
REPORT NO. 118015/1

**GEOCHEMICAL AND ISOTOPIC CONSTRAINTS ON THE SOURCES
OF ACID ROCK DRAINAGE (ARD) PRODUCTS TO
GROUNDWATER, ANVIL RANGE MINING COMPLEX, YT**



Submitted to:



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EXECUTIVE SUMMARY

The primary objectives of this study were to determine the sources of ARD products to receiving groundwater at the ARMC using stable isotope data and conventional ARD indicator species. The following is a summary of the main conclusions that were drawn from this study:

- Stable isotope data indicate that SO_4 in tailings seepage and waste rock seepage is derived primarily from the anaerobic oxidation of pyrite; hence isotope data could not be used to separate the relative contributions of each to receiving waters;
- Receiving waters could not be distinguished from precipitation based on their water isotope composition; differences in the water isotope composition of ARD sources are observed but are likely related to the timing and source of recharge, not evaporative enrichment;
- Ni:Co ratios proved to be the most valuable tracer of waste rock seepage in receiving waters; a 1:1 Ni:Co ratio was identified in waste rock seepage (at X23) and similar ratios characterized receiving waters;
- Waste rock seepage from the Faro Creek canyon (i.e. FCS) is clearly present in the Rose Creek alluvial aquifer (RCAA) near the mouth of Faro Creek canyon and in the RCAA along the north side of Rose Creek valley;
- Historic time trends in wells P01-03 and X24D (at Intermediate Dam) show a concurrent increase in SO_4 , Ni, and Co concentrations (but not zinc) since early 2002; concurrent increases of Ni, Co, Zn, and SO_4 for FCS (at X23) suggests increased loading of the RCAA by FCS (at least until start of operation of the ETA SIS).
- Zinc concentrations in the northern portion of RCAA at the Cross Valley Dam are generally lower than upgradient at the Intermediate Dam, which is consistent with the attenuation of Zn along the flow path. A gradual breakthrough of Ni and Co (likely over the next 5-10 years) can be expected to precede any breakthrough of zinc at the Cross Valley Dam reach.
- An elevated Zn concentration was identified in sample P09-C3-BR (from deep bedrock near the southern side of Rose Creek valley below the toe of the Cross Valley Dam) but SO_4 concentrations were very low (10 mg/L); because SO_4 in this sample was more depleted in ^{18}O than 'background' SO_4 , the presence of mine waste seepage in this area could not be discounted entirely; seepage from the Faro Creek diversion is believed to be a more likely source of the slightly elevated zinc concentrations than the TDS plume that affects

groundwater along the northern side of Rose Creek valley but additional data is required to further test this hypothesis.

The key aspects of groundwater quality in the Zone 2 Pit outwash area are summarized as follows:

- Groundwater in the NFRC aquifer upgradient of the Zone 2 Pit outwash area (at SRK08-P12B) is impacted primarily by seepage from the Northeast Rock Dump;
- Groundwater in the NFRC aquifer immediately downgradient of the Zone 2 Pit outwash area (at wells BH5 and BH6) is further impacted by seepage from the Zone 2 Pit;
- The geochemical characteristics of Zone 2 Pit seepage are not known exactly but only a small contribution of this type of seepage is necessary to reproduce the high Zn-low SO₄ characteristics of groundwater in the NFRC aquifer downgradient of the backfilled Zone 2 Pit.

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1 INTRODUCTION

1.1 BACKGROUND & STUDY OBJECTIVES

Elevated levels of acid rock drainage (ARD) products characterize groundwater in several areas of the Anvil Range Mining Complex (ARMC). Of particular interest are elevated levels of sulphate (SO_4), magnesium (Mg), and various other metals of interest (iron, manganese, and zinc) along the northern side of the Rose Creek alluvial aquifer (RCAA). This part of the RCAA is likely impacted by tailings seepage and waste rock seepage from Faro Creek canyon but the proportions of each in receiving groundwater is not well known.

Several ARD indicator species, including cobalt, nickel, and sulphate (SO_4), occur in unique proportions within waste rock seepage and tailings porewater. Previous studies have used these indicator species to 'fingerprint' waste rock seepage and tailings porewater and thereby detect their presence in groundwater. Robertson GeoConsultants Inc. (2009b) identified waste rock seepage as the predominant source of ARD products to groundwater near the mouth of Faro Creek canyon. ARD products from this area are thought to be transported downgradient along the northern side of Rose Creek valley and cause elevated levels of ARD products in the Intermediate Dam and Cross Valley Dam reaches.

However, ARD loading from waste rock seepage and tailings porewater to groundwater could not distinguished uniquely using groundwater quality data alone (Robertson GeoConsultants Inc., 2009b). It was therefore recommended to use stable isotopic tracers of water and sulphate to better distinguish between the different ARD sources in the RCAA. The results of this study are summarized in this report.

The primary objectives of this study were as follows:

1. Determine if stable isotope data could be used at the ARMC to separate the contributions of ARD products from waste rock seepage and tailings porewater to receiving groundwater;
2. Assess whether isotope data could confirm that waste rock seepage is the predominant source of ARD products to groundwater along the northern side of Rose Creek valley;

3. Assess whether elevated levels of Zn in deep bedrock near the southern side of Rose Creek valley (near P09-C3) are related to mine waste seepage or represent a natural source; and
4. Assess whether stable isotope data and conventional ARD indicators can explain the low sulphate-high zinc characteristics of groundwater in the Zone 2 Pit outwash area.

These objectives were accomplished by collecting a comprehensive set of water quality and isotope data in September 2009. The data set included samples of waste rock seepage in Faro Creek canyon (i.e. Faro Creek seepage) and tailings porewater in Rose Creek valley. Samples of receiving groundwater in the following 'areas of interest' were also collected:

- Upgradient of Faro Creek canyon in the Second Impoundment (at wells P03-01-02, P03-01-04, and P03-01-05);
- Near the mouth of Faro Creek canyon in the ETA (at wells P09-ETA-1 and P09-ETA-2);
- Immediately downgradient of Faro Creek canyon along the northern side of Rose Creek valley (at wells P03-06-04, P03-06-05, and X21B);
- Further downgradient of Faro Creek canyon in the Intermediate Dam reach (at wells X24D and P01-03) and in the Cross Valley Dam reach (at wells P05-02, P01-03, and P01-11);
- In deep bedrock below the toe of the Cross Valley Dam (at wells P09-C1, P09-C2, and in bedrock beneath well P09-C3); and
- In the Zone 2 Pit outwash area (at selected 'BH' wells and wells SRK08-P12A/B).

Most samples were collected from wells screened in the RCAA but several samples were collected from the lower-permeability bedrock that underlies the RCAA.

Samples from wells in the Zone 2 Pit outwash area were the only ones collected outside of the Rose Creek Valley. These samples were collected because elevated levels of dissolved zinc have recently been identified in the North Fork of Rose Creek (NFRC) aquifer but the source of mine waste seepage is unclear. For instance, the leaching of metals from outwash sediments and seepage from the Zone 2 Pit are both potential sources of ARD products in this area. Stable isotope data were thought to be of some use in determining the source of ARD products to the NFRC aquifer and hence this 'area of interest' was included in the study.

1.2 SCOPE OF WORK

A detailed scope of work for this study was provided in Robertson GeoConsultants Inc. (2009c). Phase 1 of that scope of work consisted of the following five tasks:

- Task 1. Site Visit & Detailed Sampling (Fall 2009)
- Task 2. Isotope assessment of Rose Creek aquifer upgradient of the Faro Creek canyon;

- Task 3. Geochemical and isotope assessment of Rose Creek aquifer down-gradient of Faro Creek canyon
- Task 4. Geochemical and isotope assessment of NFRC aquifer ("Zone 2 Pit outwash area")
- Task 5. Phase 1 Report

Tasks 1 to 4 were completed from September 2009 to February 2010 and this report represents the Phase 1 Report. An optional Phase 2 that would include additional sampling in the Spring 2010 was proposed but the decision to pursue this optional second phase has not yet been made.

1.3 CONCEPTS OF ISOTOPE HYDROLOGY

The following section provides a brief review of the main concepts of isotope hydrology. These basic concepts described below provide some context for the discussion of site-specific stable isotope data in the remainder of the report.

Studies from other mines in North America have shown that the stable isotope content of water and/or dissolved SO_4 can assist in the interpretation of mining impacts on groundwater (e.g. Allen and Voormeij, 2002; Sracek et al., 2004). Because an isotope tracer study has not been conducted previously at the ARMC, the principles of interpreting stable isotope data in the context of ARD contamination are briefly discussed in this section.

The specific objectives of the isotope component of this study were as follows:

1. Determine if evaporation affects the stable oxygen and hydrogen isotope contents of waste rock seepage, tailings porewater, and surface waters at the ARMC and if so, can differences be used to detect the presence of these water types in receiving groundwater; and
2. Determine if the stable sulphur and oxygen isotope contents of dissolved SO_4 in waste rock seepage and tailings porewater differ and if so, can these differences be used to trace the contributions of each ARD source to receiving groundwater.

Some of the theory and background information required to accomplish these objectives are discussed below.

1.3.1 Reference materials & the δ notation

Each isotope of a particular element has a different number of neutrons (and hence a different atomic mass) (Clark and Fritz, 2007). The two most abundant stable isotopes of hydrogen, for instance, are ^1H and ^2H , whereas the two most stable isotopes of oxygen are ^{16}O and ^{18}O . The two most stable isotopes of sulphur are ^{32}S and ^{34}S .

In terms of relative abundance, the lighter isotopes of hydrogen, oxygen, and sulphur are much more abundant than the heavier isotopes. For example, ^2H and ^{18}O represent less than 0.2% of naturally-

occurring hydrogen and oxygen atoms. 4% of naturally-occurring sulphur atoms are ^{34}S (the heaviest isotope of sulphur) and 95% are ^{32}S .

Because concentrations are so low, isotope data are presented as ratios (i.e. $^2\text{H}/^1\text{H}$, $^{18}\text{O}/^{16}\text{O}$, and $^{34}\text{S}/^{32}\text{S}$) instead of absolute concentrations. Moreover, isotope ratios are always expressed relative to a standard material. For oxygen and hydrogen isotope data, this standard is usually Vienna-Standard Mean Ocean Water (V-SMOW), whereas the standard for sulphur isotope data is Vienna-Canyon Diablo Troilite (V-CDT). The reference materials themselves were selected rather arbitrarily in the past and have little practical importance. The importance of these materials is that their isotope compositions have been certified by the International Atomic Energy Agency (IAEA) in Vienna and are used world-wide as a reference material.

Stable isotope ratios of individual samples are expressed by convention as δ values (read: 'delta'). δ values represent deviation in parts per thousand (‰) from a standard such that $\delta = [R_{\text{sample}}/R_{\text{standard}} - 1] \times 1000$. In this study, R represents $^{18}\text{O}/^{16}\text{O}$, $^2\text{H}/^1\text{H}$, or $^{34}\text{S}/^{32}\text{S}$. Recall that the $^{18}\text{O}/^{16}\text{O}$ and $^2\text{H}/^1\text{H}$ ratios of water and the $^{18}\text{O}/^{16}\text{O}$ ratio in SO_4 are expressed relative to (V-SMOW), whereas V-CDT is the standard for $^{34}\text{S}/^{32}\text{S}$.

Listed below are a few notes about the conventions of δ values that might prove helpful:

- If a water sample has a $\delta^{18}\text{O}$ value of 0‰ V-SMOW, the sample contains the same ratio of $^{18}\text{O}/^{16}\text{O}$ ratio as the V-SMOW standard material;
- If a water sample has a $\delta^{18}\text{O}$ value of +10‰ V-SMOW, the sample contains 10 parts per thousand more ^{18}O than the V-SMOW standard material; this sample is said to be 'enriched' in ^{18}O ;
- If a water sample has a $\delta^{18}\text{O}$ value of -10‰ V-SMOW, the sample contains 10 parts per thousand less ^{18}O than the V-SMOW standard material; this sample is said to be 'depleted' in ^{18}O ;

Note that the terms 'depletion' and 'enrichment' are always in reference to the heavier isotopes, not the lighter ones. In other words, a sample that has a $\delta^{18}\text{O}$ value of -10‰ is not considered 'enriched' in ^{16}O (the lighter isotope), it is 'depleted' in ^{18}O .

More important than how a δ value compares to the standard is how δ values for different samples compare to one another. Consider the following example: $\delta^{18}\text{O}$ values for two water samples are determined. One sample has a $\delta^{18}\text{O}$ value of -15‰ and the other has a $\delta^{18}\text{O}$ value of +15‰. The second sample is 'enriched' by 30‰ relative to the first sample (i.e. the second sample contains 30 parts per thousand more ^{18}O than the first sample). The isotope separation between these two samples is 30‰. The concept of isotope separation is particularly important in the discussion of $\delta^{18}\text{O}$ values of SO_4 and will be described further in Section 1.3.3.

1.3.2 Stable Water Isotopes

During the evaporation/condensation of water, the stable isotopes of water are distributed predictably based on their mass. For example, during the process of evaporation, the heavier isotopes of water (^{18}O , ^2H) prefer to remain in the denser liquid phase whereas lighter isotopes prefer the evaporating vapor. This leads to vapor phase becoming relatively 'depleted' in ^{18}O and ^2H . The residual liquid, on the other hand, is now 'enriched' in ^{18}O and ^2H due to evaporation (hence the term 'evaporative enrichment').

The process of distributing isotopes between liquid water and water vapor during evaporation and condensation is referred to as 'mass-dependent isotope fractionation'. The most important aspect of isotope fractionation is that it has a predictable influence on the distribution of water isotopes everywhere on Earth (Clark and Fritz, 1997). Consequently, the naturally-occurring stable isotopes of water in global precipitation exhibit systematic spatial and temporal variations and collectively define a regression line that is commonly referred to as the Global Meteoric Water Line (GMWL) (Craig, 1961; Dansgaard, 1964; Rozanski et al., 1993).

Based on monthly mean $\delta^2\text{H}$ and $\delta^{18}\text{O}$ values of precipitation available from the Global Network for Isotopes in Precipitation (GNIP) network (IAEA, 2009), the equation for the GMWL is $\delta^2\text{H} = 8.1 \cdot \delta^{18}\text{O} + 9\text{‰}$. The data used to define the GMWL are illustrated in Figure 1-1a. At higher latitudes, $\delta^2\text{H}$ and $\delta^{18}\text{O}$ values of precipitation are affected by the following factors:

- the source of moisture and its trajectory (i.e. weather patterns);
- seasonal changes in air temperature; and
- the form of precipitation (i.e. rain versus snow).

These factors cause precipitation from cooler, higher-latitude regions to be more depleted in ^{18}O and ^2H compared to warmer, low-latitude regions where temperatures are warm year-around and precipitation occurs only as rain (Fritz and Clark, 2007). It is these differences between warm and cold regions that cause $\delta^2\text{H}$ and $\delta^{18}\text{O}$ values for high-latitude precipitation to plot near the bottom-left of the GMWL and $\delta^2\text{H}$ and $\delta^{18}\text{O}$ values of tropical precipitation to plot near the top-right of the GMWL (Figure 1-1b).

In detail, the GMWL consists of a series of local meteoric water lines (LMWLs) for individual locations on Earth. The slopes and $\delta^2\text{H}$ -intercepts of these LMWLs are determined by intra-annual variation in the $\delta^2\text{H}$ and $\delta^{18}\text{O}$ values of precipitation within a particular region. For instance, the LMWL for Whitehorse is characterized by the equation $\delta^2\text{H} = 6.6 \cdot \delta^{18}\text{O} - 25\text{‰}$ VSMOW (Figure 1-1c). Note that $\delta^2\text{H}$ and $\delta^{18}\text{O}$ values of precipitation at Whitehorse are usually lighter during cooler months of the year (bottom-left of a LMWL) and heavier during the warmer months (top-right of LMWL). This intra-

annual variation is related primarily to temperature and is analogous to the temperature-dependent variation observed for global precipitation (i.e. the GMWL).

The LMWL is the most prominent feature on a conventional $\delta^{18}\text{O}$ - $\delta^2\text{H}$ diagram because it represents the isotope composition of water as it enters a hydrologic system. In addition to the LMWL, mass-dependent isotope fractionation often leads to the existence of a second linear trend on a conventional $\delta^{18}\text{O}$ - $\delta^2\text{H}$ diagram. This second linear trend is defined by waters that have become enriched in ^{18}O and ^2H after entering the groundwater-surface water system of a particular area (Gibson et al., 2005).

In areas where direct evaporation from soils and water bodies is volumetrically significant relative to annual water input by precipitation, $\delta^{18}\text{O}$ and $\delta^2\text{H}$ values of the residual liquid (i.e. groundwater or surface water) define a Local Evaporation Line, or LEL, with a shallower slope than the LMWL. A conceptual representation of a LEL is provided in Figure 1-1c (see dashed line).

Note that a LEL is only evident when enough data has been collected at different times of the year to define a linear feature on the $\delta^{18}\text{O}$ - $\delta^2\text{H}$ diagram. Nonetheless, the offset between $\delta^{18}\text{O}$ and $\delta^2\text{H}$ values for an individual sample and the LMWL does increase in approximate proportion to degree of evaporative enrichment. This means that samples of water that have been affected by evaporation would plot below and to the right of the LMWL (as illustrated conceptually in Figure 1-1c).

Potential variations in $\delta^{18}\text{O}$ and $\delta^2\text{H}$ values of groundwater, surface water, and seepage can be generalized by the following general statements:

- If a particular water sample has not been appreciably affected by evaporation then the $\delta^{18}\text{O}$ and $\delta^2\text{H}$ values of that sample will plot close to the LMWL because the isotope composition of that sample is indistinguishable from that of precipitation (i.e. initial water input);
- If evaporation is volumetrically significant compared to water input by precipitation then a water sample from that location will plot below the LMWL on a $\delta^{18}\text{O}$ - $\delta^2\text{H}$ diagram because that sample has become enriched in ^{18}O and ^2H relative to precipitation.

The potential of using $\delta^{18}\text{O}$ and $\delta^2\text{H}$ values to differentiate waters that have been subjected to direct evaporation from standing waters (i.e. ponds) and internal evaporation within waste rock piles has been demonstrated at Mine Doyon in Quebec (Sracek et al., 2004). Differentiating these waters was possible because evaporation from standing water and a partially-saturated porous media affect the isotope composition of ambient water differently.

Evaporation from standing water results in a LEL of slope 5 or so (Clark and Fritz, 2007). This type of LEL is commonly observed in lakes, rivers, or in groundwater that is recharged by evaporatively-enriched surface water (i.e. swamps, etc). Within a waste rock pile, evaporation results in a LEL with a much shallower slope of 2 to 3. The shallow slope is due to more resistance to diffusion in a

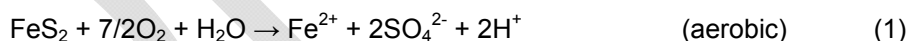
partially-saturated porous media (Allison, 1982; Allison et al., 1983). Sracek et al. (2004) confirmed this shallow slope at Mine Doyon (i.e. samples of water from waste rock piles defined a LEL of slope 2.4). At the Mine Doyon waste rock pile, internal evaporation was observed directly when a borehole acted as a chimney for the upward transport of vapor that was 54°C.

Water temperatures of 50°C to 80°C have been observed in waste rock piles at the ARMC and hence the potential to use $\delta^{18}\text{O}$ and $\delta^2\text{H}$ values to trace the influence of evaporation on waste rock seepage was identified in Robertson GeoConsultants Inc. (2009c). Specifically, the following trends in $\delta^{18}\text{O}$ and $\delta^2\text{H}$ values were expected at the ARMC:

- Waste rock seepage – $\delta^{18}\text{O}$ and $\delta^2\text{H}$ values should plot below and to the right of the LMWL due to the enrichment of seepage in ^{18}O and ^2H provided internal evaporation is significant;
- Surface water – $\delta^{18}\text{O}$ and $\delta^2\text{H}$ values should plot below and to the right of the LMWL provided direct evaporation to the atmosphere is significant (e.g. in ponds or pit lakes);
- Tailings porewater – $\delta^{18}\text{O}$ and $\delta^2\text{H}$ values should plot along the LMWL due to the anticipated weak influence of evaporation in the near-frozen tailings profile;
- Groundwater – as a mixture of several types of water, $\delta^{18}\text{O}$ and $\delta^2\text{H}$ values could plot at or slightly below the LMWL depending on the relative contributions by waste rock seepage, tailings porewater, and surface waters.

1.3.3 Stable Isotope Content of Dissolved Sulphate

It is well-established that the oxidation of pyrite is the principal source of SO_4 to groundwater at the ARMC. Pyrite can, however, be oxidized under aerobic and anaerobic conditions. The process of pyrite oxidation can be described simply by the following reactions:



Reaction (1) describes the oxidation of pyrite under aerobic conditions. Under aerobic conditions, atmospheric oxygen that has dissolved into groundwater is present in solution as O_2 . O_2 is an oxidizing agent and causes the production of Fe^{2+} , SO_4 , and acidity from pyrite (FeS_2).

Consider the sources of oxygen to SO_4 in reaction (1). Oxygen can come from either dissolved oxygen (i.e. atmospheric O_2) or the water that the reaction occurs in. The proportion of oxygen molecules from each source can be determined by stoichiometry. According to Taylor et al. (1984), 87.5% of the oxygen molecules in SO_4 generated via reaction (1) is from O_2 and 12.5% is from H_2O .

Using these percentages and an isotope mass balance equation (not shown), SO_4 that is produced under strictly aerobic conditions at the ARMC would be characterized by a $\delta^{18}\text{O}$ value of +9‰. This value assumes that the $\delta^{18}\text{O}$ value of atmospheric oxygen is +23.5‰ V-SMOW (Aggarwal et al.,

2004) and that the isotope enrichment factors from Taylor et al (1984) are representative. Also note that the mean annual $\delta^{18}\text{O}$ value of precipitation at Whitehorse (-21.6‰) was assumed to be representative of H_2O in reaction (1).

In parts of an aquifer (or mine waste) that contain little or no dissolved oxygen, pyrite is oxidized anaerobically via its exposure to Fe^{3+} (a powerful oxidizing agent). It is evident from reaction (2) that the water in which anaerobic oxidation takes place is the only source of oxygen molecules to SO_4 . This is important because groundwater at the ARMC is much more depleted in ^{18}O than atmospheric oxygen, which leads to a large isotope separation between anaerobically and aerobically produced SO_4 . Specifically, assuming a 100% contribution by H_2O in reaction (2), the theoretical $\delta^{18}\text{O}$ value of SO_4 produced in a strictly anaerobic environment would be -18‰.

Expected variations in $\delta^{18}\text{O}$ values for SO_4 are summarized in Figure 1-2 and as follows:

- Aerobic pyrite oxidation generates ^{18}O -enriched SO_4 ($\delta^{18}\text{O} = +9\text{‰}$) because most oxygen in the SO_4 molecule is derived from strongly-enriched atmospheric oxygen;
- Anaerobic pyrite oxidation generates ^{18}O -depleted SO_4 ($\delta^{18}\text{O}$ value of -18‰) because oxygen molecules in SO_4 are derived exclusively from ^{18}O -depleted groundwater.

The expected isotope separation between SO_4 generated in aerobic and anaerobic oxidation environments is 27‰. This large isotope separation is a rather specific feature of a high-latitude region such as the ARMC and it was this expected separation that made the use of $\delta^{18}\text{O}_{\text{SO}_4}$ values so promising as a tracer of SO_4 sources to groundwater (Robertson GeoConsultants Inc., 2009c).

$\delta^{34}\text{S}$ values provide information on the ultimate source of SO_4 to groundwater (i.e. pyrite versus gypsum). For pyrite dissolution, $\delta^{34}\text{S}_{\text{SO}_4}$ values may also provide information on the following:

- how the oxidation process is affected by catalysis by bacteria;
- the oxidant involved (i.e. Fe^{3+} vs. dissolved O_2); and
- the pH and temperature of ambient water.

These factors have been demonstrated in the laboratory (Taylor et al., 1984; Balci et al., 2007) and have been employed successfully in several studies of mine-waters in Europe (Migazewski et al., 2008), North America (Butler, 2007), and South America (Dold and Spangenberg, 2005).

1.4 ORGANIZATION OF REPORT

The remainder of the report is organized as follows:

- Section 2 - detailed description of sampling locations and analytical procedures;
- Section 3 - groundwater quality and isotope data are provided with a description of the quality control procedures used to check data reliability;

- Section 4 - description of the geochemical and isotopic composition of tailings porewater and waste rock seepage and how they differ from one another;
- Section 5 – discussion of isotope and groundwater quality data for receiving waters in the Rose Creek Alluvial Aquifer (RCAA) and the North Fork Rose Creek (NFRC) aquifer; and
- Section 6 – conclusions & recommendations.

DRAFT

2 SAMPLE COLLECTION & ANALYTICAL PROCEDURES

2.1 DESCRIPTION OF SAMPLING LOCATIONS

Samples for this study were collected from a selection of groundwater and surface water monitoring stations in the Rose Creek valley and in the Zone Pit 2 outwash area near the NFRC. Most of the stations are sampled bi-annually as part of the ARMC routine groundwater monitoring program (Table 2-1a/b). Those stations that are not routinely monitored were sampled during a site visit by Robertson GeoConsultants Inc. in September 2009 or by SRK Consultants Inc. in the summer/fall of 2009.

Sampling stations in the Rose Creek valley and Zone 2 area are illustrated in Figures 2-1a and 2-1b, respectively, and discussed briefly in the sections below.

2.1.1 Waste rock (Faro Creek) seepage

Samples of Faro Creek seepage (FCS) were collected from the following stations in the ETA,

- FCS-1 (at X23): located at the V-notch weir at X-23 in the old Faro Creek channel; this station is sampled monthly by Laberge Environmental Services (LES) as part of the routine surface water monitoring program; samples are representative of (undiluted) waste rock seepage from the Northwest and Main WRDs (Robertson GeoConsultants Inc., 2006b);
- FCS-3: represents sub-surface seepage discharging at the seepage face below the access road in Faro Creek canyon; seepage at FCS-3 is currently collected during the open water season (May to October) in the interim ETA seepage interception system (ETA SIS) and then discharged to the wet beach of the Intermediate Impoundment;
- FCS-4: located near the mouth of the Faro Creek canyon and represents the residual seepage by-passing the ETA SIS; this residual seepage is diverted along the northern side of the Second Impoundment and allowed to flow into the Intermediate Pond approximately 2000 m downstream.

Using a calibrated bucket and stopwatch, flow at X23 was estimated to be 1.3 L/s at 08:30 on September 9. This indicates that samples from the FCS series were collected under relatively low flow conditions characteristic for this time of the year (Robertson GeoConsultants Inc., 2006a).

2.1.2 Tailings seepage

Three samples of 'high-strength' tailings porewater were collected from the following multi-level piezometers:

- P03-02-07 (screened near the bottom of tailing profile)

- P03-02-09 (screened near the top of the tailings profile)
- P03-01-08 (screened in the middle of the tailings profile)

Each of these piezometers is located upgradient of Faro Creek canyon in the Second Impoundment (Figure 2-1a). Piezometer P03-01-08 is sampled bi-annually as part of the routine groundwater monitoring program. The two piezometers P03-02-07 and P03-02-09 are no longer routinely monitored and were sampled specifically for this study.

A sample of 'high-strength' tailings porewater was also collected from monitoring well X21A. This monitoring well is located downgradient of Faro Creek canyon near the southeastern boundary of the Intermediate Impoundment.

2.1.3 Groundwater and surface water in Rose Creek valley

Groundwater from the RCAA upgradient of Faro Creek canyon was collected from the following piezometers:

- P03-01-02 representing unimpacted ('background') groundwater
- P03-01-04 representing ARD-impacted groundwater
- P03-01-05 representing ARD-impacted groundwater

Only a modest impact by ARD is observed in the two piezometers P03-01-04 and P03-01-05. Due to their location upgradient of Faro Creek canyon, FCS is not a source of ARD products to this area of the Second Impoundment. Instead, tailings seepage is the most likely source. It is also possible that waste rock seepage from the Main WRD could be transported to this area from the northeast via groundwater.

Groundwater near the mouth of Faro Creek canyon was collected from the following monitoring wells:

- P03-06-04 and P03-06-05 (screened in the RCAA beneath relatively coarse-grained tailings in the Second Impoundment)
- P09-ETA-1 (screened in low permeability bedrock beneath the tailings profile in the ETA)
- P09-ETA-2 (screened in highly-permeable overburden near the overburden-bedrock contact in the ETA)
- X21B (screened in the RCAA downgradient of Faro Creek canyon near the southeastern boundary of the Intermediate Impoundment).

Because the tailings along the northern side of the Second Impoundment are coarse and relatively permeable, monitoring wells P03-06-04 and P03-06-05 could be affected by seepage from the overlying tailings profile and/or FCS (Robertson GeoConsultants Inc, 2006a; 2009b). These wells are

particularly important for the assessment of the impact by FCS on the RCAA and are discussed in the 2009 Groundwater Monitoring Review (Robertson GeoConsultants Inc., 2010a).

Monitoring wells P09-ETA-1 and P09-ETA-2 were recently installed at the mouth of Faro Creek canyon to assess bypass of the interim ETA SIS (SRK Consulting Inc., 2010). Tailings were identified to a depth of 16.0 m bgs in this area and bedrock was intersected at 16.8 m bgs. Both of these wells were sampled initially by SRK upon their completion and then again in November 2009 by LES as part of the routine monitoring program.

Further downgradient near the Intermediate and Cross Valley Dam, samples of impacted groundwater from each of the following wells were collected:

- X24D (Intermediate Impoundment reach)
- P01-03 (Intermediate Impoundment reach)
- P01-11 (Cross Valley Dam reach)
- P05-01-02 (Cross Valley Dam reach)
- P05-02 (Cross Valley Dam reach)

All of the wells listed above are screened in the RCAA (Table 2-1). Also collected in this area were samples of surface water from the Intermediate Pond (at X4) and the Polishing Pond (at X5).

Below the toe of the Cross Valley Dam, three samples of groundwater from deep bedrock beneath the RCAA were collected:

- P09-C1 (in deep bedrock near the northern side of the Rose Creek valley)
- P09-C2 (in deep bedrock near the center of the Rose Creek valley)
- P09-C3-BR (in deep bedrock near the southern side of the Rose Creek valley)

Samples P09-C1 and P09-C2 were collected from monitoring wells that were completed in deep bedrock (in inset in Figure 2-1a for locations). Both of these wells are screened in highly-friable phyllite bedrock (SRK Consulting Inc., 2010).

Hydraulic testing of P09-C1 and P09-C2 included packer testing (at 5 m intervals) and slug testing of the completed monitoring well. For P09-C1, K values from packer testing ranged from 10^{-6} to 10^{-7} m/s and a slug test yielded a value of 10^{-4} m/s. K values from packer and slug testing at P09-C2 were consistently lower by comparison (10^{-7} to 10^{-8} m/s). Localized zones of higher K were identified in both P09-C1 and P09-C2, likely due to fracturing.

Sample P09-C3-BR (and a duplicate sample P09-C3-BR-d) was collected from a permeable bedrock zone from 85 to 93 m bgs in borehole P09-C3 after an airlift test (SRK Consulting Inc., 2010). A monitoring well could not be completed in this permeable fracture zone for follow-up monitoring due

to problems during well installation (SRK Consulting Inc., 2010). This bedrock zone was initially identified as highly-permeable ($K = 10^{-4}$ m/s) based on packer testing but the subsequent airlift test yielded a more moderate K estimate of 10^{-6} m/s. The K value from the airlift test was considered more reliable.

Samples from two proposed wells near the Intermediate Dam (P09-ID1 and P09-ID2) were to be included in this study but neither of these proposed bedrock wells could be completed due to poor drilling conditions (SRK Consulting Inc., 2010).

2.1.4 Groundwater in the Zone 2 Pit Outwash area, NFRC

Nine samples were collected from wells near the backfilled Zone 2 Pit and the NFRC (Figure 2-1b). This area is referred to as the “Zone 2 Pit outwash area” because ‘spills’ from the Zone 2 Pit have occurred in the past and historically affected groundwater quality in the area (Robertson GeoConsultants Inc., 1996). Seasonal pumping now controls the water level in the Zone 2 Pit and thereby prevents ‘spills’ of contaminated Zone 2 Pit water.

Any residual water from the Zone 2 Pit has likely been flushed from the outwash area and historic spill water is not believed to impact groundwater quality at this time (Robertson GeoConsultants Inc., 2010a). The oxidation and leaching of metals from outwash sediments (i.e. fine-grained waste rock) that were deposited during historic spills have been identified as potential source of ARD products in this area (SRK Consulting, 2007).

Groundwater was collected from the following monitoring wells in the Zone 2 Pit outwash area:

- BH14A (weathered bedrock near the toe of the Northeast Rock Dump)
- BH14B (competent bedrock near the toe of the Northeast Rock Dump)
- SRK08-P12A (permeable mixture of bedrock and alluvium near NFRC)
- SRK08-P12B (bedrock underlying near NFRC alluvium)
- BH2 (partially screened in outwash sediments and NFRC aquifer)
- BH4 (partially screened in outwash sediments and NFRC aquifer)
- BH5 (NFRC alluvial aquifer downgradient of Zone 2 Pit)
- BH6 (NFRC alluvial aquifer upgradient of well BH5)
- BH8 (bedrock near former Zone 2 Pit spillway)

Each of the wells listed above is impacted to some extent by ARD (Robertson GeoConsultants Inc., 2010a). Impacted groundwater in this portion of the ARMC site is characterized by elevated Zn and low SO_4 concentrations.

2.2 SAMPLING PROCEDURES

Most of the samples for this study were collected in conjunction with routine groundwater monitoring conducted in September 2009. Water samples intended for major ion and dissolved metal analyses were collected by Laberge Environmental Services (LES). LES was responsible for purging the wells prior to sampling, collected field measurements of pH and electrical conductivity (EC), and filtering/preserving water samples (if required).

Samples from P09-C1, P09-C2, P09-C3-BR, P09-ETA-01, and P09-ETA-02 were collected by SRK Consulting Inc. personnel in August 2009 and later sub-sampled for purposes of isotope analysis.

