Permeable Reactive Barrier Feasibility Assessment at Goldcorp's Red Lake Gold Mines: Delineation of Groundwater Flow Paths and Contaminant Behaviour

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Abstract

At the Campbell Complex (Ontario, Canada), Goldcorp is assessing the feasibility of using permeable reactive barriers (PRBs) to intercept and treat tailings-related seepage, with As, Co and Fe representing the primary parameters of concern. Based on the distribution of hydraulic conductivity and geochemical species, most of the seepage is inferred to flow through a discontinuously confined sand and gravel aquifer. Arsenic shows a strong degree of attenuation in groundwater. In contrast, Co exhibits strongly conservative behaviour that can be linked to the presence of non-labile complexes. Dissolved Fe shows variable behaviour that is likely linked to variations in redox conditions. Implications for PRB design are discussed.

Keywords: Groundwater remediation, arsenic, cobalt, iron

Introduction

The Campbell Complex (Goldcorp's Red Lake Gold Mines) is located in Balmertown, 7 km northeast of the Town of Red Lake in northwestern Ontario, and has been the site of gold-ore mining and milling operations since 1949. Tailings have been discharged to the current tailings management area (TMA) since 1983. Mineral processing wastes within the TMA consist of: 1) flotation tailings (1983-present); 2) calcine tailings produced through roasting of sulfide concentrates (pre-1991); and 3) autoclave wastes generated through pressure oxidation and neutralization of sulfide concentrates (1991-present).

A portion of the water that accumulates in the TMA infiltrates into the subsurface and travels along groundwater flow paths that discharge to ditches draining a golf course, which in turn feed a downstream wetland and lake (pathway designated as "Red Lake Flow Path") (Figure 1). Seepage flows show tailings-related signatures related to mill process waters (SO_4, Cl, NH_3, CN, Cd, Co, Cu, Ni and Zn) and remobilization from tailings solids (Fe and As). As, Co and Fe represent the primary parameters of concern in groundwater given the magnitude of concentrations in relation to site-specific groundwater targets. Seepage waters are characterized by circum-neutral to slightly basic pH ($7<pH<8.5$).

To reduce the degradation of the aquifer and minimize the potential for adverse effects to aquatic receptors in the downstream wetland and lake, Goldcorp is assessing the feasibility of using PRBs (Blowes et al., 2000) to intercept and treat TMA-derived seepage. This paper, which describes TMA plume distribution and contaminant behaviour, represents the first of a series of three papers relating to PRB feasibility at the Campbell Complex. The other two papers, also presented as part of these proceedings, describe the results of tracer testwork designed to confirm contaminant pathways (Helsen et al., 2018) as well as hydrogeological, geochemical and geotechnical considerations driving PRB design (Crozier et al., 2018).

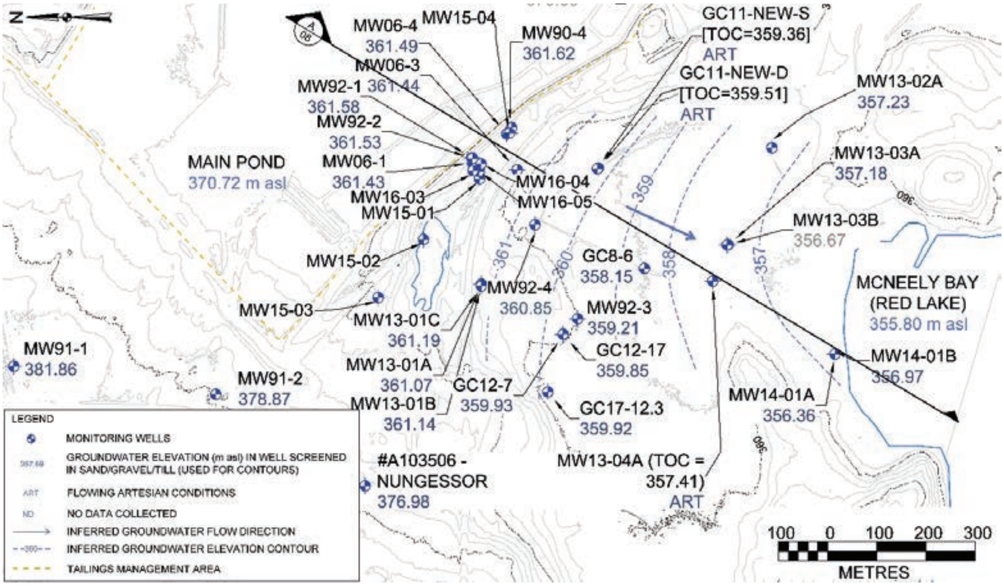

Figure 1 *Inferred groundwater elevation contours along Red Lake Flow Path. Locations of monitoring wells, plume flow direction, and Cross Section A indicated (May 2017 water levels shown).*

Results and Discussion

Physical Hydrogeology

The physical hydrogeologic conditions along the Red Lake Flow Path have been evaluated in detail since 1990 through the installation, hydraulic conductivity (K) testing and monitoring of multiple monitoring wells. The current program includes the collection of water levels and water samples from wells that span multiple locations and depths along the Red Lake Flow Path (Figure 1).

