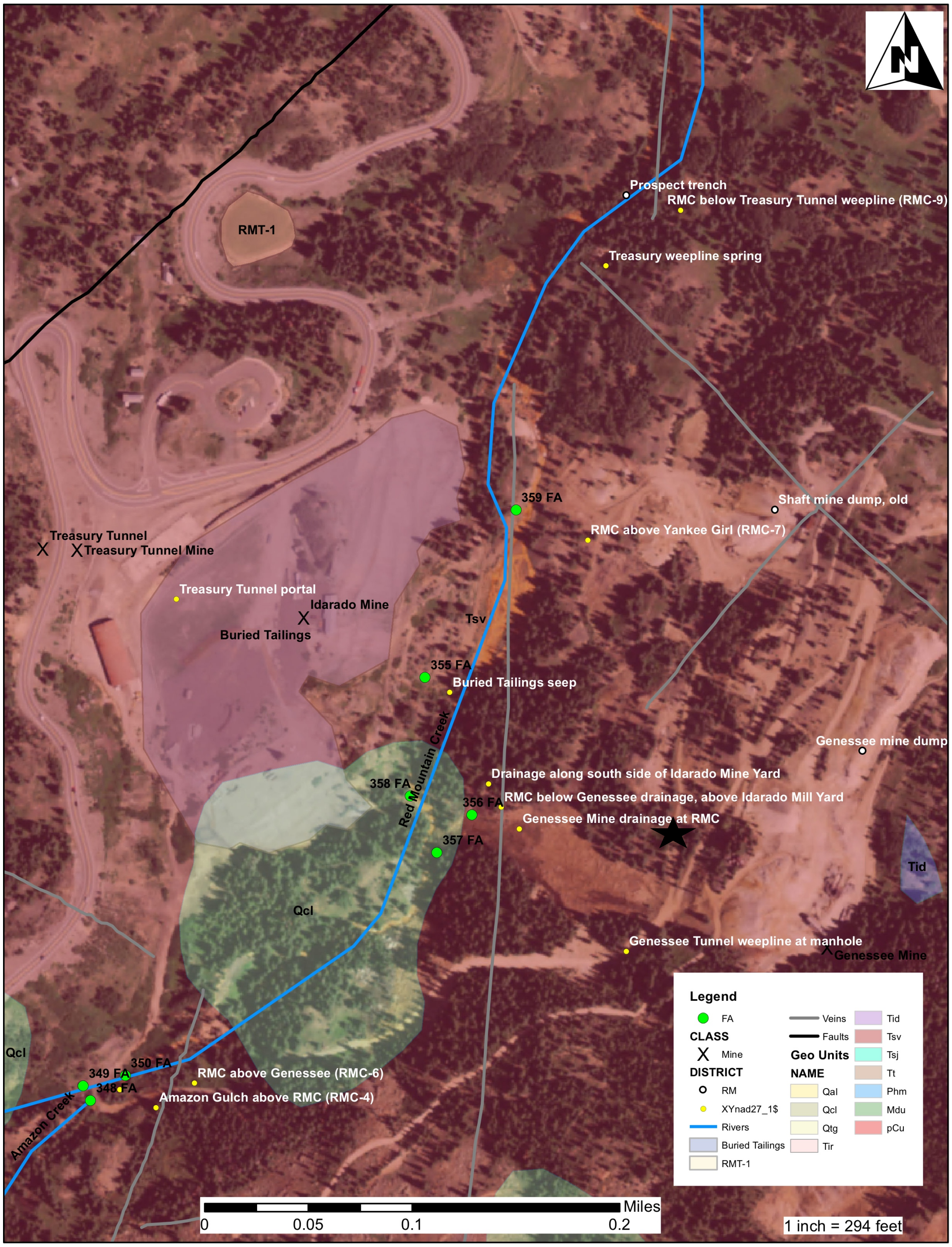


Figure 25. Geologic Map of the Genessee Mine Area The black star is the location of Figure 24B

The third dashed line is Commodore Gulch and it is represented by Sample 343, which is below the RMT2N seep (Sample 344), and above the confluence with RMC. From Figure 26, it is clear that Commodore Gulch drains the west side of the RMC watershed. This is important as Sample 343 has a pH of 7.93, which is considered circumneutral (Runkel et al., 2005; Nordstrom, 2011) and has profound affects on the dissolved trace metals. Table 6 shows dissolved trace metal concentrations for Sample 346 (RMC above Commodore) then Sample 343 and then Sample 347 (RMC below Commodore), in order to show the effects.

Table 6. Commodore Gulch dissolved metal concentrations for Filtered Acidified.