In addition to routinely-collected field data, field parameters were also measured with an YSI 556 multiprobe by Robertson GeoConsultants Inc. personnel during their site visit. The parameters measured included field pH, electrical conductivity (EC), water temperature, dissolved oxygen (DO), and oxidation-reduction potential (E_H). For each well, a single set of field parameter measurements was collected after purging at least one bore volume from the well. To ensure the precision of measurements, the YSI 556 multiprobe was calibrated in the morning prior to sample collection.

A 500 mL sample was collected for this study and sent to the Isotope Laboratory at the University of Calgary (ISL-UofC). Upon arrival at the ISL-UofC, samples were filtered through a 0.45 μm polycarbonate membrane and acidified to pH 2 with 3N environmental grade HCl. Pure BaSO_4 was then precipitated from the samples by adding BaCl_2 . The BaSO_4 precipitate was recovered on 0.45 μm nitrocellulose membranes and then rinsed with distilled water to remove residual BaCl_2 .

2.3 ANALYTICAL PROCEDURES

Sulphur isotope ratios ($^{34}\text{S}/^{32}\text{S}$) of the BaSO_4 precipitate were determined using Continuous Flow-Isotope Ratio Mass Spectrometry (CF-EA-IRMS). A Carlo Erba NA 1500 elemental analyzer interfaced to a VG PRISM II mass spectrometer was used for all of the analyses (see ISL-UofC, 2009 for additional details). $^{34}\text{S}/^{32}\text{S}$ ratios were determined by comparing the respective sample peak areas to a reference gas peak inlet from the reference bellows of the mass spectrometer during each sample run.

Oxygen isotope ratios ($^{18}\text{O}/^{16}\text{O}$) of SO_4 were determined using a high-temperature pyrolysis reactor coupled to an isotope ratio mass spectrometer in continuous flow mode. The system consisted of a Finnigan MAT TC/EA pyrolysis reactor interfaced to a Finnigan Mat Delta+XL mass spectrometer via a Conflow III open split/interface. The $^{18}\text{O}/^{16}\text{O}$ ratio of water itself was determined using the common CO_2 - H_2O equilibration technique (Epstein, 1953, O'Neil et al., 1975). The $^2\text{H}/\text{H}$ content of water was determined by the chromium reduction method (Donnelly et al., 2001).

3 RESULTS & QC ANALYSIS

3.1 RESULTS

Field and laboratory pH and EC measurements, the concentrations of major ions/metals, and isotope data are summarized in Table 3-1 for the Rose Creek valley and in Table 3-2 for the Zone 2 Pit outwash area. Selected parameters are plotted on maps of these two areas in Figures 3-1a/b to 3-4a/b:

- Temperature, lab pH, DO, and EC data (Figure 3-1a/b)
- Concentrations of total alkalinity, Mg, HCO_3 , SO_4 , and Fe (Figure 3-2a/b)
- Concentrations of dissolved Mn, Pb, Zn, Ni, and Co (Figure 3-3a/b)
- $\delta^{34}\text{S}_{\text{SO}_4}$, $\delta^{18}\text{O}_{\text{SO}_4}$, $\delta^{18}\text{O}_{\text{water}}$, and $\delta^2\text{H}_{\text{water}}$ values (Figure 3-4a/b)

Water quality data for all monitoring stations (i.e. ARD sources, groundwater and surface water) are also presented in piper plots and scatter plots in Appendix A.

The data plotted in these figures were screened using the QA/QC procedures described in the section below.

3.2 SUMMARY OF QA/QC ANALYSIS

The major ion and dissolved metal data for this study were compiled from the 2009 groundwater monitoring report for the ARMC (Robertson GeoConsultants Inc., 2010a). QA/QC of the routine monitoring data was beyond the scope of that annual monitoring report so several QC procedures were performed on the data included in this study to verify their reliability prior to interpretation.

The QC analysis of groundwater quality data included a charge balance analysis (CBA) and a comparison of field and laboratory measurements of pH and EC. Measurements of pH and EC were compared via a relative percent difference (RPD) value that is defined as the absolute value of the difference between the two parameters being compared divided by the average of the parameters. RPD values were also used for the CBA. No duplicate major ion or dissolved metal data were available for the samples included in this study.

Results of the QC analysis are summarized in Table 3-3a/b. With respect to the CBA, most samples were characterized by RPD values that were less than 15% and hence were of good quality. Other samples, including those from wells P03-02-09, P03-06-04, P03-06-05, and X21B, had RPD values of 20 – 30% (Table 3-3). These higher RPD values suggest some uncertainty in the concentrations of major ions and dissolved metals for these samples but none of the data were excluded from further interpretation.

The QC analysis did reveal that RPD values for wells BH4 and BH6 were close to or higher than 100% and field and laboratory measurements of EC for these samples did not correspond well with one another. The high RPD values are related to errors in the alkalinity (and hence HCO_3) concentration. The poor match between field and data EC values (and the much higher EC values for September 2009 than May 2009) suggests a potential mix-up in the samples that were analyzed. For this reason, the May 2009 data were used instead of the September 2009 data (i.e. the isotope data were collected in September and the major ion/metals data were collected in May).

Field pH and EC measurements collected by Robertson GeoConsultants Inc. and LES personnel generally compared well with each other (Table 3-3). Both of these sets of field pH and EC measurements also compared well with the corresponding lab data. RPD values for pH (and to a lesser extent EC) were somewhat higher in samples collected in the Zone 2 Pit outwash area. Overall, the QC analysis of the data included in this study suggests that the field protocols and procedures employed by LES personnel are effective and that the groundwater monitoring data incorporated into this study are reliable.

With respect to the stable isotope data, duplicate samples from wells P03-01-02, BH5, and P09-C3 were collected for QC purposes. RPD values for the $\delta^2\text{H}_{\text{water}}$ and $\delta^{18}\text{O}_{\text{water}}$ values and the $\delta^{34}\text{S}_{\text{SO}_4}$ values were less than 5%. RPD values were slightly higher for the $\delta^{18}\text{O}_{\text{SO}_4}$ values (10% for the samples from wells BH5 and P09-C3 and 63% for the samples from well P03-01-02). The high RPD value for well P03-01-02 was due to the low $\delta^{18}\text{O}_{\text{SO}_4}$ values themselves (<0.5‰) and not because of analytical error or uncertainty. The only data that were considered suspect were $\delta^{18}\text{O}_{\text{SO}_4}$ and $\delta^{34}\text{S}_{\text{SO}_4}$ values for the sample from well P09-C2, as ISL-UofC staff characterized the SO_4 in this sample as 'impure'.

4 CHARACTERIZATION OF ARD SOURCES

The purpose of this section is to determine what differences (if any) between tailings porewater and waste rock seepage can be used to identify the presence of either in groundwater. The following data will be discussed:

- $\delta^{18}\text{O}$ and $\delta^2\text{H}$ values of water
- $\delta^{18}\text{O}$ and $\delta^{34}\text{S}$ values of dissolved SO_4
- Conventional ARD indicators species (Ni and Co in particular)

4.1 STABLE ISOTOPES

4.1.1 *Stable Isotopes of Water*

In general, $\delta^{18}\text{O}$ and $\delta^2\text{H}$ values of Faro Creek seepage (FCS), tailings porewater, and surface water from the Intermediate Pond and Polishing Pond plot near the central portion of the LMWL for Whitehorse (Figure 4-1). The values appear to offset from the LMWL but this is likely due to scatter in the data and uncertainty in the exact position of the LMWL.

Yet, $\delta^{18}\text{O}$ and $\delta^2\text{H}$ values for FCS, tailings porewater, and surface water from the Intermediate Pond and Polishing Pond are clearly different from one another. For example, surface water from the Intermediate Pond and Polishing Pond is clearly enriched in ^{18}O and ^2H relative to FCS and tailings porewater. Hence $\delta^{18}\text{O}$ and $\delta^2\text{H}$ values plot near the top right of Figure 4-1. FCS is the most depleted of the ARD sources and plots near the bottom left. $\delta^{18}\text{O}$ and $\delta^2\text{H}$ values for the samples of tailings porewater cluster together in between $\delta^{18}\text{O}$ and $\delta^2\text{H}$ values for FCS and surface water from the Ponds.

Recall that waste rock seepage was expected to be more enriched in ^{18}O and ^2H than tailings porewater because the intensity of evaporation was expected to be higher within unsaturated waste rock piles than in near-frozen tailings (section 1.3.2). In fact, the opposite was observed with FCS samples slightly more depleted in ^{18}O and ^2H than tailings porewater and plotting closer to the LMWL. These observations suggest that evaporative enrichment is not an important process in waste rock piles at ARMC.

Together, the $\delta^{18}\text{O}$ and $\delta^2\text{H}$ values for ARD sources define a regression line of the equation $\delta^2\text{H} = 5.6 \cdot \delta^{18}\text{O} - 50\text{‰}$. This line differs slightly from the LMWL for Whitehorse, which had a slope of 6.6 and a $\delta^2\text{H}$ -intercept of -25‰ (see Section 1.4). These differences are small and hence not considered a definitive indication that evaporative enrichment has affected ARD sources at the ARMC. Instead, the regression line defined by $\delta^{18}\text{O}$ and $\delta^2\text{H}$ values of ARD sources is likely a better representation of the LMWL for the ARMC than the LMWL for Whitehorse is. This implies that slight differences in the

timing (and possibly the source) of recharge (not the influence of evaporation) causes samples of FCS, tailings porewater, and surface water to plot at different locations along the LMWL.

Note that our initial round of isotopic sampling (Phase 1) only represents a snapshot in time (fall conditions). Considering the large range in $\delta^{18}\text{O}$ and $\delta^2\text{H}$ values of winter and summer precipitation (observed in Whitehorse and inferred for ARMC) it is likely that these ARD sources also exhibit some seasonal variation in $\delta^{18}\text{O}$ and $\delta^2\text{H}$. Seasonal sampling of these ARD sources for isotopic analyses would be required to determine the extent of such seasonal variation. Such seasonal sampling would also confirm our preliminary conclusion that evaporation does not significantly influence the isotope composition of ARD sources at ARMC.

In the author's opinion there is significant potential for the use of stable isotopes in the study of recharge and flow through mine waste (i.e. waste rock piles and/or tailings). In specific circumstances (i.e. short flow paths and/or low storage) these seasonal variations in stable isotopes of water may also be used for tracing of specific ARD sources (e.g. surface ponds, pit water etc) in impacted groundwater. However, such a detailed isotopic analysis is beyond the original scope proposed for Phase 2 of this study and is not recommended at this time.

4.1.2 Stable Isotope Content of Dissolved Sulphate

The relationship between $\delta^{18}\text{O}_{\text{SO}_4}$ values and SO_4 concentrations for ARD sources is shown in Figure 4-2. The dashed line at the top of Figure 4-3a represents the hypothetical $\delta^{18}\text{O}$ value for SO_4 produced in an aerobic oxidation environment. The dashed line near the bottom of the figure represents the hypothetical $\delta^{18}\text{O}_{\text{SO}_4}$ for SO_4 produced in an anaerobic oxidation environment. The reader is referred to Section 1.3 for a description of how these hypothetical $\delta^{18}\text{O}$ values were determined.

Samples of tailings porewater plot near the bottom right of Figure 4-2. This indicates that SO_4 in tailings porewater is generated primarily in an anaerobic oxidation environment. Hence Fe^{3+} appears to be a more important oxidizing agent than dissolved oxygen in tailings. The predominance of ^{18}O -depleted SO_4 in tailings porewater is consistent with our general hypothesis that anaerobic oxidation should dominate over aerobic oxidation in a tailings deposit (see section 1.3.3).

$\delta^{18}\text{O}_{\text{SO}_4}$ values for waste rock seepage were very similar to $\delta^{18}\text{O}_{\text{SO}_4}$ values for tailings porewater, also plotting close to the anaerobic line in Figure 4-2. The only difference in the locations of waste rock seepage and tailings porewater in Figure 4-2 is the slight offset that is related to higher SO_4 concentrations in tailings porewater. Note that SO_4 produced in waste rock piles was expected to be potentially more enriched in ^{18}O owing to greater air circulation in the coarse rock piles compared to fine-grained tailings deposits (section 1.3.3). The lack of any significant ^{18}O -enriched SO_4 in waste rock seepage indicates that anaerobic oxidation of pyrite (using Fe^{3+}) also dominates over aerobic

oxidation in the Faro rock piles. In other words, the supply of O_2 into the deeper portion of the waste rock pile (via advection) is not significant, at least not at the scale of an entire waste rock pile.

The similar isotopic compositions of SO_4 produced in tailings and waste rock piles meant that $\delta^{18}O_{SO_4}$ values could not be used to separate the contributions of tailings porewater and waste rock seepage to groundwater. Instead, $\delta^{18}O_{SO_4}$ values appear to more useful in distinguishing impacted and non-impacted groundwater (which will be explored further in Section 5).

4.2 GEOCHEMICAL INDICATOR SPECIES

Waste rock and tailings porewater contain rather unique proportions of several metals that are considered ARD indicator species (Robertson GeoConsultants Inc., 2009b). The relevant suite of indicator species includes arsenic (As), cadmium (Cd), cobalt (Co), lead (Pb), manganese (Mn), nickel (Ni), and zinc (Zn). Tailings porewater generally contains higher concentrations of Mn, Pb, and Zn while waste rock seepage generally contains higher concentrations of As, Cd, Co, and Ni (see Figure A1 in Appendix A).

With respect to separating the contributions of waste rock seepage and tailings porewater, Ni and Co concentrations appear to be particularly informative. Of particular significance are the high concentrations of Ni and Co in waste rock seepage compared to tailings porewater and the different Ni:Co ratios in the two ARD sources.

At X23, which represents undiluted waste rock seepage from the Northwest and Main WRDs, Ni and Co concentrations are elevated (~2 mg/L) and occur at a Ni:Co ratio of nearly 1:1. Similar Ni:Co ratios characterize Faro Creek seepage further downgradient of the ETA area (i.e. at FCS-3 and FCS-4). Samples from FCS-3 and FCS-4 represent seepage in Faro Creek canyon/ETA but they do not represent 'pure' samples of waste rock seepage as the sample from X23 does. Instead, samples from FCS-3 and FCS-4 represent waste rock seepage that is diluted by groundwater from the ETA. Hence absolute concentrations in FCS-3 and FCS-4 are lower than in X23 but the 1:1 Ni:Co ratio is maintained.

Unlike waste rock seepage, tailings porewater is characterized by much higher Ni:Co ratios. Ni:Co ratios for tailings porewater upgradient of Faro Creek canyon in the Second Impoundment range from 4:1 to 9:1 (Figure 3-3a).

Ni:Co ratios appear to provide the clearest indication that waste rock seepage is present in groundwater. The significance of these ratios will become more apparent in Section 5 when sources of ARD products to receiving waters are discussed in more detail.

5 DISTINGUISHING THE SOURCES OF ARD PRODUCTS TO GROUNDWATER

Using the framework provided in Section 4, the sources of ARD products to groundwater in the following areas of the ARMC are discussed:

- RCAA upstream of Faro Creek canyon (Section 5.1)
- RCAA and deep bedrock near mouth of Faro Creek canyon (Section 5.2)
- RCAA in Intermediate Dam & Cross Valley Dam reaches (Section 5.3)
- Deep bedrock in Cross Valley Dam reach (Section 5.4)
- NFRC aquifer in Zone 2 Pit outwash Area (Section 5.5)

Groundwater quality data in the Rose Creek valley are discussed sequentially from the most upgradient area (Section 5.1) to the most downgradient area (Section 5.4).

The RCAA upgradient of Faro Creek canyon is discussed first because this area is not affected by Faro Creek Seepage (FCS). Tailings seepage is likely the main source of ARD products in this area. Note, however, that waste rock seepage from the area northeast of the Original Impoundment (e.g. S-cluster area) could also potentially impact groundwater in this area so ARD sources are discussed with this in mind.

FCS and tailings seepage could both affect groundwater quality near the mouth of Faro Creek canyon. It was established in Section 4.1 that stable isotope data cannot be used to separate the relative contributions of FCS and tailings porewater to receiving groundwater. Stable isotope data are hence discussed in the context of determining the extent of ARD impact and other ARD indicator species (i.e. Ni and Co) are discussed in order to determine the source(s) of ARD products.

The RCAA in the Intermediate Dam & Cross Valley Dam reaches are discussed together in Section 5.3 before a detailed discussion of possible impacts of groundwater in bedrock at the toe of the Cross Valley Dam is provided in Section 5.4. Stable isotope data is a major focus of the discussion in Section 5.4 because $\delta^{18}\text{O}$ values of SO_4 seem to offer some insight as to whether deep bedrock below the toe of the Cross Valley Dam is impacted by ARD.

5.1 ROSE CREEK ALLUVIAL AQUIFER UPSTREAM OF FARO CREEK CANYON (AT P03-01)

Impacted groundwater has been identified in the RCAA upgradient of Faro Creek canyon (Robertson GeoConsultants Inc., 2009b). This area is not affected by FCS and hence tailings seepage is the likely source of ARD products to groundwater.

Samples of groundwater were collected from the following wells:

- P03-01-02 ($\text{SO}_4 = 24 \text{ mg/L}$, $\text{Zn} < 5 \text{ }\mu\text{g/L}$), unimpacted groundwater ('background');

- P03-01-04 ($\text{SO}_4 = 58 \text{ mg/L}$, $\text{Zn} = 2500 \text{ } \mu\text{g/L}$), moderately impacted groundwater;
- P03-01-05 ($\text{SO}_4 = 140 \text{ mg/L}$, $\text{Zn} = 262 \text{ } \mu\text{g/L}$), moderately impacted groundwater.

$\delta^{18}\text{O}$ and $\delta^2\text{H}$ values for samples from each of these wells plotted close to the LMWL in Figure 5-1 and hence could not be distinguished from precipitation. Note that all three groundwater samples in this upstream reach were significantly more depleted in $\delta^{18}\text{O}$ and $\delta^2\text{H}$ than the respective tailings samples indicating different recharge regimes. However, insufficient information on seasonal time trends was available to use this difference in stable isotopes of water for mixing calculations.

SO_4 in unimpacted groundwater from well P03-01-02 is much more enriched in ^{18}O than tailings porewater (Figure 5-2). The ^{18}O -enriched nature of SO_4 and the very low SO_4 concentration cause this sample to plot near the top left of Figure 5-2a. ^{18}O -enriched SO_4 appears to be a defining characteristic of 'background' groundwater in the RCAA and it is likely that other samples of unimpacted will plot closely together in this area of Figure 5-2a.

In groundwater from wells P03-01-04 and P03-01-05, SO_4 is more depleted in ^{18}O than SO_4 in unimpacted groundwater but less depleted in ^{18}O than tailings porewater. Hence $\delta^{18}\text{O}$ values for SO_4 plotted at an intermediate location between unimpacted groundwater and tailings porewater in Figure 5-2a. ^{18}O -depleted SO_4 suggests the presence of SO_4 produced by the oxidation of pyrite in an anaerobic oxidation environment. Because of the location of these wells upgradient of Faro Creek canyon, SO_4 in wells P03-01-04 and P03-01-04 is likely derived from the anaerobic oxidation of pyrite in tailings.

However, it is possible that waste rock seepage from the Main WRD could be delivered to the RCAA from the area northeast of the Original Impoundment (e.g. S-cluster area). This hypothesis cannot be tested with $\delta^{18}\text{O}$ values because of the similarities between SO_4 in tailings porewater and waste rock seepage. Ni:Co ratios do, however, provide some insight.

Ni:Co ratios in samples from wells P03-01-04 and P03-01-05 are 15:1 and 13:1, respectively. These ratios are much higher than the 1:1 ratio observed in waste rock seepage (at X23) but are comparable to ratios for tailings porewater (i.e. 9:1 at well P03-01-08). This suggests that ARD products in the RCAA upgradient of Faro Creek canyon are derived primarily from tailings porewater and that waste rock seepage from the northeast does not contribute substantially to this reach of the Rose Creek alluvial aquifer at this time.

5.2 RCAA AND DEEP BEDROCK NEAR FARO CREEK CANYON

It was established in the previous section that tailings seepage is the only source of ARD products to groundwater upgradient of Faro Creek canyon. Because tailings are not a point source of contamination, the distribution of ARD products in groundwater is rather homogenous in the RCAA

upgradient of Faro Creek canyon. In other words, there are no obvious differences between the north and south sides of the RCAA in this area. This is not the case downgradient of Faro Creek canyon.

Downgradient of Faro Creek canyon, concentrations of SO_4 , Mg, and various metals of interest are significantly higher in the RCAA along the northern side of Rose Creek valley than along the southern side. The location of Faro Creek canyon on the north side of Rose Creek valley suggests that FCS represents a point source of ARD products to the RCAA. The RCAA along the northern side of Rose Creek valley would therefore receive ARD products from both FCS and tailings seepage, whereas only tailings would contribute to groundwater along the southern side of the valley (Robertson GeoConsultants Inc., 2009b).

The purpose of this section is to determine whether FCS supplies the majority of ARD products to groundwater near the mouth of Faro Creek canyon. This is an important issue because ARD products from this area are likely transported to the downgradient reaches of the RCAA (i.e. near the Intermediate Dam and Cross Valley Dam) In other words, the mouth of Faro Creek canyon could represent the source of the “TDS plume” that seems to have propagated down the northern side of Rose Creek valley.

Samples of groundwater were collected from five wells near the mouth of Faro Creek canyon:

- P09-ETA-01 ($\text{SO}_4 = 25 \text{ mg/L}$, $\text{Zn} = 1 \text{ } \mu\text{g/L}$), unimpacted groundwater (in bedrock);
- P09-ETA-02 ($\text{SO}_4 = 4,500 \text{ mg/L}$, $\text{Zn} = 70,600 \text{ } \mu\text{g/L}$), highly-impacted groundwater;
- P03-06-04 ($\text{SO}_4 = 1,100 \text{ mg/L}$, $\text{Zn} = 4,460 \text{ } \mu\text{g/L}$), moderately-impacted groundwater;
- P03-06-05 ($\text{SO}_4 = 940 \text{ mg/L}$, $\text{Zn} = 15,300 \text{ } \mu\text{g/L}$), moderately impacted groundwater; and
- X21B ($\text{SO}_4 = 1,300 \text{ mg/L}$, $\text{Zn} = 1,710 \text{ } \mu\text{g/L}$), moderately-impacted groundwater.

Each of the wells listed above (except wells P09-ETA-01 and -02) is screened in the RCAA. These wells provide information on three key areas:

- o At the mouth of Faro Creek canyon (at wells P09-ETA-01 and P09-ETA-02)
- o Immediately downgradient of Faro Creek canyon in the Second Impoundment (at wells P03-06-04 and P03-06-05);
- o Further downgradient near the western boundary of the Second Impoundment (at well X21B).

Also relevant is the sample from FCS-4. The FCS-4 sample represents FCS that currently bypasses the ETA SIS and reports to the mouth of Faro Creek canyon. At this point it is important to acknowledge recent changes in the ETA due to seasonal operation of the ETA SIS. Earlier surveys had indicated that seepage losses along this diversion channel contributed a substantial load of ARD

products from FCS to the Rose Creek aquifer (Robertson GeoConsultants Inc., 2006b). However, concentrations of ARD products at FCS-4 (and the flow of FCS) have recently been decreased by the ETA SIS. Hence the groundwater-surface water system in this area may be transitioning towards a new steady-state condition. The significance of this is that the RCAA may have received more concentrated FCS in the past before the ETA SIS was completed. This would mean that the FCS-4 sample collected for purposes of this study is not representative of past conditions and this should be kept in mind during the following discussion of ARD sources (and mixing calculations in particular).

$\delta^{18}\text{O}$ and $\delta^2\text{H}$ values for groundwater from each of the wells listed above plotted close to the LMWL in Figure 5-1 and hence could not be distinguished from precipitation; each of these samples was more enriched in ^{18}O and ^2H than tailings porewater and the samples plotted close to $\delta^{18}\text{O}$ and $\delta^2\text{H}$ values for FCS. The differences in isotope composition were small, however, and did not provide additional information on water sources.

5.2.1 Mouth of Faro Creek Canyon

At the mouth of Faro Creek canyon, $\delta^{18}\text{O}$ and $\delta^{34}\text{S}$ values of SO_4 and Ni and Co concentrations revealed the following about the impact of ARD on receiving groundwater:

- The isotope composition of SO_4 in unimpacted groundwater from well P09-ETA-01 is enriched in ^{18}O and is similar to SO_4 in unimpacted groundwater from upgradient of Faro Creek canyon (at well P03-01-02) (Figure 5-3); this suggests that natural SO_4 in the RCAA and bedrock beneath the RCAA is ^{18}O -enriched; potential source(s) of natural SO_4 include oxidation of trace pyrite and/or dissolution of (trace) gypsum in local bedrock;
- SO_4 in highly-impacted groundwater in the ETA (at well P09-ETA-02) is much more depleted in ^{18}O than SO_4 in unimpacted groundwater; the depleted nature of SO_4 in highly-impacted groundwater is a clear indication that SO_4 is derived from the anaerobic oxidation of pyrite; given the proximity of well P09-ETA-02 to Faro Creek canyon, FCS is likely the predominant source of SO_4 (and other ARD products) to groundwater at this location; the near 1:1 Ni:Co ratio in the sample from well P09-ETA-02 supports this assertion (see Figure 3-3a).

Conservative mixing calculations were performed to determine the proportions of FCS and unimpacted groundwater that could explain observed groundwater quality at well P09-ETA-02. FCS-3, tailings porewater (at wells P03-02-09 and P03-01-08), and unimpacted groundwater (at well P09-ETA-01) were assumed to be end-members. Proportions of each end-member were varied in order to reproduce the concentration of SO_4 in well P09-ETA-02 while maintaining the near 1:1 Ni:Co ratio.

The mixing calculations for well P09-ETA-02 (immediately below the tailings profile at the mouth of Faro Creek canyon) can be summarized as follows (see Table B2):

- FCS accounts for ~20% of receiving groundwater near the mouth of Faro Creek canyon; tailings seepage accounts for slightly less (~14%) of groundwater at this location; these proportions suggest that 60% of ARD products come from FCS and 40% come from tailings seepage;
- Zn and Fe concentrations in receiving groundwater were overestimated, possibly due to their non-conservative behaviour in groundwater; SO₄, Ni, and Co concentrations were close to observed concentrations;
- The proportions of FCS and tailings porewater are not known exactly but it is clear that the Ni and Co concentrations in receiving groundwater at P09-ETA-02 cannot be predicted without a substantial contribution by FCS.

5.2.2 Downgradient of Faro Creek Canyon

Ni:Co ratios in samples from wells P03-06-04 and P03-06-05 suggest that groundwater quality in the RCAA downgradient of Faro Creek canyon in the Second Impoundment is also impacted by FCS. The impact by FCS is particularly evident at well P03-06-04. Well P03-06-04 is screened deeper in the RCAA aquifer than well P03-06-05.

Conservative mixing calculations were performed to explain groundwater quality at wells P03-06-04 and P03-06-05 (Tables B3 and B4). Initially, only two end-members were assumed: (i) unimpacted groundwater from well P03-01-01 and (ii) highly-impacted groundwater from well P09-ETA-02. A 21% contribution by highly-impacted groundwater was found to predict concentrations at well P03-06-05 reasonably well (Table B3). This suggests a relatively strong hydraulic connection between the seepage at the mouth of Faro Creek canyon (at P09-ETA-02) flowing along the overburden/bedrock contact and the RCAA at P03-06.

This mixing scenario described above did not explain observed concentrations at well P03-06-04 as well as it did at well P03-06-05. At well P03-06-04, Ni and Co concentrations are actually higher than at well P09-ETA-02 (the end-member). This suggests a more concentrated FCS end-member (possibly pre-dating ETA SIS operation?) is contributing to deeper parts of the RCAA. Predictions of groundwater quality at well P03-06-04 were improved by incorporating FCS-3 as an end-member (7% contribution) and reducing the contribution of highly-impacted groundwater from well P09-ETA-02 to 10% (Table B4). The very high concentrations of Ni and Co at well P03-06-04 were still underestimated and Zn concentrations were too high. However, it is important to acknowledge that these high Ni and Co concentrations cannot be explained by tailings porewater and hence confirm that the deeper RCAA is more impacted by FCS than tailings seepage.

The mixing calculations described above suggest that the ETA SIS could improve groundwater quality in the deeper parts of the RCAA more significantly than in the shallower RCAA (which is more

affected by tailings seepage). A modest improvement in groundwater quality (especially reduction in zinc) has been observed in the RCAA at wells P03-06-04 and P03-06-05 (Robertson GeoConsultants Inc., 2010a). However, additional monitoring data will be required to better assess the influence of FCS seepage (and recent operation of the ETA SIS) on groundwater quality at this location.

$\delta^{18}\text{O}$ and $\delta^{34}\text{S}$ values for SO_4 in samples from wells P03-06-04 and P03-06-05 did not provide much additional information on the sources of ARD products in this area. SO_4 in both wells is less depleted in ^{18}O than tailings porewater and FCS and therefore plotted to the left of the 'ARD sources' field in Figure 5-3a. SO_4 in these wells is more depleted in ^{18}O than 'slightly-impacted' groundwater from the RCAA upgradient of Faro Creek canyon and hence plotted to the right of samples from wells P03-01-04 and P03-01-05.

5.2.3 Western Boundary of Second Impoundment

SO_4 in the sample from well X21B plotted close to samples from wells P03-06-04 and P03-06-05 in Figure 5-3. Concentrations of SO_4 and metals of interest at well X21B suggest that groundwater in this location is also moderately-impacted by ARD. The Ni:Co ratio at well X21B is very similar to that observed further upgradient at P03-06-05 (see above) suggesting some influence from both tailings seepage and FCS seepage. $\delta^{18}\text{O}$ values of SO_4 were consistent with moderately-impacted groundwater.

The apparent gradual enrichment of $\delta^{18}\text{O}$ values in groundwater with distance from the Faro Creek canyon suggests that $\delta^{18}\text{O}$ value for SO_4 provide some information on the extent of ARD impact in receiving waters. Near the mouth of Faro Creek canyon, this type of information has limited value because elevated SO_4 concentrations alone provide a clear indication of the extent of ARD impact. However, such a trend is relevant to the discussion of potential ARD impacts in deep bedrock below the Cross Valley Dam (see Section 5.5).

5.3 RCAA IN THE INTERMEDIATE DAM & CROSS VALLEY DAM REACHES

5.3.1 Intermediate Dam Reach

The RCAA in the Intermediate Dam reach is characterized by elevated concentrations of SO_4 , Mg, and Mn. Robertson GeoConsultants Inc. (2008) attributed these elevated concentrations to the "leading edge" of a TDS front that is moving downgradient along the northern side of Rose Creek valley. Zn concentrations are lower in the Intermediate Dam reach than upgradient near the mouth of Faro Creek canyon. This is likely due to sorption, which retards the transport of Zn in groundwater but does not affect SO_4 or Mg.

The Intermediate Dam reach is an 'area of interest' because groundwater in this reach likely originates near Faro Creek canyon and terminates in the Cross Valley Dam reach. In addition to a

surface water sample from the Intermediate Pond (at X4), samples from two wells were collected in the Intermediate Dam reach:

- P01-03 ($\text{SO}_4 = 1,700 \text{ mg/L}$, $\text{Zn} = 33 \text{ } \mu\text{g/L}$), moderately-impacted groundwater in RCAA
- X24D ($\text{SO}_4 = 1,900 \text{ mg/L}$, $\text{Zn} = 102 \text{ } \mu\text{g/L}$), moderately-impacted groundwater in RCAA

$\delta^{18}\text{O}$ and $\delta^2\text{H}$ values for samples from the RCAA in the Intermediate Dam reach clustered close together near the LMWL in Figure 5-1 and hence could not be distinguished from precipitation. Note that the $\delta^{18}\text{O}$ and $\delta^2\text{H}$ values for the Intermediate Pond water are 2‰ heavier than groundwater from wells P01-03 and X24D. The enriched isotope composition of water from the Intermediate Pond suggests some potential for determining the contribution of the Intermediate Pond to the RCAA. However, additional (seasonal) monitoring of the pond water would be required to determine if this isotopic composition prevails throughout the year.

In the Intermediate Dam reach, $\delta^{18}\text{O}$ and $\delta^{34}\text{S}$ values of SO_4 in the RCAA are consistent with moderately-impacted groundwater. Hence samples plotted slightly to the left of the 'ARD sources' in Figure 5-4. Ni and Co concentrations offer more insight into the source of ARD products in the Intermediate Dam reach.

Note the high Zn concentration and the elevated Ni and Co concentrations (with a Ni:Co ratio of ~ 1:1) in the Intermediate Pond at X4 (Figure 3-4a). This chemical composition in the Intermediate Pond is indicative of significant contributions from the FCS which is collected in the ETA SIS (during the open water season) and is discharged into the Intermediate Pond via the gravity line (Robertson GeoConsultants Inc., 2010a).

The shallow RCAA at well P01-03 is also characterized by a near 1:1 Ni:Co ratio but Zn concentrations are very low in comparison to the Intermediate Pond. This discrepancy in Zn concentrations suggests that the Intermediate Pond is an unlikely source of ARD products to the shallow RCAA. Instead, it is more likely that the shallow RCAA is impacted by a TDS front that originates further upgradient.

Historic time trends for Ni, Co, Zn and SO_4 are provided in Figure 5-5a. Note the concurrent increases in SO_4 , Ni, and Co concentrations since early 2002. Zn concentrations remained low in wells P01-03 and X24D over this time period. This suggests that Zn is attenuated at some point upgradient (possibly in the RCAA) but that Ni and Co are not attenuated to the same degree as Zn. Historic time trends for Ni, Co, Zn, and SO_4 for FCS at X23 are shown in Figure 5-5b. Concentrations of Ni, Co, Zn, and SO_4 in FCS at X23 have increased since about the time that these ARD products began increasing in wells P01-03 and X24D. This suggests increased loading of the RCAA in the Intermediate Dam reach by FCS (at least until start of operation of the ETA SIS) and supports our conclusion that elevated Ni and Co concentrations originate from the RCAA upgradient and not from the Intermediate Pond.