The hydrostratigraphy of the Red Lake Flow Path can be broadly described as a leaky sand and gravel aquifer, overlain by a discontinuous confining clay and clayey-silt, underlain by a discontinuous sandy to gravelly till, and confined at depth by bedrock (Figure 2). Hydraulic conductivities (K) and thicknesses of the various units are presented in Table 1. K values were determined through slug testing. Recharge enters the groundwater system from two main source areas: 1) the TMA Main Pond, either through the peat and silt layers or through stratigraphic windows in these layers inferred by others (e.g., Ross 1998); and 2) from infiltration of precipitation, snowmelt, and runoff downgradient of the Main Pond. Based on the distribution of measured hydraulic conductivities and geochemical species, most of the TMA seepage is inferred to flow through the sand and gravel, and, to a lesser extent, the till.

Water elevations of the Main Pond (≈370 m asl) and McNeely Bay (Red Lake) (≈356 m asl) act as gradient controls on the Red Lake flow path. The horizontal hydraulic gradient within the sand and gravel aquifer ranges between 0.001 and 0.01 (average of 0.007), with groundwater flow directed southwest, from the TMA towards Red lake. Groundwater levels in monitoring wells completed along the Red Lake Flow Path fluctuate seasonally by approximately 0.1 m to 2.5 m.

Chemical Hydrogeology

The distribution of the TMA-related plume was evaluated through the generation of 2-D contour maps (Figure 3). These were generated by hand using data collected between August and December, 2016. At locations where nested wells were installed in two or more stratigraphic units (e.g., sand+gravel, clay+silt, etc.), the highest concentration at a given site was selected for contouring. Tracers of TMA seepage (Cl and SO_4) show maximum concentrations in deeper portions of the sand and gravel aquifer and till zones. Elevated concentrations of Cl and SO_4 are evident at

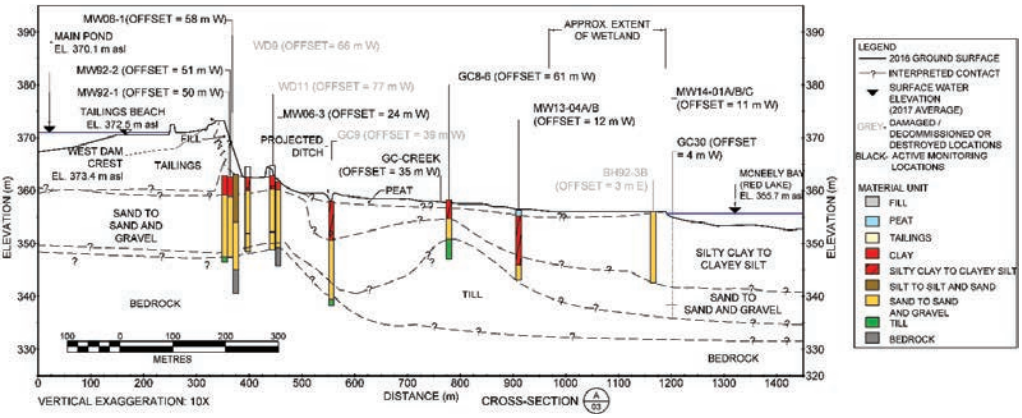

Figure 2 *Stratigraphic Cross Section A along Red Lake Flow Path (as shown in Figure 1)*

Table 1. *Stratigraphy and hydraulic parameters of the groundwater system along Red Lake Flow Path.*