Sample #	Mg (ppm)	Zn (ppm)	Cd (ppm)	Pb (ppm)	Al (ppm)	Mn (ppm)	Fe (ppm)	Cu (ppm)
346 FA	8.45	4.0	0.23	0.17	59.32	2.31	41.02	4.07
343 FA	3.56	0.4	0.27	0.0004	0.1	0.46	0.05	0.02
347 FA	6.86	2.89	0.19	0.11	39.21	1.76	17.4	2.64

From Table 6, there is a clear drop off of dissolved trace metal concentrations from Sample 346 to Sample 347. The reason for the decrease in dissolved metal concentrations begins with geological setting of the western side of the watershed. Propylitic altered rock contains acid neutralizing minerals such as calcite and chlorite (Figure 27)(Church et al., 2007). These minerals dissolve and produce circumneutral waters (pH ~7, Nordstrom, 2011) with low dissolved trace metal concentrations (Neubert et al., 2011). Sample 343 has a pH of 7.93 and mixes with Sample 346, which has a pH of 3.12. Intermixing streams of high and low pH can contribute decreased dissolved metal concentrations by which both iron and aluminum can precipitate (Wright et al., 2007).

Alteration Map of Commodore Gulch and the West Side

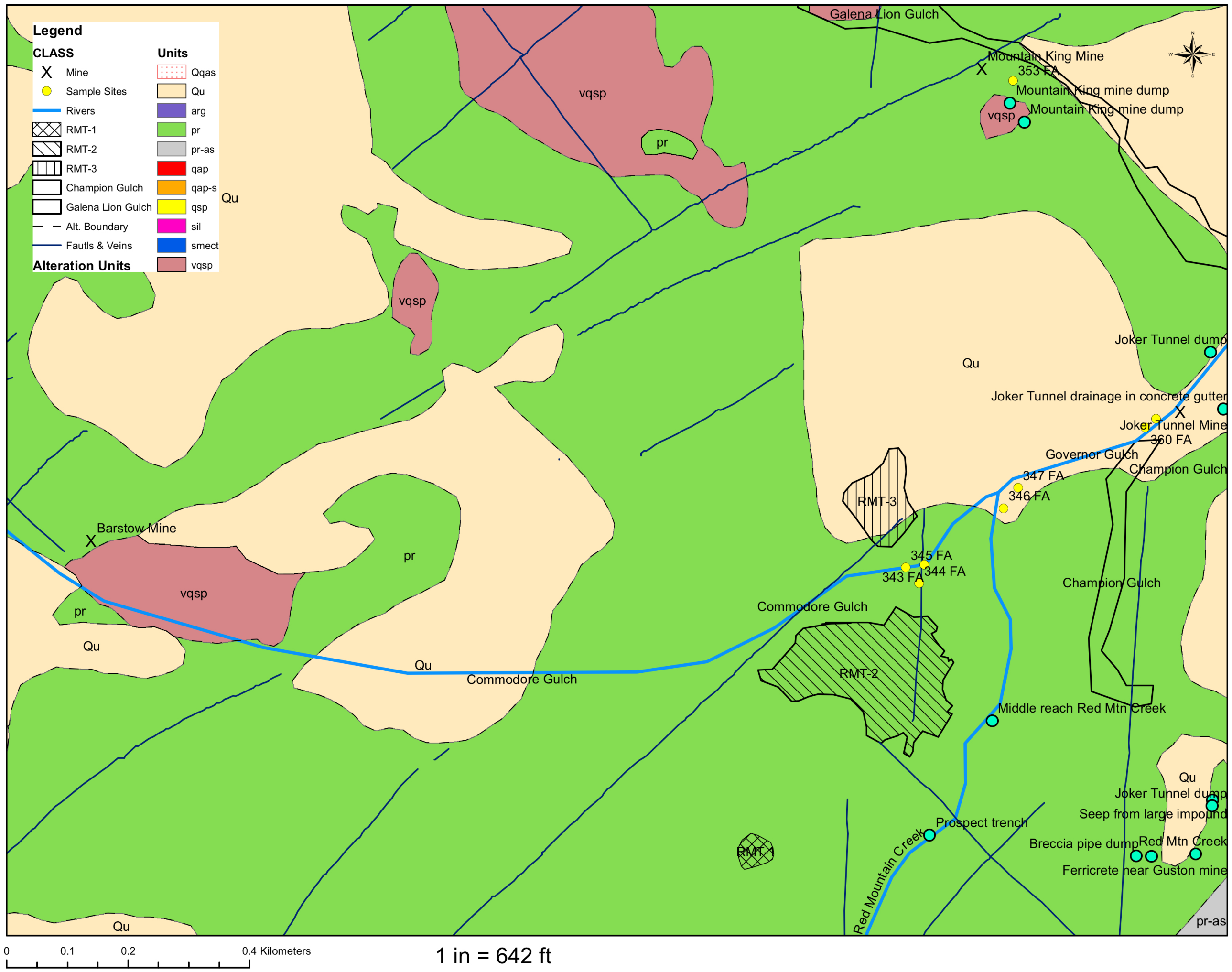


Figure 26. The west side of RMC watershed is dominated by propylitic altered assemblages