5.3.2 Cross Valley Dam Reach

In the Cross Valley Dam reach, a sample of surface water from the Polishing Pond (at X5) was collected in addition to samples from the following wells:

- P05-01-02 (SO₄ = 1,200 mg/L, Zn < 1 µg/L), moderately-impacted groundwater
- P01-01 (SO₄ = 1,200 mg/L, Zn = 4 µg/L), moderately-impacted groundwater
- P05-02 (SO₄ = 1,200 mg/L, Zn = 36 µg/L), moderately-impacted groundwater

Elevated SO₄ and Mn concentrations indicate that the TDS front that impacts the RCAA in the Intermediate Dam reach also impacts the RCAA in the Cross Valley Dam reach. Zn concentrations in the RCAA of the Cross Valley Dam reach are generally lower than upgradient in the Intermediate Dam reach, which is consistent with the attenuation of Zn along the flow path. Also note from Figure 5-5a that Ni and Co concentrations in wells P01-11, P05-01-02, and P05-02 have not increased since 2002. Based on the experience further upgradient, a gradual breakthrough of Ni and Co (likely over the next 5-10 years) can be expected to precede a breakthrough of zinc in the northern portion of the RCAA in the Cross Valley Dam reach.

$\delta^{18}\text{O}$ and $\delta^{34}\text{S}$ values of SO₄ for samples from the RCAA in the Cross Valley Dam reach plotted close to samples from the Intermediate Dam reach and hence were consistent with moderately-impacted groundwater. $\delta^{18}\text{O}$ and $\delta^{34}\text{S}$ values for the surface water sample from the Polishing Pond was slightly offset from samples from the RCAA but not to the extent that it could be distinguished from groundwater.

5.4 DEEP BEDROCK AT TOE OF CROSS VALLEY DAM

In deep bedrock below the toe of the Cross Valley Dam, SO₄, As, and Mn are elevated near the northern side of the Rose Creek valley (at well P09-C1) but remain low in the middle of the valley (at well P09-C2) and near the southern side of the valley (sample P09-C3-BR). This suggests that tailings porewater and/or waste rock seepage are present in deep bedrock near the northern side of Rose Creek valley but that the southern side of Rose Creek valley remains unimpacted. This spatial trend mimics the trend observed in the RCAA in the Cross Valley Dam and Intermediate Dam reaches.

$\delta^{18}\text{O}$ values for SO₄ in wells P09-C1 and P09-C2 support the assertion that groundwater near the north side of Rose Creek valley is impacted whereas groundwater further south is not. Specifically, SO₄ in the sample from well P09-C1 is depleted in ^{18}O and plots close to other samples of 'moderately-impacted' groundwater in Figure 5-5. SO₄ in groundwater from well P09-C2 is enriched in ^{18}O and plots near other samples of unimpacted groundwater. This suggests that the "TDS front" terminates somewhere between well P09-C1 and P09-C2.

Elevated Zn concentrations in the duplicate samples from P09-C3-BR are an anomalous feature of deep bedrock below the Cross Valley Dam. Specifically, Zn concentrations in the samples from P09-C3-BR and P09-C3-BR-d are 176 µg/L and 200 µg/L, respectively. These Zn concentrations are two orders of magnitude higher than Zn concentrations in the other two bedrock wells (P09-C1 and P09-C2) and in the deep alluvial well P09-C3.

Note the following about SO₄ in deep groundwater near the southern side of Rose Creek valley:

- The SO₄ concentration in P09-C3-BR is only 10 mg/L. This is much lower than in wells P09-C1 and P09-C2 and does not suggest any impact by ARD (i.e. the 'background' SO₄ concentration for the ARMC is 25 mg/L). The low SO₄ concentration in P09-C3-BR suggests that tailings porewater and/or waste rock seepage from upgradient near the Intermediate Dam reach is not a likely source to deep bedrock near P09-C3.
- SO₄ in the P09-C3-BR sample is depleted in ¹⁸O (i.e. $\delta^{18}\text{O}_{\text{SO}_4} = -7.7\text{‰}$). This suggests some contribution of SO₄ derived from the anaerobic oxidation of pyrite (i.e. mine waste seepage). The location of the P09-C3-BR sample in Figure 5-6a does not suggest any appreciable impact by ARD since the sample plots to the left of unimpacted groundwater.

A slightly elevated Zn concentration and ¹⁸O-depleted SO₄ are the only indications of ARD impact at this location. Based on this evidence alone, it seems unlikely that groundwater in deep bedrock near the southern side of Rose Creek valley is affected by the same TDS front that affects groundwater on the northern side. Instead, a Zn source near the southern side of the valley seems more likely. A potential source of Zn in this area is the Rose Creek Diversion that tracks along the southern side of Rose Creek valley approximately 250 m southwest of well P09-C3.

Surface water flowing in the Rose Creek Diversion has a similar chemical composition to that observed in the bedrock sample from P09-C3-BR (i.e. very low sulphate and slightly elevated zinc concentrations). Furthermore, the RC diversion near the Cross Valley Dam is cut into fractured bedrock and significant seepage losses have been inferred in the reach of the diversion in previous studies (Robertson GeoConsultants Inc., 2006b). It is therefore conceivable that seepage from the RC diversion is the source of the slightly elevated zinc observed in the bedrock sample from P09-C3-BR. Further drilling and sampling (in overburden and bedrock) on the southern side of the Rose Creek valley will be required to further test this hypothesis.

In the author's opinion, consideration should be given to further study the potential seepage losses from the Rose Creek diversion and their influence on the groundwater quality (in overburden as well as underlying bedrock) on the southern side of the Rose Creek valley. Such a study should include installation of at least one bedrock well near P09-C3 and a more detailed isotopic sampling campaign in this reach of the Rose Creek valley (in RC diversion, seeps, overburden and deep bedrock).

5.5 ZONE 2 PIT OUTWASH AREA

The Zone 2 Pit outwash area is located immediately down-gradient of the Zone 2 Pit (backfilled with waste rock). Groundwater quality in this area differs from groundwater quality in other areas of the ARMC that are impacted by waste rock seepage (e.g. ETA or S-cluster). Specifically, Zn concentrations are elevated in groundwater from the Zone 2 Pit outwash area but the concentrations of SO_4 , Mg, Fe, and Mn remain low by comparison. This characteristic of groundwater quality could be related to the metals content of sulphide-rich waste rock in the Zone 2 Pit and/or seepage from the Northeast Rock Dump (RGC, 2010a).

Four key areas of the Zone 2 Pit outwash area are identified:

- Weathered bedrock near the toe of Northeast Rock Dump (at wells BH14A/B)
- Bedrock/alluvium near NFRC (at wells SRK08-P12A/B)
- Bedrock immediately downgradient of Zone 2 Pit near the former spillway (well BH8)
- Outwash sediments and/or the NFRC alluvial aquifer downgradient of the Zone 2 Pit well (wells BH2, BH4, BH5, and BH6)

Well locations are shown in Figure 2-1b. Groundwater from each of these wells is impacted by ARD (Robertson GeoConsultants Inc., 2010a). The extent of ARD impact (and potential sources of ARD products) is discussed below.

$\delta^{18}\text{O}$ and $\delta^2\text{H}$ values for groundwater in the Zone 2 Pit outwash area are shown in Figure 5-7. $\delta^{18}\text{O}$ and $\delta^2\text{H}$ values in this area were similar to values observed in the Rose Creek valley. Some differences were observed within the area. Groundwater from SRK08-P12A/B is the most depleted in ^{18}O and ^2H . Hence $\delta^{18}\text{O}$ and $\delta^2\text{H}$ values for SRK08-P12A/B plotted near the bottom left of Figure 5-6c near the LMWL. Samples from wells BH8 and BH14A/B were more enriched in ^{18}O and ^2H than other samples of groundwater collected from the Zone 2 Pit outwash area but still plotted along the LMWL. Despite the small differences in $\delta^{18}\text{O}$ and $\delta^2\text{H}$ values, groundwater could not be distinguished from precipitation and hence these data provided little information on water sources to receiving groundwater.

Well BH8 is located immediately downgradient of the Zone 2 Pit and is screened in a low-permeability fault zone within weathered bedrock. Groundwater from well BH8 contains high concentrations of SO_4 and metals of interest (including Mn, Zn, Co, and Ni) and is considered 'highly-impacted' by ARD. Historic seepage from the Zone 2 Pit is a potential source of ARD products to well BH8. Note, however, that seepage currently pumped from the Zone 2 Pit (at X26) has significantly lower sulphate and zinc concentrations (2800 mg/L and 76 mg/L, respectively) compared to those observed in BH8 (3900 mg/L and 287 mg/L, respectively). Note also that Zone 2 seepage has a higher Ni:Co ratio (3:1 at X26) compared to the 1:1 Ni:Co ratio observed at BH8 (and FCS).

SO₄ in groundwater from well BH8 is depleted in ¹⁸O and hence plots close to the 'ARD sources' field in Figure 5-8a. This field was established by data for the Rose Creek valley but is applicable to the Zone 2 Pit outwash area. Again, SO₄ in samples from this field is derived primarily from anaerobic pyrite oxidation. Strongly-depleted SO₄ in groundwater from well BH8 is consistent with groundwater that is 'highly-impacted' by waste rock seepage.

SO₄ in groundwater from wells BH14A/B is also strongly-depleted in ¹⁸O. This is indicative of 'highly-impacted' groundwater near the toe of the Northeast Rock Dump (Figure 5-8a).

SO₄ from wells screened at least partially in outwash sediments (wells BH2 and BH4) and/or the NFRC alluvial aquifer (wells SRK08-P12A/B, BH5, and BH6) is less depleted in ¹⁸O than 'highly-impacted' from wells BH8 and BH14A/B. This is consistent with these receiving waters being only 'moderately-impacted' ('BH' wells) to slightly-impacted by ARD (wells SRK08-P12A/B).

Groundwater from wells SRK08-P12A/B, for instance, is characterized by low SO₄ concentrations and elevated Zn concentrations. The Zn concentration at SRK08-P12B is 0.2 mg/L, whereas the Zn concentration at SRK08-P12A is ~1 mg/L. Concentrations of SO₄ and other ions are also higher in well SRK08-P12A than in well SRK08-P12B. Groundwater from well SRK08-P12B is considered more characteristic of the NFRC aquifer than groundwater from well SRK08-P12A because it is screened at least partially in shallow alluvium (whereas well SRK08-P12A is screened in weathered bedrock).

Conservative mixing calculations were performed to determine the principal source of ARD products to groundwater at SRK08-P12B (Table B5). Seepage from the Northeast Rock Dump (at wells BH14A/B) and seepage from the Zone 2 Pit (at well BH8 and at X26) were identified as the two sources of ARD products to SRK08-P12B. Unimpacted groundwater from P09-UN-2 (screened in the NFRC alluvial aquifer upgradient of the Zone 2 Pit outwash area) was used as a (diluting) end-member.

Mixing calculations suggest that groundwater quality at SRK08-P12B cannot be predicted by assuming that Zone 2 Pit is the primary source of ARD products. Instead, seepage from the Northeast Rock Dump appears to be the primary source. Specifically, a 3% contribution by 'highly-impacted' groundwater at well BH14A to unimpacted groundwater at P09-UN-2 can explain groundwater quality at well SRK08-P12B.

SO₄ and Zn concentrations are higher in groundwater in the NFRC alluvial aquifer and/or outwash sediments downgradient of SRK08-P12B. Samples from wells BH5 and BH6 are considered representative of the NFRC aquifer in this area. SO₄ concentrations in wells BH5 and BH6 are 140 mg/L and 110 mg/L, respectively. The Zn concentrations in groundwater from wells BH5 and BH6 range from 3 – 4 mg/L. SO₄ and Zn concentrations could not be adequately predicted by using seepage from the Northeast Rock Dump (at well BH14A) as an end-member. Instead, groundwater

quality at wells BH5 and BH6 could be predicted as a mixture of groundwater from well SRK08-P12B and seepage from the Zone 2 Pit. Seepage from the Zone 2 Pit was characterized as a mixture of Zone 2 Pit water and 'highly-impacted' groundwater from BH8. Note that only a small (~2%) contribution of this inferred Zone 2 Pit seepage was required to explain SO₄ and Zn concentrations at both wells BH5 and BH6. Ni and Co concentrations were also adequately predicted but Ca and Mg concentrations were overestimated (mainly due to the high Ca and Mg content of groundwater from well SRK09-P12B).

The key conclusions regarding ARD sources in the Zone 2 Pit outwash area are summarized as follows:

- Groundwater that is representative of the NFRC aquifer upgradient of outwash sediments (at SRK08-P12B) is impacted primarily by seepage from the Northeast Rock Dump;
- Groundwater in the NFRC aquifer immediately downgradient of the Zone 2 Pit outwash area (at wells BH5 and BH6) is further impacted by seepage from the Zone 2 Pit;
- The geochemical characteristics of Zone 2 Pit seepage are not known exactly but only a small contribution of this type of seepage is necessary to reproduce the high Zn-low SO₄ characteristics of groundwater in the NFRC aquifer downgradient of the backfilled Zone 2 Pit.

6 CONCLUSIONS & RECOMMENDATIONS

6.1 CONCLUSIONS

This study yielded the following conclusions regarding groundwater quality in Rose Creek valley:

- Stable isotope data indicate that SO_4 in tailings seepage and waste rock seepage is derived primarily from the anaerobic oxidation of pyrite; hence isotope data could not be used to separate the relative contributions of each to receiving waters;
- Receiving waters could not be distinguished from precipitation based on their water isotope composition; differences in the water isotope composition of ARD sources are observed but are likely related to the timing and source of recharge, not evaporative enrichment;
- Ni:Co ratios proved to be the most valuable tracer of waste rock seepage in receiving waters; a 1:1 Ni:Co ratio was identified in waste rock seepage (at X23) and similar ratios characterized receiving waters;
- Waste rock seepage from the Faro Creek canyon (i.e. FCS) is clearly present in the Rose Creek alluvial aquifer (RCAA) near the mouth of Faro Creek canyon and in the RCAA along the north side of Rose Creek valley;
- Historic time trends in wells P01-03 and X24D (at Intermediate Dam) show a concurrent increase in SO_4 , Ni, and Co concentrations (but not zinc) since early 2002; concurrent increases of Ni, Co, Zn, and SO_4 for FCS (at X23) suggests increased loading of the RCAA by FCS (at least until start of operation of the ETA SIS).
- Zinc concentrations in the northern portion of RCAA at the Cross Valley Dam are generally lower than upgradient at the Intermediate Dam, which is consistent with the attenuation of Zn along the flow path. A gradual breakthrough of Ni and Co (likely over the next 5-10 years) can be expected to precede any breakthrough of zinc at the Cross Valley Dam reach.
- Near the northern side of Rose Creek valley, groundwater in deep bedrock below the toe of the Cross Valley Dam is characterized by elevated SO_4 , Mg, and Mn concentrations that are related to mine waste seepage; Ni, Co, and Zn concentrations remain very low in this area; groundwater at well P09-C1 is most likely affected by the same TDS front that impacts the RCAA in the Cross Valley Dam reach;
- An elevated Zn concentration was identified in sample P09-C3-BR (from deep bedrock near the southern side of Rose Creek valley below the toe of the Cross Valley Dam) but SO_4 concentrations were very low (10 mg/L); because SO_4 in this sample was more depleted in ^{18}O than 'background' SO_4 , the presence of mine waste seepage in this area could not be

discounted entirely; seepage from the Faro Creek diversion is believed to be a more likely source of the slightly elevated zinc concentrations than the TDS plume that affects groundwater along the northern side of Rose Creek valley but additional data is required to further test this hypothesis.

The key aspects of groundwater quality in the Zone 2 Pit outwash area are summarized as follows:

- Groundwater in the NFRC aquifer upgradient of the Zone 2 Pit outwash area (at SRK08-P12B) is impacted primarily by seepage from the Northeast Rock Dump;
- Groundwater in the NFRC aquifer immediately downgradient of the Zone 2 Pit outwash area (at wells BH5 and BH6) is further impacted by seepage from the Zone 2 Pit;
- The geochemical characteristics of Zone 2 Pit seepage are not known exactly but only a small contribution of this type of seepage is necessary to reproduce the high Zn-low SO₄ characteristics of groundwater in the NFRC aquifer downgradient of the backfilled Zone 2 Pit.

6.2 RECOMMENDATIONS

The following is a summary of recommendations from this study:

- This Phase 1 study has demonstrated that the stable isotopes of water and sulphate cannot be used to separate the contributions of ARD products from waste rock seepage and tailings seepage to receiving groundwater; we therefore DO NOT recommend to proceed with the second phase of this isotope study (as originally proposed in Robertson GeoConsultants Inc. (2009c); instead, consideration should be given to using the stable isotopes of water and sulphate to assess the influence of seepage from the Rose Creek Diversion on groundwater quality on the southern side of Rose Creek valley (in overburden and underlying bedrock);
- The results of this study have demonstrated that cobalt and nickel are good indicator species of mine waste seepage (in particular for waste rock) which appear to be less attenuated along the flow path than zinc; time trends of those two metals should therefore be included in future routine monitoring of groundwater quality at ARMC;
- Recent drilling and sampling has indicated significant permeability in bedrock underlying the RCAA at the Cross valley dam. The anomalous water quality in the bedrock sample at P09-C3 (with slightly elevated zinc concentrations) may be a result of seepage from the Rose Creek Diversion which may have implications for the design of a seepage interception system at this location. Consideration should therefore be given to further study the potential seepage losses from the Rose Creek diversion and their influence on the groundwater quality (in overburden as well as underlying bedrock) on the southern side of the Rose Creek valley. Such a study should include installation of at least one bedrock well near P09-C3 and a more

detailed isotopic sampling campaign in this reach of the Rose Creek valley (in RC diversion, seeps, overburden and deep bedrock).

Additional consultation with Robertson GeoConsultants Inc. would be recommended prior to sample collection in order to limit the collection of redundant or unnecessary data. Also recommended is that any additional sampling be conducted in the spring in order to further understand any seasonal variability in the isotope composition of groundwater or SO₄ at the ARMC.

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7 CLOSURE

Robertson GeoConsultants Inc. is pleased to submit this report entitled **Geochemical and Isotopic Constraints on the Sources of Acid Rock Drainage (ARD) Products to Groundwater, Anvil Range Mining Complex, YT.**

This report was prepared by Robertson GeoConsultants Inc. for the use of **Yukon Government.**

We trust that the information provided in this report meets your requirements at this time. Should you have any questions or if we can be of further assistance, please do not hesitate to contact the undersigned.

Respectfully Submitted,

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8 REFERENCES

- Aggarwal, P.K., Dillon, M.A., and A. Tanweer (2004), Isotope fractionation at the soil-atmosphere interface and the ^{18}O budget of atmospheric oxygen, *Geophysical Research Letters*, 31, doi:10.1029/2004GL019945.
- Allison, G.B. (1982), The relationship between ^{18}O and deuterium in water in sand columns undergoing evaporation, *Journal of Hydrology*, 55, 163 – 169.
- Allison, G.B., C.J. Barnes, and M.W. Hughes (1983), The distribution of deuterium and ^{18}O in dry soils 2: Experimental, *Journal of Hydrology*, 64, 377 – 397.
- Clark, I.D. and P.O. Fritz (1997), *Environmental Isotopes in Environmental Isotopes*, Lewis Publishers, New York.
- Craig, H., and L. Gordon (1965), Deuterium and oxygen-18 variation in the ocean and marine atmosphere, In: *Stable Isotopes in Oceanographic Studies and Paleotemperatures*, Taylor, H.P., O'Neil, J.R., and I.R. Kaplan (Eds.), 9 – 130.
- Daansgard, W. (1964), Stable Isotopes in Precipitation, *Tellus*, 16, 436 – 468.
- Donnelly, T., Waldron, S., Tait, A., Dougans, J., Bearhop, S. (2001), Hydrogen isotope analysis of natural abundance and deuterium-enriched waters by reduction over chromium on-line to a dynamic dual inlet isotope-ratio mass spectrometer, 15, 1297 – 1303.
- Epstein, S. and T. K. Mayeda (1953), Variation of O^{18} content of waters from natural sources: *Geochimica et Cosmochimica Acta*, v. 4, p. 213-224.
- Gibson, J.J., Edwards, T.W.D, Birks, S.J., St Amour, N.A., Buhay, W.M., McEachern, P., Wolfe, B.B., and D.L. Peters (2005), Progress in isotope tracer hydrology in Canada, *Hydrological Processes*, 19, 303 – 327.
- International Atomic Energy Agency (IAEA), Global Network for Isotopes in Precipitation (GNIP) data, Whitehorse, 1985 – 1990, http://www-naweb.iaea.org/naweb/ih/GNIP/IHS_GNIP.html
- O'Neil, J.R., Adami, L.H., Epstein, S. (1975), Revised value for the ^{18}O fractionation factor between CO_2 and water at 25°C : *J. Res. U.S. Geol. Surv.*, v. 3, p. 623-624.
- Robertson GeoConsultants Inc. (2006a), Results of Faro Creek Seepage Surveys (Oct '05 to May '06), RGC Report 118007/1, July 2006.
- Robertson GeoConsultants Inc. (2006b), Water & Load Balance Study for the Rose Creek Tailings Facility, Faro Mine, Yukon Territory, RGC Report 118001/1, March 2006.

- Robertson GeoConsultants Inc. (2009a), 2008 Groundwater Review: Anvil Range Mining Complex, RGC Report 118014/1, January 2009.
- Robertson GeoConsultants Inc. (2009b), Geochemical Assessment of Groundwater Quality in Rose Creek aquifer, Anvil Range Mine, Yukon Territory, RGC Report 118013/1, January, 2009.
- Robertson GeoConsultants Inc. (2009c), PROPOSAL – Distinguishing the sources of ARD products in groundwater via geochemical mixing calculations and isotope tracer studies, Anvil Range Mining Complex, Yukon Territory, May 2009.
- Robertson GeoConsultants Inc. (2010a), 2009 Annual Groundwater Review, Anvil Range Mining Complex, Yukon Territory, February 2010.
- Robertson GeoConsultants Inc. (2010b), 2009 Performance Review of ETA SIS, Faro mine, Yukon Territory, February 2010.
- Rozanski, K., Araguas-Araguas, L., and R. Gonfiantini (1993), Isotopic patterns in modern global precipitation, *In: Continental Isotopic Indicators of Climate, (Eds.)*, American Geophysical Union Monograph 78.
- Sracek, O., M. Choquette, P. Gelinas, R. Lefebvre, and R.V. Nicholson (2004), Geochemical characterization of acid mine drainage from a waste rock pile, Mine Doyon, Québec Canada.
- SRK Consulting Inc. (2010), Faro Mine Complex 2009 Groundwater Investigations, January 2010.
- SRK Consulting Inc. (2009), 2008 Groundwater Assessment at Medium Priority Waste Rock Areas, Faro Mine Complex, April 2009.
- Taylor, B.E., Wheeler, M.C., and D.K. Nordstrom (1984), Stable isotope geochemistry of acid mine drainage: Experimental oxidation of pyrite, *Geochimica et Cosmochimica Acta*, 48, 2669 – 2678.

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TABLES

Table 2-1a. Description of sampling locations for geochemical & isotope tracer study, RCTF

SAMPLE ID	DESCRIPTION/LOCATION	Northing UTM z8 NAD27	Easting UTM z8 NAD27	Year of Construction	Stickup (m)	Total Depth (m btoc)	Total Depth (m bgs)	Ground Elevation (m asl)	Top of Screen (m asl)	Bottom of Screen (m asl)	Top of Screen (m bgs)	Bottom of Screen (m bgs)	Top of Casing Elevation (m asl)	Current Status of Monitoring	Formation
Waste rock seepage															
FCS-1 at X23	Faro Creek seepage (FCS) from Main WRD	6913912	583360	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	for ETA SIS monitoring	surface water
FCS-3	SIS seepage	6913788	582883	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	for ETA SIS monitoring	surface water
FCS-4	ETA SIS bypass at mouth of canyon	6913635	582797	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	for ETA SIS monitoring	surface water
Tailings porewater															
P03-01-08	High-strength' tailings porewater	6912580	583301	2003	0.53	9.82	9.30	1060.58	1051.59	1051.29	8.99	9.30	1061.11	bi-annual	Tailings
P03-02-07	High-strength' tailings porewater (bottom of tailings profile)	6912572	583135	2003	0.69	12.58	11.89	1059.91	1048.32	1048.02	11.58	11.89	1060.60	not routinely monitored	Tailings
P03-02-09	High-strength' tailings porewater (top of tailings profile)	6912572	583135	2003	0.69	8.31	7.62	1059.91	1052.59	1052.29	7.32	7.62	1060.60	not routinely monitored	Tailings
X21A	High strength' tailings porewater in Intermediate Impoundment	6913417	581989	1996	0.69	9.22	8.53	1051.40	1048.97	1042.87	2.43		1052.09	bi-annual	Tailings
RCAA upgradient of Faro Creek canyon															
P03-01-02	Background groundwater (unimpacted by ARD)	6912580	583301	2003	0.53	39.39	38.86	1060.59	1022.03	1021.82	38.56	38.86	1061.11	bi-annual	Alluvium
P03-01-04	Groundwater up-gradient of Faro Creek canyon	6912580	583301	2003	0.53	25.06	24.54	1060.58	1036.35	1036.05	24.23	24.54	1061.11	bi-annual	Alluvium
P03-01-05	Groundwater up-gradient of Faro Creek canyon	6912580	583301	2003	0.53	18.97	18.44	1060.58	1042.45	1042.14	18.14	18.44	1061.11	bi-annual	Alluvium
RCAA and bedrock near mouth of Faro Creek canyon															
P09-ETA-1	Groundwater in bedrock near mouth of Faro Creek canyon	6913635	582807	2009	0.93	30.73	29.8	1073.73	1046.83	1043.93	26.9	29.8	1074.7	bi-annual	bedrock
P09-ETA-2	Groundwater in overburden near mouth of Faro Creek canyon	6913633	582832	2009	0.71	18.41	17.7	1073.75	1057.60	1056.05	16.15	17.7	1074.46	bi-annual	bedrock/alluvium
P03-06-04	Groundwater cross-gradient of Faro Creek	6913309	582573	2003	0.87	17.33	16.46	1061.93	1045.77	1045.47	16.15	16.46	1062.79	bi-annual	Alluvium
P03-06-05	Groundwater cross-gradient of Faro Creek	6913309	582573	2003	0.87	15.19	14.33	1061.93	1047.90	1047.60	14.02	14.33	1062.79	bi-annual	Alluvium
X21B	ARD-impacted groundwater in Intermediate Impoundment	6913417	581989	1996	0.74	15.43	14.69	1051.40	1039.76	1036.71	11.64		1052.14	bi-annual	Alluvium
RCAA and surface water in Intermediate Dam reach															
X24D	ARD-impacted groundwater at Intermediate Dam	6914124	580655	1996	0.70	29.04	28.34	1032.20	1005.46	1003.96	26.84	28.34	1032.90	bi-annual	Alluvium
P01-03	ARD-impacted groundwater at Intermediate Dam	6914071	580639	2001	0.56	9.86	9.30	1031.65	1023.87	1022.35	7.78	9.30	1032.21	bi-annual	Alluvium
X4	Intermediate Pond at spillway	6914227	580759	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	routinely monitored	surface water
X5	Polishing Pond at spillway	6914456	580306	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	routinely monitored	surface water
RCAA in Cross Valley Dam reach															
P01-11	Shallow groundwater at Cross Valley Dam	6914306	580214	2001	0.55	11.22	10.67	1017.28	1008.13	1006.61	9.15	10.67	1017.83	bi-annual	Alluvium
P05-01-02	Deep groundwater at Cross Valley Dam	6914335	580165	2005	0.68	20.50	19.82	1017.32	997.65	997.50	19.67	19.82	1018.00	bi-annual	Alluvium
P05-02	Shallow groundwater at Cross Valley Dam	6914265	580144	2005	0.93			1015.74			1.83	4.88	1016.67	bi-annual	Alluvium
Deep bedrock below toe of Cross Valley Dam															
P09-C1	Groundwater in bedrock below toe of Cross Valley Dam	6914314	580171	2009	0.85	34.85	34	1016.51	983.91	982.51	32.6	34	1017.4	bi-annual	Bedrock
P09-C2	Groundwater in bedrock below toe of Cross Valley Dam	6914228	580119	2009	0.75	60.05	59.3	1015.83	962.33	956.53	53.5	59.3	1016.6	bi-annual	Bedrock

Table 2-1b. Description of sampling locations for geochemical & isotope tracer study, Zone 2 Pit outwash area

SAMPLE ID	DESCRIPTION/LOCATION	Northing UTM z8 NAD27	Easting UTM z8 NAD27	Year of Construction	Stickup (m)	Total Depth (m btoc)	Total Depth (m bgs)	Ground Elevation (m asl)	Top of Screen (m asl)	Bottom of Screen (m asl)	Top of Screen (m bgs)	Bottom of Screen (m bgs)	Top of Casing Elevation (m asl)	Current Status of Monitoring	Formation
NFRC aquifer upgradient of Zone 2 Pit outwash area															
BH14A	Groundwater impacted by waste rock seepage (u/g of Zone 2)	6913826	585676	1994	0.19	6.44	6.25	1157.33	1152.61	1151.08	4.72	6.25	1157.52	bi-annual	Bedrock
BH14B	Groundwater impacted by waste rock seepage (u/g of Zone 2)	6913826	585676	1994	0.83	10.13	9.30	1157.33	1149.56	1148.03	7.77	9.30	1158.16	bi-annual	Bedrock
SRK08-P12A (deep)	Groundwater in NFRC aquifer upgradient of Zone 2 area	6913506	585348	2008	0.67	12.86	12.19	1106.00	1096.86	1093.81	9.14	12.19	1106.67	bi-annual	Bedrock
SRK08-P12B (shallow)	Groundwater in NFRC aquifer upgradient of Zone 2 area	6913509	585345	2008	0.75	8.37	7.62	1106.00	1101.43	1098.38	4.57	7.62	1106.75	bi-annual	Alluvium
NFRC aquifer within Zone 2 Pit outwash area															
BH2	Shallow groundwater in Zone 2 outwash sediments	6913523	585206	1992	0.66								1099.70	bi-annual	n/a
BH4	Shallow groundwater in Zone 2 outwash sediments	6913467	585247	1992	0.72								1097.02	bi-annual	n/a
BH6	Impacted groundwater in NFRC aquifer in Zone 2 area	6913466	585198	1994	0.76	7.01	6.25	1097.08	1092.36	1090.83	4.72	6.25	1097.84	not routinely monitored	Alluvium
BH8	Groundwater impacted by Zone 2 Pit seepage	6913599	585253	1994	0.79	21.36	20.57	1122.58	1103.53	1102.01	19.05	20.57	1123.37	not routinely monitored	Bedrock
NFRC aquifer downgradient of Zone 2 Pit outwash area															
BH5	Impacted groundwater in NFRC aquifer d/g of Zone 2 area	6913377	585194	1994	0.46	8.08	7.62	1095.11	1089.10	1087.49	6.01	7.62	1095.57	not routinely monitored	Alluvium