Stratigraphic Unit	Location and Description	Thicknes (m)	Hydraulic Conductivity (K) (m/s)
Peat	Peat interpreted to be present in undisturbed areas along the Red Lake Flow Path	0 to 1	$1x10^{-5}$
[Glacio-Lacustrine] Clay and Silt	Mainly low- to high-plastic clay with some low/non-plastic silt intervals, particularly encountered at the base of the deposit, and less frequently at the top of the deposit.	3 to 5	$1x10^{-8}$ to $5x10^{7}$
[Glacial Outwash] Sand and gravel	Overall fining-upwards sequence, grading from a well-graded sand and/or gravel at depth to a silty and poorly sorted sand, in some places interbedded with silt, in the upper portion of the deposit.	8 to 11	$1x10^{-7}$ to $3x10^{3}$
[Glacial] Till	Mainly sands of varying coarseness, gravel, cobbles and occasional boulders, within a matrix of fine silts and sands.	2 to 3	$1x10^{-8}$ to $1x10^{-4}$
Bedrock	Moderately weathered to fresh mafic volcanic. Undulating, and present at depths between 16 and 19 m below ground surface	Not Applicable	$5x10^{-9}$ to $2x10^{7}$

the most downstream monitoring wells, illustrating that the influence of the TMA seepage plume extends to Red Lake (Figure 3). At the most downstream well (MW14-01A), the 2017 concentration of chloride (181 mg/L) is 35% of the concentration observed in the Main Pond of the TMA (2017 median = 518 mg/L), reflecting some dilution of the Main Pond signature. Using chloride as an indicator of plume distribution, the cross-sectional area of the plume along the West Dam alignment extends for over 200 m in width, and a depth defined by the thickness of the sand-gravel aquifer (9-15 m).

Based on comparison to site-specific groundwater targets, As, Co and Fe represent the primary parameters of concern for groundwater management along the Red Lake Flow Path. Secondary parameters of concern include SO_4, Cd, Cu, Ni, Zn and NH_3, given the elevated concentrations of these parameters in the Main Pond. All the primary and secondary parameters of concern listed (except for NH_3) are amenable to PRB treatment using a common design (USEPA 2005).

The main source of tailings-derived Fe originates from the reductive dissolution of Fe(III)-oxide tailings materials in suboxic