Figure 27. View of RMC to the west. Propylitic (acid neutralization) assemblages are dominant, thus creating a much more green and mellow colored landscape; RMT2 is in the center of the photo and RMT3 is just to the right of it. No sulfide oxidation here

Dissolved iron in streams is very dependent on pH, as low pH (~ less than 3.2 (Wright et al., 2007, 530) makes iron soluble, compared to high pH, which makes iron insoluble (Wright et al., 2007). When Commodore Gulch mixes with RMC, the result is the precipitation of iron oxyhydroxides (Wright et al., 2007), as seen in Figure 28. Aluminum like iron, is very dependent on pH, and if pH is ~ 4.5-5, it should precipitate (Nordstrom and Alpers, 1999; Wright et al., 2007). In the case of mixing circumneutral water with acidic waters, the result is a white aluminum hydroxysulfate precipitation that coats streambeds as seen in Figure 29 (Nordstrom and Alpers, 1999, 151; Wright et al., 2007). Copper can also be adsorbed to both the iron and aluminum precipitates, as part of the pH increasing (Wright et al., 2007). It appears the other dissolved trace metal decreased concentrations are caused by dilution.

Figure 28. RMC is the orange water on the left and Commodore Gulch water is on the right. The low pH of RMC mixes with high pH of Commodore, and precipitation occurs

Figure 29. Notice the white aluminum staining occurring at the streams edge

The fourth dashed line is Champion Gulch, which is represented by Sample 360 (Champion Creek) above the confluence with RMC as seen in Figure 15. Sample 347 (RMC above Sample 360) has a pH of 3.3 and Sample 361 (RMC below Champion) has a pH of 3.1. Sample 360 has a pH of 2.77, which is very acidic, so dissolved metal concentrations are expected to be high and can be seen in Table 7.

Table 7. Champion Creek dissolved metal concentrations for Filtered Acidified.

Sample #	Mg (ppm)	Zn (ppm)	Cd (ppm)	Pb (ppm)	Al (ppm)	Mn (ppm)	Fe (ppm)	Cu (ppm)
347 FA	6.86	2.89	0.19	0.11	39.21	1.76	17.4	2.64
360 FA	8.46	0.78	0.03	0.02	36.63	0.81	59.55	0.54
361 FA	7.45	3.2	0.08	0.13	61.4	2.43	68.5	3.11

Champion Gulch experiences a variety of hydrothermal alterations, which have affected aluminum and iron concentrations, as well as magnesium levels. As seen in Figure 30, there are multiple alteration types present: arg (argillic), qap (mixed quartz-alunite-pyrite and quartz-kaolinite-pyrophyllite-pyrite), pr-as (mixed propylitic and alteration units of acid sulfate suite), pr (propylitic), and qsp (quartz-sericite-pyrite) (Bove et al., 2007; Neubert et al., 2011). Argillic and qap assemblages are found on the Southwestern side of Figure 30, and have a fault that runs slightly to the Northeast through pr-as, such that it eventually crosses Champion Gulch and end at the boundary of the propylitic assemblage. Argillic assemblages contain kaolinite and dickite (aluminosilicates), as does qap (Bove et al., 2007; Neubert et al., 2011). However, qap also includes alunite, pyrophyllite (aluminosilicate), and 20 to 30% pyrite by weight (Bove et al., 2007, 3; Neubert et al., 2011, 16). The unit pr-as has the same mineral assemblages as qap as that is what acid sulfate assemblages are typically composed of (Neubert et al., 2011). The pr or propylitic part is composed of calcite, biotite, and aluminosilicates: chlorite, epidote, illiite, and sericite (is a potassium mica that is an alteration product of aluminosilicates) (Neubert et al., 2011). The unit qsp contains 10-20% finely disseminated and fracture filling pyrite (Bove et al., 2007; Runkel et al., 2005). When weathered, pyrite produces acidic water, sulfate and ferrous iron, and as pH becomes more acidic, dissolved metal concentrations increase. The acidic water at the small spot of qsp travels downhill through pr-as and pr assemblages. These assemblages are full of aluminosilicate minerals and when that acidic water comes into contact with those minerals, they react producing high concentrations of aluminum in surface water (Church et al., 2007).