Table 3-1. Groundwater quality and isotope data, Rose Creek valley, ARMC																																					
SAMPLE ID	DESCRIPTION/LOCATION	DATE	FIELD (LES)		FIELD (RGC)							LABORATORY																									
			EC µS/cm	pH	Temp °C	pH	EC µS/cm	Sal.	DO %	DO mg/L	Eh mV	pH	EC µS/cm	TDS mg/L	Alkalinity mg/L CaCO3	Hardness mg/L CaCO3	Ca mg/L	Mg mg/L	Na mg/L	K mg/L	HCO3 mg/L	SO4 mg/L	Cl mg/L	Al_f µg/L	As_f µg/L	Cd_f µg/L	Co_f µg/L	Cu_f µg/L	Fe_f µg/L	Mn_f µg/L	Ni_f µg/L	Pb_f µg/L	Zn_f µg/L	δ ³⁴ S ‰	δ ¹⁸ O _{SO4} ‰	δ ¹⁸ O _{water} ‰	δ ² H _{water} ‰
Waste-rock seepage																																					
FCS-1 at X23	Waste rock seepage from NW and Main WRD	9-Sep-09	-	-	6.2	6.0	7915	4.4	80	9.5	207	5.6	8520	11000	8.0	6240	521	1200	67	19	10	8300	12	30	1.0	271.0	1750	36	341000	121000	1910	2	969000	13.9	-17.2	-21.3	-169
FCS-3	SIS seepage	9-Sep-09	-	-	3.5	5.4	8555	4.7	97	12.1	231	4.0	9290	15000	0.5	3850	492	728	69	13	1	9400	5	2470	20	10.2	921	12	2160000	79000	930	4.4	536000	14.3	-16.7	-21.1	-169
FCS-4	ETA SIS bypass at mouth of canyon	9-Sep-09	-	-	6.6	6.7	5609	3.0	120	14.2	194	5.3	6000	6600	2.6	4230	433	671	63	11	3	5200	15	9	1.6	11.5	298	9	377000	54700	405	0.4	144000	14.1	-15.0	-20.9	-167
Tailings porewater																																					
P03-01-08	High-strength' tailings porewater	11-Sep-09	29148	5.2	-	-	-	-	-	-	-	3.3	26400	18480	0.5	4010	423	718	361	95	1	46000	-	4210	10.0	1.0	50	20	2.1E+07	150000	450	20	2480000	16.1	-13.0	-20.3	-165
P03-02-07	High-strength' tailings porewater (bottom of tailings profile)	10-Sep-09	-	-	8.9	5.6	17584	10.4	32	3.5	236	3.2	15900	29000	0.5	2560	369	398	182	70	1	17000	5	30	1.0	0.1	5	2	9810000	53500	22	22.0	429000	16.2	-14.8	-20.5	-165
P03-02-09	High-strength' tailings porewater (top of tailings profile)	10-Sep-09	-	-	8.5	5.1	19997	11.9	68	7.7	307	3.2	17200	34000	0.5	1590	352	173	32	19	1	19000	5	59	1.0	0.1	5	99	7560000	54100	30	55.0	1110	16.5	-13.4	-20.4	-165
X21A	High-strength' tailings pore water in intermediate impoundment	9-Sep-09	17006	5.6	5.2	5.6	17006	9.9	31	3.7	207	3.4	15600	10920	0.5	3640	382	654	37	13	1	25000	-	505	11.0	0.9	14.0	2.0	1E+07	460000	55	45.0	147000	15.9	-16.1	-21.4	-171
RCAA upgradient of Faro Creek canyon																																					
P03-01-02	Background groundwater (unimpacted by ARD)	11-Sep-09	402	6.5	-	-	-	-	-	-	-	7.7	92	64	49	211	66	11	5	3	59	24	-	3	0.9	0.01	1.0	0.2	324	702	1	0.4	5	18.7	-0.4	-22	-171
P03-01-04	Groundwater up-gradient of Faro Creek canyon	11-Sep-09	194	6.0	-	-	-	-	-	-	-	7.0	206	144	39	73.7	23	4	2	1	47	58	-	7	0.1	1.2	10.4	1.7	6	6180	149	0.2	2500	15.3	-10.6	-22.5	-174
P03-01-05	Groundwater up-gradient of Faro Creek canyon	11-Sep-09	376	5.8	-	-	-	-	-	-	-	6.9	402	281	29	171	55	8	4	2	36	140	-	6	0.1	1.5	9.6	0.3	57	6790	128	0.2	262	15.6	-12.7	-21.9	-169
RCAA and bedrock near the mouth of Faro Creek canyon																																					
P09-ETA-1	Groundwater in bedrock near mouth of Faro Creek canyon	4-Aug-09	670	7.7	-	-	-	-	-	-	-	8.0	447	313	210	222	70	11	17	0	260	25	1	2	0.1	0.01	0.1	0.1	11	15.8	0	0.1	1	34.6	3.9	-21.1	-167
P09-ETA-2	Groundwater in overburden near mouth of Faro Creek canyon	4-Aug-09	4000	6.4	-	-	-	-	-	-	-	6.6	5150	3605	160	3550	551	529	50	8	190	4500	14	16	54	0.1	181	0.5	254000	39500	184	1.2	70600	13.8	-17.7	-20.9	-166
P03-06-04	RCAA downgradient of Faro Creek canyon	10-Sep-09	2110	6.4	5.3	6.6	1981	1.0	29	3.4	132	6.3	1910	1337	22	1020	292	71	17	4	27	1100	-	16	1.0	1.5	222	5.0	184000	35600	228	0.3	4460	15.7	-14.3	-21.4	-167
P03-06-05	RCAA downgradient of Faro Creek canyon	10-Sep-09	1920	6.8	5.8	6.6	1835	0.9	76	9.3	175	5.0	1690	1183	0.5	737	173	74	23	3	1	940	-	4	6	0.0	13.8	0.2	214000	18900	24	0.8	15300	16.0	-13.2	-21.6	-167
X21B	RCAA downgradient of Faro Creek canyon	9-Sep-09	2435	6.6	3.6	6.6	2435	1.2	38	4.9	136	6.2	2300	1610	14	1140	333	75	64	5	17	1300	-	12	6.6	0.1	14.3	0.2	250000	36700	25	0.2	1710	16.1	-14.1	-21.2	-166
RCAA and surface water in the Intermediate Dam reach																																					
X4	Intermediate Pond at spillway	10-Sep-09	-	-	10.9	7.1	1896	1.0	112	12.4	595	3.2	2100	1800	0.5	935	215	97	14	4	1	1100	1	986	1.2	22	142	148	54200	20600	141	940	52500	15.8	-16.1	-19.5	-160
X5	Polishing Pond at spillway	10-Sep-09	-	-	10.9	7.3	1275	0.6	95	10.5	459	7.7	1420	1200	81	778	217	58	18	7	99	720	1	6	0.3	0.3	7.3	0.5	150	3960	15	0.3	432	14.9	-15.1	-19.8	-160
X24D	ARD-impacted groundwater at Intermediate Dam	9-Sep-09	3244	6.4	4.5	6.5	2938	1.5	32	3.5	240	7.6	3550	2485	430	2510	738	162	46	8	520	1900	-	3	0.5	3.8	90.3	2.4	57	75300	327	0.2	102	15.4	-14.2	-21.2	-167
P01-03	ARD-impacted groundwater at Intermediate Dam	10-Sep-09	2110	6.3	4.9	6.2	2805	1.5	25	3.2	403	7.6	3090	2163	370	2210	642	148	38	7	450	1700	-	10	0.5	1.3	147	0.8	391	69000	195	0.8	33	15.5	-13.9	-21.3	-167
RCAA in the Cross Valley Dam reach																																					
P01-11	Shallow groundwater at Cross Valley Dam	10-Sep-09	2402	6.8	5.0	6.6	2450	1.3	72	9.3	249	7.9	2420	1694	340	1620	494	94	45	7	410	1200	-	1	31	0.0	4.1	0.3	36700	21000	9	0.0	4	16.4	-12.2	-21.3	-167
P05-01-02	Deep groundwater at Cross Valley Dam	10-Sep-09	2640	6.8	4.9	6.5	2444	1.3	36	4.4	178	7.4	2590	1813	350	1660	511	94	43	7	420	1200	-	1	0.4	0.03	0.1	0.3	19800	21000	2	0.03	1	16.3	-11.7	-21.3	-166
P05-02	Shallow groundwater at Cross Valley Dam	10-Sep-09	2301	6.8	6.6	6.5	2297	1.2	81	9.7	348	7.5	2500	1750	350	1550	475	89	44	7	430	1200	-	4	3.7	0.2	9.6	0.3	5490	18200	12	0.1	36	16.5	-10.8	-21.2	-166
Deep bedrock below toe of Cross Valley Dam																																					
P09-C1	Groundwater in bedrock below toe of Cross Valley Dam	31-Jul-09	-	-	-	-	-	-	-	-	-	7.7	2400	-	410	1470	433	95	77	7	510	1000	3	11	7.5	0.1	0.2	0.4	9720	12200	3	0.3	2	16.3	-12.1	-21.5	-168
P09-C2	Groundwater in bedrock below toe of Cross Valley Dam	2-Aug-09	-	-	-	-	-	-	-	-	-	7.6	2520	-	1500	877	207	88	305	10	1900	28	20	48	0.6	0.0	0.5	0.2	3120	167	5	0.2	8	6.1	5.8	-22.6	-174
P09-C3-BR	Groundwater in bedrock below toe of Cross Valley Dam	29-Jun-09	-	-	-	-	-	-	-	-	-	7.9	3100	2000	2000	1660	418	149	315	9	2500	11	33	8	0.5	0.1	0.3	0.1	8530	457	3	0.1	176	17.0	-7.7	-21.7	-167
QA/QC																																					
P03-01-02	Background groundwater (unimpacted by ARD)	11-Sep-09	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	19	-0.7	-22	-170	
RPD, %			-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1.6	-54.5	0.0	-0.6	
P09-C3-BR-d																																					
P09-C3-BR-d	Groundwater in bedrock below toe of Cross Valley Dam	29-Jun-09	-	-	-	-	-	-	-	-	-	7.9	3200	2100	430	1570	386	146	298	9	520	10	33	18	0.5	0.2	0.4	0.8	7330	419	3	0.2	200	16.4	-6.9	-21.5	-168
RPD, %			-	-	-	-	-	-	-	-	-	0.0	3.2	4.9	129.2	5.6	8.0	2.0	5.5	7.9	131.1	13.6	0.0	76.9	6.2	44.9	10.8	140.4	15.1	8.7	23.3	50.0	12.8	3.6	-11.0	-0.9	-0.6

0.01

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210

Concentration less than indicated detection limit

Data not available

Italicized TDS values calculated from EC

Suspect data

Table 3-2. Groundwater quality and isotope data, Zone 2 Pit outwash area, ARMC																																					
SAMPLE ID	DESCRIPTION/LOCATION	DATE	FIELD (LES)		FIELD (RGC)							LABORATORY																									
			EC µS/cm	pH	Temp °C	pH	EC µS/cm	Sal.	DO %	DO mg/L	Eh mV	pH	EC µS/cm	TDS mg/L	Alkalinity mg/L CaCO3	Hardness mg/L CaCO3	Ca mg/L	Mg mg/L	Na mg/L	K mg/L	HCO3 mg/L	SO4 mg/L	Cl mg/L	Al_f µg/L	As_f µg/L	Cd_f µg/L	Co_f µg/L	Cu_f µg/L	Fe_f µg/L	Mn_f µg/L	Ni_f µg/L	Pb_f µg/L	Zn_f µg/L	δ ³⁴ S _{SO4} ‰	δ ¹⁸ O _{SO4} ‰	δ ¹⁸ O _{water} ‰	δ ² H _{water} ‰
X26	Zone 2 Pit water	9-Sep-09	3500	6	-	-	-	-	-	-	-	7	3990		410		523	313	49	14	500	2800	3	26	2.1	20.8	426	0.4	65300	13000	1160	52.6	75900	-	-	-	-
Bedrock and NFRC aquifer upgradient of Zone 2 Pit outwash area																																					
BH14A	Groundwater impacted by waste rock seepage (u/g of Zone 2)	11-Sep-09	5311	6.7	-	-	-	-	-	-	-	7.7	3960	2772	490	3180	683	358	17	4	590	2800	-	11	0.2	1.7	0.5	2.0	56	25	116	27.7	11800	12.8	-17.7	-20.7	-165
BH14B	Groundwater impacted by waste rock seepage (u/g of Zone 2)	11-Sep-09	4890	7.0	-	-	-	-	-	-	-	7.9	3810	2667	430	3030	732	292	16	4	530	2000	-	6	0.1	0.1	0.1	0.9	48	2	11	2.2	1050	12.9	-17.9	-20.8	-165
SRK08-P12A (deep)	Groundwater in NFRC aquifer upgradient of Zone 2 area	10-Sep-09	838	5.5	1.8	5.6	1497	0.7	35	4.7	350	6.5	1240	868	600	689	191	52	26	3	730	140	-	38	0.5	0.0	7.7	0.3	14800	851	13	0.1	989	13.9	-12.8	-22.9	-174
SRK08-P12B (shallow)	Groundwater in NFRC aquifer upgradient of Zone 2 area	10-Sep-09	596	5.5	1.5	5.5	1081	0.5	33	4.6	366	6.4	884	619	410	466	134	32	17	4	500	94	-	53	0.1	0.0	3.7	0.2	5640	597	6	0.1	227	13.7	-10.3	-22.7	-172
Bedrock and NFRC aquifer within Zone 2 Pit outwash area																																					
BH2	Shallow groundwater in Zone 2 outwash sediments	10-Sep-09	512	6.0	7.0	6.0	512	0.3	62	7.7	345	7.0	444	311	110	204	57	15	5	2	140	100	-	206	0.1	19.5	0.2	0.9	25	5	32	0.9	7370	15.4	-13.2	-21.5	-168
BH4	Shallow groundwater in Zone 2 outwash sediments	4-Aug-09	464	5.9	4.9	5.7	700	0.3	84	10.4	366	7.0	452	316	100	-	62	13	4	2	130	120	-	284	0.1	5.4	13.9	8.5	50	180	22	0.6	1850	16.0	-14.3	-22.1	-173
BH6	Impacted groundwater in NFRC aquifer in Zone 2 area	30-May-09	419	6.1	4.7	6.1	552	0.3	39	5.0	298	7.0	423	296	110	-	55	15	5	2	130	110	-	46	0.1	1.6	32.5	0.2	5010	1370	30	1.1	3690	15.8	-12.1	-21.5	-167
BH8	Groundwater impacted by Zone 2 Pit seepage	11-Sep-09	4300	4.7	-	-	-	-	-	-	-	4.4	4620	3234	0.5	1690	308	224	30	7	1	3900	-	32700	14	991	781	5800	813000	15700	675	1500	287000	14.6	-15.6	-21.0	-165
NFRC aquifer downgradient of Zone 2 Pit outwash area																																					
BH5	Impacted groundwater in NFRC aquifer d/g of Zone 2 area	10-Sep-09	621	6.3	3.0	5.4	744	0.8	32	4.2	369	6.9	611	428	190	286	73	25	11	3	230	140	-	64	0.6	1.1	16	0.4	19600	1500	25	1.3	3280	16.8	-10.5	-21.7	-169
QA/QC																																					
BH5-d	Impacted groundwater in NFRC aquifer d/g of Zone 2 area	10-Sep-09	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	17.9	-11.7	-21.6	-169
RPD, %																																		6.3	-10.8	-0.5	0.0

0.01

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210

Concentration less than indicated detection limit
Data not available
Italicized TDS values calculated from EC

Table 3-3a. Summary of QA/QC analysis, Rose Creek valley, ARMC

SAMPLE ID	DESCRIPTION/LOCATION	DATE	Charge balance analysis			Comparison of RGC and LES Field Data						LES Field Data vs. Lab Data				
			Cations, meq/L	Anions, meq/L	RPD, %	RGC EC, uS/cm	LES EC, uS/cm	RPD for EC, %	RGC pH, pH units	LES pH, pH units	RPD for pH %	Lab C uS/cm	Lab pH pH units	RPD for EC %	RPD for pH %	
Waste-rock seepage																
FCS-1 at X23	Waste-rock seepage	9-Sep-09	180	173	4	7915	n/a	-	6.0	-	-	8520	5.6	-	-	
FCS-3	SIS seepage	9-Sep-09	188	196	4	8555	n/a	-	5.4	-	-	9290	4.0	-	-	
FCS-4	ETA SIS bypass at mouth of canyon	9-Sep-09	101	108	7	5609	n/a	-	6.7	-	-	6000	5.3	-	-	
Tailings seepage																
P03-01-08	High-strength' tailings porewater	11-Sep-09	933	958	3	-	29148	-	-	5.2	-	26400	3.3	9	45	
P03-02-07	High-strength' tailings porewater (bottom of tailings profile)	10-Sep-09	430	354	19	17584	-	-	5.6	-	-	15900	3.2	-	-	
P03-02-09	High-strength' tailings porewater (top of tailings profile)	10-Sep-09	307	396	25	19997	-	-	5.1	-	-	17200	3.2	-	-	
X21A	'High strength' tailings pore water in Intermediate Impoundment	9-Sep-09	463	521	12	17006	-	-	5.6	5.6	1	15600	3.4	-	48	
RCAA upgradient of Faro Creek canyon																
P03-01-02	Background groundwater (unimpacted by ARD)	11-Sep-09	5	5	1	-	402	-	-	6.5	-	92	7.7	76	17	
P03-01-04	Groundwater up-gradient of Faro Creek	11-Sep-09	2	2	3	-	194	-	-	6.0	-	206	7.0	6	15	
P03-01-05	Groundwater up-gradient of Faro Creek	11-Sep-09	4	4	10	-	376	-	-	5.8	-	402	6.9	7	17	
RCAA and bedrock near the mouth of Faro Creek canyon																
P09-ETA-01	Monitoring well near mouth of Faro Creek canyon	4-Nov-09	5	5	7	-	670	-	-	7.7	-	447	8.0	33	4	
P09-ETA-02	Monitoring well near mouth of Faro Creek canyon	4-Nov-09	87	97	11	-	4000	-	-	6.4	-	5150	6.6	29	3	
P03-06-04	Groundwater cross-gradient of Faro Creek	10-Sep-09	29	23	23	1981	2110	6	6.6	6.4	3	1910	6.3	9	2	
P03-06-05	Groundwater cross-gradient of Faro Creek	10-Sep-09	25	20	23	1835	1920	5	6.6	6.8	3	1690	5.0	12	30	
X21B	Impacted groundwater in Intermediate Impoundment	9-Sep-09	36	27	28	2435	-	-	6.6	6.6	0	2300	6.2	-	6	
RCAA and surface water in the Intermediate Dam reach																
X4	Intermediate Pond at spillway	10-Sep-09	24	23	5	1896	n/a	-	7.1	-	-	2100	3.2	-	-	
X5	Polishing Pond at spillway	10-Sep-09	17	17	0	1275	n/a	-	7.3	-	-	1420	7.7	-	-	
X24D	Deep impacted groundwater at Intermediate Dam	9-Sep-09	55	48	13	2938	3244	10	6.5	6.4	1	3550	8	9	17	
P01-03	Shallow impacted groundwater at Intermediate Dam	10-Sep-09	49	43	13	2805	2757	2	6.2	6.3	2	3090	7.6	12	18	
RCAA in the Cross Valley Dam reach																
P01-11	Shallow impacted groundwater at Cross Valley Dam	10-Sep-09	37	32	14	2450	2460	0	6.6	6.8	4	2420	7.9	2	15	
P05-01-02	Deep impacted groundwater at Cross Valley Dam	10-Sep-09	37	32	14	2444	2640	8	6.5	6.8	5	2590	7.4	2	8	
P05-02	Shallow impacted groundwater at Cross Valley Dam	10-Sep-09	34	32	6	2297	2301	0	6.5	6.8	4	2500	7.5	9	11	
Deep bedrock below toe of Cross Valley Dam																
P09-C1	Groundwater in bedrock below toe of Cross Valley Dam	31-Jul-09	34	29	14	-	-	-	-	-	-	-	-	-	-	
P09-C2	Groundwater in bedrock below toe of Cross Valley Dam	2-Aug-09	31	32	3	-	-	-	-	-	-	-	-	-	-	
P09-C3-BR	Groundwater in bedrock below toe of Cross Valley Dam	29-Jun-09	47	42	12	-	-	-	-	-	-	-	-	-	-	
P09-C3-BRd	Groundwater in bedrock below toe of Cross Valley Dam	29-Jun-09	45	9	134	-	-	-	-	-	-	-	-	-	-	

Note: RPD values for P03-01-02, BH4, and BH6 were close to or higher than 100% so 2008 alkalinity data was used instead of 2009 data

RPD values that are higher than 15% are highlighted to emphasize the uncertainty in these data

LES did not collect field measurements at stations that are not part of the routine groundwater monitoring program, which include FCS-1, FCS-3, FCS-4, X4, X5, P09-C1, P09-C2, and P09-C3

Table 3-3b. Summary of QA/QC analysis, Zone 2 Pit outwash area

SAMPLE ID	DESCRIPTION/LOCATION	DATE	Charge balance analysis			Comparison of RGC and LES Field Data						LES Field Data vs. Lab Data			
			Cations, meq/L	Anions, meq/L	RPD, %	RGC EC, uS/cm	LES EC, uS/cm	RPD for EC, %	RGC pH, pH units	LES pH, pH units	RPD for pH %	Lab EC uS/cm	Lab pH pH units	RPD for EC %	RPD for pH %
X26	Zone 2 Pit water	9-Sep-09	60	67	10	-	-	-	-	-	-	-	-	-	-
Groundwater upgradient of Zone 2 Pit outwash area															
BH14A	Groundwater impacted by waste rock seepage (u/g of Zone 2)	11-Sep-09	65	68	5	-	5311	-	-	6.7	-	3960	7.7	25	13
BH14B	Groundwater impacted by waste rock seepage (u/g of Zone 2)	11-Sep-09	61	51	20	-	4890	-	-	7.0	-	3810	7.9	22	13
SRK08-P12A (deep)	Groundwater in NFRC aquifer upgradient of Zone 2 area	10-Sep-09	16	15	3	1497	838	56	5.6	5.5	1	1240	6.5	48	17
SRK08-P12B (shallow)	Groundwater in NFRC aquifer upgradient of Zone 2 area	10-Sep-09	10	10	1	1081	596	58	5.5	5.5	0	884	6.4	48	16
Groundwater within Zone 2 Pit outwash area															
BH2	Shallow groundwater in Zone 2 outwash sediments	10-Sep-09	5	4	5	512	-	-	6.0	6.0	1	444	7.0	-	15
BH4	Shallow groundwater in Zone 2 outwash sediments	10-Sep-09	6	6	3	-	464	-	5.7	6.1	7	452	7.0	3	13
BH6	Impacted groundwater in NFRC aquifer in Zone 2 area	30-May-09	5	4	5	-	419	-	-	5.9	-	423	7.0	1	16
BH8	Groundwater impacted by Zone 2 Pit seepage	11-Sep-09	78	81	4	-	4300	-	-	4.7	-	4620	4.4	7	7
Groundwater downgradient of Zone 2 Pit outwash area															
BH5	Impacted groundwater in NFRC aquifer d/g of Zone 2 area	10-Sep-09	7	7	6	744	621	18	5.4	6.3	14	611	6.9	2	10

Note: RPD values for P03-01-02, BH4, and BH6 were close to or higher than 100% so 2008 alkalinity data was used instead of 2009 data

RPD values that are higher than 15% are highlighted to emphasize the uncertainty in these data

LES did not collect field measurements at stations that are not part of the routine groundwater monitoring program, which include FCS-1, FCS-3, FCS-4, X4, X5, P09-C1, P09-C2, and P09-C3

DRAFT

FIGURES

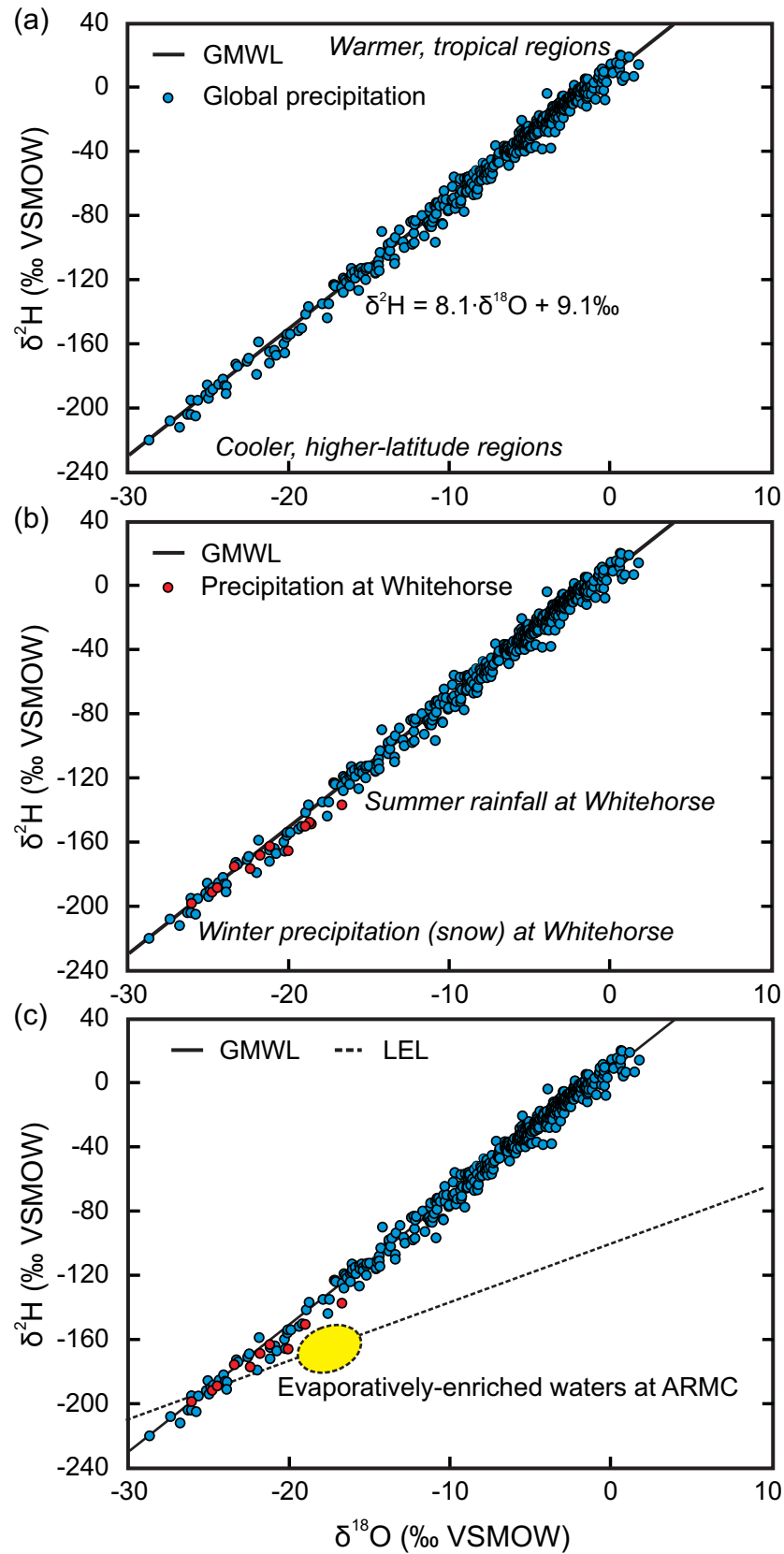


Figure 1-1. (a) $\delta^{18}\text{O}$ and $\delta^2\text{H}$ values for global precipitation and the associated Global Meteoric Water Line (GMWL) (b) mean monthly $\delta^{18}\text{O}$ and $\delta^2\text{H}$ values for precipitation at Whitehorse with GMWL (c) conceptual representation of the relationship between a local evaporation line (LEL) and LMWL.

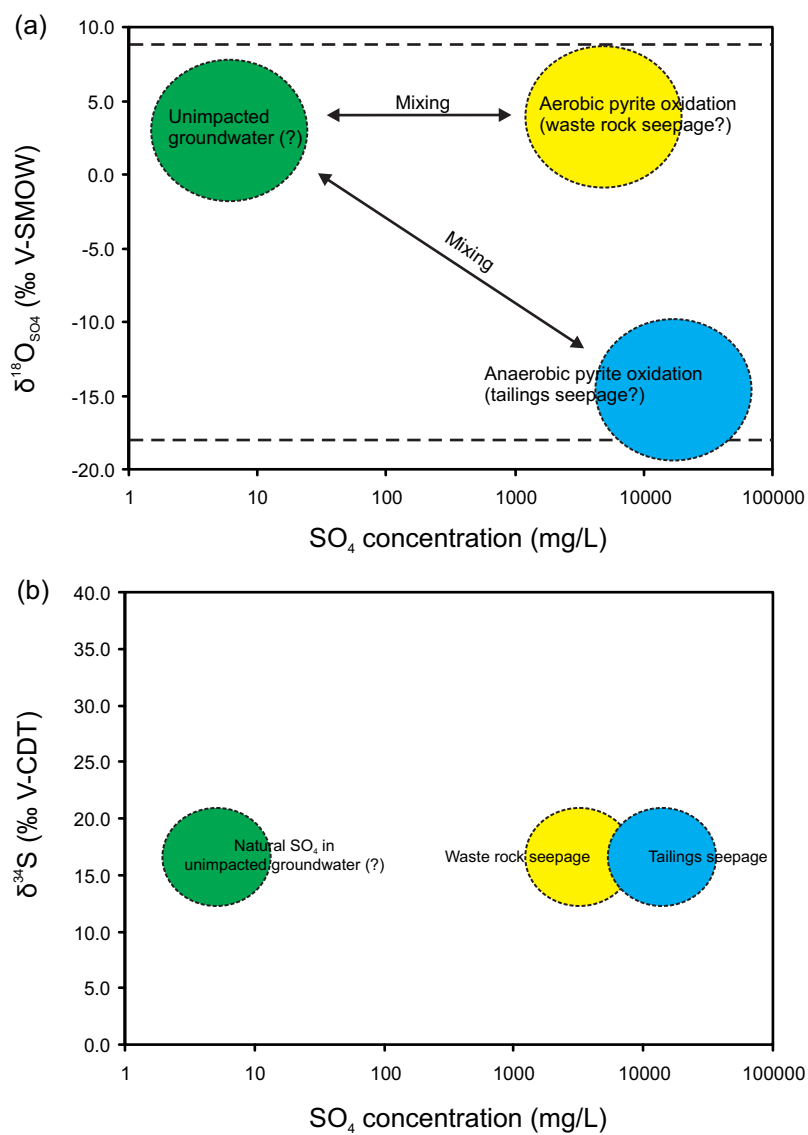
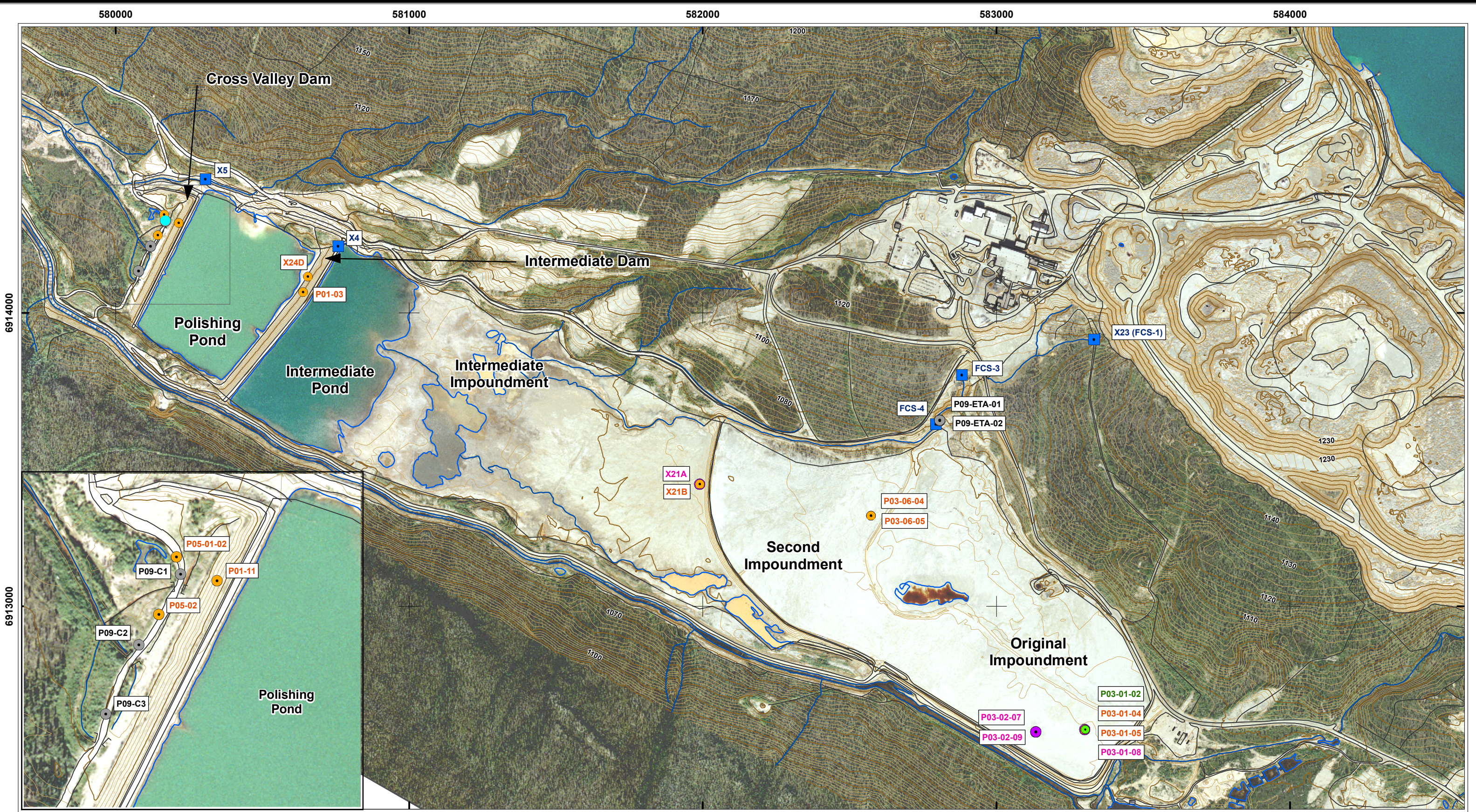


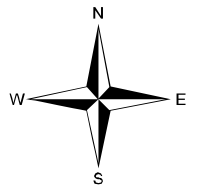
Figure 1-2. Expected $\delta^{18}\text{O}$ and $\delta^{34}\text{S}$ values for SO_4 in ARD sources, ARMC.