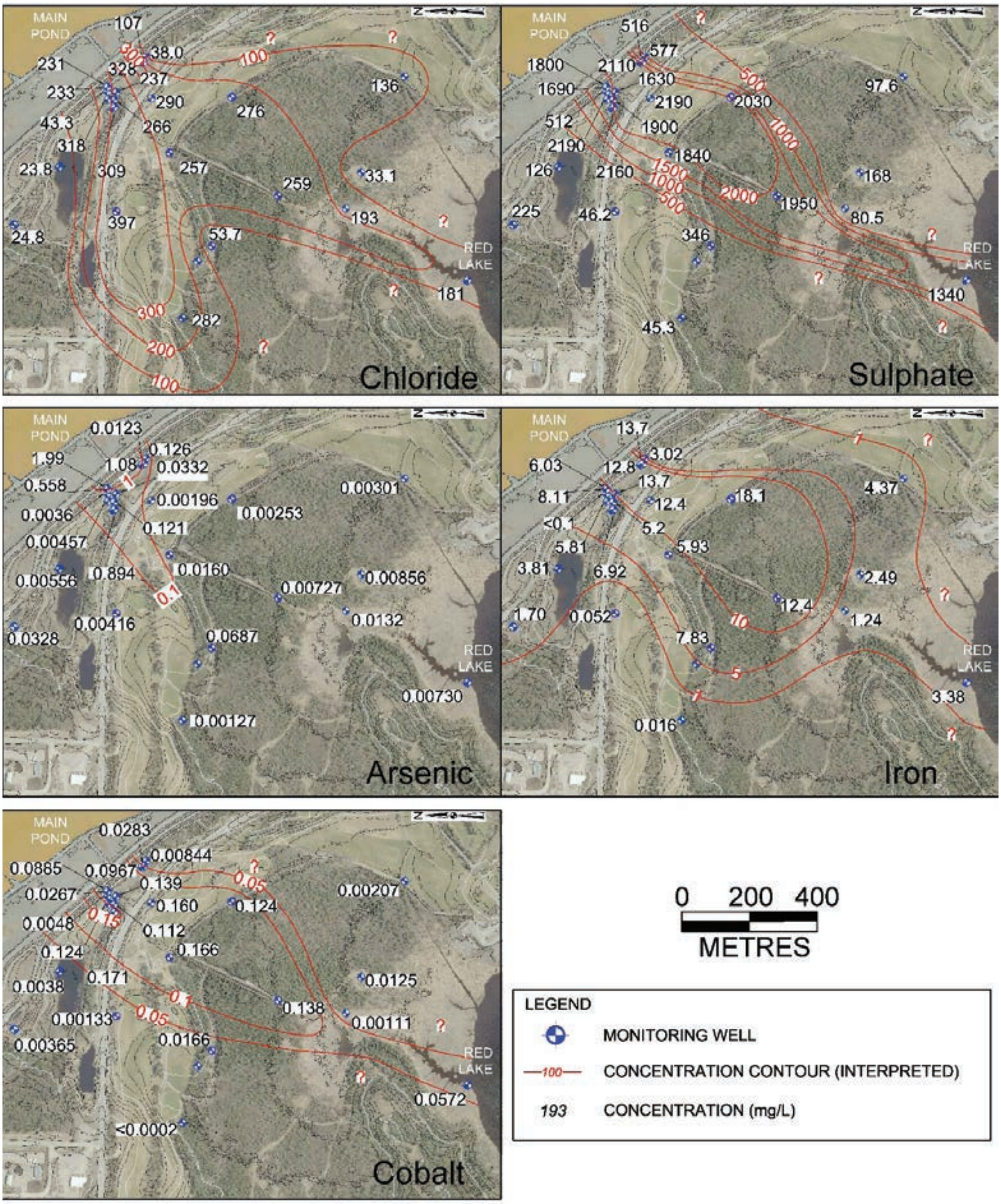

Figure 3 *Inferred concentration contours of dissolved chloride, sulphate, arsenic, iron and cobalt along the Red Lake Flow Path (November-December, 2016 data). Monitoring well labels shown in Figure 1.*

horizons associated with both autoclave and roaster tailings. Within the sand aquifer along the West Dam, dissolved Fe concentrations of 3 to 15 mg/L are evident (Figure 3). At intermediate zones along the flow path, a slight increase in dissolved Fe is evident in some wells (Figure 3). This is inferred to reflect variations in local redox conditions, which in turn may be related to the presence of organic-rich pond zones associated with beaver activity.

The reductive dissolution of As-bearing Fe oxides is the principle source of As within tailings materials, as described by McCreadie et al. (1996) and Martin et al. (2002). Along the West Dam in wells screened in the sand and gravel aquifer (e.g., MW92-1), there is clear evidence of As enrichment (1 to 2 mg/L) (Figure 3). In contrast, further downgradient at MW06-3 (≈150 m downgradient of the West Dam), dissolved As concentrations are low and within background ranges (0.005 to 0.015 mg/L). Overall, the low As values at the intermediate and downstream portions of the plume indicate that As is strongly attenuated along the groundwater flow path within close proximity to the West Dam. Attenuation mechanisms may include: 1) precipitation as secondary sulfides in zones of SO_4 reduction in upgradient portions of the plume that migrate through peat; 2) adsorption to clay minerals; 3) sorption of As with Fe oxides in aerobic zones. Of these, the precipitation of secondary As-sulfides is supported by the occurrence of As removal from solution in zones of sulfate reduction (the latter inferred by measurements of dissolved H_2S and δ34S) (McCreadie et al. 1996).

In contrast to Fe and As, the bulk of the Co in TMA seepage originates from mill process waters that are discharged to the Main Pond (Figure 1). Within the conductive sand and gravel aquifer in proximity to the West Dam (e.g., MW92-1), concentrations range from 0.10 to 0.20 mg/L (Figure 3). Downgradient of the West Dam, dissolved Co concentrations show a progressive decline to values of approximately 0.06 mg/L at MW14-01A (at Red Lake). However, the persistence of elevated Co concentrations along the Red Lake Flow Path all the way to Red Lake indicate that Co is behaving in a more conservative manner than As.

Cobalt Speciation

To further the understanding of Co behaviour along the Red Lake Flow Path, and to provide information in support of closure planning, Co speciation analysis was conducted on groundwater samples collected between the TMA and Red Lake. Speciation analysis was conducted using diffusive gradients in thin films (DGT) (methods described in Davison and Zhang, 1994). DGT is a diffusion-based method that measures free Co ions (Co^{2+}) and kinetically-labile Co complexes which exhibit dissociation kinetics within the timeframe of their transport through a diffusive gel layer (on the order of minutes), thus providing a proxy for the labile metal fraction (Martin and Goldblatt, 2007). The method excludes particles, colloids and strongly-bound complexes.

The results for groundwater samples collected along the Red Lake Flow Path show that the vast proportion (≈90%) of Co in the groundwater system is present as non-labile Co complexes (Figure 4). These speciation results can explain the conservative nature of Co behaviour within the groundwater/surface water system, as well as poor removal of Co observed in PRB lab column experiments (data not shown).