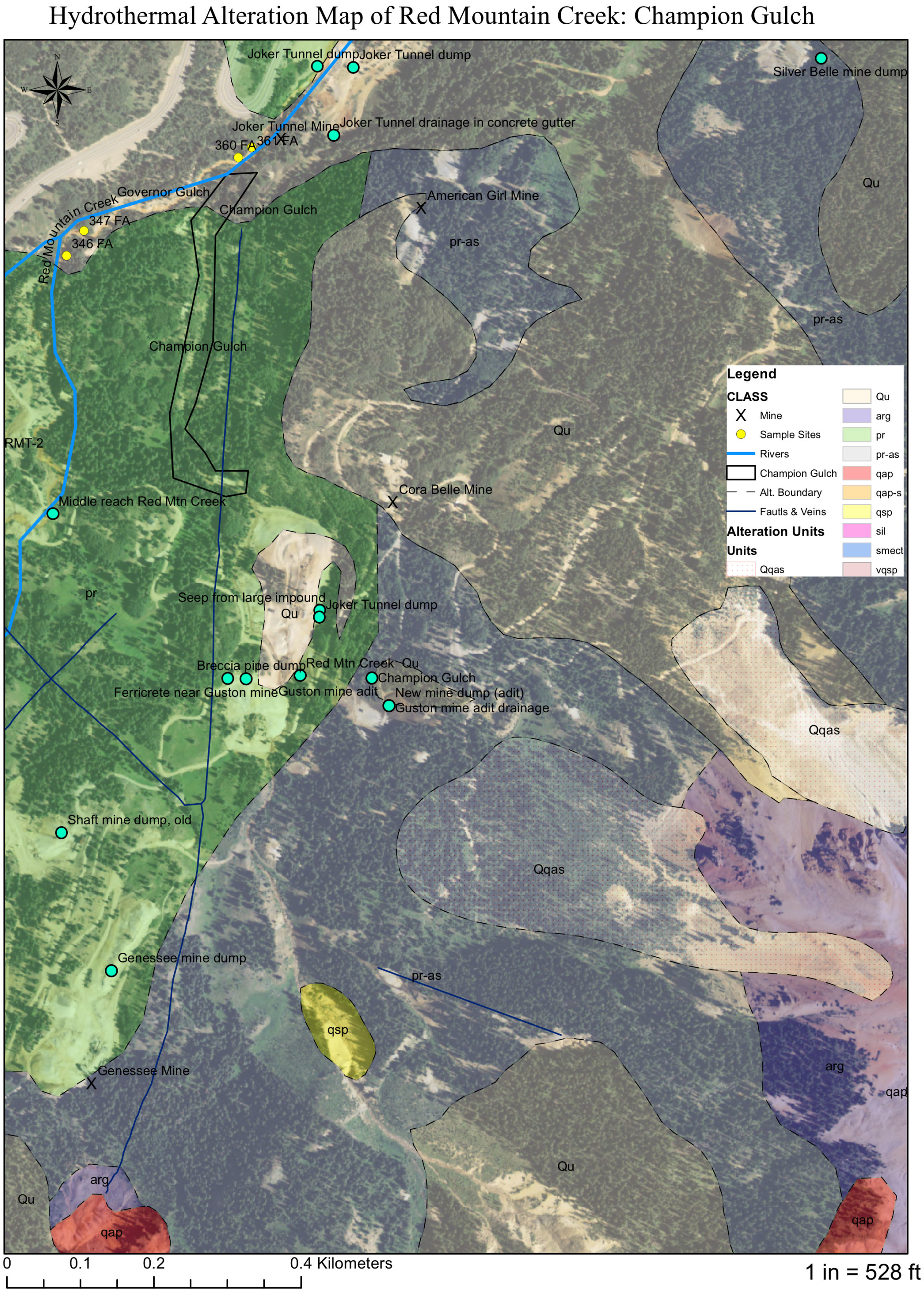


Figure 30. Champion Gulch alteration assemblages. Note Champion disappears around the Guston mine area, but continues where the unit qsp is

Ferrous iron is also being oxidized to ferric iron and when ferric iron reacts with pyrite and water it produces more acid, allowing for dissolved concentrations to increase. Also, argillic assemblages can weather releasing both iron and aluminum (Neubert et al., 2011). It could be suggested both cadmium and lead levels were low, due to dilution as water flows downhill. Also, zinc levels are significant, it is speculated it may be attributed to the dissolution of pyrite, as sulfides have been known to have trace amounts of zinc (Church et al, 2007, 59). Manganese is significant, but levels are higher downstream and could be because manganese oxides can form very far from acid formation sources such as qsp (Nordstrom and Alpers, 1999).