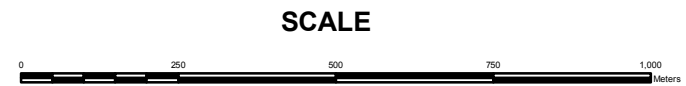
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 - Monitoring Well (Deep Bedrock)
 - Monitoring Well (Tailings Seepage)
 - Monitoring Well (Unimpacted Groundwater)
 - Surface Water Station (Waste Rock Seepage & Intermediate/Polishing Pond at Spillway)

PROJECTION: UTM
ZONE: 8
DATUM: NAD 27
UNITS: Meters

CONTOUR INTERVAL: 2M



Sampling Locations for Isotope Study
Rose Creek Tailings Facility
Anvil Range Mining Complex



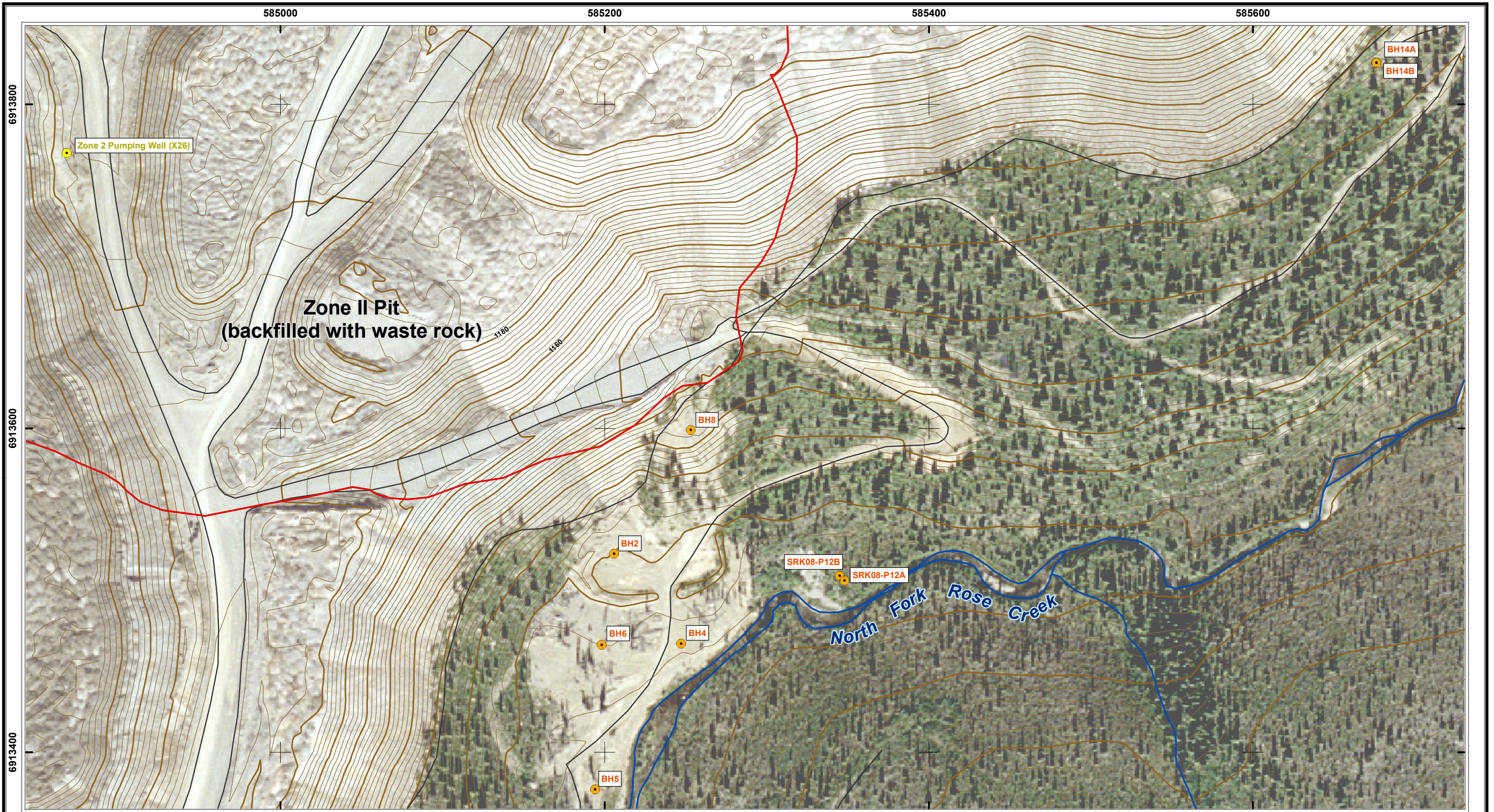
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PROJECT: Geochem & Isotope Study
REPORT: RGC 118015
LOCATION: Anvil Range Mining Complex, YT, Canada



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Consulting Geotechnical and Environmental Engineers

FIGURE: 2-1a

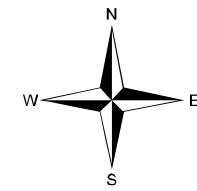
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- LEGEND**
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 - Monitoring Well (Deep Bedrock)
 - Monitoring Well (Tailings Seepage)
 - Monitoring Well (Unimpacted Groundwater)
 - Surface Water Station (Waste Rock Seepage & Intermediate/Polishing Pond at Spillway)

PROJECTION: UTM
ZONE: 8
DATUM: NAD 27
UNITS: Meters

CONTOUR INTERVAL: 2M



Sampling Locations for Isotope Study
Zone II Pit Outwash Area
Faro Mine Site

SCALE

0 50 100 150 200 Meters

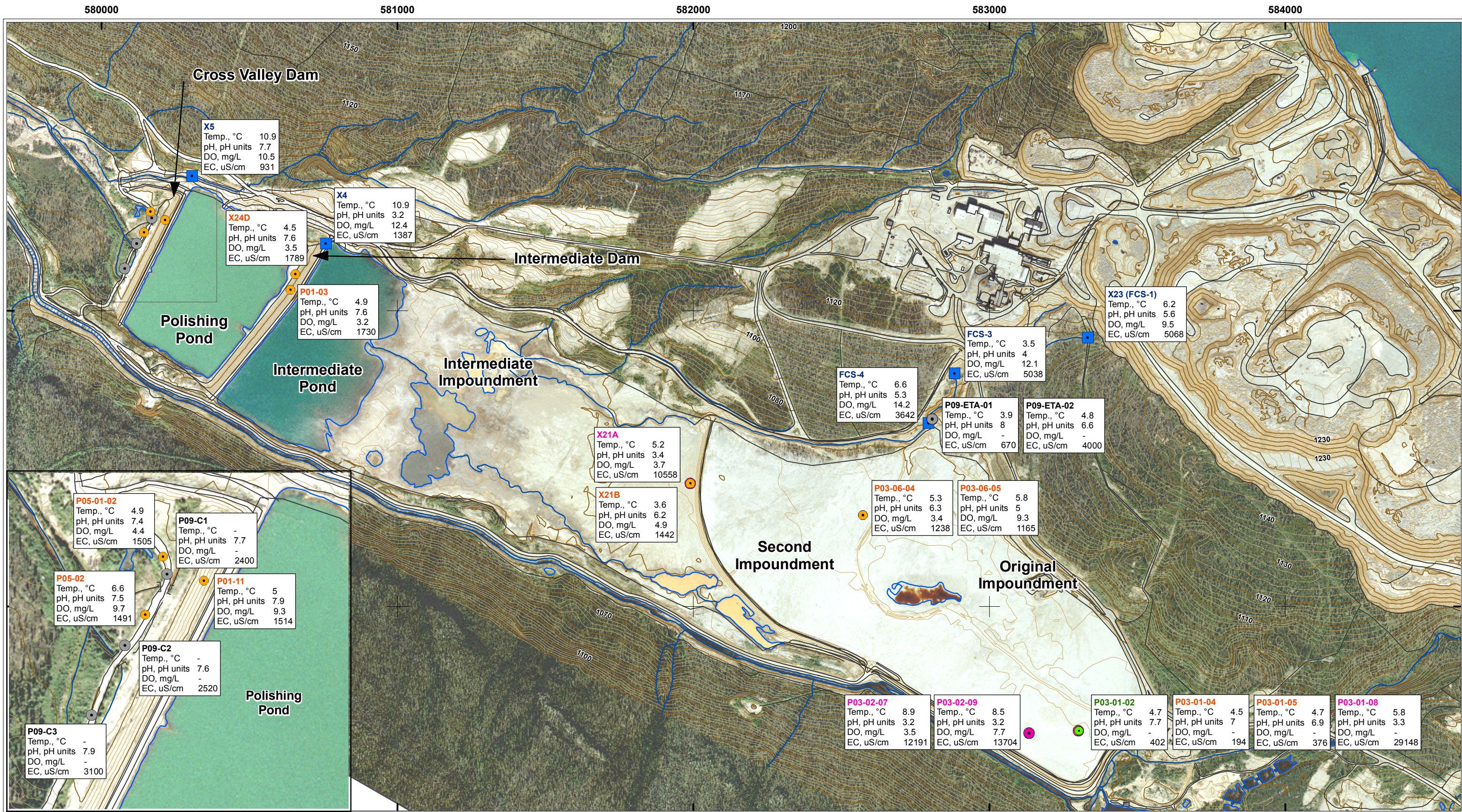
Yukon
Government

CLIENT: Yukon Government
PROJECT: Geochem & Isotope Study
REPORT: RGC 118015
LOCATION: Anvil Range Mining Complex, YT, Canada

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FIGURE: 2-1b

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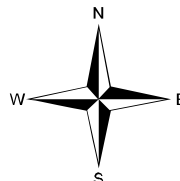


LEGEND

- Monitoring Well (ARD - Impacted Groundwater)
- Monitoring Well (Deep Bedrock)
- Monitoring Well (Tailings Seepage)
- Monitoring Well (Unimpacted Groundwater)
- Surface Water Station (Waste Rock Seepage & Intermediate/Polishing Pond at Spillway)

PROJECTION: UTM
ZONE: 8
DATUM: NAD 27
UNITS: Meters

CONTOUR INTERVAL: 2M



Physical Characteristics
Rose Creek Tailings Facility
Anvil Range Mining Complex

SCALE



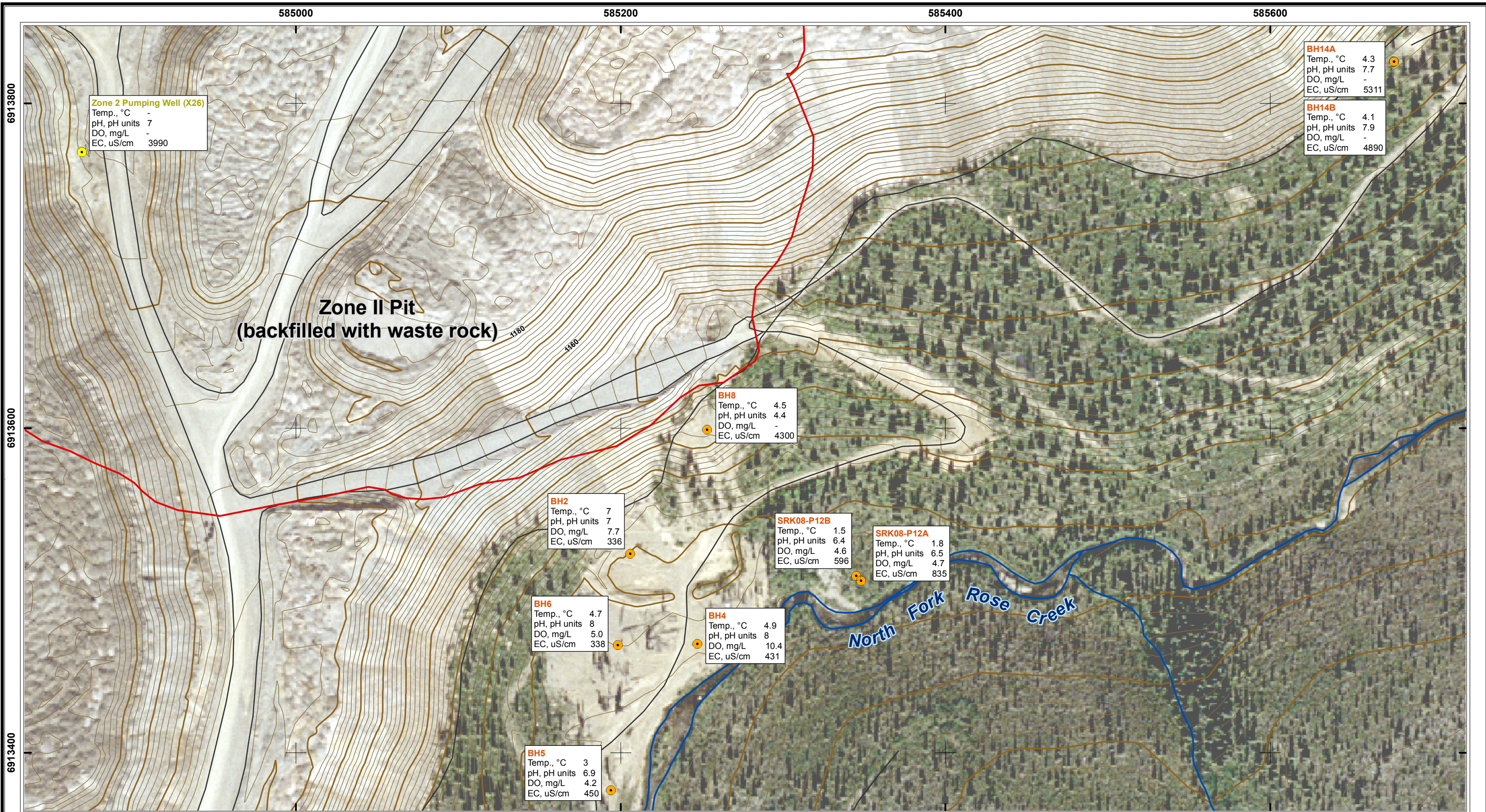
CLIENT: Yukon Government
PROJECT: Geochem & Isotope Study
REPORT: RGC 118015
LOCATION: Anvil Range Mining Complex, YT, Canada



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FIGURE: 3-1a

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FILE: Faro_Physical_Tailing.mxd

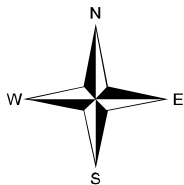


LEGEND

- Monitoring Well (ARD - Impacted Groundwater)
- Monitoring Well (Deep Bedrock)
- Monitoring Well (Tailings Seepage)
- Monitoring Well (Unimpacted Groundwater)
- Surface Water Station (Waste Rock Seepage & Intermediate/Polishing Pond at Spillway)

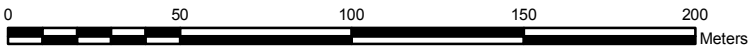
PROJECTION: UTM
ZONE: 8
DATUM: NAD 27
UNITS: Meters

CONTOUR INTERVAL: 2M



Physical Characteristics
Zone II Pit Outwash Area
Faro Mine Site

SCALE



CLIENT: Yukon Government
PROJECT: Geochem & Isotope Study
REPORT: RGC 118015
LOCATION: Anvil Range Mining Complex, YT, Canada

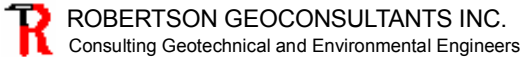
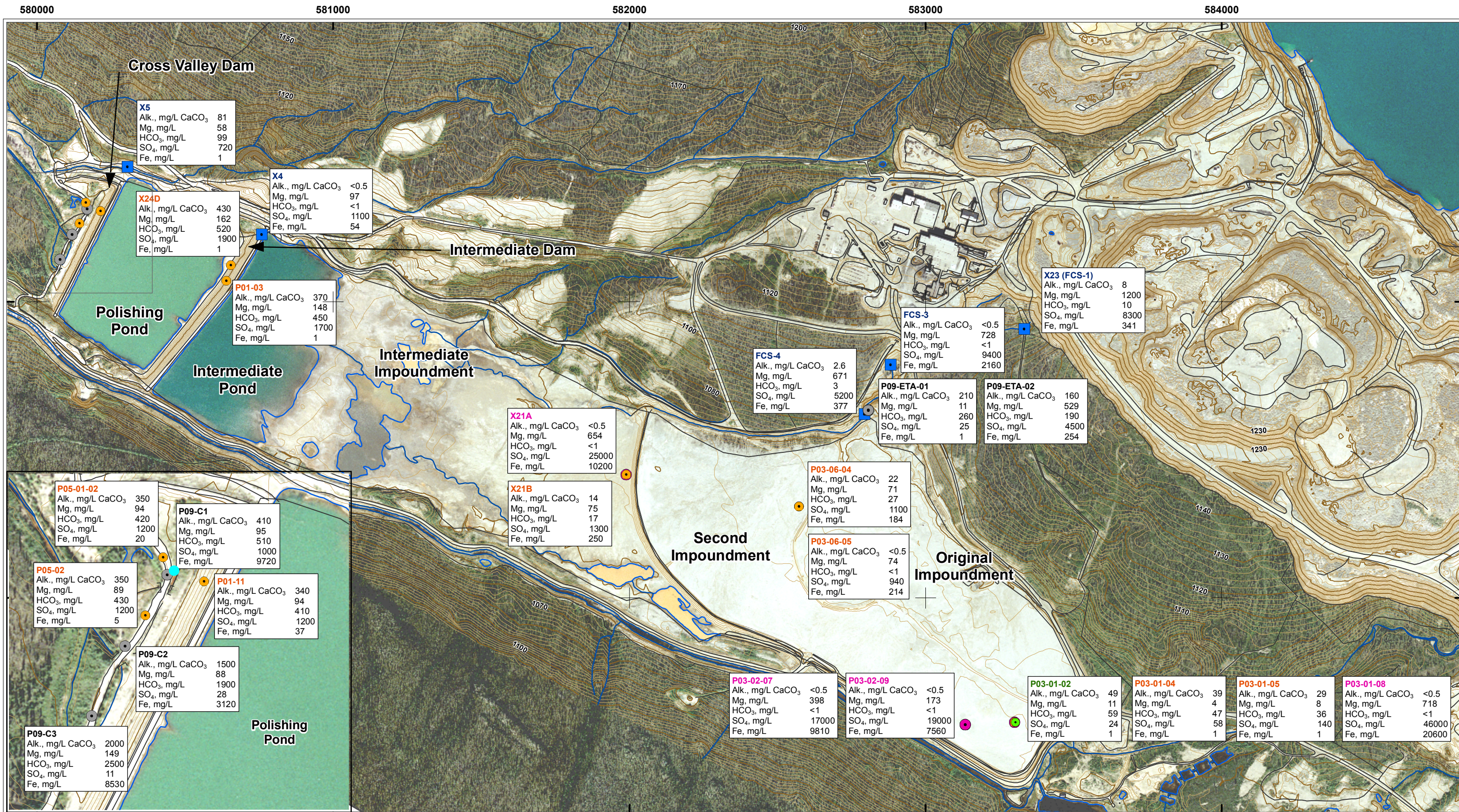


FIGURE: 3-1b

DATE: 012810
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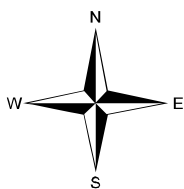


LEGEND

- Monitoring Well (ARD - Impacted Groundwater)
- Monitoring Well (Deep Bedrock)
- Monitoring Well (Tailings Seepage)
- Monitoring Well (Unimpacted Groundwater)
- Surface Water Station (Waste Rock Seepage & Intermediate/Polishing Pond at Spillway)

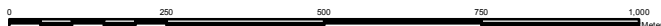
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DATUM: NAD 27
UNITS: Meters

CONTOUR INTERVAL: 2M



Alkalinity and Major Ion Content Rose Creek Tailings Facility Anvil Range Mining Complex

SCALE



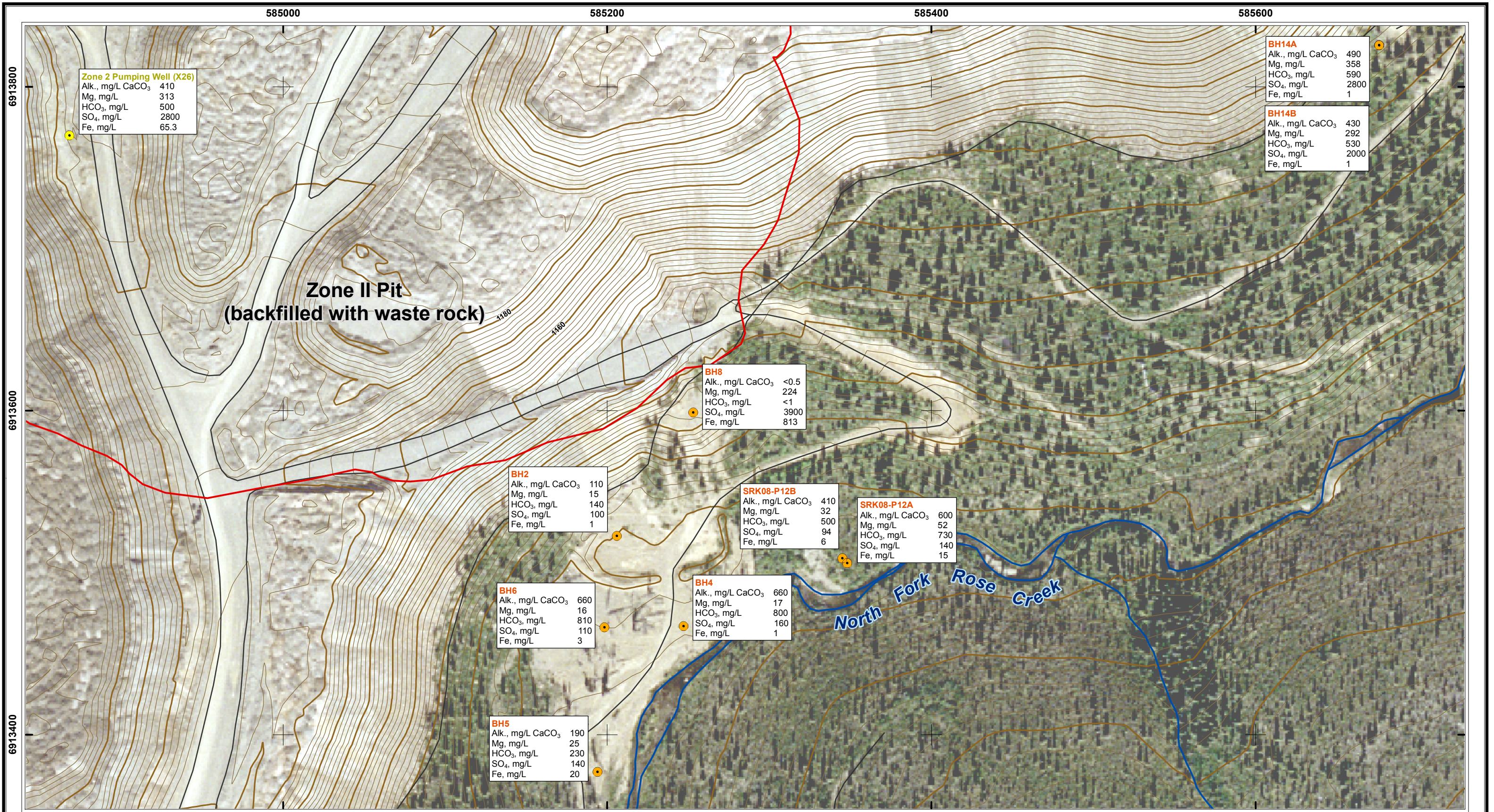
CLIENT: Yukon Government
PROJECT: Geochem & Isotope Study
REPORT: RGC 118015
LOCATION: Anvil Range Mining Complex, YT, Canada



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Consulting Geotechnical and Environmental Engineers

FIGURE: 3-2a

DATE: 012710
DRAWN BY: OM
FILE: Faro_Alkalinity_Tailing.mxd



Zone 2 Pumping Well (X26)

Alk., mg/L CaCO ₃	410
Mg, mg/L	313
HCO ₃ , mg/L	500
SO ₄ , mg/L	2800
Fe, mg/L	65.3

BH14A

Alk., mg/L CaCO ₃	490
Mg, mg/L	358
HCO ₃ , mg/L	590
SO ₄ , mg/L	2800
Fe, mg/L	1

BH14B

Alk., mg/L CaCO ₃	430
Mg, mg/L	292
HCO ₃ , mg/L	530
SO ₄ , mg/L	2000
Fe, mg/L	1

BH8

Alk., mg/L CaCO ₃	<0.5
Mg, mg/L	224
HCO ₃ , mg/L	<1
SO ₄ , mg/L	3900
Fe, mg/L	813

BH2

Alk., mg/L CaCO ₃	110
Mg, mg/L	15
HCO ₃ , mg/L	140
SO ₄ , mg/L	100
Fe, mg/L	1

SRK08-P12B

Alk., mg/L CaCO ₃	410
Mg, mg/L	32
HCO ₃ , mg/L	500
SO ₄ , mg/L	94
Fe, mg/L	6

SRK08-P12A

Alk., mg/L CaCO ₃	600
Mg, mg/L	52
HCO ₃ , mg/L	730
SO ₄ , mg/L	140
Fe, mg/L	15

BH6

Alk., mg/L CaCO ₃	660
Mg, mg/L	16
HCO ₃ , mg/L	810
SO ₄ , mg/L	110
Fe, mg/L	3

BH4

Alk., mg/L CaCO ₃	660
Mg, mg/L	17
HCO ₃ , mg/L	800
SO ₄ , mg/L	160
Fe, mg/L	1

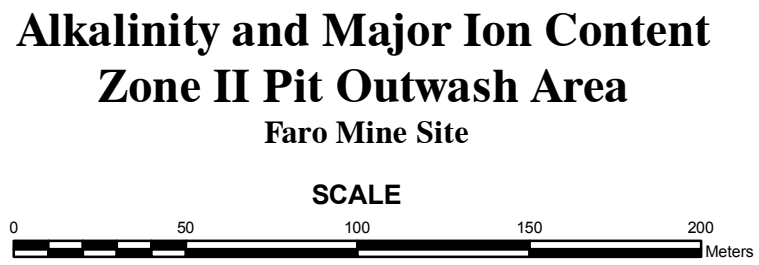
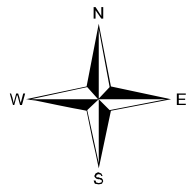
BH5

Alk., mg/L CaCO ₃	190
Mg, mg/L	25
HCO ₃ , mg/L	230
SO ₄ , mg/L	140
Fe, mg/L	20

- LEGEND**
- Monitoring Well (ARD - Impacted Groundwater)
 - Monitoring Well (Deep Bedrock)
 - Monitoring Well (Tailings Seepage)
 - Monitoring Well (Unimpacted Groundwater)
 - Surface Water Station (Waste Rock Seepage & Intermediate/Polishing Pond at Spillway)

PROJECTION: UTM
ZONE: 8
DATUM: NAD 27
UNITS: Meters

CONTOUR INTERVAL: 2M



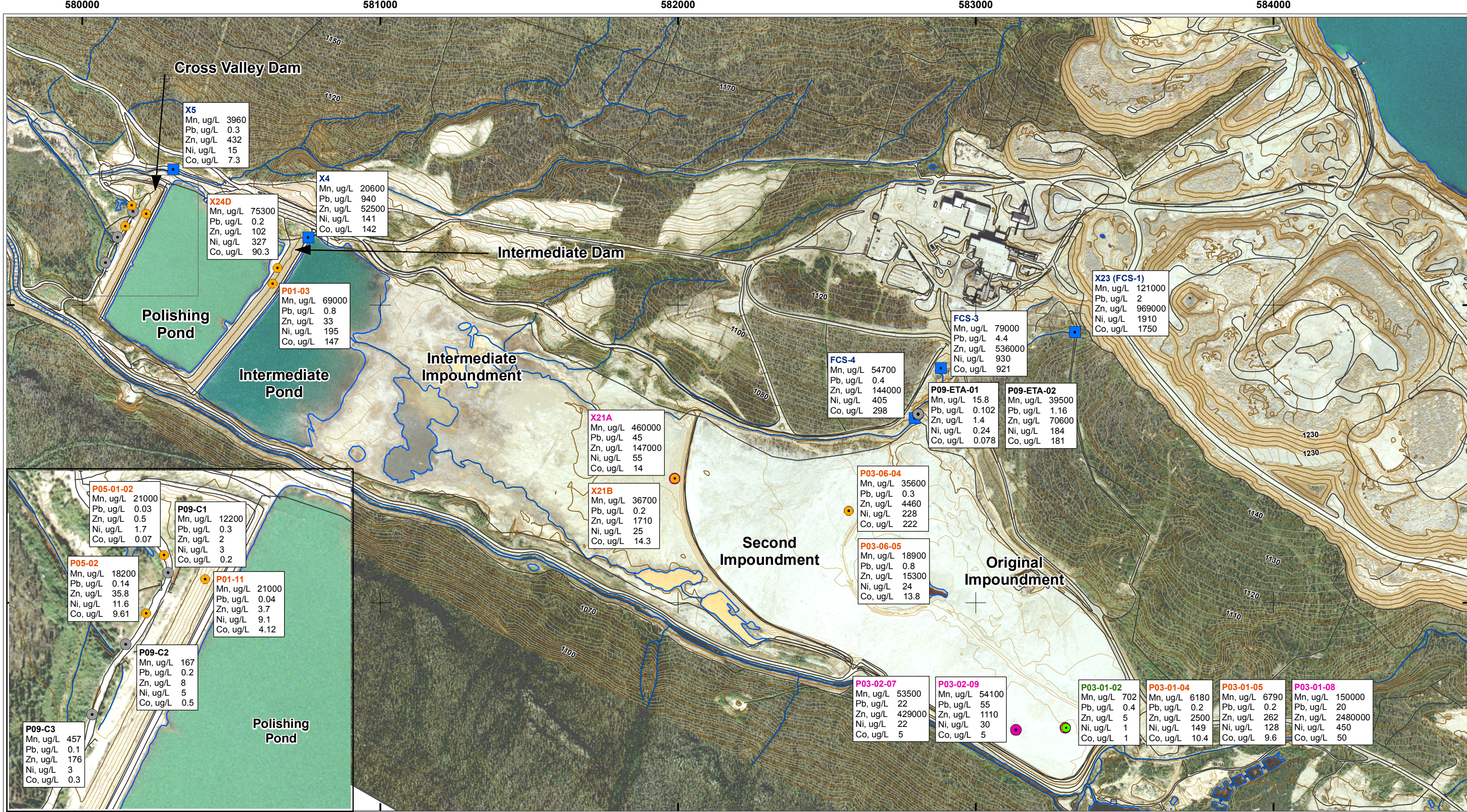
Yukon
Government

CLIENT: Yukon Government
PROJECT: Geochem & Isotope Study
REPORT: RGC 118015
LOCATION: Anvil Range Mining Complex, YT, Canada

ROBERTSON GEOCONSULTANTS INC.
Consulting Geotechnical and Environmental Engineers

FIGURE: 3-2b

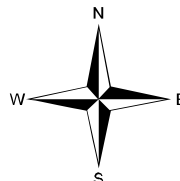
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- LEGEND**
- Monitoring Well (ARD - Impacted Groundwater)
 - Monitoring Well (Deep Bedrock)
 - Monitoring Well (Tailings Seepage)
 - Monitoring Well (Unimpacted Groundwater)
 - Surface Water Station (Waste Rock Seepage & Intermediate/Polishing Pond at Spillway)

PROJECTION: UTM
ZONE: 8
DATUM: NAD 27
UNITS: Meters

CONTOUR INTERVAL: 2M



Concentrations of Selected Dissolved Metals Rose Creek Tailings Facility Anvil Range Mining Complex



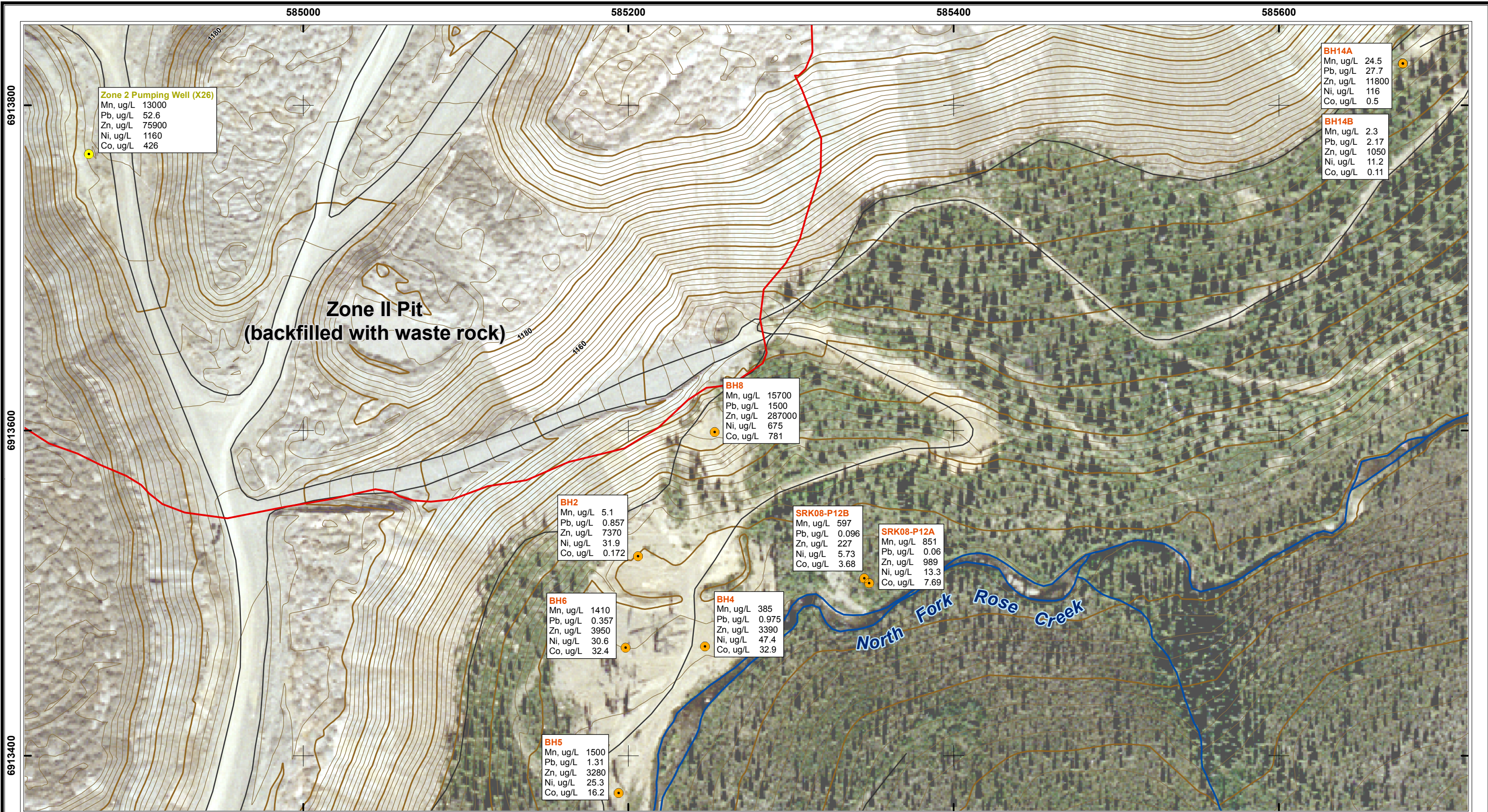
CLIENT: Yukon Government
PROJECT: Geochem & Isotope Study
REPORT: RGC 118015
LOCATION: Anvil Range Mining Complex, YT, Canada



ROBERTSON GEOCONSULTANTS INC.
Consulting Geotechnical and Environmental Engineers

FIGURE: 3-3a

DATE: 012710
DRAWN BY: OM
FILE: Faro_Metals_Tailing.mxd

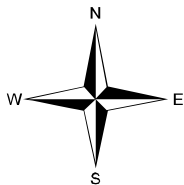


LEGEND

- Monitoring Well (ARD - Impacted Groundwater)
- Monitoring Well (Deep Bedrock)
- Monitoring Well (Tailings Seepage)
- Monitoring Well (Unimpacted Groundwater)
- Surface Water Station (Waste Rock Seepage & Intermediate/Polishing Pond at Spillway)

PROJECTION: UTM
ZONE: 8
DATUM: NAD 27
UNITS: Meters

CONTOUR INTERVAL: 2M



Concentrations of Selected Dissolved Metals
Zone II Pit Outwash Area
Faro Mine Site



CLIENT: Yukon Government
PROJECT: Geochem & Isotope Study
REPORT: RGC 118015
LOCATION: Anvil Range Mining Complex, YT, Canada