The specific nature of the Co complexes present along the Red Lake Flow Path cannot be ascertained with the available data. Possible species may include Co-cyanide complexes and/or Co-organic complexes (associated with the addition of carbon-based flotation reagents used in ore processing). The strong positive correlation of dissolved Co with T-CN (r^2=0.95) may indicate the importance of Co-CN complexes (Figure 4).

Conclusions

Overall, robust delineation of seepage flow paths and contaminant behaviour is critical to the design of groundwater remediation measures. In this regard, multiple studies were required to define the hydrostratigraphy, unit thicknesses, spatial variability in K, hydraulic gradients, groundwater velocities, contaminants of concern and contaminant behaviour. This field-based information, combined with lab-scale testwork, formed the basis for PRB design with regards to location, dimensions, hydraulic retention time, and reactive matrix (as presented in Crozier et al., 2018).

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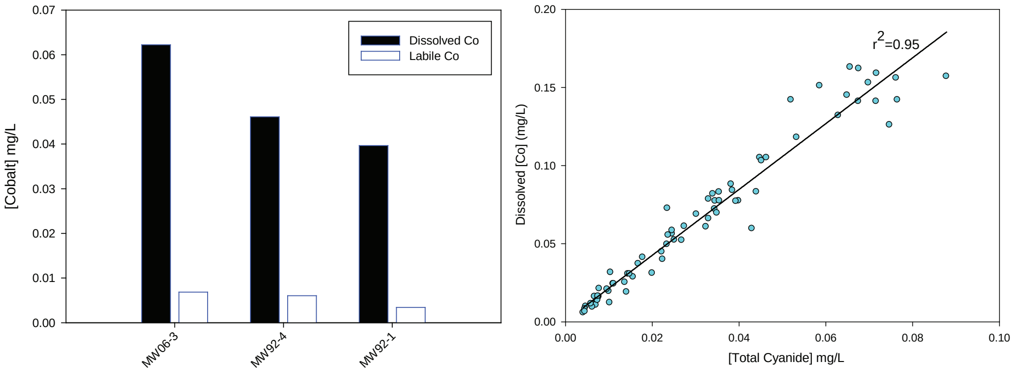

Figure 4 *(Left) Concentrations of dissolved Co and labile Co (as determined by diffusive gradients in thin films) for samples at various monitoring wells along the Red Lake Flow Path (2017 data). (Right) Regression plot showing dissolved Co versus total cyanide (2017 data for groundwater wells and surface waters along Red Lake Flow Path).*

References

Blowes DW, Ptacek C, Benner SG, McRae CWT., Bennett TA, Puls RW (2000) Treatment of inorganic contaminants using permeable reactive barriers. J Contam Hydrol 45: 123-137.

Crozier TW, Paszkowski D, Parent G, Cook D, Mann V, Mendoza C, Provost H, Martin AJ, Helsen J, Bain J, Blowes DW, Gaspar C, Russell J (2018) Permeable Reactive Barrier Feasibility Assessment at Goldcorp's Red Lake Gold Mines: Hydrogeological, Geochemical and Geotechnical Design Considerations, 11th International Conference on Acid Rock Drainage, Pretoria, South Africa, September 10-14, 2018.

Davison W, Zhang H (1994). In situ speciation measurements of trace components in natural waters using thin-film gels. Nature 367:545-548.

Helsen J, Martin AJ, Crozier T, Parent G, Mann V, Gaspar C., Russell J (2018) Permeable Reactive Barrier Feasibility Assessment at Goldcorp's Red Lake Gold Mines: Validation of Seepage Flow Paths through Tracer Testwork., 11th International Conference on Acid Rock Drainage, Pretoria, South Africa, September 10-14, 2018.

Martin, AJ, Pedersen TF (2002) Seasonal and interannual mobility of arsenic in a lake impacted by metal-mining. Env Sci Tech 36:1516-1523.

Martin AJ, Goldblatt R. (2007). Speciation, behaviour and bioavailability of copper downstream of a mine-impacted lake. Environ Toxicol Chem 26: 2594-2603.

McCreadie H, Blowes DW, Ptacek C, Jambor JL (2000) Influence of reduction reactions and solid-phase composition on porewater concentrations of arsenic. Env Sci Tech 34:3159-3166.

Ross C (1998) A Hydrogeological and Geochemical Study of a Gold Mine Tailings-Derived Plume, Campbell Mine, Balmertown Ontario. M.Sc. Thesis, University of Waterloo.

USEPA (2005). Permeable Reactive Barriers for Inorganic and Radionuclide Contamination. Prepared by K. Bronstein for the U.S. Environmental Protection Agency, August, 2005.