Sample 367 represents the fifth and final dashed line, which is Crystal Lake above RMC. Sample 366 is RMC after RMT4 and Sample 368 is below the confluence of Crystal Lake and RMC, and their concentrations are shown in Table 8.

Table 8. Crystal Lake dissolved metal concentrations for Filtered Acidified.

Sample #	Mg (ppm)	Zn (ppm)	Cd (ppm)	Pb (ppm)	Al (ppm)	Mn (ppm)	Fe (ppm)	Cu (ppm)
366 FA	12.26	2.87	0.06	0.1	52.2	2.66	17.86	2.29
367 FA	8.0	0.01	0.0006	0.001	0.18	0.94	0.47	0.004
368 FA	12.11	1.8	0.04	0.05	29.14	2.58	3.56	1.18

Sample 366 has a pH of 3.07, and Sample 367 has a pH of 6.35, and after the mixing of the two pHs, Sample 368 has a pH of 3.47. As dilute waters from Crystal Lake mix with RMC, concentrations decrease (Runkel et al., 2005). As pH increases precipitation and sorption reactions, decreases in all constituent concentrations occurs (Runkel et al., 2005).

6.3 Confluences with No influence

There are two gulches, one on the west side of RMC and one on the eastside. Galena Lion Gulch is on the west side, where Sample 353 and Sample 362 were taken as seen in Figure 31. Sample 353 was taken below the collapsed portal of Mt. King mine and Sample 362 was taken just above Highway 550, in a meadow. Sample 353 has a pH of 6.71 and Sample 362 has a pH of 7.93. As this stream flows downstream, it is being remediated by the natural growing meadow. In addition to the vegetation remediating, the west side has propylitc alteration (Figure 6), which as stated in previous sections, is associated with circumneutral waters. Cadmium, lead, aluminum, iron, and copper are all very low in concentration by the time they reach Sample 362. Manganese enrichment due to propylitic alteration is responsible for Sample 362 having a 0.75 ppm concentration. Magnesium has 12.1 ppm and is due to the biotite and chlorite dissolution. Zinc is at 0.13 ppm and could be caused by the dissolution of pyrite, as propylitic alteration usually contains the lowest amount of pyrite (Neubert et al., 2011).

Corkscrew Gulch is located on the eastside and lies between Red Mountain #1 and #2. Three samples were taken here: Sample 351 was at the headwaters and above the un-named adit. Sample 352 was taken below the un-named adit. Sample 364 was taken above RMC (Figure 32). The pHs go from 3.27 to 3.35 to 2.96 respectively. As expected with low pH, metal concentrations did go up at Sample 364, however, only for