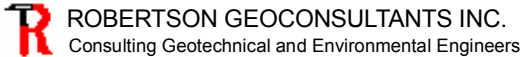
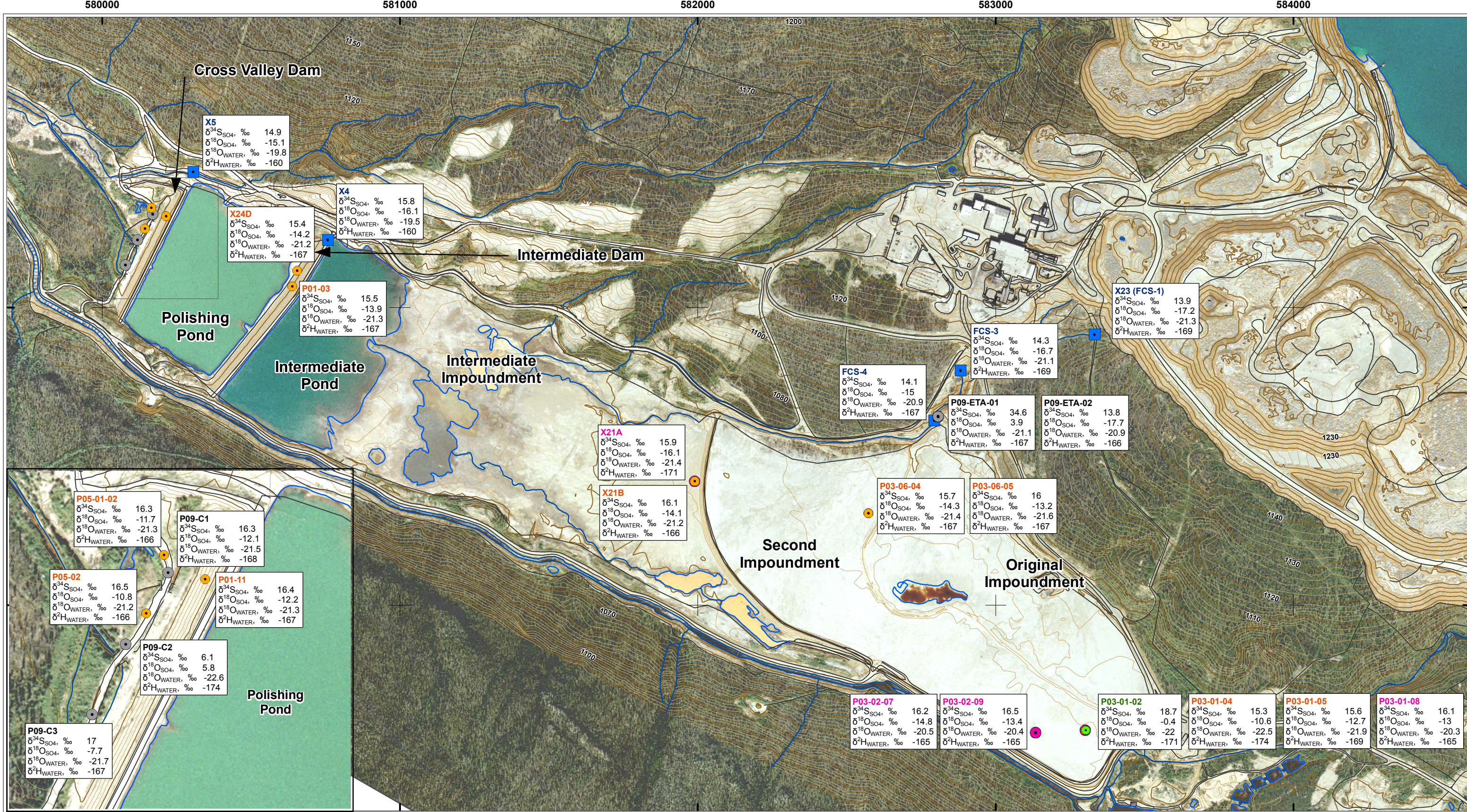


FIGURE: 3-3b

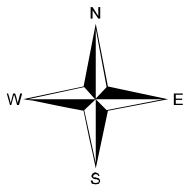
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LEGEND

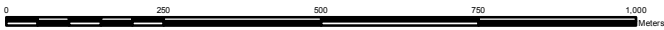
- Monitoring Well (ARD - Impacted Groundwater)
- Monitoring Well (Deep Bedrock)
- Monitoring Well (Tailings Seepage)
- Monitoring Well (Unimpacted Groundwater)
- Surface Water Station (Waste Rock Seepage & Intermediate/Polishing Pond at Spillway)

PROJECTION: UTM
 ZONE: 8
 DATUM: NAD 27
 UNITS: Meters
 CONTOUR INTERVAL: 2M



Stable Isotope Data
Rose Creek Tailings Facility
 Anvil Range Mining Complex

SCALE



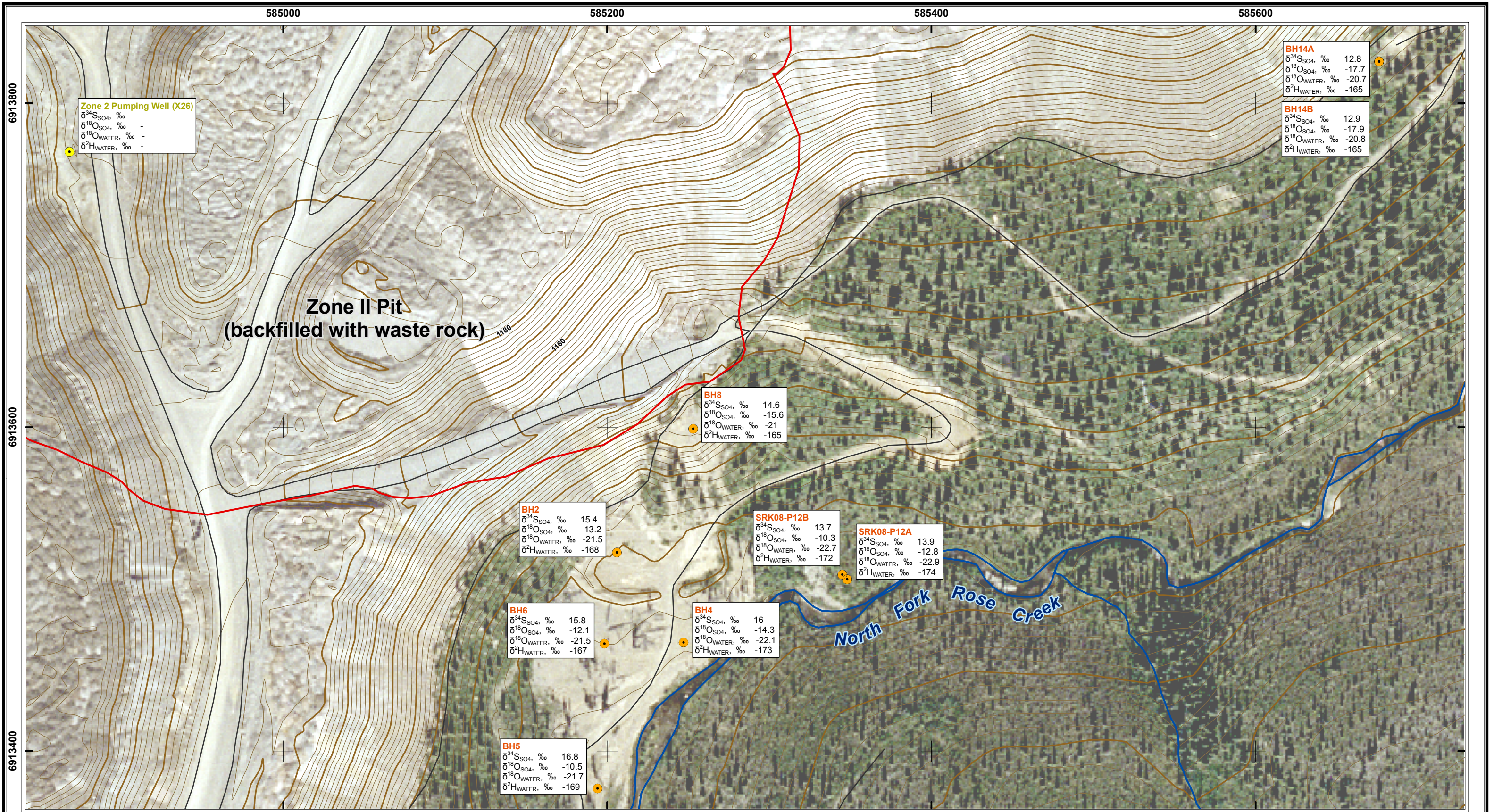
CLIENT: Yukon Government
 PROJECT: Geochem & Isotope Study
 REPORT: RGC 118015
 LOCATION: Anvil Range Mining Complex, YT, Canada



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 Consulting Geotechnical and Environmental Engineers

FIGURE: 3-4a

DATE: 012710
 DRAWN BY: OM
 FILE: Faro_Isotope_Tailing.mxd



Zone 2 Pumping Well (X26)
 $\delta^{34}\text{S}_{\text{SO}_4}$, ‰ -
 $\delta^{18}\text{O}_{\text{SO}_4}$, ‰ -
 $\delta^{18}\text{O}_{\text{WATER}}$, ‰ -
 $\delta^2\text{H}_{\text{WATER}}$, ‰ -

BH14A
 $\delta^{34}\text{S}_{\text{SO}_4}$, ‰ 12.8
 $\delta^{18}\text{O}_{\text{SO}_4}$, ‰ -17.7
 $\delta^{18}\text{O}_{\text{WATER}}$, ‰ -20.7
 $\delta^2\text{H}_{\text{WATER}}$, ‰ -165

BH14B
 $\delta^{34}\text{S}_{\text{SO}_4}$, ‰ 12.9
 $\delta^{18}\text{O}_{\text{SO}_4}$, ‰ -17.9
 $\delta^{18}\text{O}_{\text{WATER}}$, ‰ -20.8
 $\delta^2\text{H}_{\text{WATER}}$, ‰ -165

**Zone II Pit
(backfilled with waste rock)**

BH8
 $\delta^{34}\text{S}_{\text{SO}_4}$, ‰ 14.6
 $\delta^{18}\text{O}_{\text{SO}_4}$, ‰ -15.6
 $\delta^{18}\text{O}_{\text{WATER}}$, ‰ -21
 $\delta^2\text{H}_{\text{WATER}}$, ‰ -165

BH2
 $\delta^{34}\text{S}_{\text{SO}_4}$, ‰ 15.4
 $\delta^{18}\text{O}_{\text{SO}_4}$, ‰ -13.2
 $\delta^{18}\text{O}_{\text{WATER}}$, ‰ -21.5
 $\delta^2\text{H}_{\text{WATER}}$, ‰ -168

SRK08-P12B
 $\delta^{34}\text{S}_{\text{SO}_4}$, ‰ 13.7
 $\delta^{18}\text{O}_{\text{SO}_4}$, ‰ -10.3
 $\delta^{18}\text{O}_{\text{WATER}}$, ‰ -22.7
 $\delta^2\text{H}_{\text{WATER}}$, ‰ -172

SRK08-P12A
 $\delta^{34}\text{S}_{\text{SO}_4}$, ‰ 13.9
 $\delta^{18}\text{O}_{\text{SO}_4}$, ‰ -12.8
 $\delta^{18}\text{O}_{\text{WATER}}$, ‰ -22.9
 $\delta^2\text{H}_{\text{WATER}}$, ‰ -174

BH6
 $\delta^{34}\text{S}_{\text{SO}_4}$, ‰ 15.8
 $\delta^{18}\text{O}_{\text{SO}_4}$, ‰ -12.1
 $\delta^{18}\text{O}_{\text{WATER}}$, ‰ -21.5
 $\delta^2\text{H}_{\text{WATER}}$, ‰ -167

BH4
 $\delta^{34}\text{S}_{\text{SO}_4}$, ‰ 16
 $\delta^{18}\text{O}_{\text{SO}_4}$, ‰ -14.3
 $\delta^{18}\text{O}_{\text{WATER}}$, ‰ -22.1
 $\delta^2\text{H}_{\text{WATER}}$, ‰ -173

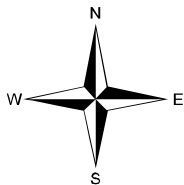
BH5
 $\delta^{34}\text{S}_{\text{SO}_4}$, ‰ 16.8
 $\delta^{18}\text{O}_{\text{SO}_4}$, ‰ -10.5
 $\delta^{18}\text{O}_{\text{WATER}}$, ‰ -21.7
 $\delta^2\text{H}_{\text{WATER}}$, ‰ -169

LEGEND

- Monitoring Well (ARD - Impacted Groundwater)
- Monitoring Well (Deep Bedrock)
- Monitoring Well (Tailings Seepage)
- Monitoring Well (Unimpacted Groundwater)
- Surface Water Station (Waste Rock Seepage & Intermediate/Polishing Pond at Spillway)

PROJECTION: UTM
ZONE: 8
DATUM: NAD 27
UNITS: Meters

CONTOUR INTERVAL: 2M



**Stable Isotope Data
Zone II Pit Outwash Area
Faro Mine Site**



CLIENT: Yukon Government
PROJECT: Geochem & Isotope Study
REPORT: RGC 118015
LOCATION: Anvil Range Mining Complex, YT, Canada



FIGURE: 3-4b

DATE: 012810
DRAWN BY: OM
FILE: Faro_Isotope_Zone2.mxd

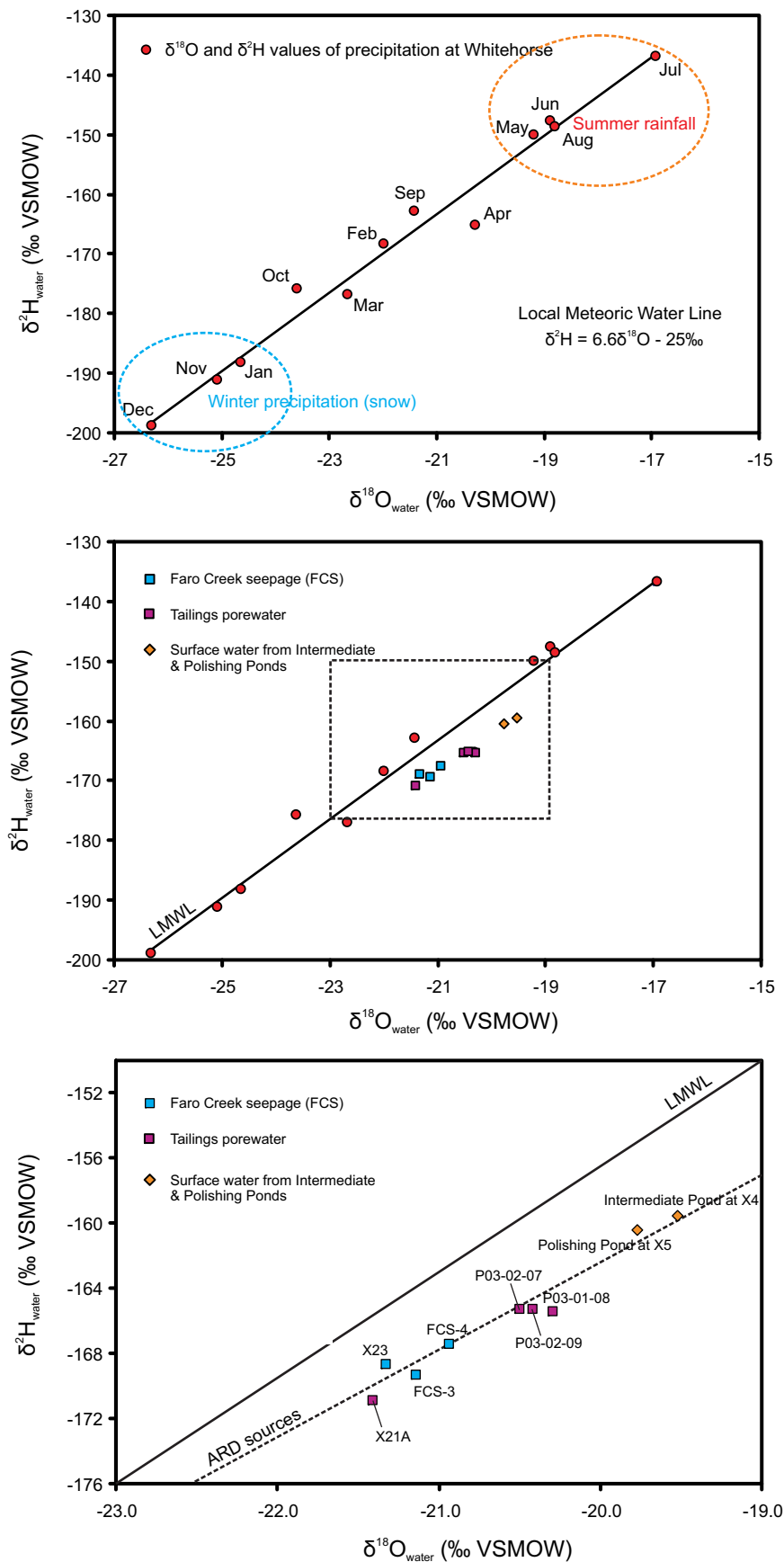


Figure 4-1. Comparison of mean monthly $\delta^{18}\text{O}$ and $\delta^2\text{H}$ values of precipitation at Whitehorse and $\delta^{18}\text{O}$ and $\delta^2\text{H}$ values for ARD sources in Rose Creek valley

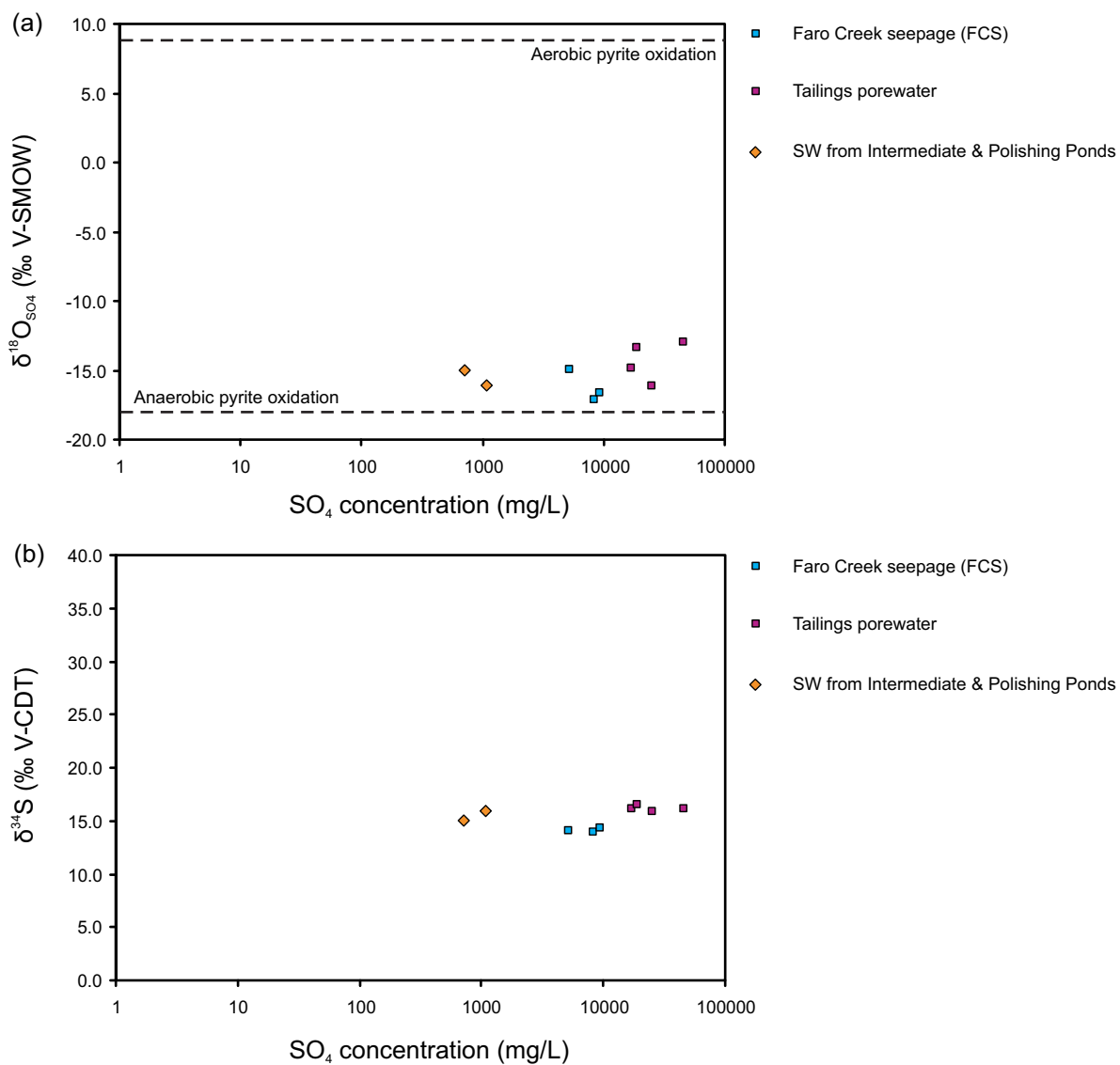
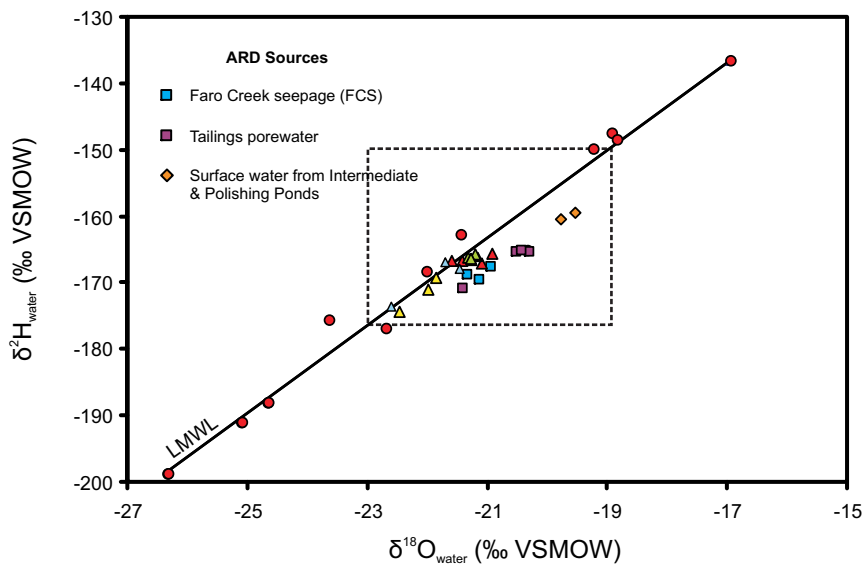
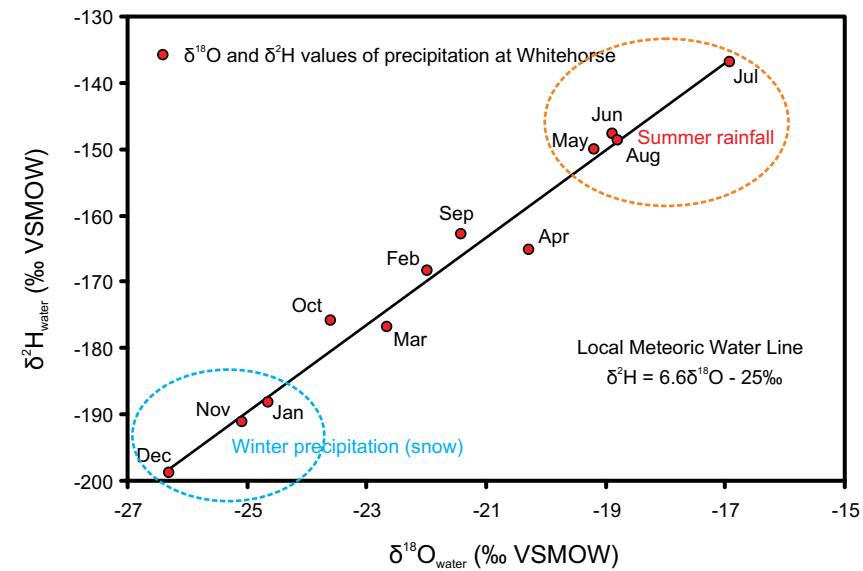
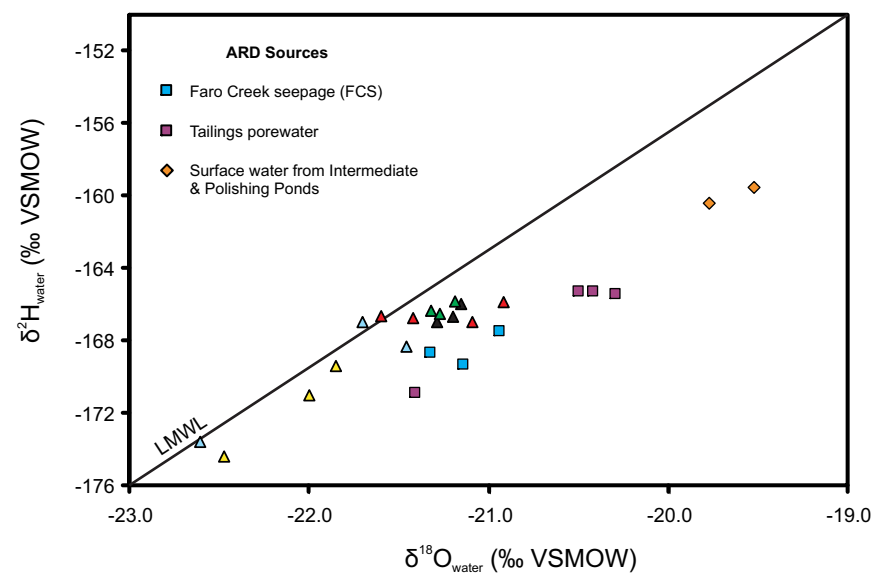


Figure 4-2. $\delta^{18}\text{O}_{\text{SO}_4}$ and $\delta^{34}\text{S}_{\text{SO}_4}$ values for 'ARD sources' and their relationship to SO_4 concentration. Note that the hypothetical $\delta^{18}\text{O}_{\text{SO}_4}$ values for SO_4 generated by aerobic and anaerobic pyrite oxidation are provided in (a).



- ▲ RCAA upgradient of Faro Creek canyon
- ▲ RCAA and bedrock near mouth of Faro Creek canyon
- ▲ RCAA in the Intermediate Dam reach
- ▲ RCAA in the Cross Valley Dam reach
- ▲ Deep bedrock below toe of Cross Valley Dam



- ▲ RCAA upgradient of Faro Creek canyon
- ▲ RCAA and bedrock near mouth of Faro Creek canyon
- ▲ RCAA in the Intermediate Dam reach
- ▲ RCAA in the Cross Valley Dam reach
- ▲ Deep bedrock below toe of Cross Valley Dam

Figure 5-1. Mean monthly $\delta^{18}\text{O}$ and $\delta^2\text{H}$ values of precipitation at Whitehorse and $\delta^{18}\text{O}$ and $\delta^2\text{H}$ values of groundwater, surface water, and seepage, Rose Creek valley, ARMC

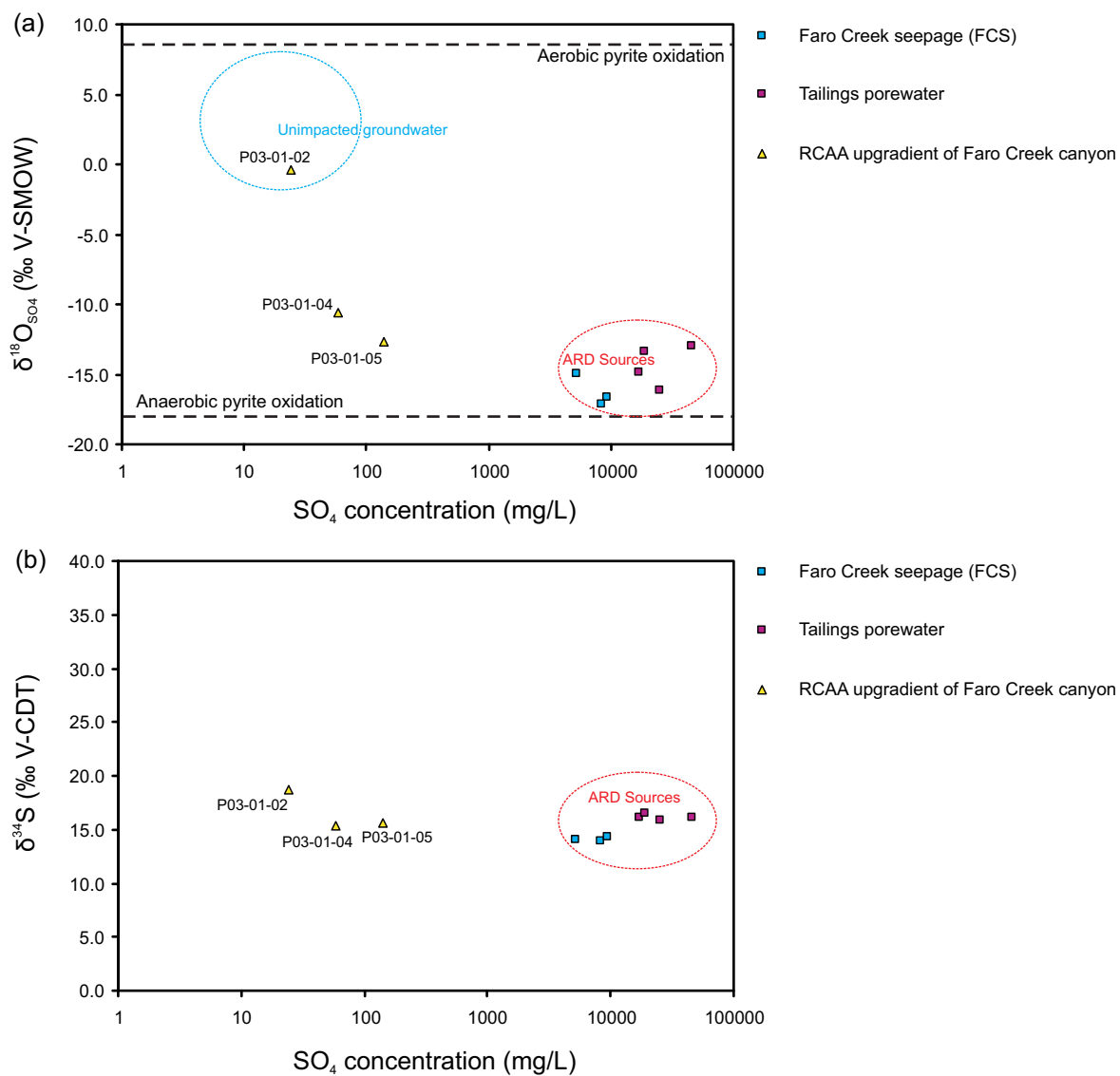


Figure 5-2. $\delta^{18}\text{O}$ and $\delta^{34}\text{S}$ values and their relationship to SO_4 concentration, RCAA upgradient of Faro Creek canyon in Second Impoundment, Rose Creek valley, ARMC.

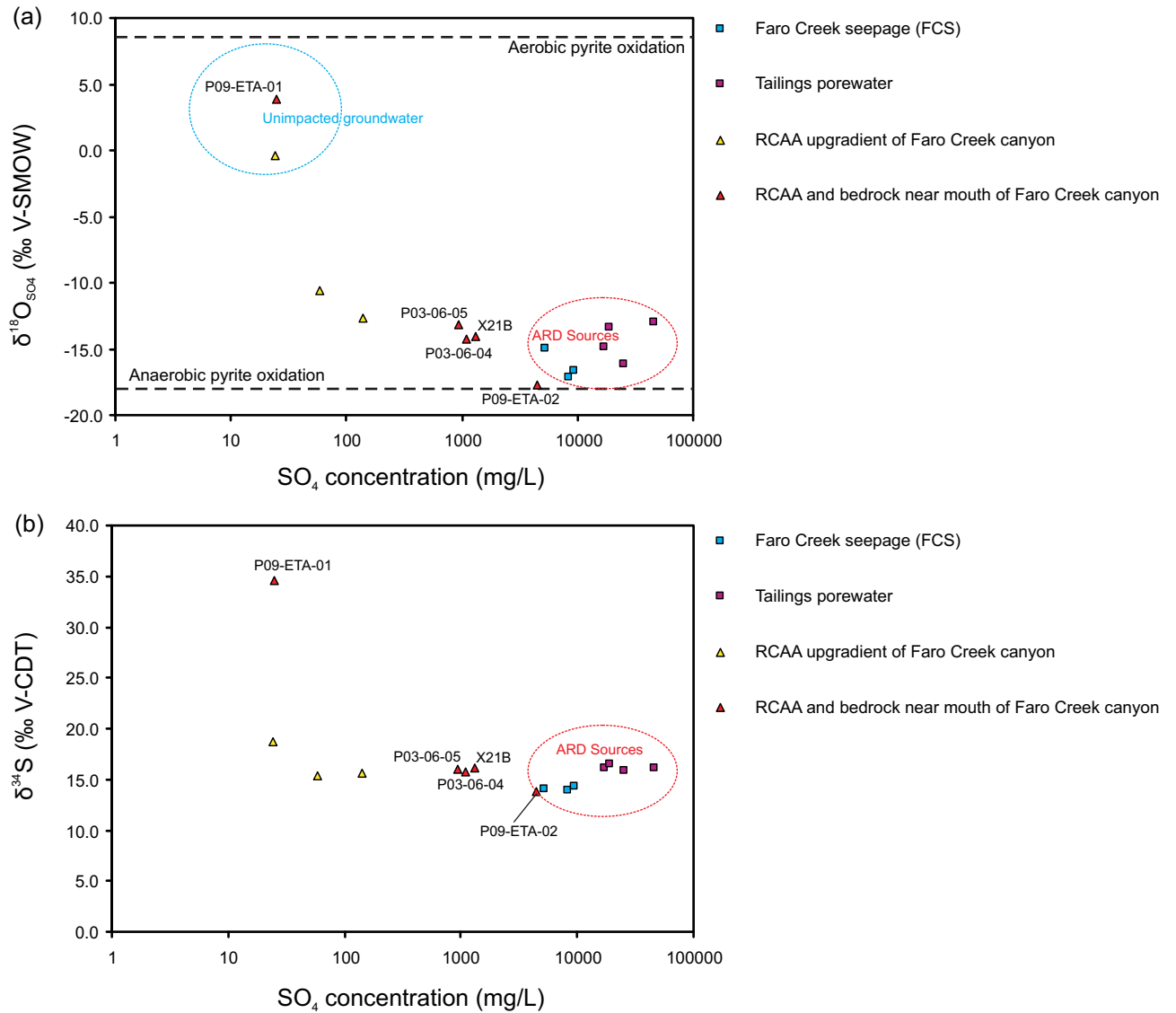


Figure 5-3. $\delta^{18}\text{O}$ and $\delta^{34}\text{S}$ values and their relationship to SO_4 concentration, RCAA and bedrock near the mouth of Faro Creek canyon, Rose Creek valley, ARMC.