Sample Locations for Galena Lion Gulch

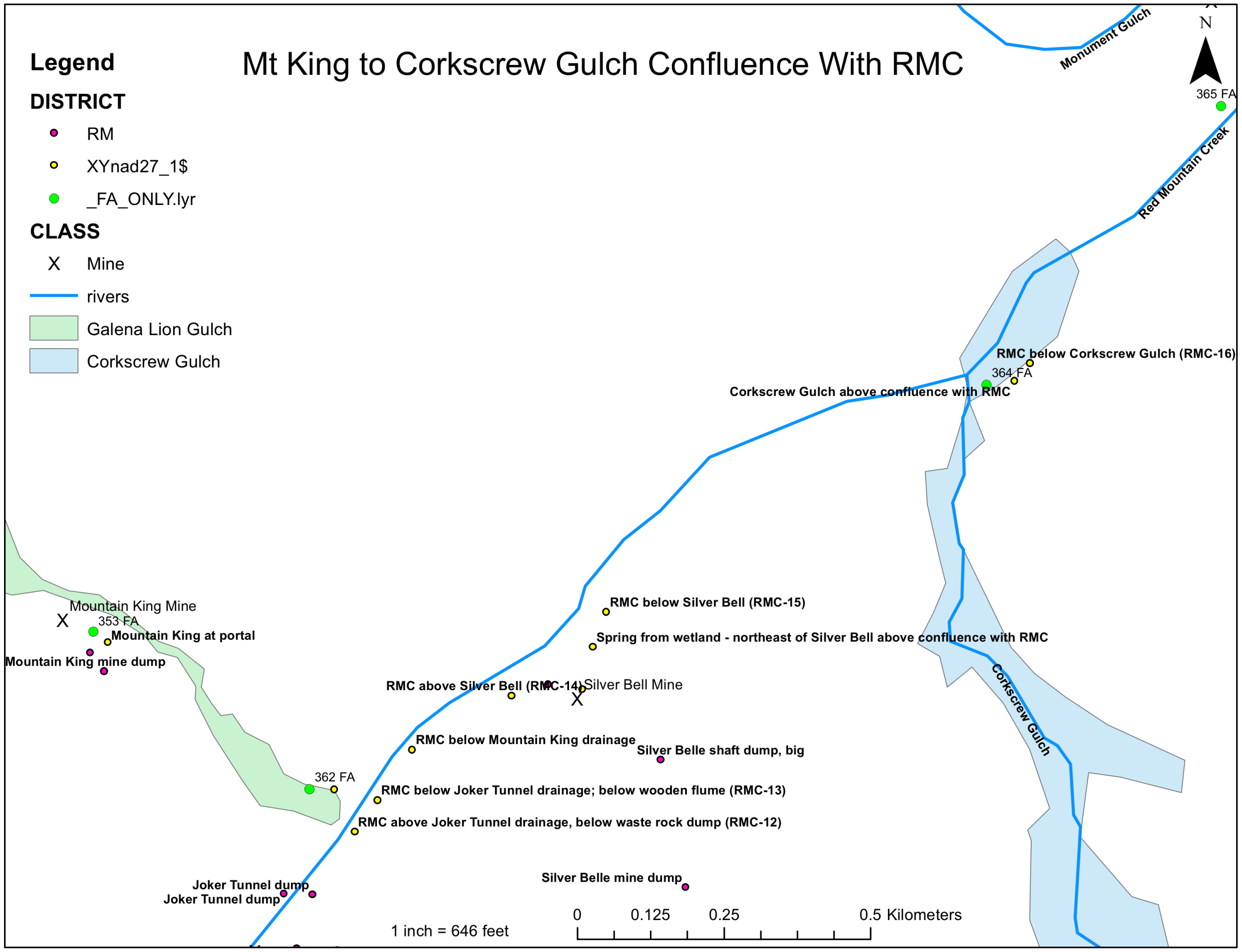


Figure 31. Sample locations for Galena Lion Gulch to the base of Corkscrew Gulch

Map of Corkscrew Gulch

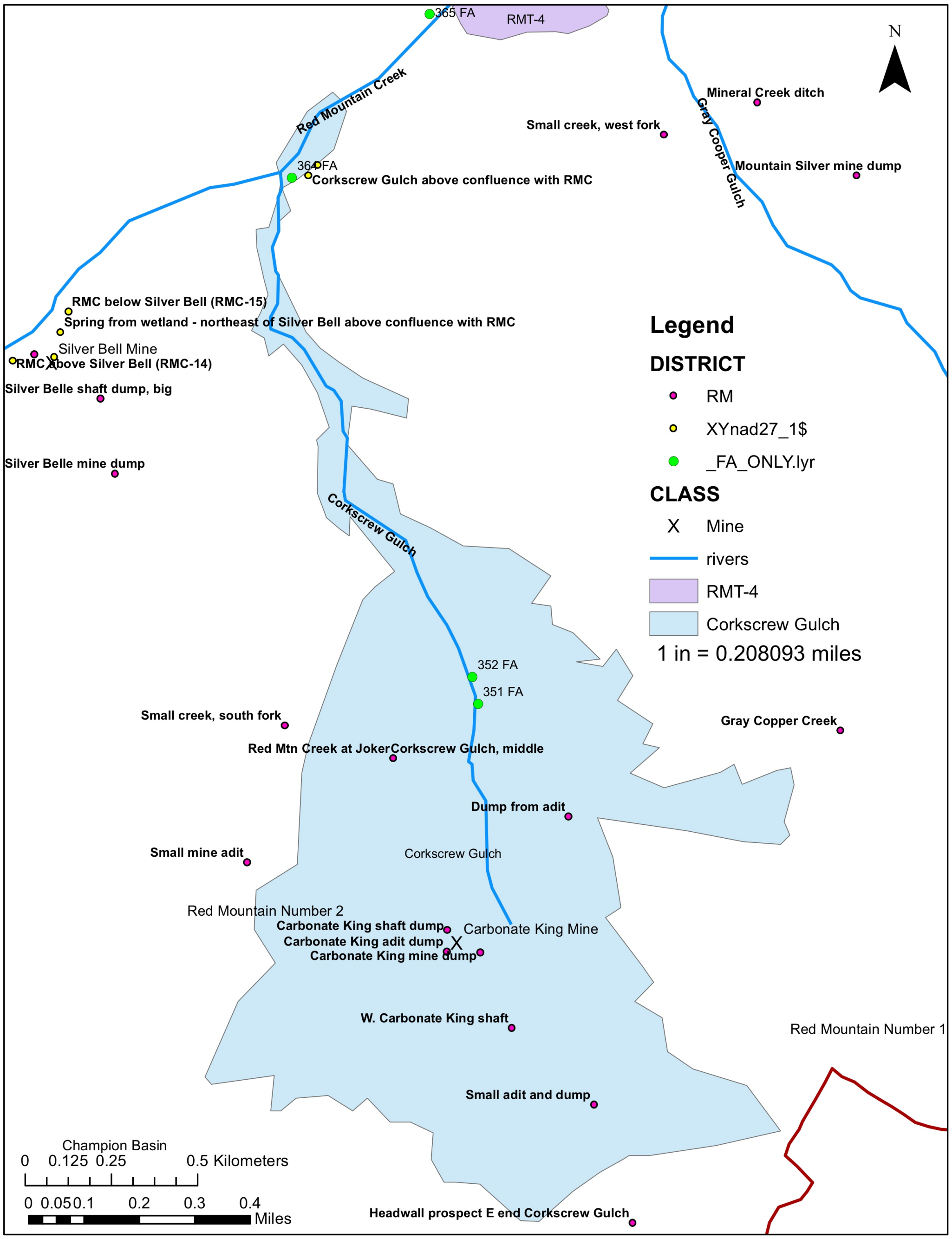


Figure 32. Sample locations for Corkscrew Gulch

aluminum and copper. The other six, decreased in concentrations. There is no significant dissolved metal loading to RMC.

6.4 Overall

From Sample 354 (headwaters of RMC) to Sample 368 (last sample on RMC), there is a remarkable change in pH and in dissolved trace metal concentrations. At the headwaters, pH is at 8.02 and by the end, pH is 3.47. Dissolved metal concentrations are shown in Table 9. Table 9 also shows the US EPA drinking water standards.

Table 9. Comparison of the Headwaters to the last Sample 368 and US EPA.

Sample #	Mg (ppm)	Zn (ppm)	Cd (ppm)	Pb (ppm)	Al (ppm)	Mn (ppm)	Fe (ppm)	Cu (ppm)
354 FA	2.51	0.05	0.03	0.0008	0.04	0.07	0.25	0.003
368 FA	12.11	1.8	0.04	0.05	29.14	2.58	3.56	1.18
US EPA		5.0	0.005	0.0	0.05-2.0	0.05	0.3	1.0-1.3

All eight of the constituents have increased in concentration. Beginning with the smallest increase and moving to the largest, cadmium increases 0.01 ppm. Lead follows with an increase of 0.0492 ppm and copper by 1.177 ppm. Zinc increases by 1.75 ppm and then manganese by 2.51 ppm. Iron increases 3.31 ppm and magnesium by 9.6 ppm. Aluminum has the largest increase by 29.1 ppm. Cadmium is 0.039 ppm less than the state of Colorado’s basic metal stream standards for aquatic life (Nash, 2002). The other constituents when compared to this aquatic standard are as follows: Lead is 0.025 ppm over the standard. Copper is 1.17 ppm over the standard and zinc is 1.75 ppm over.