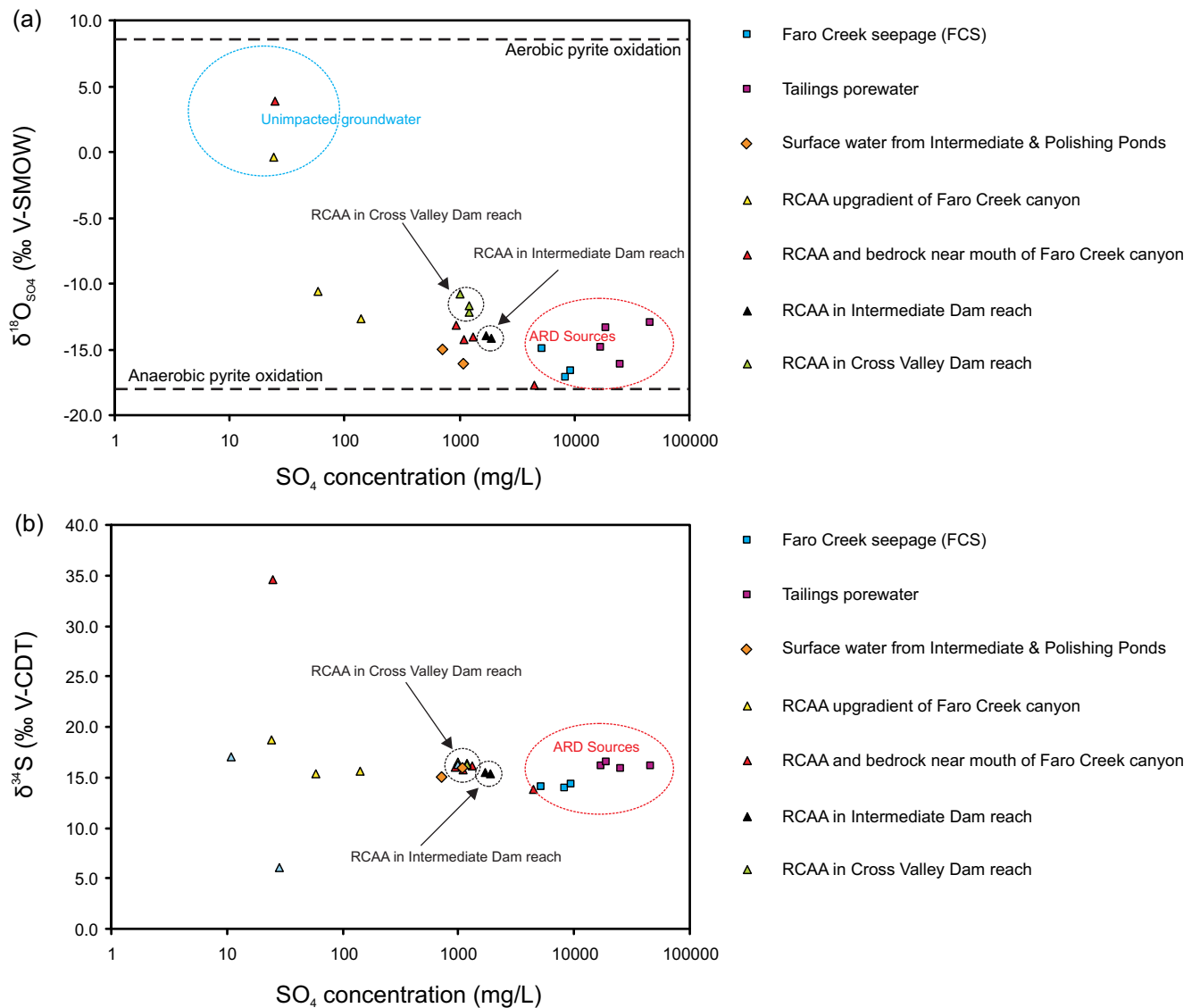


Figure 5-4. $\delta^{18}\text{O}$ and $\delta^{34}\text{S}$ values and their relationship to SO_4 concentration, RCAA in Intermediate Dam and Cross Valley Dam reaches, Rose Creek valley, ARMC.

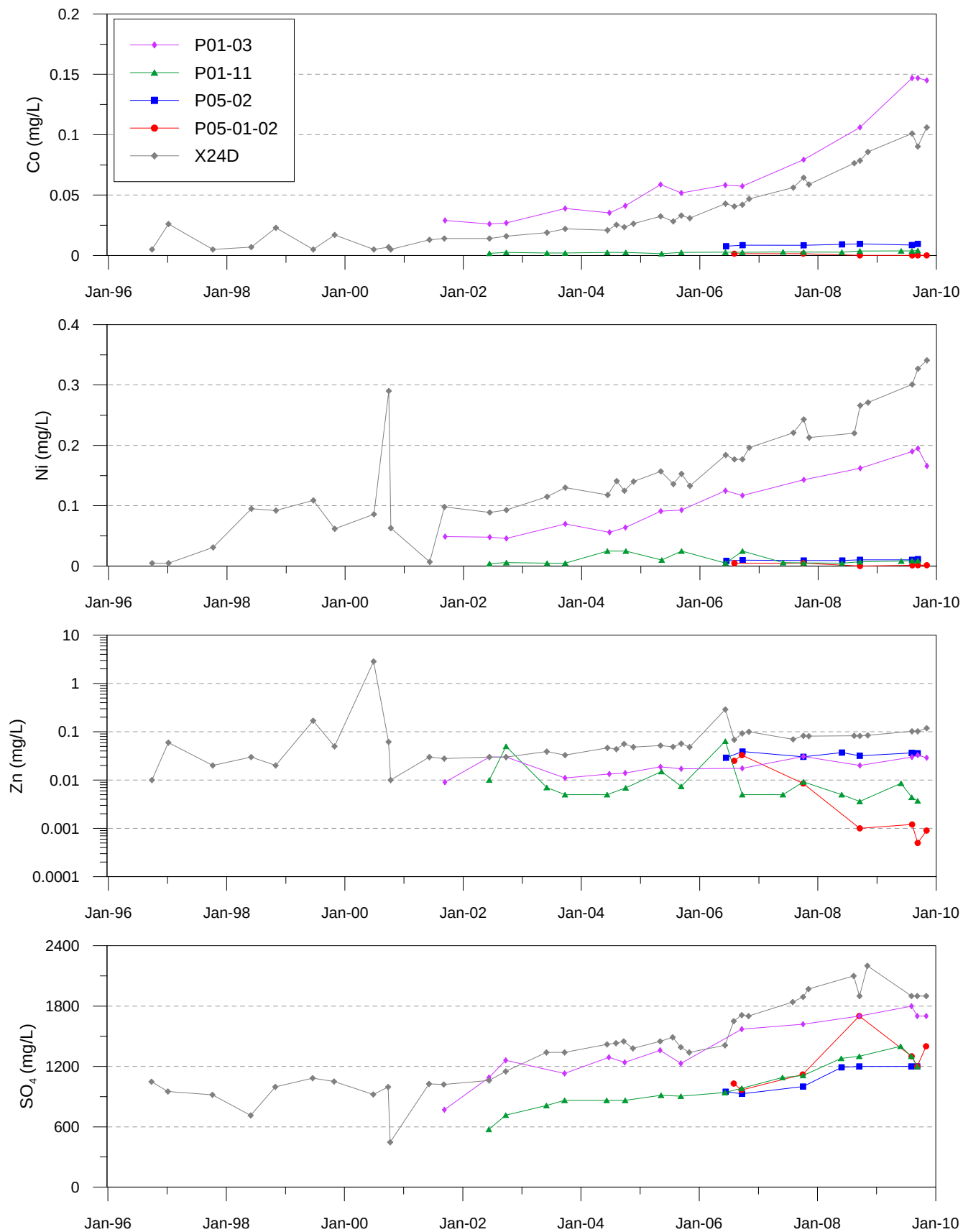


Figure 5-5a. Time trends for Co, Ni, Zn and SO₄ in RCAA in Intermediate Dam reach

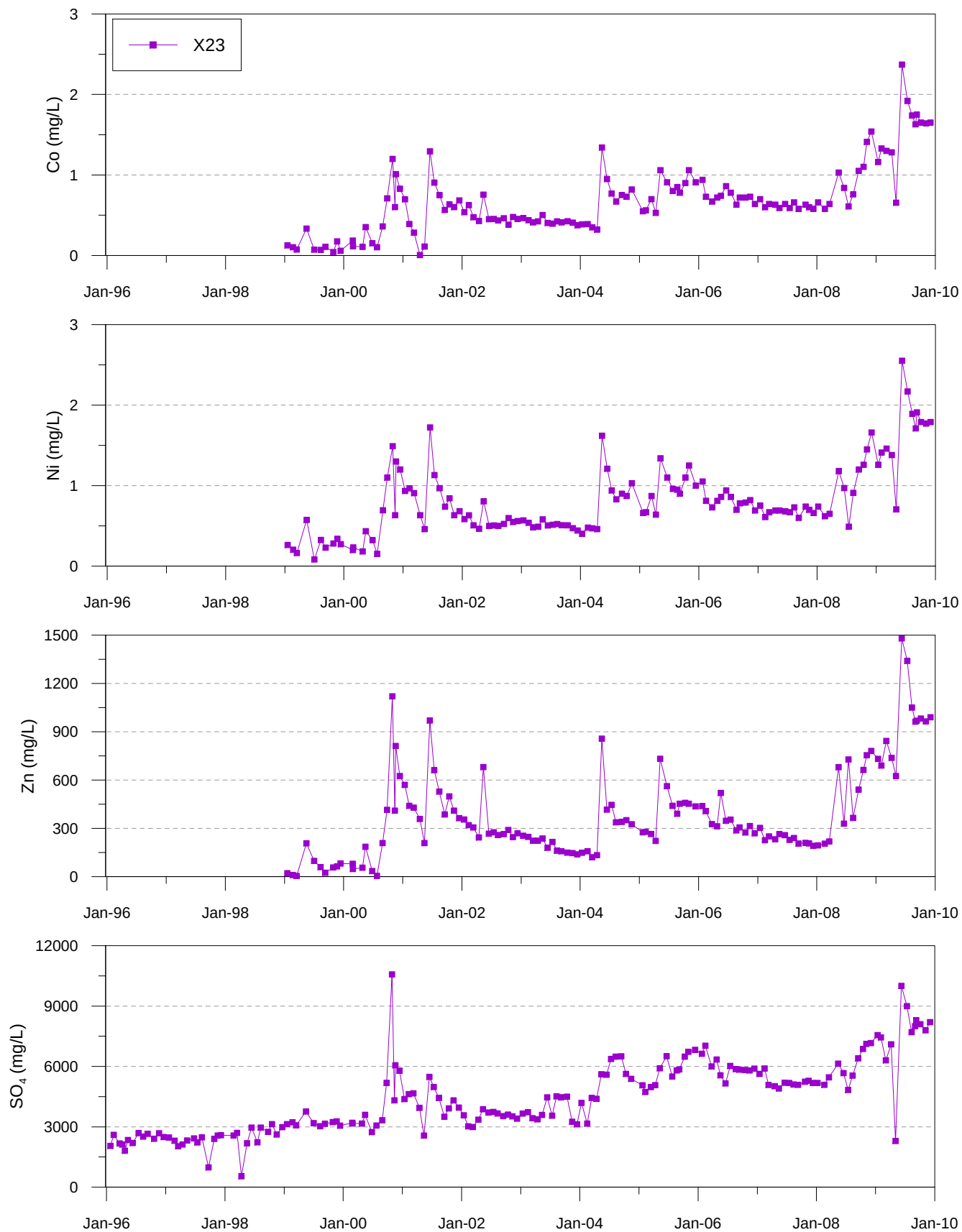


Figure 5-5b. Time trends for Co, Ni, Zn and SO₄ at X23

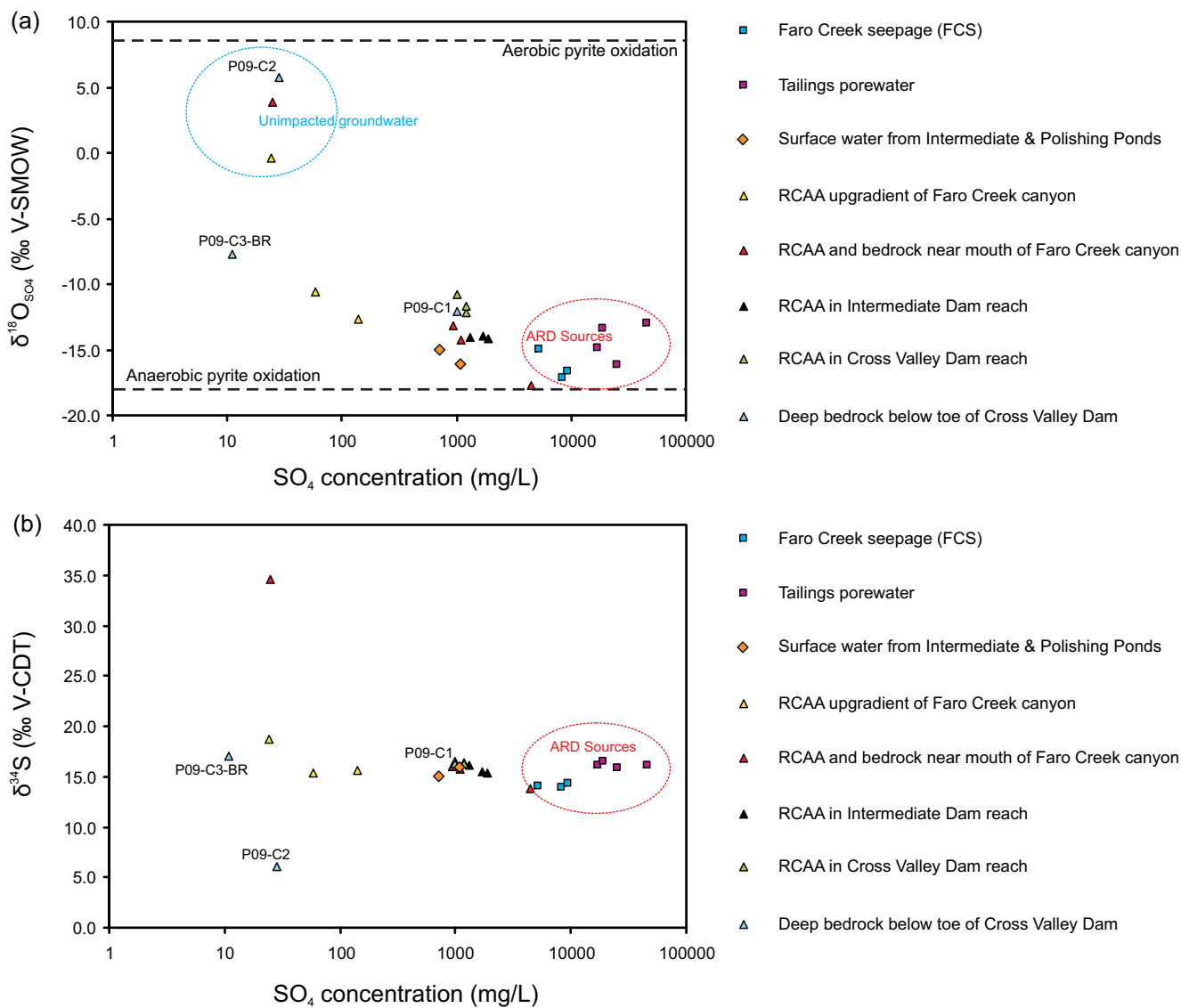


Figure 5-6. $\delta^{18}\text{O}$ and $\delta^{34}\text{S}$ values and their relationship to SO_4 concentration, Deep bedrock below toe of Cross Valley Dam, Rose Creek valley, ARMC.

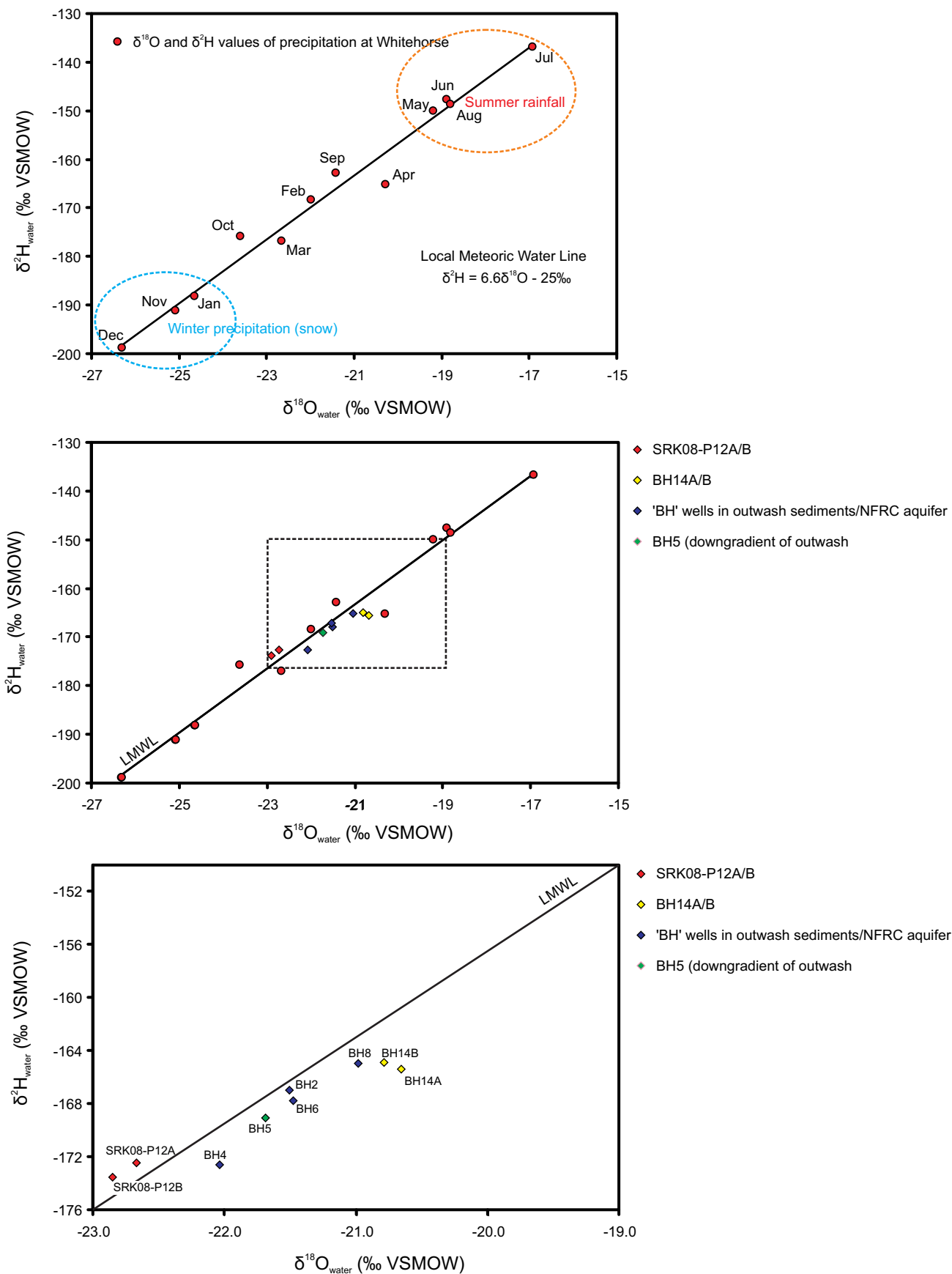


Figure 5-7. Comparison of mean monthly $\delta^{18}\text{O}_{\text{water}}$ and $\delta^2\text{H}_{\text{water}}$ values of precipitation at Whitehorse and $\delta^{18}\text{O}$ and $\delta^2\text{H}$ values for groundwater in Zone 2 Pit outwash area

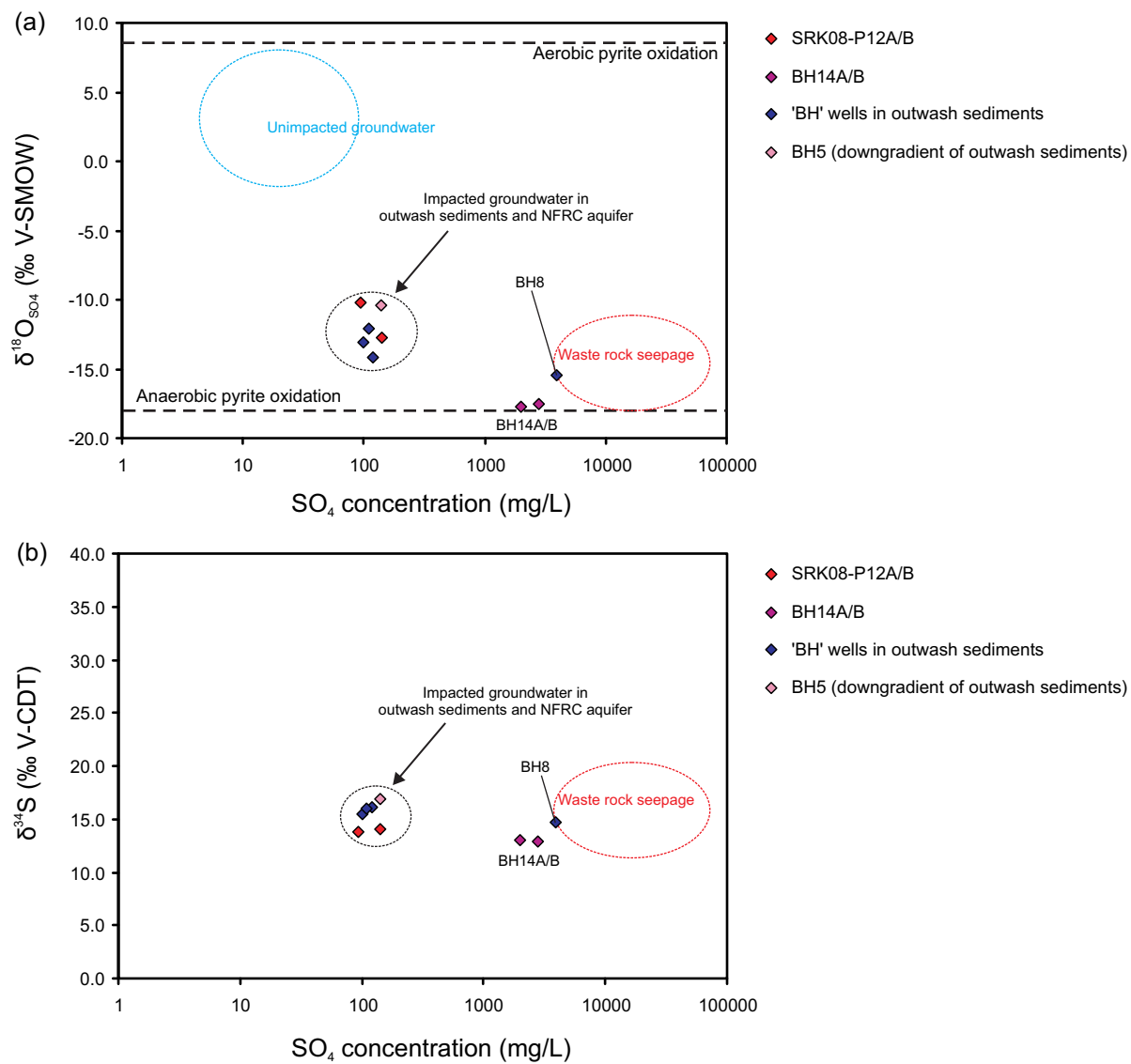


Figure 5-8. $\delta^{18}\text{O}$ and $\delta^{34}\text{S}$ values and their relationship to SO_4 concentration, Zone 2 Pit outwash area, ARMC.

APPENDIX A

Piper & scatter plots of groundwater quality data

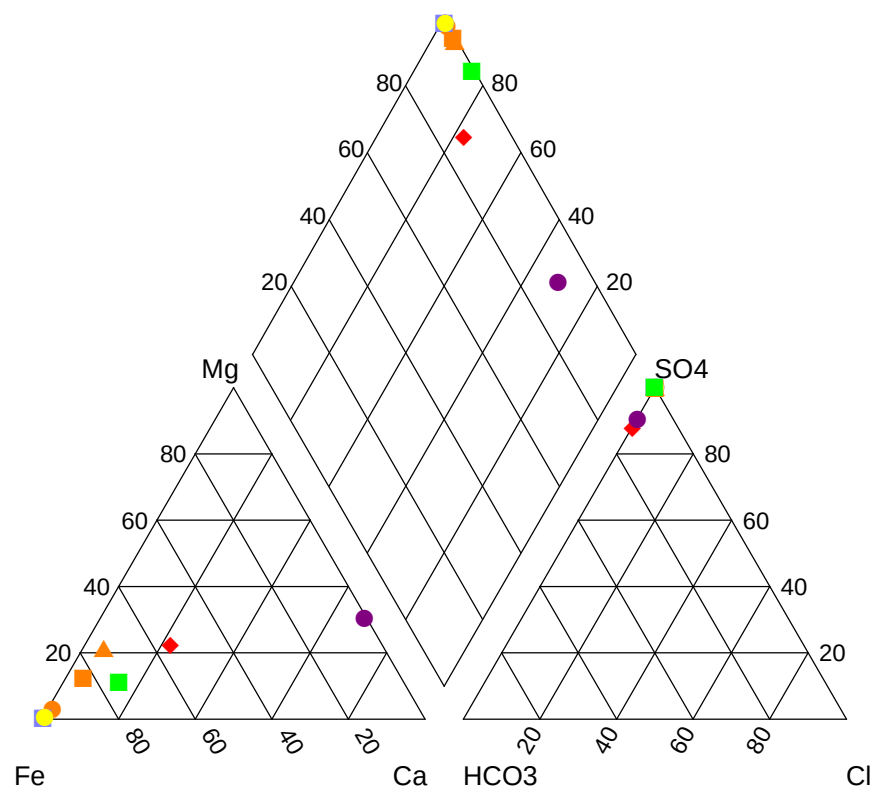
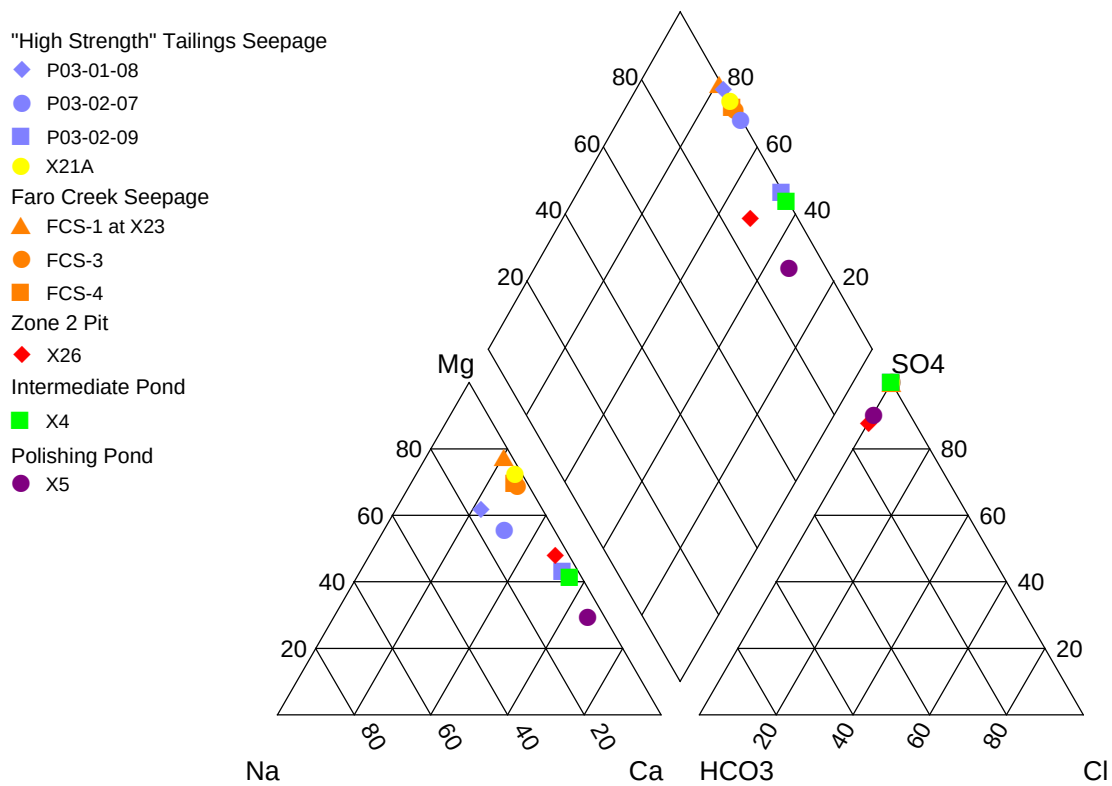


Figure A1a. Piper Plots for ARD Sources, Rose Creek valley, ARMC

"High Strength" Tailings Seepage

◆ P03-01-08

● P03-02-07

■ P03-02-09

● X21A

Faro Creek Seepage

▲ FCS-1 at X23

● FCS-3

■ FCS-4

Zone 2 Pit

◆ X26

Intermediate Pond

■ X4

Polishing Pond

● X5

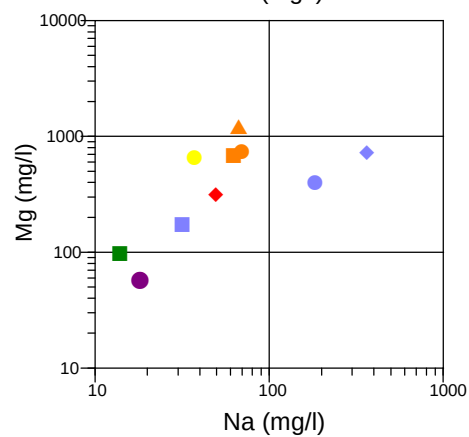
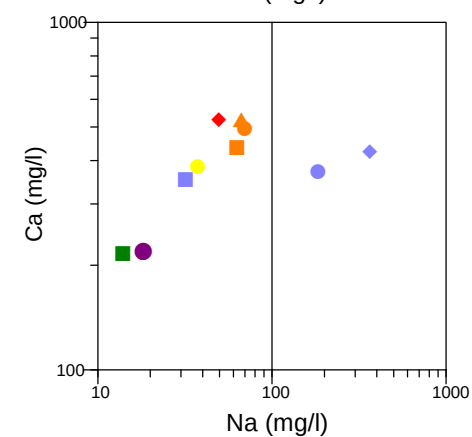
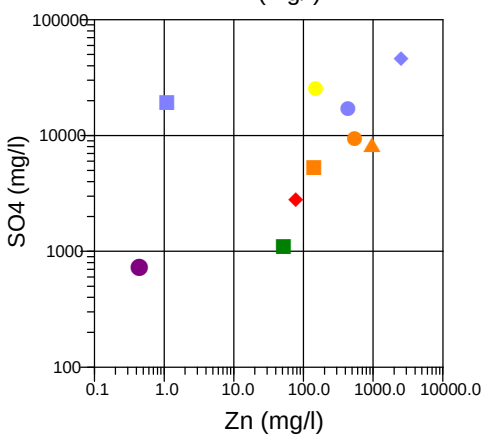
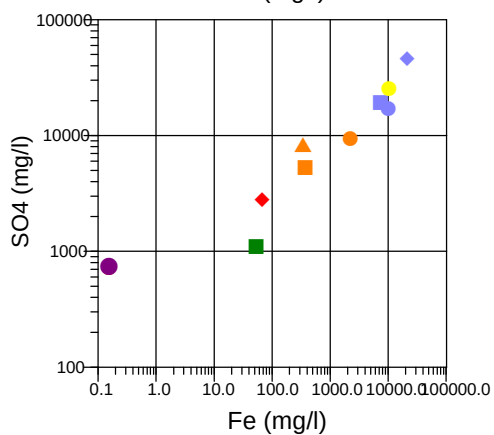
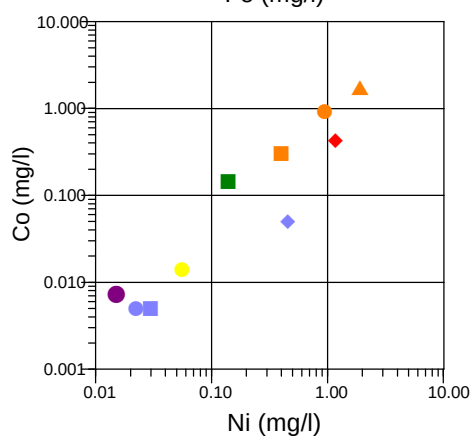
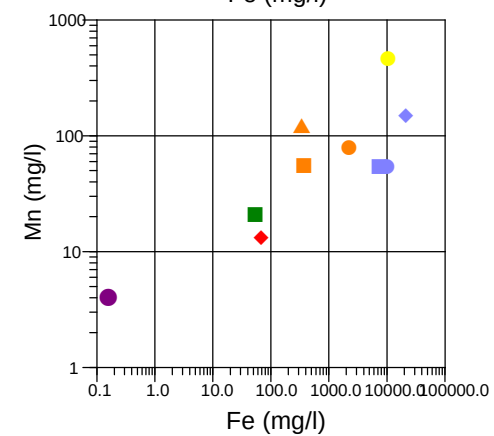
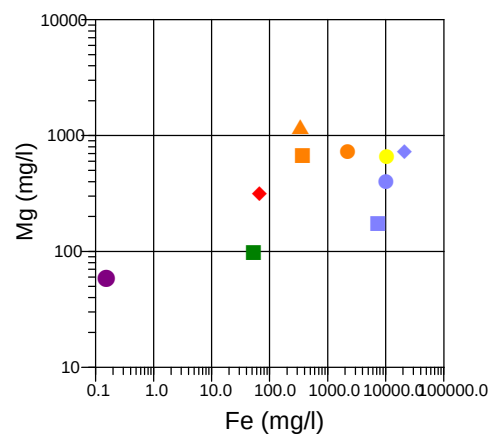
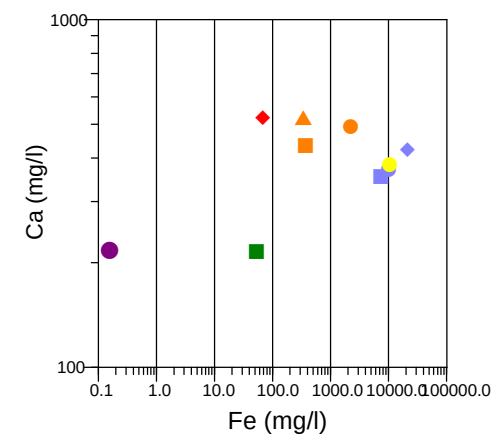