Manganese is 1.58 ppm and iron is 2.56 ppm greater than the standard. Lastly, aluminum is 29.04 ppm over the aquatic standard (Nash, 2002). Compared to the US EPAs drinking water standards, at the headwaters, aluminum, copper, iron, zinc and pH pass their standards. Failing is cadmium, lead and manganese. At Sample 368, only copper and zinc pass those drinking water standards. Aluminum, cadmium, iron, lead, manganese and pH fail these standards. The pH for drinking water should be from 6.5-9, and Sample 368 is at 3.47. Magnesium is higher than the North American average (4.9 ppm) and the world average for river water (3.7) (Berner and Berner, 1987).

In order to understand water quality degradation, when dealing with both NARD and AMD, determining whether it is possible to proportion them is a must. To do this, the difference between areas with and without mines on the east and west side of the watershed must be determined. In addition, determining if the geology controls the geochemistry of the stream must be examined.

Mining related activities occur on both sides of RMC. However, the majority of mines lie on the east side, where the pH of streams entering RMC here are acidic. Genessee is at 2.67, Amazon is at 2.95, Champion is at 2.77, and Corkscrew Gulch is at 2.96 (these four locations drain mines). Mines on the west side are few in numbers and the pH of streams here are often circumneutral (~7). Both Commodore and Galena Lion have pH at 7.9, and both drain mines. At the Mt. King portal (Figure 31), pH is at 6.7. This suggests Natural Acid Rock Drainage is the cause for high metal concentrations and low pH. However, when examining Figure 11, one can see at Amazon Creek, there is a significant drop in pH and increase in dissolved metal concentrations. This would suggest Acid Mine Drainage is the blame here. To further determine if NARD or AMD is or is not to blame, the local geology must be examined.