Figure A1b. Scatter plots for ARD Sources, Rose Creek valley, ARMC

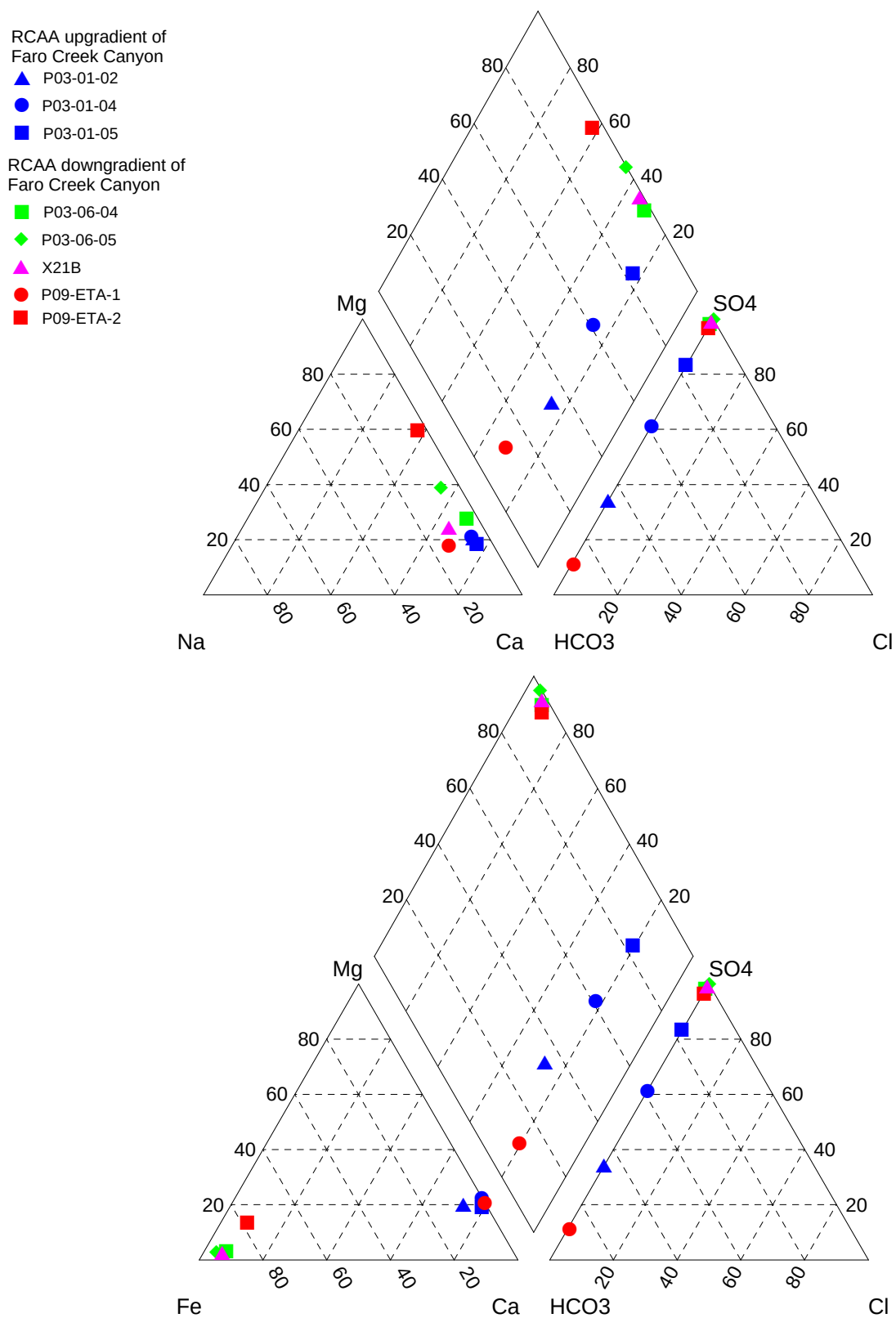


Figure A2a. Piper plots for groundwater in RCAA upgradient of Faro Creek Canyon in Second Impoundment and in the RCAA/bedrock near the mouth of Faro Creek Canyon

RCAA upgradient of
Faro Creek Canyon

▲ P03-01-02
● P03-01-04
■ P03-01-05

RCAA downgradient of
Faro Creek Canyon

■ P03-06-04
◆ P03-06-05
▲ X21B
● P09-ETA-1
■ P09-ETA-2

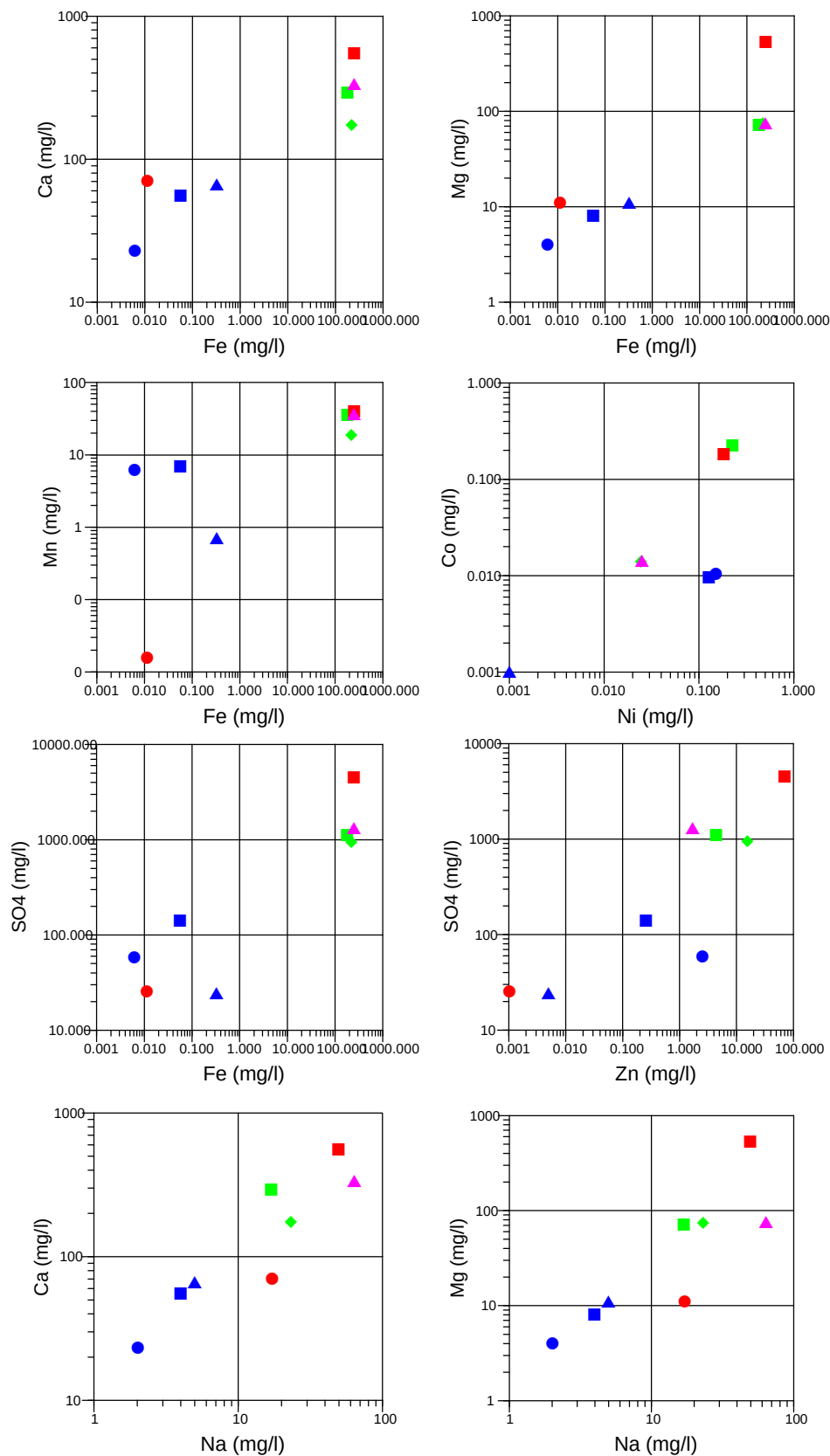


Figure A2b. Scatter plots for groundwater in RCAA upgradient of Faro Creek Canyon in Second Impoundment and in the RCAA/bedrock near the mouth of Faro Creek Canyon

Rose Creek alluvial aquifer near Intermediate Dam

▲ P01-03

● X24D

Rose Creek alluvial aquifer near Cross Valley Dam

◆ P05-01-02

■ P05-02

▼ P01-11

Deep bedrock below toe of Cross Valley Dam

▲ P09-C1

● P09-C2

◆ P09-C3

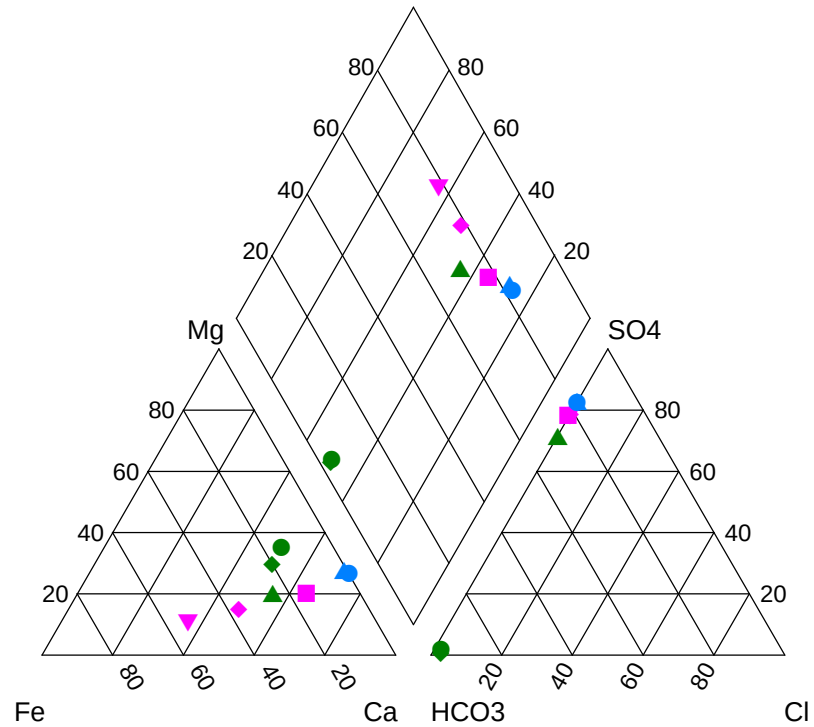
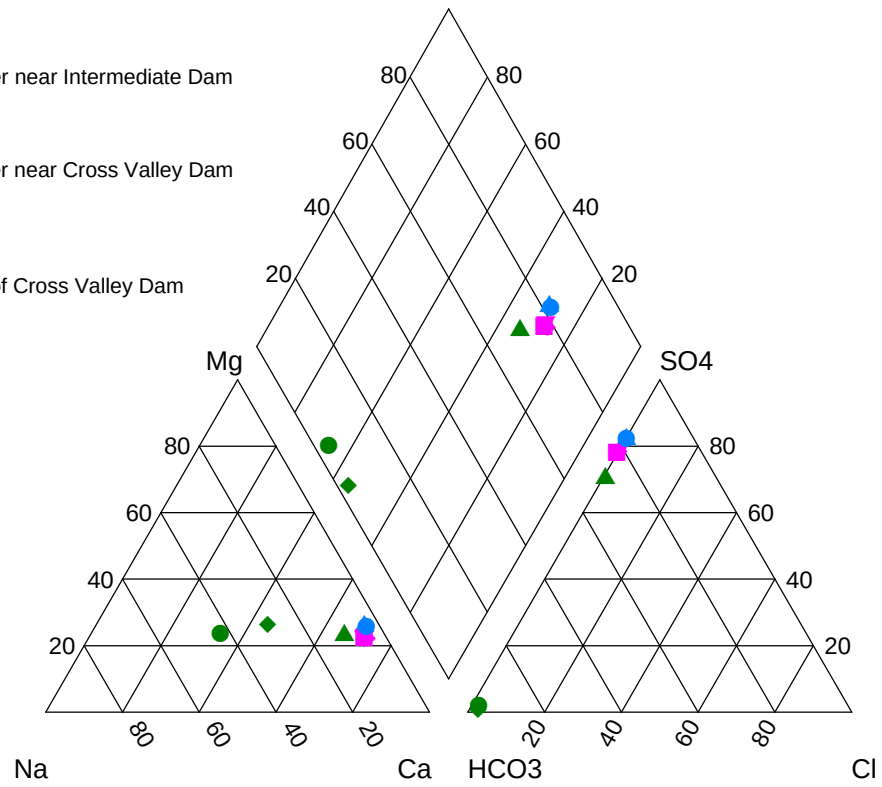


Figure A3a. Piper plots for groundwater in RCAA in the Intermediate Dam and Cross Valley Dam reaches and in deep bedrock below toe of Cross Valley Dam

Rose Creek alluvial aquifer
near Intermediate Dam

▲ P01-03

● X24D

Rose Creek alluvial aquifer
near Cross Valley Dam

◆ P05-01-02

■ P05-02

▼ P01-11

Deep bedrock below toe
of Cross Valley Dam

▲ P09-C1

● P09-C2

◆ P09-C3

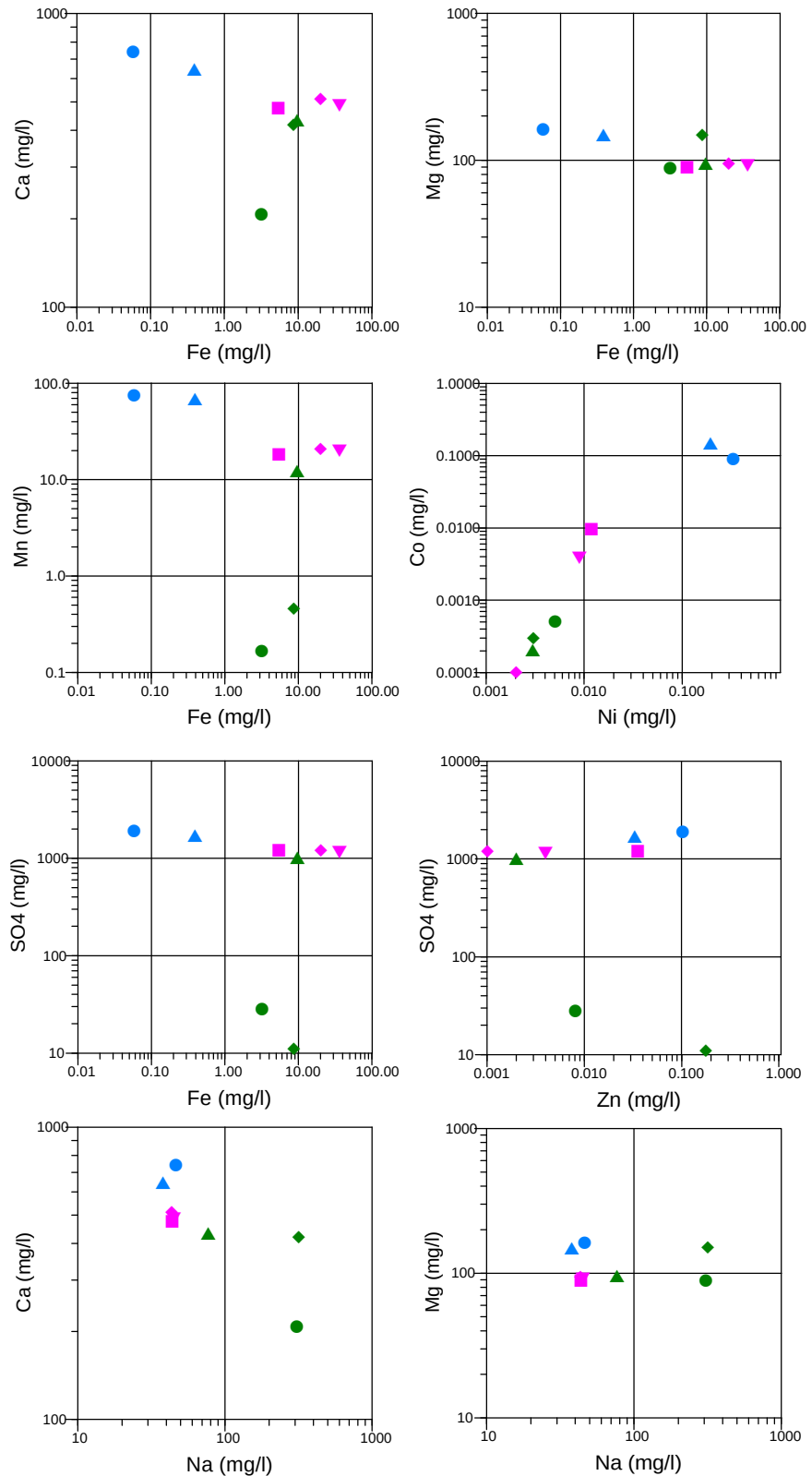


Figure A3b. Scatter plots for groundwater in RCAA in the Intermediate Dam and Cross Valley Dam reaches and in deep bedrock below the toe of the Cross Valley Dam

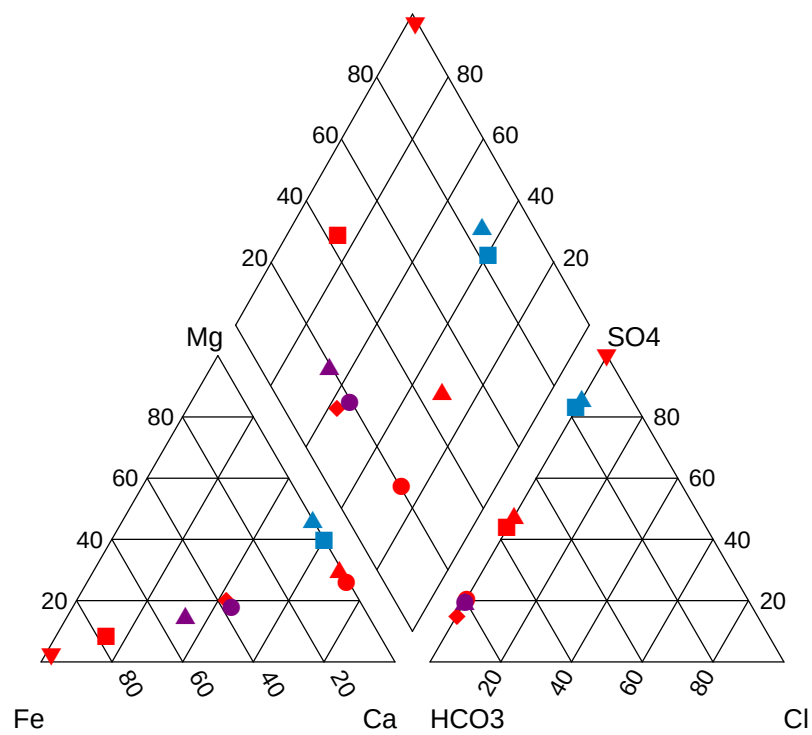
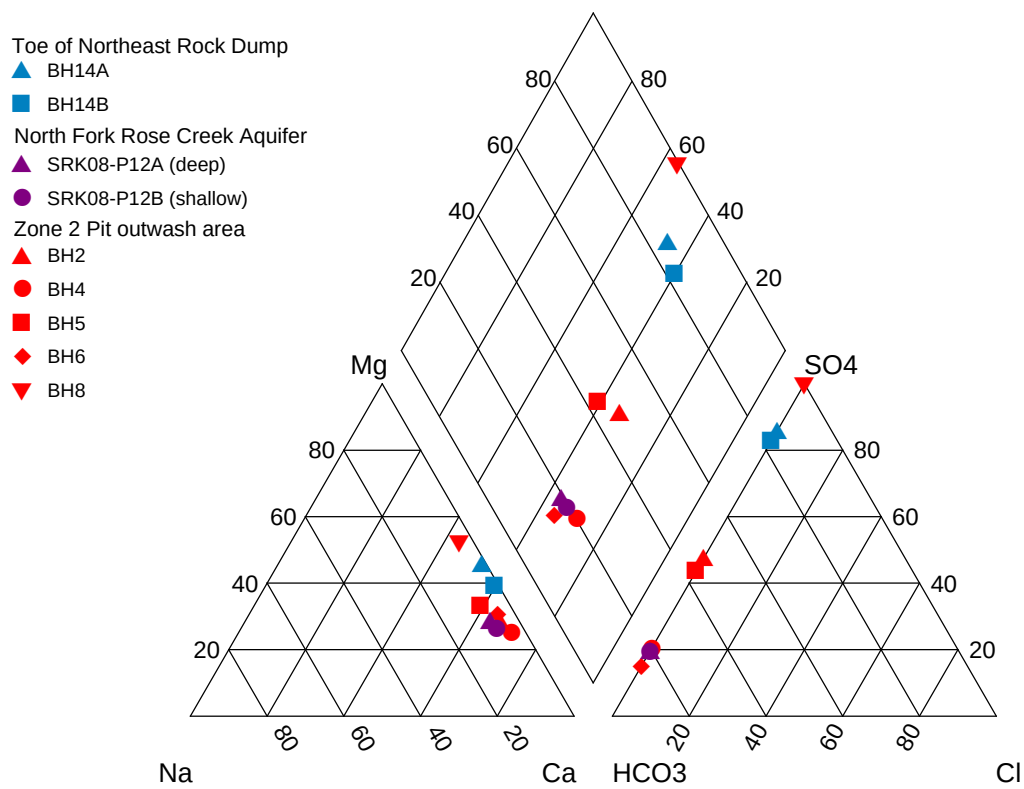


Figure A4a. Piper plots for groundwater in the Zone 2 Pit outwash area

Toe of Northeast Rock Dump
 ▲ BH14A
 ■ BH14B
 North Fork Rose Creek Aquifer
 ▲ SRK08-P12A (deep)
 ● SRK08-P12B (shallow)
 Zone 2 Pit outwash area
 ▲ BH2
 ● BH4
 ■ BH5
 ◆ BH6
 ▼ BH8

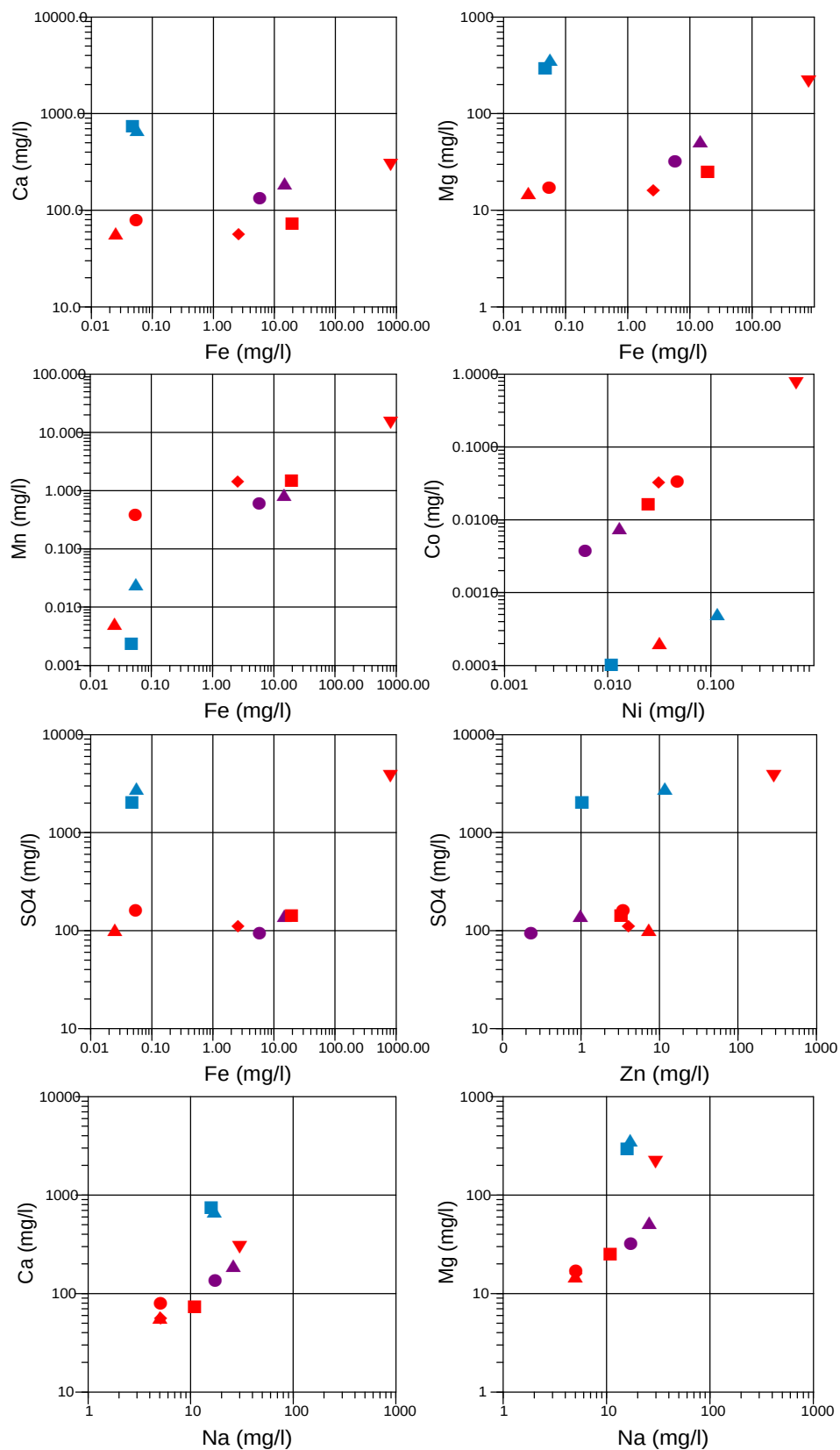


Figure A4b. Scatter plots for groundwater in the Zone 2 Pit outwash area

APPENDIX B

Summaries of Conservative Mixing Calculations

Table B1. Summary of conservative mixing calculations for wells P03-01-04 and P03-01-05

End-members				
	Unimpacted GW P03-01-02	A. Tailings porewater P03-02-07	B. Tailings porewater P03-02-09	C. Tailings porewater P03-01-08
Ca, mg/L	66	369	352	423
Mg, mg/L	11	398	173	718
Na, mg/L	5	182	32	361
SO ₄ , mg/L	24	17000	19000	46000
Zn, mg/L	0.005	429	1	2480
Co, mg/L	0.001	0.05	0.10	0.05
Ni, mg/L	0.001	0.022	0.03	0.45
Fe, mg/L	0.324	9810	7560	2060

Estimated contributions				
	Unimpacted GW	Tailings porewater	Tailings porewater	High-strength tailings porewater
	1	0.005	0	0
% contribution:	99.5%	0.5%	0.0%	0.0%

Comparison of predicted and observed concentrations in groundwater

	Predicted at P03-01	P03-01-04	P03-01-05
Ca, mg/L	68	23	55
Mg, mg/L	13	4	8
Na, mg/L	6	2	4
SO ₄ , mg/L	108	58	140
Zn, mg/L	2	2.5	0.262
Co, mg/L	0.001	0.010	0.010
Ni, mg/L	0.001	0.149	0.128
Fe, mg/L	49	0.006	0.057

Table B2. Conservative mixing calculations for well P09-ETA-02

End-members				
	Unimpacted groundwater	Weak tailings porewater	Strong tailings porewater	Faro Creek Seepage
	P09-ETA-01	P03-02-09	P03-01-08	FCS-3
Ca, mg/L	70	352	423	492
Mg, mg/L	11	173	718	728
Na, mg/L	17	32	361	69
SO4, mg/L	25	19000	46000	9400
Zn, mg/L	0.001	1.1	2480	536
Co, mg/L	0.00010	0.005	0.05	0.9
Ni, mg/L	0.00024	0.03	0.45	0.9
Fe, mg/L	0.011	7560	2060	2160

Estimated contributions				
	Unimpacted groundwater	Weak tailings porewater	Strong tailings porewater	FCS
	0.2	0.04	0.0009	0.06
% contribution:	66.5%	13.3%	0.3%	19.9%

Comparison of predicted and observed concentrations in groundwater

	Predicted at P09-ETA-02	Observed at P09-ETA-2
Ca, mg/L	193	551
Mg, mg/L	178	529
Na, mg/L	30	50
SO4, mg/L	4554	4500
Zn, mg/L	114	70.6
Co, mg/L	0.1803	0.181
Ni, mg/L	0.1850	0.184
Fe, mg/L	1442	254

Table B3. Conservative mixing calculations for wells P03-06-04 and P03-06-05

End-members				
	Upgradient Aquifer	Weak tailings porewater	Strong tailings porewater	P09-ETA-2
	P03-01-01	P01-08A	P03-01-08	
Ca, mg/L	76.1	6.03	423	551
Mg, mg/L	13.9	1.67	718	529
Na, mg/L	8	122	361	50
SO4, mg/L	24.9	165	46000	4500
Zn, mg/L	< 0.005	0.929	2480	70.6
Co, mg/L	< 0.0003	0.0012	0.05	0.181
Ni, mg/L	< 0.001	< 0.01	0.45	0.184
Fe, mg/L	4.03	6.03	2060	254

Estimated contributions				
	Upgradient Aquifer	Weak tailings porewater	Strong tailings porewater	P09-ETA-02
	1.1			0.30
% contribution:	78.6%	0.0%	0.0%	21.4%

Comparison of predicted and observed concentrations in groundwater

	Predicted at P03-06	Observed At P03-06-04	Observed At P03-06-05
Ca, mg/L	178	292	173
Mg, mg/L	124	71	74
Na, mg/L	17	17	23
SO4, mg/L	984	1100	940
Zn, mg/L	15	4.5	15.3
Co, mg/L	0.0390	0.222	0.0138
Ni, mg/L	0.0402	0.228	0.024
Fe, mg/L	58	184	214

Table B4. Conservative mixing calculations for well P03-06-04 (with FCS-3)

End-members				
	Unimpacted groundwater	Weak' tailings porewater	Faro Creek Seepage	Highly impacted groundwater
	P09-ETA-01	P03-02-09	FCS-3	P09-ETA-02
Ca, mg/L	70	352	492	551
Mg, mg/L	11	173	728	529
Na, mg/L	17	32	69	50
SO4, mg/L	25	19000	9400	4500
Zn, mg/L	0.001	1.1	536	70.6
Co, mg/L	0.00010	0.005	0.9	0.181
Ni, mg/L	0.00024	0.03	0.9	0.184
Fe, mg/L	0.011	7560	2160	254

Estimated contributions				
	Unimpacted groundwater	Tailings porewater	FCS	Highly-impacted groundwater
	1		0.08	0.12
% contribution:	83.3%	0.0%	6.7%	10.0%

Comparison of predicted and observed concentrations in groundwater

	Predicted at P03-06-04	Observed at P03-06-04
Ca, mg/L	146	292
Mg, mg/L	111	71
Na, mg/L	24	17
SO4, mg/L	1098	1100
Zn, mg/L	43	4.46
Co, mg/L	0.0782	0.222
Ni, mg/L	0.0786	0.228
Fe, mg/L	169	184

Table B5. Conservative mixing calculations for wells SRK08-P12A/B (NE Rock Dump as source)

End-members				
	Unimpacted groundwater	Zone 2 Pit water	Seepage from NE Rock Dump	Seepage from NE Rock Dump
	P09-UN-2	X26	BH14A	BH14B
Ca, mg/L	25	523	683	732
Mg, mg/L	15	313	358	292
Na, mg/L	17	47	17	16
SO4, mg/L	16	2800	2800	2000
Zn, mg/L	0.031	75.9	11.8	1.05
Co, mg/L	0.00010	0.426	0.0005	0.0001
Ni, mg/L	0.00010	1.16	0.116	0.011
Fe, mg/L	0.1	65.3	0.056	0.048

Estimated contributions				
	Unimpacted groundwater	Zone 2 Pit water	NE Rock Dump	NE Rock Dump
	1		0.029	
% contribution:	97.2%	0.0%	2.8%	0.0%

Comparison of predicted and observed concentrations in groundwater

	Predicted at SRK08-P12A/B	Observed at SRK08-P12A	Observed at SRK08-P12B
Ca, mg/L	44	191	134
Mg, mg/L	25	52	32
Na, mg/L	17	26	17
SO4, mg/L	94	140	94
Zn, mg/L	0.363	0.989	0.227
Co, mg/L	0.0001	0.0077	0.0037
Ni, mg/L	0.0034	0.013	0.006
Fe, mg/L	0.10	14.8	5.6

Table B6. Conservative mixing calculations for 'BH' wells, Zone 2 Pit outwash area (Zone 2 Pit as source)

Source-term concentrations				
	Upgradient GW	Zone 2 Pit seepage	Zone 2 Pit water	Highly-impacted groundwater
	SRK08-P12B	X26/BH8	X26	BH8
Ca, mg/L	134	350	523	308
Mg, mg/L	32	250	313	224
Na, mg/L	17	50	47	30
SO4, mg/L	94	3000	2800	3900
Zn, mg/L	0.227	200	75.9	287
Co, mg/L	0.0037	0.4	0.426	0.781
Ni, mg/L	0.006	1.2	1.16	0.675
Fe, mg/L	5.6	60	65.3	0.056

Estimated contributions				
	SRK08-P12B	X26/BH8		
	1	0.016		
% contribution:	98.4%	1.6%		

Comparison of predicted and observed concentrations in groundwater

	Predicted at 'BH' wells	Observed at BH5	Observed at BH6
Ca, mg/L	137	73	55
Mg, mg/L	35	25	15
Na, mg/L	18	11	5
SO4, mg/L	140	140	110
Zn, mg/L	3.373	3.28	3.69
Co, mg/L	0.0099	0.016	0.0325
Ni, mg/L	0.0248	0.025	0.03
Fe, mg/L	6	19.6	5.01