RMC splits its' watershed into east and west sides, which from Figure 4 shows the separation of Silverton and San Juan volcanics. The east side hosts units of Qcl (colluvium and landslide deposits, Holocene and Pleistocene), Qtg (talus, glacial deposits, and rock glaciers, Holocene and Pleistocene), Tid (dacite intrusions, Oligocene to Miocene), and Tsv, which is the Silverton Volcanic Group. This group contains many aluminum, iron, and magnesium rich minerals (pyroxenes, enstatite, diopside, hornblende). The east side is also dominated my acid-sulfate assemblages containing pyrite. Compared to the west side, units are Qtg and Tsj (San Juan Volcanics). The San Juan Volcanics dominate the west side. Hornblende is commonly found in this formation. Unlike the east side, there is little to none metal rich sulfides present here, which allows for propylitic alteration to dominate the landscape.

Due to the complexity of hydrothermal alteration (Figure 33) occurring in this area and the large volume of mines, proportioning whether it is NARD or AMD, is tricky. Based solely on mining, NARD is clearly the major contributor. If the lithology is examined, the east side contains acid-sulfate assemblages rich in pyrite compared to the acid neutral, propylitic west side. The Silverton Volcanic Group also is on the east side, and weathering has caused dissolution of its minerals adding additional metal concentrations to streams. This again points at NARD being the sole contributor. The east side also has a high number of mines, all of which have brought sulfide deposits to the surface. These deposits weather from exposure to water and air, creating AMD, but had the mining not occurred, there still would be NARD. Mining has only exacerbated the situation. Pre-mining conditions have been estimated and concluded that RMC was acidic before mining ever started (Runkel et al., 2007).

For future studies, it would be recommended sample size be over 100 samples. This would require extensive funding. Sampling the headwaters of each tributary and of each tailings seep would be recommended. Taking samples of the water in the drainage channels around the tailings would also be ideal.

Figure 33. Reflection of the Red Mountains at Crystal Lake

7. CONCLUSIONS

The goal of this research was to provide an understanding of the relationship between natural and anthropogenic contamination of surface waters. Determining whether dissolved metal concentrations are due to the leaching of surrounding geology or whether it is the product from mining is a difficult task. Are the remediated tailings the sole source of dissolved metal concentrations in Red Mountain Creek, or are there additional sources? In order to do this, there were three objectives made. The first two were to establish the geochemistry in streams above and below all mining activity, as well as above and below remediated tailings. The third was to evaluate the impact of remediation on the geochemistry. In order to determine if the objectives had been completed, the following three questions were asked: 1) When dealing with Natural Acid Rock Drainage (NARD) vs. Acid Mine Drainage (AMD), is it possible to proportion them? 2) What is the difference between the mined areas and non-mined areas of both the east and west side of the watershed? 3) Does geology control the geochemistry of the stream?

Mines located on the east side, had much lower pH compared to the west, and this indicated that NARD was the contributor and not AMD. Only Amazon Creek, indicates AMD, as in Figure 21, propylitic alteration surrounds the National Belle mine and Amazon Creek, thus suggesting AMD is the cause here. When comparing the hydrothermal alteration of the east to west, the difference is significant. Acid-sulfate assemblages with pyrite dominate compared to the west where there is no sulfide present and where propylitic assemblages dominate. Again this points to NARD as the sole contributor. Pre-mining conditions also indicate RMC was acidic.

It is the conclusion of this paper the remediated tailings are not the sole source of dissolved metal concentrations in Red Mountain Creek, but are rather caused by Natural Acid Rock Drainage, with the one exception being at Amazon Creek.

1) The water quality at the headwaters of RMC, Commodore, and Crystal Lake were where the geochemistry was excellent as it had circumneutral pH and low metal concentrations. The water quality in areas of acid-sulfate assemblages, such as Amazon, Genessee, and Champion all had low pH and high metal concentrations due to NARD. The east side alteration assemblages have been exacerbated by mining.
2) Overall, the dissolved metal concentrations are all higher at Sample 368 when compared to the headwaters of RMC. When comparing Sample 368 to Sample 350 (post-Amazon), pH is lower, as is lead, iron and copper. The increase in the other five metals proves the remediation only through tailings piles is part of the solution. The addition of circumneutral waters into the acidic RMC remediated the streams better.

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